Application of air classification and formulation to manage feedstock cost, quality and availability for
bioenergy

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Abstract

Biomass such as agricultural residues, energy crops and yard waste has significant potential to be used as renewable feedstocks for production of fuels, chemicals and energy. However, in a given location, biomass availability, cost and quality can vary markedly. Strategies to manage these traits must be identified and implemented so that consistent low-cost and high-quality feedstocks can be delivered to biorefineries year round. In this study, we examine air classification as a method to mitigate high ash concentrations in corn stover, switchgrass, and grass clippings. Formulation techniques were then used to produce blends that met ash quality and biomass quantity specifications at the lowest possible cost for biopower and biochemical conversion applications. It was found that air classification can separate the biomass into light fractions which contain concentrated amounts of elemental ash components introduced through soil contamination such as sodium, alumina, silica, iron and titania; and heavy fractions that are depleted in these components and have relatively lower total ash content. Light fractions of corn stover and grass clippings were found to be suitable for combustion applications since they had less propensity to slag than the whole biomass material. The remaining heavy fractions of corn stover or grass clippings could then be blended with switchgrass to produce blends that met the 5% total ash specifications suggested for biochemical conversions. However, ternary blends of the three feedstocks were not possible

due to the high ash content of grass clippings. It was determined that air classification by itself was not suitable to prepare these feedstocks for pyrolysis due to high ash content.

1.0 Introduction

Renewable non-food lignocellulosic biomass such as agricultural residues, energy crops and yard wastes are important contributors to the more than one billion tons of biomass that could be sustainably available in the United States by 2030 [1, 2]. To contribute significantly to U.S. energy independence, these feedstocks will need to be available at low cost, in large quantities, and be of consistent quality. Unfortunately, the composition and quality of these biomass sources can vary widely depending on weather patterns, agronomic practices, harvest methods and geographical location [3, 4]. Current quality specifications applicable to many conversion processes include flowability (ability to feed to the reactor), particle size (reactivity), moisture (grinding, densification, transport and aerobic storage stability), convertible organics (yield potential) and cell wall structure (convertibility) [5]. However, composition and chemical differences in biomass can impact yield and convertibility in different ways among conversion processes depending upon chemistries and reaction conditions employed. Examples include ash content, ash composition, biocatalyst inhibitors such as acetate and soluble phenolics, and heteroatoms that foul or poison inorganic catalysts such as sulfur and phosphorus [6-8].

Biomass ash is comprised of “physiological ash”, derived from the plant tissue, and non-physiological ash or “exogenous ash,” from soil contamination during the harvest [9]. Physiological ash in corn stover is typically 5-6 wt. %, while exogenous ash from multi-pass harvesting can exceed 20% [9]. Switchgrass tends to be lower in physiological ash because it utilizes water efficiently [10], and lower in exogenous ash because it is cut 10-15 cm above the ground for improved drying times and less introduction of soil during windrowing and baling [11]. Grass clippings, a common yard waste, have been shown to have high ash content [12]. For thermochemical conversions, ash content and composition are of concern due to slagging, fouling and corrosion (for biopower and gasification [8, 13]), bio-oil yield decreases (for uncatalyzed fast pyrolysis [7]), and catalyst fouling (for catalyzed fast pyrolysis and gasification [7, 8]). In

biochemical conversions, the abrasive nature of the silica and alumina ash components leads to excessive equipment wear, and disposal of the non-convertible ash incurs costs [9].

Local feedstock depots [3, 4] offer the opportunity to adjust feedstock quality before the feedstock reaches the biorefinery [14]. Air classification is a low-cost separation technology that could be used in a depot to alter feedstock quality. The technology takes advantage of differences in shape, size and density of particles to separate them into unique fractions [15], and has been demonstrated to concentrate and remove exogenous ash from chipped pine forest residues [16]. Herbaceous biomass is comprised of different tissue types, each having unique physical and chemical properties that lead to differences in particle density, shape and size when ground [17], and thus may be well suited for air classification. Differing physical and chemical properties of these fractions may increase their value in conversion pathways, and could make them useful feedstock blend ingredients to meet quality specifications.

Feedstock depots also have the ability to receive both high- and low-quality biomass which increases the quantity of total biomass available. Through formulation and blending, more biomass will be available at specification to biorefineries [14]. Feedstock formulation is already used in many market sectors including coal power generation, grain, animal feeds, and biopower where formulation is used to reduce costs and improve product quality [18-21]. For bioenergy applications, formulation and blending of different biomass types and/or fractions of biomass types obtained through preprocessing may be required if targets for quality and quantity are to be achieved cost effectively [14].

In this paper, we present the results of air classification of corn stover, switchgrass and grass clippings into high and low ash fractions. We then consider formulation and blending strategies to meet feedstock cost and quality specifications for three conversion technologies including biopower, biochemical conversion to ethanol, and uncatalyzed fast pyrolysis.

2.0 Materials and Methods

2.1 Materials:

Corn stover was harvested single-pass in Story County, Iowa in 2012. The bales were ground with a Vermeer BG480 grinder (Pella, Iowa) fitted with a 6-inch (152.4mm) screen and then dried to

approximately 8.3% moisture. Alamo switchgrass bales harvested 2012 in Garvin County, OK were size reduced with the Vermeer BG480 grinder fitted with a 2-inch screen (50.8 mm) and later ground through a Bliss Hammermill (Eliminator E4424; Ponca City, OK) fitted with a 1-inch screen. The samples were dried to approximately 10% moisture. Kentucky bluegrass clippings were collected in 2014 from Bonneville County, Idaho. These samples were stored at 4°C and dried from approximately 60% to 10% moisture within 48 hours. No size formatting was required for this material.

For each of the biomass sources, the ground and dried (corn stover and switchgrass) or dried (grass clippings) were thoroughly mixed and then successively split into representative 3-5 kg fractions using a custom eight-way rotary splitter. These samples were placed into indoor storage until utilized for air classification. Ash content and ash speciation analyses were completed by Huffman Laboratories (Golden, CO), as previously described [16].

2.2 Air Classification:

A 2x Air Cleaner (Key Technologies, Walla Walla, WA) equipped with an Iso-Flo dewatering infeed shaker set to 58 Hz was used for air classification. Fan speeds were selected to best separate the biomass feedstocks into anatomical or visually unique fractions. For corn stover, fan speeds were 7.5 Hz, 10 Hz, 15 Hz, 18 Hz and 28.5 Hz; with approximate air velocities of 73 m/min, 111 m/min, 186 m/min, 231 m/min, and 389 m/min, respectively. Fan speeds used for switchgrass and grass clippings were 7.5 Hz, 10 Hz and 15 Hz. For each separation, the fan was set to the lowest selected speed and the shaker table turned on. A bag (3-5 kg) of biomass was manually poured onto the infeed shaker table such that it was one layer thick as it passed over the classifier's air stream. The upward flow of air separated the sample into a light and heavy fraction. The fan speed was increased and the heavy fraction was fed through the air classifier to generate a new light and heavy fraction. This process was repeated until light fractions were collected for all fan speeds and the remaining heavy fraction was collected. During the experiment, smaller and denser particles fell through the blower screen and into the fan ducting. This fraction, referred to as the "below screen" or "BS" fraction, was collected from the ducting for each feedstock. This procedure was repeated in triplicate. A layer of fine, dark particles was observed in the 7.5 Hz light fraction and it was size

fractionated through a #80 sieve (0.18mm) to isolate this visually unique fraction. The fine fraction recovered through the sieve is referred to as “7.5 Hz sieved” in this paper and the fraction retained on the sieve is “7.5 Hz.” Collected fractions were analyzed for total ash and elemental ash (Huffman Laboratories; Golden, CO). This system is rated at 40 m³/hour, which at an assumed corn stover bulk density of 80 kg/m³, gives a mass load of 3.4 tons/hour. Because our goal was to determine how good a separation could be achieved at each fan speed, the heavy fraction was passed through the air stream repeatedly until no further fines were collected, and the final collected masses of lights and heavies were recorded. We operated well below rated mass load to obtain the best possible separation.

2.3 Feedstock Formulation:

Blends that meet ash specifications were developed using WinFeed 2.8 (www.winfeed.com). This software provides least cost formulation blends for animal feed where inputs include a database of animal feed ingredients, their composition, nutrients and the costs. The user specifies criteria such as nutrients, moisture, fiber and protein; and a linear programming algorithm produces blends that meet user specified constraints at the least cost. For this study, the database was altered to include corn stover, switchgrass and grass clippings, air classified fractions of these feedstocks, the ash and elemental ash composition of each feedstock and fraction, and the costs associated with producing the various feedstocks.

3.0 Results and Discussion

3.1 Air classification

3.1.1 Mass fractionation:

Mass fractionation of the air classified biomass is shown in Table 1. The 7.5 Hz sieved fraction contained significant amounts of soil for all biomass types. The below screen fraction was highly variable, but small stones and sand were present from the stover and grass clippings. The heavy fraction of the grass clippings contained little grass, and consisted of tree and shrub leaves collected with the grass. Corn stover, the most anatomically diverse feedstock tested, showed separation of anatomical fractions. Leaves concentrated in the lightest fraction, while nearly all of the cobs were in the heavy fraction (approximately 75 wt%) with the remainder stem pieces with nodes, corn grain and small stones.

Husks and sheaths were found in the 15Hz light fraction, while the stems and sheaths fractionated in the 18Hz and 28.5Hz light fractions. Anatomical differences were more subtle in switchgrass, with the lighter fractions containing mostly leaves and the heavier fractions containing mostly stems.

3.1.2 Ash and elemental ash segregation:

Table 2 shows the whole ash content for each collected fraction. The 7.5Hz sieved fraction contained the most ash for all biomass types. Ash concentrations decreased as fan speed increased. Grass clippings had the highest ash content ranging from $46.33 \pm 1.65\%$ in the 7.5Hz sieved fraction to $11.38 \pm 0.77\%$ in the heaviest fraction. Switchgrass contained the lowest ash content, with $10.43 \pm 0.26\%$ in the 7.5Hz sieved fraction and $2.46 \pm 0.49\%$ in the heaviest fraction.

The elemental ash for the collected fractions is shown in Table 3. The trend of higher ash content in lighter fractions was also observed for each element (highlighted rows in Table 3). Ash elements were higher in nearly every fraction of grass clippings which is not surprising given that the grass clippings had overall higher ash than corn stover or switchgrass. Grass clippings were high in manganese, as well as iron, potassium and phosphorous, the latter of which is consistent with regular grass fertilization. Although the switchgrass had overall lower concentrations of elemental ash, the elemental compositions of corn stover and switchgrass mirrored each other with silica being the most abundant, followed by calcium and potassium.

3.1.3 Total and elemental ash removal:

Figures 1A-C show the cumulative removal of total ash and biomass as each light fraction is removed and the total amount of ash left in the heavy fractions after each removal. For corn stover, over 30% of the ash can be removed if the below screen, 7.5 Hz sieved, 7.5 Hz and 10 Hz fractions were removed, at the expense of 20% biomass loss which would reduce yields in down-stream processes. For switchgrass, removing the same fractions yields 41% ash and 34% biomass removal; and for grass clippings 32% ash and 24% biomass removal. Compared to a previous study of ash removal by air classification of pine thinnings and forest residues, the ash removal for herbaceous residues was not pronounced. In that study, 41% of the total ash was removed with the loss of only 6.7% of the biomass [16].

For the elemental ash, two types of separations were observed. The first was for exogenous elements that are introduced from soil contamination during harvest and include Si, Al, Fe, Na, and Ti. These elements were found primarily in the lightest fractions and fairly good separation of these ash components with moderate biomass loss was demonstrated. Figures 2A-C and 3A-C show removal of silica and alumina for the three feedstocks. Removing the same four light fractions yielded 39% silica removal with 20% biomass loss for corn stover; 56% silica removal and 34% biomass loss for switchgrass; and 32% silica removal with 24% biomass loss for grass clippings. Similarly for alumina, 36% removal with 20% biomass loss for corn stover; 53% removal with 34% biomass loss for switchgrass; and 48% removal and 24% biomass loss for grass clippings was observed. The second type of ash separation occurred with physiologically important elements to the plant and includes Ca, K, Mg, S, Mn, and P. In contrast to the exogenous ash, these elements are found inside the cell walls and remain part of the cells throughout preprocessing steps such as grinding, drying and air classification, making them more evenly distributed throughout the air classified fractions. This results in a proportional removal with biomass as demonstrated in Figures 4A-C for potassium. Removing the same four fractions yields potassium removal of 21% for corn stover with a biomass loss of 20%; 40% for switchgrass with 34% biomass loss; and 20% for grass clippings with 24% biomass loss. These collective results demonstrate that air classification works well to remove exogenous ash resulting from soil contamination. In particular, it would be especially applicable to biomass materials with very high ash content from soil introduced during harvest and collection such as multipass harvested corn stover where ash contents can exceed 20% [9]. If removal of physiological ash is desired, air classification alone would not work and methods that can remove ash components from within the cells such as water or acid leaching would be required.

3.2 Costs of preprocessing and feedstock supply

3.2.1 Air Classification Cost Model:

A throughput of 25 tons/hour was assumed which is in line with the expected 200,000 tons per year capacity of a biomass depot [22, 23]. The air classifier design consists of 3 air classifiers rated at 8.16 tons/hour with an equipment cost of \$56,440 each [16]. It was assumed that conveyers and hoppers

needed to move material to and from the air classifiers will be the same as the air classifier costs which gives an uninstalled capital cost of \$338,640. The Lang Factor method was used to calculate the total installed capital cost (multiplier of 3.1) of \$1.05 million. Operating costs for electricity for blowers (2 at 15 HP usage) assumes \$0.10/kWh and maintenance and operation costs are assumed to be 6%/year of capital (personal communication, Hu et al., 2015). An annual capital charge rate of 12% gives a capital charge of \$0.64/ton of biomass processed. Total operation and maintenance costs are \$0.41/ton (\$0.09 for electricity and \$0.32 for operation and maintenance) for a total air classification cost of \$1.05/ton of biomass. All costs are calculated on a per ton basis for one ton of air classified product that meets quality specifications. Therefore, additional feedstock must be processed to have an output of 1 ton. For example, if 7% of the feedstock is removed as a high ash fraction after air classification, then 1.075 tons must be processed to produce 1 ton of product. This design was for air classification of woody biomass and it is recognized that herbaceous materials have lower bulk density and will increase the capital costs. However, a recent sensitivity analysis on air classification costs (unpublished data) found that doubling the air classification capital costs only increases the total costs (grower payment, logistics costs and air classification costs) by 0.2%. It is clear from Table 4 that the air classification cost is very small in relationship to the other logistics costs, so this is not surprising. Based upon this, we chose to utilize the published air classification design.

3.2.2 Feedstock Logistics Costs:

Feedstock logistics includes costs for harvest and collection from the farmer's field; material storage; preprocessing including size reduction, drying, densification and formulation, and transportation and handling. Feedstock logistics costs for corn stover and grass clippings were taken from the 2015 herbaceous feedstock state of technology report [24]. Logistics costs for switchgrass were obtained from the 2017 Design Case report [25] and were updated to the 2015 state of technology. Assumptions include corn stover and switchgrass gathered from a twelve county region in northwestern Kansas and the grass clippings located in Denver, CO and shipped to the depot by rail. The moisture content of corn stover was 30%, switchgrass was 20% and grass clippings were 60%. The logistics costs for each operation

are provided in Table 4. The transportation costs for corn stover and switchgrass vary with quantity since larger quantities have to be procured from a larger distance. Preprocessing costs include grinding and drying are considerably higher for the grass clippings due to the high drying costs associated with the high moisture content.

3.2.3 Farm Gate Price and Quantities Available:

Switchgrass and corn stover quantities and farm gate prices were obtained from the Bioenergy Knowledge Discovery Framework (www.bioenergykdf.net, Accessed 11/4/2015) for Kansas in the harvest year 2015. Twelve counties were selected in northwestern Kansas (Cheyenne, Decatur, Gove, Graham, Logan, Norton, Rawlins, Sheridan, Sherman, Thomas, Trego and Wallace) which together had sufficient quantities of both switchgrass and corn stover to feed a 200,000 ton depot. In these counties, 733,200 tons of corn stover is available at a farm gate price of \$40/ton while there is no switchgrass available until the farm gate price reaches \$45/ton with 350,500 tons available at that price. The farm gate price is defined to include both the grower payment and an assumed cost of \$12/ton for harvest and collection. As improved harvest and collection costs are available [24, 25], \$12/ton was subtracted to obtain the actual grower payment. Corn stover has higher availability in these counties and thus a lower grower payment compared to switchgrass. However, there was sufficient switchgrass present to examine a full range of blends between corn stover and switchgrass. Currently available data does not include either farm gate prices or quantities for grass clippings, so a grower payment of \$0 was assumed for this study. This was deemed to be a reasonable assumption since producers of grass clippings currently pay for these materials to be either landfilled or composted and providing the grass clippings for free would save the producers those costs.

3.3 Applications for air classified fractions and formulation

3.3.1 Biopower:

The previous results indicate that air classification has potential to alter biomass ash and elemental ash composition. We examine several potential applications in the next sections. A flow diagram shows how different air classifications fractions are used for these applications (Figure 5). Biomass combustion

by itself or co-firing with coal is of interest to reduce CO₂ emissions as biomass is considered close to carbon neutral [26]. However, biomass is chemically different from coal and contributes to slagging and fouling deposits and decreased combustion efficiency [27]. Agricultural residues tend to be high in silica and potassium and lower in calcium [28]. In particular, potassium in the presence of chlorine, silica and sulfur forms alkali-chlorides, silicates and sulfates, respectively, with low melting temperatures that contribute to slagging and fouling. Indices have been developed for coal to predict the propensity for slagging [29] although they do not always reflect the important elements that are present in agricultural residues. The most common index employed is given below (Equation 1).

$$\frac{B}{A} = \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O}{SiO_2 + TiO_2 + Al_2O_3} \text{ (Equation 1)}$$

This index represents the ratio between basic components and acidic components where basic components tend to lower melting temperatures and acidic components raise them [13]. This index takes into account effects from calcium, potassium and silica which are important in biomass. It does not include chlorine effects, but will likely be predictive for biomass slagging [27]. A B/A ratio of less than 0.2 has only a slight chance of slagging, a ratio between 0.2 and 0.4 is moderately likely to slag, while a ratio over 0.4 is likely to have severe slagging [29]. Calculating index values for whole corn stover, switchgrass and grass clippings yields 0.8, 0.7 and 0.5, respectively, indicating that these materials would experience severe slagging if combusted by themselves. This is why the amount of biomass co-fired with coal is generally limited to 20% [31]. As discussed in section 3.1.4, air classification selectively removes soil components such as iron, silica, titania, sodium and alumina and concentrates them into the light fractions which has the desired effect of reducing the B/A ratio. Although concentrating sodium and iron would increase the B/A ratio, the overall low concentrations of these elements in biomass has little effect on the ratio. Figure 6 shows the B/A ratios for the light air classified fractions. For both corn stover and grass clippings, the ratios for the below screen, 7.5 Hz sieved and 7.5 Hz light fractions (grass clippings only) are decreased from unclassified material into the moderate slagging risk range. The 7.5 Hz sieved corn stover fraction ratio (0.22) is at the low end of the moderate risk range, and very nearly into the light

slagging risk regime. Utilizing these fractions from corn stover and grass clippings would be valuable for biopower applications either by themselves or when co-fired with coal and would allow higher biomass blends with coal to be realized. The switchgrass B/A ratios did not see as dramatic a drop with the lowest ratio (0.4) seen for the 7.5 Hz sieved fraction. For successive removals of light fractions, the ratio starts to increase again as the acidic soil elements are depleted and the basic elements are concentrated relative to the starting materials. These fractions would have a severe likelihood of slagging during combustion and would be better utilized in other applications.

3.3.2 Biochemical conversion:

Corn stover, switchgrass and grass clippings can also be utilized in biochemical conversion to fuels and chemicals. Although ash does not cause direct problems in biochemical conversions as it does in biopower, it is inert, occupies physical space in the reactor, and has associated disposal costs. In addition, ash is abrasive and causes wear on equipment. Recent literature has suggested a maximum total ash specification for biochemical conversion processes of 5% [9].

Whole corn stover, switchgrass and grass clippings have total ash contents of 6.2, 4.2 and 14.3%, respectively. Clearly switchgrass could be utilized by itself since it is below the 5% specification. However, corn stover and grass clippings have to be treated to reduce ash, blended with lower ash switchgrass or a combination of the two to achieve the specification. Example blends with whole biomass materials that meet the 5% ash specification are 40% corn stover:60% switchgrass, and 8% grass clippings:92% switchgrass. With a 200,000 ton/year depot sited in northwestern Kansas, formulating these blends would require 120,000 tons and 184,000 tons of switchgrass per year with grower payments of \$41.71/ton and \$42.62/ton, respectively, to access these quantities. The costs for these two blends including logistics and grower payments would be \$96.32/ton for the corn stover/switchgrass blend and \$100.15/ton for the switchgrass/grass clipping blend, with the cost of the latter blend higher due to higher grower payments and transportation costs for switchgrass. While this area of Kansas has sufficient quantities of both switchgrass and corn stover to develop a range of blends, other areas of the state do not. As an example, southeastern Kansas has virtually no corn stover available, so other types of blends with

switchgrass would be required. Clearly, a variety of solutions will be needed to provide feedstocks that meet quality specifications to biorefineries and these solutions are location dependent.

In areas where insufficient switchgrass is available or it is too expensive for a depot, air classification offers a solution to reduce ash content in corn stover or grass clippings and enable more blends. Combining this with the biopower application described in section 3.3.1 would enable two products to be realized in a depot. Assuming that the below screen and 7.5 Hz sieved fractions are removed from the corn stover and the below screen, 7.5 Hz sieved and 7.5 Hz fractions are removed from the grass clippings for biopower application, a corn stover heavy fraction with 6.0% total ash and a grass clipping heavy fraction with 14.1% total ash would be available for blends. Costs for the blends include a credit for the biopower fraction calculated assuming an average biomass heating value of 10 MMBTU/ton and a fuel value of \$3/MMBTU (reduced from natural gas values to account for transport, handling and ash disposal costs; Hu et al, personal communication). Initial blend calculations showed that ternary blends were not possible since the ash content of the grass clippings was too high. Binary blends of switchgrass and air classified corn stover over a range of possible combinations for a 200,000 ton per year depot are shown in Figure 7. The lowest blend cost occurred for the 75:25 mixture of stover/switchgrass at \$96.65/ton; however, this blend has an ash content of 5.54% and exceeds the ash specification. It was not possible to generate corn stover/switchgrass blends that meet the 5% specification when the corn stover content became higher than 50%. The INL State of Technology reports for feedstock logistics [24] introduced a dockage which represents the cost to the biorefinery for a feedstock that does not meet quality specifications. In the 2015 State of technology report [24], an ash dockage of \$1.90/ton for every percentage point of ash above 5% is utilized. Applying this to the stover/switchgrass blends that are above 5% total ash yields a second cost curve shown in Figure 7. When the dockage is applied, the optimum blend shifts to 62.5:37.5 mixture of stover:switchgrass at a cost of \$97.36/ton slightly lower than the 50:50 blend cost of \$97.40/ton indicating that the range of blends can be extended and still account for extra ash. Blends ranging from 25:75 to 87.5:12.5 stover/switchgrass can be utilized that are within 2% of the minimum blend cost. These blends also demonstrate that using two feedstocks results in materials

that are lower in cost than either of the single feedstocks (\$102.54/ton for switchgrass alone and \$99.45/ton for corn stover alone) because smaller amounts of each feedstock are used; and, therefore, transportation costs are lower. This cost reduction is despite having had the additional air classification step and the desired ash specification is still met.

Similarly, blends with air classified grass clippings and switchgrass were also possible (Figure 8), with up to 8% grass clippings which met the 5% ash specification with an associated cost of \$101.48/ton. Use of the lower cost grass clippings also reduced the blend cost over switchgrass by itself while still meeting the ash specifications. There was no minimum cost in this case since the grower payment for grass clippings does not increase as its content in the blend increased and the transportation costs for grass clippings are fixed. As demonstrated for the corn stover/switchgrass blends, dockage can also be applied to the switchgrass/grass clipping blends with a blend cost for 10% grass clippings almost the same as the 8% blend at \$101.49/ton. With dockage, grass clipping blends up to 23% (Figure 8) could be utilized and still have a lower cost than switchgrass by itself.

Alternatively, as discussed in Section 3.1.1, air classification also separates the biomass into anatomical fractions. In a 2009 study, corn stover was hand fractionated into leaves, husks, stems and cobs and each fraction was pretreated with 0.8wt% sodium hydroxide for 2 hours at room temperature. The glucan yields were 76%, 92%, 48%, and 92%, respectively; while the xylan yields were 96%, 82%, 64% and 82%, respectively [30]. These are in contrast to a 68% glucan and a 76% xylan yield for whole corn stover. Based on this, air classification could be used to generate leaf, husk and cob fractions, which would be the 7.5 Hz (leaf), 15 Hz (husk) and the 28.5 Hz heavy fractions (cobs). These could be removed from the corn stover and utilized as a higher yielding material in a biochemical conversion process. However, a use for the lower yielding 18 Hz and 28.5 Hz light fractions would need to be found. Several studies have suggested that switchgrass leaves are more easily digested in pretreatment processes [31-33]. In the present study, switchgrass leaves were easily removed in the lightest air classified fractions and could be valuable as an easily convertible feedstock fraction.

3.3.3. Pyrolysis:

Another application for biomass feedstocks is pyrolysis. A recent Pacific Northwest National Laboratory process design report examining fast pyrolysis of lignocellulosic biomass had acceptable bio-oil yields using a feedstock with 0.9% total ash [34]. Another study found that bio-oil yields were reduced from 62% for pine (0.1% ash) to 44.7% for rapeseed straw (6.1% ash) [35]. It is clear that even with air classification, none of the feedstocks discussed above would be able to meet a 0.9% ash specification and some other type of treatment would be required to utilize those feedstocks in pyrolysis.

4.0 Conclusions

The use of biomass and other non-traditional feedstocks for energy and chemical production is increasing in both the United States and globally. As the use of such feedstocks increases, so does the need for a consistent and cost-effective supply system that can service multiple energy conversion platforms across both geographical locations and variations in the market value of potential feedstocks. A challenge to establishing a consistent feedstock supply is variations in feedstock quality attributes, which impact the various conversion pathways differently. One potential solution to this challenge is the development and integration of feedstock preprocessing methodologies with feedstock formulation and blending. This approach may effectively utilize the available feedstocks for any geographical area and/or market and preprocess and blend them in a way that produces a least-cost blend that will meet quality specifications for a given conversion application. To this end, the results presented here demonstrate the integration of a mechanical preprocessing technology, air classification, with a feedstock formulation model to develop feedstock blends based on combinations of corn stover, switchgrass, grass clippings, and fractions of these feedstocks that minimize cost while meeting selected quality specifications.

It was demonstrated in this paper that air classification can be used to separate corn stover and grass clippings into light fractions that are less likely to cause slagging or fouling for biopower applications and heavy fractions that can be blended with lower ash switchgrass to produce low cost blends that meet ash specifications for biochemical conversion.

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Table

Table 1: Mass fractionation among air classified fractions of biomass feedstocks. Values represent mean $\pm$ 1 standard deviation, n=3.

Fraction	Corn Stover (%)	Switchgrass (%)	Grass Clippings (%)
Below Screen	3.29 $\pm$ 0.60	3.47 $\pm$ 0.17	2.73 $\pm$ 0.83
7.5 Hz sieved	0.85 $\pm$ 0.17	6.61 $\pm$ 0.24	2.46 $\pm$ 0.53
7.5 Hz	15.49 $\pm$ 3.84	23.86 $\pm$ 3.45	18.40 $\pm$ 4.84
10 Hz	13.31 $\pm$ 1.72	20.17 $\pm$ 2.80	38.84 $\pm$ 7.03
15 Hz light	26.92 $\pm$ 2.41	30.62 $\pm$ 0.98	30.88 $\pm$ 1.44
15 Hz heavy	n/a	15.27 $\pm$ 0.65	6.70 $\pm$ 0.53
18 Hz	10.45 $\pm$ 0.24	n/a	n/a
28.5 Hz light	13.32 $\pm$ 0.35	n/a	n/a
28.5 Hz heavy	16.37 $\pm$ 0.86	n/a	n/a
MASS CLOSURE	95.9 $\pm$ 0.5	n/m	98.5 $\pm$ 1.2

n/a = Not applicable because this fraction was not collected for the feedstock.

n/m = Not measured/recorded.

Table 2: Whole ash concentrations in air classified fractions of biomass feedstocks. Values represent mean $\pm$ 1 standard deviation, n=3. "n/a" = "not applicable."

Fraction	Corn Stover (%)	Switchgrass (%)	Grass Clippings (%)
Below Screen	19.19 $\pm$ 0.82	3.41 $\pm$ 0.10	27.23 $\pm$ 2.17
7.5 Hz sieved	30.35 $\pm$ 2.71	10.43 $\pm$ 0.26	46.33 $\pm$ 1.65
7.5 Hz	7.70 $\pm$ 0.20	6.55 $\pm$ 0.08	14.4 $\pm$ 0.83
10 Hz	6.85 $\pm$ 0.65	5.35 $\pm$ 0.31	13.18 $\pm$ 0.53
15 Hz light	6.44 $\pm$ 2.53	2.70 $\pm$ 0.43	12.19 $\pm$ 0.20
15 Hz heavy	n/a	2.46 $\pm$ 0.49	11.38 $\pm$ 0.77
18 Hz	4.28 $\pm$ 0.15	n/a	n/a
28.5 Hz light	4.00 $\pm$ 0.09	n/a	n/a
28.5 Hz heavy	4.32 $\pm$ 0.51	n/a	n/a
UNCLASSIFIED BIOMASS	6.26 $\pm$ 0.14	4.65 $\pm$ 0.32	14.18 $\pm$ 1.25

n/a = Not applicable because this fraction was not collected for the feedstock.

Table 3: Elemental ash analysis of air classified fractions of corn stover, switchgrass, and grass clippings. Whole stover results are the actual measurements of stover, while whole switchgrass and whole grass clippings results were calculated based upon the results of the individual fractions.

Stover	% Ash	as SiO ₂	as Fe ₂ O ₃	as Al ₂ O ₃	as Na ₂ O	as TiO ₂	as CaO	as K ₂ O	as MgO	as SO ₃	as P ₂ O ₅	as MnO	Halogens
Below Screen	19.19%	12.25%	0.49%	0.72%	0.20%	0.028%	1.50%	1.31%	0.32%	0.18%	0.24%	0.011%	719.30
7.5 Hz - Light < #80 Sieve	30.35%	22.77%	0.89%	1.14%	0.28%	0.051%	1.82%	1.79%	0.58%	0.32%	0.38%	0.020%	1101.55
7.5 Hz - Light > #80 Sieve	7.70%	3.83%	0.04%	0.03%	0.02%	0.002%	0.94%	1.70%	0.29%	0.21%	0.37%	0.009%	367.33
10 Hz - Light	6.85%	3.53%	0.08%	0.07%	0.02%	0.004%	0.73%	1.65%	0.25%	0.17%	0.28%	0.007%	332.37
15 Hz - Light	6.44%	3.22%	0.06%	0.06%	0.02%	0.003%	0.67%	1.59%	0.24%	0.16%	0.25%	0.007%	305.33
18 Hz - Light	4.28%	1.27%	0.03%	0.03%	0.01%	0.001%	0.44%	1.41%	0.20%	0.12%	0.16%	0.004%	220.90
28.5 Hz - Light	4.00%	0.90%	0.03%	0.03%	0.02%	0.001%	0.37%	1.59%	0.19%	0.13%	0.17%	0.003%	221.21
28.5 Hz - Heavy	4.32%	1.80%	0.13%	0.08%	0.02%	0.004%	0.25%	1.42%	0.12%	0.10%	0.14%	0.003%	223.37
Whole Stover	6.26%	2.98%	0.09%	0.09%	0.03%	0.005%	0.59%	1.53%	0.22%	0.14%	0.22%	0.006%	309.41

Switchgrass	% Ash	as SiO ₂	as Fe ₂ O ₃	as Al ₂ O ₃	as Na ₂ O	as TiO ₂	as CaO	as K ₂ O	as MgO	as SO ₃	as P ₂ O ₅	as MnO	Halogens
Below Screen	3.41%	1.59%	0.09%	0.05%	0.13%	0.004%	0.24%	0.61%	0.38%	0.11%	0.14%	0.008%	153.19
7.5 Hz - Light < #80 Sieve	10.43%	6.69%	0.21%	0.22%	0.15%	0.016%	0.76%	0.90%	0.74%	0.22%	0.28%	0.018%	550.71
7.5 Hz - Light > #80 Sieve	6.55%	4.05%	0.04%	0.02%	0.12%	0.001%	0.59%	0.72%	0.62%	0.18%	0.21%	0.014%	319.95
10 Hz - Light	5.35%	3.12%	0.05%	0.02%	0.11%	0.001%	0.42%	0.67%	0.53%	0.15%	0.18%	0.011%	256.97
15 Hz - Light	2.70%	1.22%	0.03%	0.01%	0.11%	0.001%	0.17%	0.55%	0.35%	0.09%	0.11%	0.006%	120.71
15 Hz - Heavy	2.46%	1.05%	0.03%	0.01%	0.12%	0.001%	0.16%	0.54%	0.32%	0.09%	0.10%	0.005%	108.73
Whole Switchgrass	4.65%	2.62%	0.05%	0.03%	0.12%	0.002%	0.36%	0.64%	0.47%	0.13%	0.16%	0.010%	223.44

Grass Clippings	% Ash	as SiO ₂	as Fe ₂ O ₃	as Al ₂ O ₃	as Na ₂ O	as TiO ₂	as CaO	as K ₂ O	as MgO	as SO ₃	as P ₂ O ₅	as MnO	Halogens
Below Screen	27.23%	17.33%	1.88%	0.72%	0.35%	0.090%	2.35%	1.84%	0.66%	0.02%	0.62%	0.426%	988.37
7.5 Hz - Light < #80 Sieve	46.33%	29.75%	2.00%	0.71%	0.34%	0.106%	3.58%	5.17%	1.45%	0.03%	1.93%	1.483%	2836.92
7.5 Hz - Light > #80 Sieve	14.40%	9.84%	0.84%	0.28%	0.14%	0.042%	0.93%	1.15%	0.37%	0.01%	0.37%	0.300%	691.40
10 Hz - Light	13.18%	6.85%	0.31%	0.14%	0.06%	0.016%	1.52%	2.13%	0.55%	0.01%	0.83%	0.614%	1077.80
15 Hz - Light	12.19%	5.65%	0.25%	0.10%	0.05%	0.012%	2.11%	1.99%	0.58%	0.01%	0.70%	0.545%	801.86
15 Hz - Heavy	11.38%	5.25%	0.52%	0.19%	0.10%	0.028%	2.43%	1.38%	0.54%	0.01%	0.47%	0.333%	294.85
Whole Grass Clippings	14.18%	7.77%	0.49%	0.19%	0.09%	0.025%	1.73%	1.92%	0.55%	0.01%	0.71%	0.532%	909.93

Table 4. Feedstock Logistics costs for corn stover, switchgrass and grass clippings. Logistics costs are per ton of feedstock. Ranges are shown for transportation costs of corn stover and switchgrass because transportation costs increase as more feedstock is utilized (must go farther to get additional feedstock).

Logistics Operations	Corn Stover	Switchgrass	Grass Clippings
Harvest and collection	\$20.29	\$26.59	\$0.00
Transportation	\$2.28 - \$6.44	\$2.74 - \$7.75	\$15.84
Preprocessing	\$31.42	\$27.12	\$59.07
Storage	\$5.64	\$8.89	\$0.47
Handling	\$1.93	\$1.33	\$3.69
TOTAL LOGISTICS	\$61.56 - \$65.72	\$66.67 - \$71.68	\$79.07

Figure

Figures 1A-1C: Whole ash concentrations in stover, switchgrass, and grass clippings as high ash fractions are removed. All data points represent the mean of 3 replicate samples. Error bars represent propagated standard deviations of the measured data.

Figures 2A-2C: Silicon (as SiO₂) concentrations in stover, switchgrass, and grass clippings as high ash fractions are removed. All data points represent the mean of 3 replicate samples. Error bars represent propagated standard deviations of the measured data.

Figures 3A-3C: Aluminum (as Al_2O_3) concentrations in stover, switchgrass, and grass clippings as high ash fractions are removed. All data points represent the mean of 3 replicate samples. Error bars represent propagated standard deviations of the measured data.

Figures 4A-4C: Potassium (as K_2O) concentrations in stover, switchgrass, and grass clippings as high ash fractions are removed. All data points represent the mean of 3 replicate samples. Error bars represent propagated standard deviations of the measured data.

Figure 5. Flow diagram for an air classification process that separates corn stover and grass clippings into heavy and light fractions. The heavy fractions are blended with switchgrass to produce biochemical conversion feedstocks (green) and the light fractions are used to produce a biopower feedstock (blue).

Figure 6. Basic element to acidic element ratio for air classified fractions of corn stover, switchgrass and grass clippings

Figure 7. Feedstock blends of air classified corn stover and switchgrass as a function of ash content and cost. The dockage curve represents the blend cost plus dockage.

Figure 8. Blends of air classified grass clippings and switchgrass as a function of ash content and cost. The dockage curve represents the blend cost plus dockage.