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Impact of drying-grinding sequence on loblolly pine chips preprocessing effectiveness

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ABSTRACT

The high amount of energy consumed during the processing of biomass inflates the production cost of bio-fuels and bio-products. This study was therefore carried out to evaluate the influence of drying and grinding sequence on biomass energy consumption and properties (specific grinding energy requirement, specific drying energy requirement, particle size distribution, bulk density, tap density, aspect ratio, and flow index of grinds). Among the six drying-grinding sequences (12-S, 30-S, 50-S, 30-*L*-12-*S*, 50-*L*-12-*S*, and 50-*L*-30-*S*), sequence 50–S had the lowest geometric mean diameter and sequence 30–S had the highest geometric mean diameter. Drying-grinding sequence significantly affected the bulk density and tap density of grinds. The bulk density of grinds varied from 267.1 kg/m^3 (sequence 12-S) to 98.0 kg/m^3 (sequence 50-S) while the tap density ranged from 342.6 kg/m^3 (sequence 12-S) to 153.7 kg/m^3 (sequence 50-S). This variation in the densities followed the changes the particle morphology and aspect ratio distribution. A trade-off was noted between specific grinding energy requirement and specific drying energy requirement. The grinding of samples at higher moisture content consumed higher grinding energy than the grinding of samples at lower moisture content. Moisture loss during grinding however increased as the moisture content of woodchips increased, hence resulted in lower drying energy requirements. The least specific drying energy consumption was (1581 kJ/kg d.b.) for sequence 50-S and the highest specific drying energy consumption was (3933 kJ/kg d.b.) for sequence 12-S.

1. Introduction

Fossil fuels (coal, natural gas and crude oil) are used to produce fuels, energy, chemicals and products. There is the obvious need to replace some of the consumed fossil fuels with renewable alternatives (such as biobased energy, wind, solar and geothermal) because of the limited nature of fossil fuels (Cherubini and Strømman, 2011). Secondly, greenhouse gases are released into the atmosphere during the mining, exploration and/or conversion of these fossil fuels into energy. Greenhouse gases have been linked to climate change (EPA, 2012). Biomass is the only renewable resource that can be used to directly produce the liquid transportation fuels, chemicals, and polymers currently obtained from fossil fuels (Soetaert and Vandamme, 2009; USDA, 2015). In the Southeastern United States, loblolly pine (*Pinus taeda*) is the most abundant biomass resources, with about 12.9 million hectares of cultivated loblolly pine plantation cultivated (Samuelson et al., 2013; Zhao et al., 2014).

Biomass have to be dried and ground before they can be fed into the throat of biorefineries conversion plants (for fuels and products production), and into pelleting mills and combustion power plants (for power and heating applications) (Tabil et al., 2011). Biomass drying is needed because most biomass feedstocks are harvested/gathered at high moisture contents (~50% for forest biomass and ~25% for energy crops). At these high harvest moisture levels, significant loss in quality of biomass feedstocks will occur due to microbial spoilage (which is typical for biological materials) after 1 to 3 days in storage (Lin and Pan, 2015). In addition, optimum conversion efficiency is obtained when dried biomass feedstocks (i.e. < 15%) are used in thermochemical conversion processes such as gasifiers and combustion chambers (McKendry, 2002) and in pelleting operations (Kaliyan and Morey, 2009). The size of biomass feedstocks after harvest/gathering can be up to 100 fold of the particle size that can be efficiently handled by biorefinery equipment. Grinding reduces particle size and in general changes the particle shape, bulk density, flow properties, porosity and increases rate of reaction due to increase in surface area (Bitra et al., 2009; Naimi et al., 2013). However, drying and grinding are highly energy intensive processes. For example, biomass drying can account for about 15% of the total industrial energy consumption (Chua et al., 2001).

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The energy consumed in the size reduction of biomass accounts for one-third of the total energy consumed in the production of bioethanol (Cadoche and López, 1989). Minimizing the energy consumed during biomass drying and grinding is therefore pivotal to the viability and economic competitiveness of biomass-based fuels and products.

Energy consumption during grinding depends on the initial and final particle sizes, biomass type, moisture content, pretreatments, grinding equipment type, and grinding equipment operating variables (Kokko et al., 2012; Phanphanich and Mani, 2011). Mani et al. (2004) studied the grinding of wheat straws, barley straws, corn stover, and switchgrass using a hammer mill fitted with 3.2 mm, 1.6 mm, or 0.8 mm screen sizes. As expected, the authors reported that there was a negative correlation between specific grinding energy requirement and hammer mill screen size. Furthermore, specific grinding energy consumption was significantly affected by biomass type. Switchgrass grinding consumed the highest energy of 113 kJ/kg d.b. and 231 kJ/kg d.b. (3.2 mm and 0.8 mm screen size, respectively) while corn stover grinding consumed the least specific energy consumption of 45 kJ/kg d.b. and 140 kJ/g d.b. (3.2 mm and 0.8 mm screen size, respectively). Souček et al. (2003) reported that the specific grinding energy for knotweed increased from 210 kJ/kg d.b. to 1040 kJ/kg d.b. when the moisture content of the material increased from 9.2% to 19.7%. Another study reported that the specific grinding energy for switchgrass through a 1 mm screen size was about 213 kJ/kg d.b. for hammer mill and about 573 kJ/kg d.b for knife mill (Miao et al., 2011).

The properties of biomass and the degree of bonding of water molecules to the biomass constituents influence the amount of energy required to dry biomass (Earle, 1983; Pirasteh et al., 2014). Other factors that affect drying energy consumption include the amount of moisture removed, drying method, air temperature, and air velocity (Koyuncu et al., 2007). Even though the latent heat of evaporation of water is 2247 kJ/kg, dryers require 3400 to 5000 kJ/kg of energy to dry wood chips because the dryers are not 100% efficient (Price, 2011).

The typical sequence is to dry biomass feedstocks after harvest/gathering and then grind the dried material partly because grinding energy generally decreases as the moisture content of biomass decreases (Mani et al., 2004; Miao et al., 2011; Souček et al., 2003). However most of the studies involving grinding energy and moisture content have been carried out on grassy biomass at moisture contents equal or lower than 20%. Apart from the study of Oyedeji et al. (2016), no other documented study has been carried out on energy consumption during grinding of woodchips at moisture contents between 12% (stable storage moisture content) and 50% (harvest moisture content for woody biomass). When grinding was carried out with a hammer mill fitted with 3.18 mm screen, the authors found that the specific grinding energy increased from 550 kJ/kg d.b. to 739 kJ/kg d.b. as moisture content increased from 30% to 50%. However, when the hammer mill was fitted with 6.35 mm screen size, specific grinding energy reduced from 183 kJ/kg d.b. to 137 kJ/kg d.b. as moisture content increased from 30% to 50%.

One of the limitations of grinding biomass at low moisture contents is the excessive production of dust (Dooley et al., 2013) which translates into material loss. For example, Hehar et al. (2014) showed that up to 22% (by mass) of loblolly pine can be in dust form after grinding this biomass chips through 3.19 mm screen and at 8% moisture content. The main hazards that can result from the presence of dust in processing plants are (1) health problems (respiratory, skin and eye effects) due to dust inhalation, and contact with eyes and skin; and (2) fire/explosion. Dust in processing plants can also cause abrasion damage to equipment, impaired visibility, unpleasant odors, material loss and community relation problems (Barbosa-Canovas et al., 2005). High-moisture grinding will therefore minimize dust generation and problems associated with presence of dust in biomass processing plants. One benefit of high moisture grinding that has not been fully explored in biomass preprocessing is partial drying of biomass due to heat generated in the grinding chamber. Ghorbani et al. (2010) reported moisture loss of about 4.10% to 9.37% during grinding of alfalfa chops. Probst et al. (2013) reported that moisture loss during grinding increased with an increase in the moisture content of corn and corncobs before grinding. There is therefore the potential that high moisture grinding can be used to pre-dry biomass feedstocks and therefore reduce the amount of moisture to remove in subsequent drying process hence reducing the total amount of combined energy to grind and dry biomass feedstocks.

Table 1
Ash, volatile matter and energy contents of loblolly pine chips used in this study[a].

Property	Standard	Value
Ash content (%)	NREL (Sluiter et al., 2008)	0.46 (0.08)
Volatile matter content (%)	ECN 15148 (SIS, 2006)	85.5 (0.19)
Energy content (MJ/kg)	Calorimeter[b]	20.1 (0.07)

[a] Values of ash, volatile matter, and energy contents are on dry basis. Values in parenthesis are standard deviation from triplicate.

[b] IKA C200 calorimeter (IKA Works, Wilmington, NC).

Most biomass feedstocks are initially dried and then ground when they are being prepared for conversion into fuel, chemicals and products. However, no study has been conducted to verify the suitability of this drying-grinding sequence or to whether insertion of partial drying or partial grinding will improve energy utilization and properties of resulting biomass grinds. Therefore, the novelty of this work is to determine the appropriate drying-grinding sequence for preparing woody biomass for conversion based on energy consumption and properties of the grinds. The specific objectives were to: i) investigate the influence of the drying-grinding sequence on the energy required to grind and dry loblolly pine, and ii) quantify and compare the physical and flow properties (particle size distribution, aspect ratio, bulk density, tap density, flow index, and compressibility index) of the grinds resulting from the drying-grinding sequences.

2. Materials and methods

2.1. Sample preparation

Loblolly pine woodchips were obtained from West Fraser Mill, Opelika, Alabama. The chips were air dried to about 12% moisture content and stored indoor at Auburn University Center for Advanced Science, Innovation, and Commerce (CASIC) building until the time of use. Representative sample from the chips was prepared for proximate analysis (ash, volatile matter and energy contents – Table 1) by grinding through the 1 mm screen of a Wiley mill. Moisture content of samples at each stage of any sequence was measured using the ASTM standard E871-82 (ASTM, 2006) by oven drying about 10 g samples at 103 °C for 24 h. Unless otherwise stated, moisture contents are reported in wet basis. Eq. (1) was used to compute the total mass of moisture removed per unit mass of dry biomass (M_{loss}) from the measured moisture content of samples before (m_i) and after grinding (m_f). The measured ash, volatile matter and energy content of the loblolly pine woodchips are given in Table 1.

$$M_{loss} = \left(\frac{m_i}{1 - m_i}\right) - \left(\frac{m_f}{1 - m_f}\right) \quad (1)$$

Six drying-grinding sequences were used in this study. A description of these sequences is summarized in Table 2. Woodchips used for each of the drying-grinding sequence was adjusted to initial moisture contents of 12%, 30% or 50% by adding and mixing