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Research paper

Improving bioenergy feedstock quality of high moisture short rotation woody crops using air classification

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ABSTRACT

Short rotation woody crops have many advantages as perennial bioenergy feedstocks, including high biomass yields, high carbohydrate and low ash contents, and marginal land utilization. Through short rotation coppicing management, these biomass resources can be harvested year round. The challenge of year round harvesting is feedstock quality variability due to leaf content during periods of non-senescence. The low quality leaf fraction results in higher ash and moisture contents and lower carbohydrate content. Mechanical techniques, such as air classification, provide an economically feasible process to separate heterogeneous biomass samples based on particle density, size, and shape. In this work high moisture (> 45%) hybrid poplar and shrub willow short rotation crops were air classified using a series of fan speeds for anatomical fractionation of the material. Air classification using an air velocity of ~4.7 m/s removed a majority of the leaf material while retaining 88% and 87% of the hybrid poplar and shrub willow, respectively. At this velocity, the ash content was reduced from 2.34% to 1.67% for hybrid poplar and 2.60% to 2.14% for shrub willow. Concurrently, the carbohydrate content increased from 56.32% to 60.62% and from 54.03% to 55.99% for these same materials. As drying is a cost intensive step for processing high moisture biomass materials, the cost benefits (~$3/Mg dry biomass) for removing low quality, high moisture materials prior to drying were also demonstrated.

1. Introduction

Biomass resources, including agricultural and forestry residues, energy crops, and wastes, are widely available renewable feedstocks for bioenergy and bioproducts. It is projected that by 2030 these resources will potentially be sustainably available at quantities over one billion tons in the United States to help meet energy needs [1]. Hurdles to using biomass as a feedstock for continuous energy production in biorefineries include inconsistencies in the quality and available quantity of the feedstock throughout the year [2]. Ideally, biomass feedstocks would be harvested year round on an as-needed basis, or harvested annually and stored in ways to minimize changes in quality or dry matter loss due to microbial degradation.

Woody energy crops, like poplar and willow, have many advantages as bioenergy resources. Under the right management strategy, they can be freshly harvested year round, unlike many herbaceous resources which are harvested annually. Poplar has a rapid growth rate, high biomass yields, and advantageous chemical properties for biochemical conversion processes, including high cellulose and low ash contents [3,4]. Shrub willow has also been identified as a promising perennial feedstock for bioenergy. Willow, like poplar, has high biomass yields, is capable of resprouting, reducing the need for replantation, contain high concentrations of carbohydrates, and has similar energy contents to other hardwoods [5–7]. Additionally, both of these woody energy crops can be managed as short rotation coppice [5,8] and grown on marginal and abandoned agricultural land [1,5,9]; although, this often results in lower biomass yields [9]. Advantages of short rotation coppicing include accelerated plant growth to maximize land productivity and frequent year round harvesting without the need for replantation [10]. Year round harvesting reduces or eliminates the need for pile storage, which can lead to dry matter loss, degradation, and changes to quality [11]. Moisture, ash, and energy contents of willow piles were shown to become more variable over several months of storage and overall ash increased from 1% to 2% while moisture increased from 42% to 47%

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[12]. Changes like these to feedstock quality and variability can have significant cost impacts on a biorefinery during processing steps like comminution and conversion [2,13].

While short rotation woody crops (SRWC) show promise as bioenergy feedstocks, there are still obstacles preventing their use in biorefineries. These biomass types typically contain higher moisture and ash contents when compared to other woody resources [14], and there is also high variability in these key characteristics [15]. Measured ash content for 300 shrub willow samples ranged from 0.8% to 3.7%, over multiple harvest years, coppice practices, cultivars, and locations in the Northeast [14,16] while reported moisture contents of comparable samples ranged from 37% to 51% [14]. Similarly, variability in ash content for 42 hybrid poplar samples ranged from 0.8% to 4.5% [16].

Feedstock variability and quality for year round harvested poplar and willow coppice needs to be better understood. Both of these species senesce during winter, losing leaves and translocating plant nutrients to the roots. Harvesting SRWC with leaves during the growing season impacts moisture, ash, and available carbohydrates. Dou et al. found that the leaves accounted for 37% of the biomass composition in poplar short rotation coppice [10,17]. The inclusion of leaves with the biomass decreased the total carbohydrate content from 49.5% to 41.3%, while increasing the ash content from 3.4% to 5.5% [10]. Additionally, leaf moisture content can be as high as 70%, which not only increases overall moisture content, but also accelerates degradation during storage [2,10]. Increases in moisture content impacts drying costs, which significantly contribute to the overall processing costs for high moisture resources [18]. Reported processing costs for 60% moisture content grass clippings were significantly higher, $59, than other herbaceous feedstocks with 20–30% at $27–31 [19,20]. In addition to leaves, bark is also a low quality fraction having lower carbohydrate content, higher ash and lignin contents in poplar lending to adverse effects in biochemical conversion [10,17]. To minimize chemical and physical variability, improve conversion properties, and reduce the cost of delivered SRWC biomass, removal of lower quality fractions such as leaves and bark is necessary.

Air classification (AC) techniques offer a low cost mechanism to separate physiological heterogeneous samples by shape, size and density [21]. Previous studies using air classification to separate physiologically diverse components within biomass feedstocks have demonstrated the removal of fines and higher ash content fractions, such as needles, from chipped pine forest residues [22], and anatomical fractionation of leaves, husks and stems from corn stover [20]. The physical differences between leaf, bark and chips in SRWC [23] make AC a potentially effective separation option for these anatomical fractions. These previous AC studies showed the impacts of air classification after drying. As the cost of drying is a significant factor for processing SRWC, using AC to remove low quality, high moisture material prior to drying could reduce processing costs. The objective of this work is to investigate the feasibility of using AC to remove low quality leaves and bark from freshly harvested, high moisture hybrid poplar and shrub willow samples prior to drying to facilitate quality improvement for samples harvested during periods of non-senescence.

2. Materials and methods

2.1. Materials

Materials were harvested using a New Holland FR 9080 forage harvester with a FB130 coppice header producing chip dimensions about 1″ x 2″ x ½”. The materials selected for this study were harvested during periods of non-senescence to ensure the presence of leaf. Hybrid poplar (*P. deltoides* × *P. nigra*.) was harvested July 14, 2017 from Kootenai County, Idaho. The crop was a three year coppice with five year old roots. Shrub willow was harvested September 5, 2017 from Jefferson County, New York from Celtic Energy Farms plots. Approximately 200 kg (wet basis) of each of material was divided into representative subsamples consisting of 2.5–3.5 kg using a custom rotary splitter within a week of harvesting. The moisture content was measured following ASABE S358.2. The samples were dried at 105 °C for 24–30 h using a high performance horizontal air flow drying oven (SHEL LAB, model no. FX28-2, Cornelius, OR).

2.2. Air classification and anatomical fractionation

Air classification (AC) separates the samples into two fractions, light and heavy, as the material is passed over a screen covered fan. The lighter fraction is blown upward and removed while the heavy fraction (air classified material) remains. Air classification was performed on wet samples using a 2x Air Cleaner equipped with an Iso-flo dewatering infeed shaker set to 58 Hz (Key Technologies, Walla Walla, WA). Material was air classified using two methods referred to in this work as sequential AC and selected AC. The fans speed settings for sequential AC were 10, 12, 15, 18, 22, 28, 32, and 40 Hz corresponding approximately to 2.1, 2.5, 3.2, 3.8, 4.7, 6.2, 7.1, and 9.2 m/s air velocities. These fan speeds were selected based on the ability of each speed to separate the materials into anatomical or visually unique fractions and previous air classification work evaluating these same fan speeds for pine residue materials [22]. For sequential AC, the light fractions were collected and the heavy fractions from each fan speed were processed through the air classifier again using the next highest fan speed. The final heavy fraction after the 9.2 m/s separation and “below screen” fractions were also collected for analysis. The “below screen” fraction resulted from small, thin, dense particles that fell through the blower screen from each fan speed setting. For the selected AC, material was classified into a heavy and light fraction based on a single selected fan speed. Fan speeds of 4.7 and 6.2 m/s were used for the selected AC, based on the visual removal of leaf content and considering the rate of ash removal compared to the amount of biomass removed.

Anatomical fractions were separated by hand using 2.5–3.5 kg subsamples of each material into leaves, twigs, branches, free bark, chips with bark, clean chips, and fines. In order to reduce manufactured fines, each material was separated wet to prevent breaking of fragile fractions, such as leaves. Twigs were defined as full branches that were small enough to go through chipping with bark attached. Branches were similar to twigs but were distinct in that they were larger in diameter and broken along the axis during chipping. The fines fraction consisted of material that was too small to identify and screened using a 2.0 mm standard sieve (W.S. Tyler Co., Mentor, OH). Both air classification and anatomical fractionation were done in triplicate for all samples using one of the 2.5–3.5 kg subsamples for each replicate.

2.3. Analytical characterization and statistical analysis

For ash analysis and compositional characterization, the raw samples, air classified fractions, and anatomical fractions were ground to pass a 2.0 mm screen using a Thomas Model 4 Wiley knife mill (Thomas Scientific, model no. 3375-E55, Swedesboro, NJ). Aliquots of 1–2 g of each sample were analyzed for ash content using a LECO Thermogravimetric Analyzer 701 (St. Joseph, MI) following ASTM D3174-04. Compositional analysis was performed following the standard Laboratory Analytical Procedures for Compositional Analysis developed at NREL [24]. The ash measurements for the heavy fractions of the 4.7 m/s and 6.2 m/s of the selected AC fan speeds and the raw samples were compared using two sample t-tests assuming equal variances to assess whether or not the differences were significant based on $p < 0.05$.

2.4. Feedstock logistics cost models

The processing costs estimated were estimated by Idaho National Laboratory's Biomass Logistics Model (BLM) [25]. The BLM, using Powersim™ software, is designed to work with both thermochemical