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Torrefaction of Conservation Reserve Program biomass: A techno-economic evaluation

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ABSTRACT

The Conservation Reserve Program (CRP), which was initiated to prevent soil erosion, provides a large amount of cellulosic biomass that is potentially useful for bioenergy production. We investigated the effects of torrefaction conditions on the physicochemical properties of CRP biomass using an elemental analyzer, a thermogravimetric analyzer, and a calorimeter. Results suggest that the upgraded biomass is a hydrophobic, high-energy density, and low-moisture-content material. The study on biomass polymer composition showed how polymer components changed with processing conditions. The polysaccharides in biomass were degraded significantly at 300 °C, suggesting that processing conditions should be managed properly for sugar or energy recovery. Our economic analysis suggested that the processing cost for a torrefaction plant with an annual capacity of 100,000 tons of CRP biomass is $16.3 per ton of feedstock. Further analysis of the effects of torrefaction on the biomass supply chain suggested that processing could save pelletization and transportation costs.

1. Introduction

Cellulosic biomass from agricultural residues has become an important energy source because its use for biofuels production does not compete with food production; however, overuse of this biomass could cause a decrease in soil quality, and agricultural crop production could then be affected if the residue is not left for soil amendment (Lal, 2009). The Conservation Reserve Program (CRP) began in 1985 as an effort to prevent soil erosion and enhance groundwater recharge from highly erodible lands. About 30 million acres of CRP land prevent 0.3 million tons of nitrogen and 50,000 tons of phosphorous annually from flowing into river or lakes (USDA, 2012). About 50 million tons of dry biomass could be harvested annually from CRP land, indicating great potential for bioenergy production (Perlack et al., 2005). A recent study suggested that CRP biomass is a potential bioenergy feedstock if appropriate management practices are applied (Lee et al., 2013). Compared with conversion of CRP land for starch-based agricultural production such as corn and soybean, direct use of the CRP land for cellulosic biomass production would avoid carbon debt according to a recent analysis (Gelfand et al., 2011). Therefore, CRP biomass, the mixed grass from the CRP land, becomes a competitive feedstock because it does not compete with food production and could minimize soil erosion. Assuming that 20% of the total amount of CRP biomass is harvested for bioenergy production and all other biomass is left for land conservation, more than 2 million tons of cellulosic ethanol (as a representative biofuel) could be produced annually, which is equal to 5% of the 2022 cellulosic biofuels objective (16 billion gallons) made by the Energy Independence and Security Act of 2007 (EISA, P.L. 110-140) (Schnepf, 2011).

Although recent biomass-processing techniques have proven effective in biomass conversion, the production cost of developing cellulosic biofuel remains high. Biomass upgrading through torrefaction shows great potential to benefit both the supply chain and downstream processing units (Batidzirai et al., 2013; Chin et al., 2013; Ciolkosz and Wallace, 2011). The torrefaction of biomass is basically a thermal process conducted in the temperature range of 200–300 °C under anaerobic conditions atmospheric conditions (Van der Stelt et al., 2011). Biomass moisture content (MC) is reduced in the initial drying process and biomass is partially degraded. Studies have shown that torrefaction enhanced the properties of different biomass materials (Couhert et al., 2009; Ren et al., 2012). Torrefaction is being applied to bioenergy production in thermal–chemical and biochemical platforms, and the enhanced properties after torrefaction were reported to improve the efficiency of biomass gasification and conserve chemical energy (Prins et al., 2006). Energy consumption was reported to be lower for torrefied biomass than for untorrefied biomass in the production of cellulosic ethanol (Chiaramonti et al., 2011). Torrefaction also improves biomass properties by increasing hydrophobicity.

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Most agricultural wastes, including grass biomass, show significant hydrophilicity, which results in problems during biomass storage, transportation, and processing; for example, biomass easily absorbs moisture, which results in decreased energy density. More importantly, hydrophilic biomass needs much more water to reduce viscosity of the slurry, resulting in increased energy consumption in the subsequent separation process. In addition, moisture absorption during storage causes fungi formation that could decrease the quality of feedstock (Rentizelas et al., 2009), whereas torrefaction provided microbial-resistant biomass, which reduces storage cost (Medic et al., 2012). Thus, torrefaction offers great potential for the biomass processing chain.

In this paper, we report the first study of CRP biomass enhancement through torrefaction. Changes in CRP biomass were investigated through different techniques. To integrate the torrefaction unit into the biomass processing system, an economic evaluation is critical for commercial application. We conducted our technical analysis including the results of mass and energy balances. Following the analysis of torrefaction unit, we analyzed how torrefaction affected related biomass processing units such as transportation, grinding, and pelletization.

2. Experimental

2.1. Materials

The CRP biomass was harvested in 2012 from Valley Falls, Kansas, and field-dried to reduce the MC to about 20%. The biomass was then stored in plastic bag at 4 °C. All chemicals used in this study were from Sigma–Aldrich, Inc. (St. Louis, MO).

2.2. Torrefaction

The torrefaction experiments were conducted using a Parr 4570 pressure reactor with a Parr 4848 temperature controller (Parr Instrument Co., Moline, IL). CRP biomass was cut to about 10 cm in length before loading. After biomass loading, the reactor was filled with a nitrogen flux to completely remove oxygen. Experiments tested different combinations of temperature (200, 250, and 300 °C) and time (15, 30, and 45 min). Volatile chemicals were collected with a cold trap before exhausting to the atmosphere. After treatment, the reactor was immediately cooled with water. Samples were weighed and collected for further analysis.

2.3. Compositional analysis

The structural polymer (cellulose, hemicellulose, and lignin) and MC of the CRP biomass were analyzed following procedures from the National Renewable Energy Laboratory (NREL) (Sluiter et al., 2004). The elemental composition was measured with CHNS/O Elemental Analyzer (PerkinElmer 2400 Series II, PerkinElmer Inc., Waltham, MA). About 3 mg of the ground sample was weighed using a PerkinElmer AD-6 Autobalance (PerkinElmer Inc., Waltham, MA), and was then introduced into the combustion chamber for burning under pure oxygen atmosphere. The gases from combustion were separated in a quartz column containing copper wires and detected by a thermoconductometer. Results are reported as a percentage of initial dry weight (w/w).

2.4. Thermogravimetric analysis (TGA)

Decomposition characteristics of the biomass were analyzed by thermal gravimetric analysis (TGA) (Perkin-Elmer TGA Pyris 7, Norwalk, CT). Around 5 mg of sample was measured at a heating rate of 20 °C/min from 40 to 700 °C under a dry nitrogen flux. Both percentage weight change and derivative weight were reported.

2.5. High heating value (HHV)

The HHV of the CRP biomass was determined by a calorimeter (IKA-Calorimeter C 200, IKA-Werke GmbH and Co. KG, Staufen, Germany) with a benzoic acid standard. After grinding, about 1 g of sample was pelletized then loaded into an adiabatic bomb for burning. The released energy was reported in Megajoule (MJ) per kg. The HHV was also calculated using the elemental results for comparison according to the equation (Sheng and Azevedo, 2005):

$$HHV\,(\mathrm{MJ/kg}) = -1.3675 + 0.3137 \times \mathrm{C} + 0.7009 \times \mathrm{H} + 0.0318 \times \mathrm{O}$$

2.6. Energy balance

The energy and mass flow was modeled using Aspen Plus 7.3, as shown in Fig. 1. The energy balance for torrefaction unit was studied by considering the total energy input (EI), the total energy output (EO), the high heating value of biomass before and after torrefaction (HHV_m and HHV_{tm}, respectively), process energy input (E_p), and energy loss (E_l) and using the following equations. Energy analysis was conducted assuming the volatiles are combusted to supply energy to the system.

$$EI = EO$$

$$EI = HHV_m + E_p$$

$$EO = HHV_{tm} + E_l$$

The net energy efficiency (e_{net}) was defined here as the ratio of HHV_{tm} to EI.

$$e_{net} = \frac{HHV_{tm}}{E_I} \times 100\%$$

2.7. Economic analysis

Economic analysis employs spreadsheet investment analysis calculations. Equipment costs were estimated by Aspen software. Operation conditions were either from the literature or current study. Other key assumptions were discussed in Section 3.2.

3. Results and discussion

3.1. Characteristics of torrefied biomass

3.1.1. Mass loss

The effects of torrefaction temperature and time on the dry mass loss of CRP biomass were investigated; results are shown in Fig. 2. Previous reports showed that biomass MC significantly affected the dry mass recovery after torrefaction and almost 50% (wet base) of biomass lost (Van der Stelt et al., 2011). In this study, the mass loss was up to 35% at 300 °C because the CRP biomass has a relatively low MC (about 20%) after a field dry. As shown in Fig. 2, the dry mass loss increased as processing temperature and time increased. A significant jump in dry mass loss occurred when the temperature increased from 250 to 300 °C, probably because one or more biomass components was degraded at the higher temperature. Further composition analysis is necessary to better understand the increase in mass loss.

3.1.2. Polymer composition analysis

Since temperature significantly affects biomass loss, a detailed composition analysis including structural polymers and elements was conducted to understand how the processing temperature