



Washing sorghum biomass with water to improve its quality for combustion



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HIGHLIGHTS

- Washing sorghum biomass with water improves its quality for combustion.
- Biomass composition changes based on the amount of water used as part of the washing treatment.
- The value of leachates within a closed-loop system of sorghum production needs to be evaluated.

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ABSTRACT

Sorghum [*Sorghum bicolor* (L.) Moench] is ideally suited as an energy feedstock given its versatility as a single source of starch, sugar, and lignocellulose. Alkali oxides, halides and ash content can be problematic when feedstock is intended for combustion applications because these elements can lead to slagging and fouling of boilers. Solutions for counteracting the alkali content of herbaceous biomass include chemical addition to neutralize alkali, blending high-alkali biomass with low-alkali sources to achieve an acceptable ash-fusion temperature in the resulting mixture, and removal of the alkali content through washing techniques. The objective of this experiment was to investigate the effect of washing sorghum biomass with water to improve its quality for combustion. Biomass separated in 1-kg replicates were washed with 7.6, 15.2 and 22.8 L of water and analyzed for composition. Ash content was reduced by up to 20% while lignin content increased up to 53% with washing. Higher heating values significantly increased by washing and were inversely correlated with ash and positively correlated with lignin content. Nitrogen, chlorine, calcium, magnesium and potassium were reduced by washing. In contrast, carbon, hydrogen, silicon, aluminum, titanium, iron, sodium, sulfur (as % of ash), and phosphorus significantly increased by washing. When calculated, total alkali kg/GJ decreased with washing to levels close to those known to be acceptable for combustion. Further experiments should be performed to understand the economics of washing sorghum biomass at a commercial scale as well as the potential value of leachates within a closed-loop system of sorghum feedstock production.

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1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a fast-growing, C4 photosynthesis crop that has established low-cost, mechanized agronomics, harvesting and logistics. Compared with corn [*Zea Mays* L.] production, sorghum consumes 30–50% less water, significantly less pesticides and much less energy from the reduced irrigation and fewer chemical inputs [1]. Sorghum production is also expected to minimize indirect land use change impacts by utilizing more marginal lands [2]. Sorghum is ideally suited as an energy feedstock given its versatility as a single source of starch, sugar and lignocellulose. These attributes make sorghum uniquely

positioned as an adaptable, economically viable biomass source that is fit-for-purpose for both traditional and advanced liquid bio-fuel products and technologies as well as for emerging markets such as green power and renewable chemical production.

Alkali content in annual grasses such as corn and sorghum can be problematic when the biomass is intended for combustion applications [3]. The alkali content in biomass causes a low ash fusion temperature which can lead to slagging and fouling of boilers [3]. Solutions for counteracting the alkali content of herbaceous biomass include addition of chemicals to neutralize the alkali [4], blending high-alkali biomass with low-alkali biomass to achieve an acceptable ash fusion temperature in the resulting mixture, and removal of the alkali content through washing techniques [3,5–9].

There is a general agreement in the literature of the utility of washing biomass in order to reduce several undesirable chemical

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constituents including potassium, sodium, and chlorine [5,10–12]. A high proportion of alkali, over 90% in some cases, can be present in a water-soluble form [5,7–9]. However, the process of washing with water has different levels of impact on biomass quality depending on the nature of the biomass and also the physical processing (e.g., chopping and milling) prior to washing [5]. Washing techniques are more effective at removing ash and alkali from herbaceous biomass than woody biomass, presumably because of the nature of the interactions between the alkali components and the differences in structure of the cell wall [8,13]. To our knowledge, the use of water washes to improve biomass quality by reducing ash and/or alkali content of sorghum has not been reported in the literature. Therefore, we set out to investigate the effect of washing sorghum biomass with water to determine its effect on quality for combustion in power-generating plants.

2. Materials and methods

2.1. Sorghum biomass samples

Sorghum forage samples (sweet forage sorghum hybrid SS405; Chromatin Inc., Chicago, IL, USA) were collected on 29 November, 2011 from Chromatin's sorghum breeding nursery located near Idalou, TX, USA. The sorghum hybrid used was relatively dry ($\approx 50\%$ moisture content) at the time of harvest. Thirty-two sorghum stalks were cut at approximately 8 cm from the base of the plant and the panicles removed. Stalks were processed through a wood chipper with a 20:1 waste reduction ratio (Earthquake Lawn and Garden series 1150; Earthquake Company, Cumberland, WI, USA). After processing the stalks, the resulting chopped biomass was thoroughly mixed and immediately separated into 15 individual 27.9×45.7 cm muslin cloth bags (Hubco Inc; Hutchinson, KS, USA) containing one kg of material each.

2.2. Washing treatments

Washing treatments were conducted with tap water obtained from New Deal, TX, USA public water supply with a temperature of $\approx 20^\circ\text{C}$. A total of five washing treatments were applied to the processed and bagged sorghum biomass. Washing treatments were carried by holding the bags open and pouring water over the material slowly (45 s per 7.6 L) ensuring even application over the entire exposed area. Water was applied in five different treatments: 7.6 (single wash), 15.2 (double washed) and 22.8 L (triple washed); 1 h soak with 7.6 L (soaked biomass); and an untreated control. For the rinsing treatments, water was applied in 7.6 L aliquots. The soaked biomass treatment was conducted using plastic containers filled with 7.6 L of water with samples being submerged for one hour. After each washing treatment, samples were hung on the side of a 117 L plastic container (Roughneck Storage Box, Newell Rubbermaid, Inc.; Atlanta, GA, USA) for 24 h to drain excess water. All treatments were independently replicated three times.

2.3. Drying and milling biomass

Twenty-four hours after each washing treatment, moist samples were dried at $\approx 50^\circ\text{C}$ degree for three days. Dried samples were then brought to the laboratory and each sample was milled to a size of 2 mm (No. 4 Thomas Wiley mill, Thomas Scientific, Swedesboro, NJ, USA) and submitted for compositional analysis. At all times, processed biomass samples were handled with extreme care to avoid biomass losses (e.g., pieces and dust) or contamination that could have affected its compositional analysis.

2.4. Analytical

Analysis of biomass samples for compositional quality was performed by Huffman Laboratories, Inc (Golden, CO, USA) and included ultimate analysis (i.e., carbon, hydrogen, nitrogen, sulfur, and oxygen by difference; ASTM D3176), proximate analysis (i.e., moisture, ash, volatile matter and fixed carbon; ASTM 3172), higher heating value (HHV; ASTM D5865), total halogen (i.e., chlorine, bromine, and iodine), chlorine, and ash elemental composition analysis (i.e., refractory, alkali, alkali-earths, metallic and non-metallic materials; ASTM D6349). In addition to the aforementioned analyses, alkali kg/GJ was also calculated using the following equation:

$$\text{Alkali (kg/GJ)} = \frac{1 \times 10^6}{\text{HHV (kJ/kg)}} \times \frac{\% \text{Ash}}{100} \times \left(\frac{\% \text{K}_2\text{O} + \% \text{Na}_2\text{O}}{100} \right) \quad (1)$$

where ash is reported as percentage of fuel and the sum of the alkali metals ($\% \text{K}_2\text{O}$ and $\% \text{Na}_2\text{O}$) is reported as % of the ash content [3]. Ash content (as a percent of fuel) was measured after sample incineration at 750°C for 8 h. In addition, to determine the effect of washing on lignin content, samples were also submitted to Dairyland Laboratories, Inc (Arcadia, WI, USA) for lignin content analysis using an acid detergent lignin method [14].

2.5. Statistical analysis

Analysis of variance (ANOVA) was used to determine differences among treatments [15]. Prior to ANOVA analysis, residual plot analysis and the Box–Cox procedure [15] were used to determine if transformations of the data were needed to fulfill ANOVA assumptions. When significant effects of treatments were found, means were separated using Tukey's studentized range test (HSD) at $\alpha = 0.05$. In addition, regression analysis was used to understand the relationship between HHV and ash and HHV and lignin [16].

3. Results and discussion

3.1. Total ash and lignin

There was a reduction (i.e., compared to the untreated check) in % ash as a result of washing sorghum biomass with tap water ($F = 35.4$; $df = 4, 10$; $P < 0.0001$) (Table 1). A 14% ash content reduction was achieved after a single wash. In addition, a further reduction in ash content was observed with a triple washing for a maximum reduction of approximately 20%. Interestingly, soaking sorghum biomass was comparable to all other washing treatments. The reduction in ash content by washing is likely the result of the removal of soluble ash components from the biomass (e.g., as indicated by the soaked treatment) and the potential physical removal of some water-insoluble ash elements by the water stream. Jenkins et al., 1996 [5] also reported a reduction in ash content for both rice (maximum ash reduction of 10%) and wheat straw (maximum ash reduction of 68%) after washing biomass with both tap and distilled water. Differences in ash reduction among fuel sources appear to be related to both experimental procedures and the inherent nature of the fuel.

Washing sorghum biomass caused an increase in lignin concentration ($F = 25.6$; $df = 4, 10$; $P < 0.0001$) (Table 1). Lignin content in sorghum biomass samples increased up to 53% by washing; however, no differences among washing treatments were observed (Table 1). This increase in lignin concentration with washing likely resulted from the inherent insolubility of lignin in water. Therefore, after water-soluble components are removed during the

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