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Original Research Paper

Comparison and explanation of predictive capability of pellet quality metrics based on fundamental mechanical properties of ground willow and switchgrass

Apoorva Karamchandani *, Hojae Yi, Virendra M. Puri

Department of Agricultural and Biological Engineering, The Pennsylvania State University, PA, United States

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ABSTRACT

Willow is a light-weight and uniform-grained hardwood, which is a promising bioenergy crop. In this study, physical and mechanical properties of ground willow and quality of willow pellets were determined and compared with already published properties of more commonly used bioenergy crop, i.e., switchgrass. Rational explanations were provided for why certain mechanical properties were correlated well with pellet qualities. To that end, willow was ground with two different screen sizes (3.175 mm and 6.350 mm) and conditioned at two moisture contents (17.5% and 20.0% w.b.). The physical and mechanical properties of ground willow and pellet qualities were determined. Ground willow and switchgrass exhibited similar trends of mechanical properties, however, the magnitudes were different. For ground willow, compression index correlated well with strength of willow pellets, however, bulk modulus and spring-back index showed high correlations in case of switchgrass. This could be an attribute of different physical properties, i.e., particles size distribution, bulk density, and particle density, and chemical compositions. Higher levels of lignin present in willow than switchgrass might produce significant effect of resistance to compressibility. Ground willow underwent plastic deformation, which resulted in a high correlation to compression index. Ground switchgrass was dominated by elastic responses thus highly correlated to bulk modulus and spring-back index.

1. Introduction

Wood pellets are gaining popularity as one of the most effective and cost-saving bioenergy resource. To meet the U.S. Department of Energy (DOE)'s goal to supply 36 billion gallons of renewable transportation fuels by 2022 [1], more potential bioenergy crops should be researched for better utilization possibilities. In recent years, studies have shown the importance of short rotation woody crops, such as willow, as another promising candidate in meeting bioenergy demand in the U.S. [2,3]. Willow is a light weight and uniform grained wood, which has ability to resprout after multiple cuts including tolerance for dense planting [4,5]. Willow's bending and breaking strengths are very low, but the shear strength and side hardness are comparable to the weaker intermediate weight woods [5]. In addition, these willow crops have a low nutrient and nitrogen demand compared to other crops [6]. These properties and growth characteristics suggest that the short rotation willow is a high yield crop suitable to be a sustainable bioenergy source.

Willow wood chips can be pelletized to increase the energy density and bulk density of loose biomass. Several factors such as moisture content, temperature, feedstock constituents, and physical properties of feedstocks, play an important role in achieving the desired pellet quality [7,8]. However, the current practice of pelletization lacks quality control of raw biomass [9] resulting in pellets with inconsistent quality. Since pelletization is greatly affected by physical and mechanical properties of ground biomass [7], it is important to study and monitor these ground biomass' properties to ensure reliable production of pellets with desirable quality. Monitoring ground biomass' properties will enable more systematic control of pellet quality and reduce energy input of production. Bulk modulus, compression index, and spring-back index (Table 1) are three of the most relevant mechanical properties of ground biomass for pellet quality assessment since these properties are indicators of elastic and elastoplastic deformation of granular materials [10]. In a previous study conducted by Karamchandani et al. [9], the values for mechanical properties at 70 kPa and

* Corresponding author.
E-mail address: axk1005@psu.edu (A. Karamchandani).

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Table 1
Fundamental mechanical properties and their significance.

Parameter	Significance
Bulk modulus	Measure of material's resistance to volumetric deformation
Compression index	Quantification of compressibility of powder at given isotropic pressure
Spring-back index	Characterization of powder's ability to swell or relax after release of pressure

95 kPa are highly correlated, i.e. $R^2 > 0.80$, with the strength of pellets, which reports a direct and positive correlation between fundamental mechanical properties of ground switchgrass and pellet qualities. It was observed that, during the early densification stage (<100 kPa), the loose biomass compresses by volume about 40% based on the hydrostatic triaxial compression (HTC) data [9]. This illustrates the importance of the volume reduction during early stages of the densification process and its contributions to the eventual pellet quality. Measurement of various properties for both the biomass feedstock as brought to a biomass densification processing facility and the quality of the densified product will enhance the efficiency of densification systems and improve the quality of products.

In a recent study, relationships between the mechanical properties, such as bulk modulus, compression index, and spring-back index, of ground switchgrass and the pellets qualities, were developed [9]. Following that approach, mechanical characterization of ground willow would be the first step towards the systematic and quantitative control of willow pellets qualities. Investigation of the fundamental properties at low pressures to understand the rationale of why certain parameters work for a biomass material will provide deeper insights in the science of densification. Accordingly, a hypothesis is formulated that willow forms pellets of comparable quality as of switchgrass and mechanical characterization can be correlated to the quality metrics of the end product, i.e. pellet. Therefore, the goal of this research is to compare and, for the first time, provide a rational explanation of why the ground materials' fundamental properties enable the predictive capability of pellet quality metrics for switchgrass and willow despite their differing biochemical composition. To achieve this goal, two specific objectives of this study are; (1) to measure physical and mechanical properties of the ground and pelletized willow and (2) to compare and explain these properties used in predictive relationships to determine qualities metrics of willow *and* switchgrass pellets.

2. Methodology

Willow wood chips (with bark) were obtained in March 2013 from Cornell University, New York State Agricultural Experiment station, Geneva, NY (Fig. 1). Two important parameters, size reduction, and moisture content, were considered for preconditioning of the materials for better pellet quality, which are the basis of the design of experiment [9]. To obtain an optimum particle size distribution as well as to minimize time and cost of pellet production, two screen sizes; 3.175 mm, and 6.35 mm, were selected for the size reduction process. Based on the review of literature and preliminary runs, two moisture content levels considered for conditioning of ground willow were 17.5% (w.b.) and 20.0% (w.b.). The moisture content of ground willow, i.e. after grinding the willow was measured by the oven drying method according to ASABE S358.2 standard [11]. Pelletization of conditioned material was performed with a farm-scale pellet mill (PelletPros, Model VI84TTFB4026AA, Dubuque, Iowa) and material was fed manually to the pelletizer hopper with a steep angle [9]. Hydrostatic triaxial compression (HTC) tests were performed using the Cubical Triaxial Tester (CTT) to determine bulk modulus, compression index, and spring back index below 100 kPa. In the HTC stress path, equal stress and stress increment is applied in all three principal directions. Details of methods and test conducted, number of replicates, and instruments used for this study are given in and explained by Karamchandani et al. [9]. Samples of willow chips were sent to the New York State Agricultural Experiment Station (Cornell University, Geneva, NY) for high-resolution thermogravimetric analysis (HR-TGA) to obtain its biochemical composition [12,13] (Table 2).

3. Results and discussion

3.1. Physical properties of ground willow

Fig. 2 presents the particle size distribution of ground willow size reduced with 3.175 mm and 6.35 mm screen size. The values of D_{50}, particle density, and bulk density of ground willow reduced with screen sizes 3.175 mm and 6.35 mm are presented in Table 3a. Particle density and bulk density of ground willow size-reduced using 3.175 mm screen is higher compared with than that size-reduced using 6.35 mm screen The screen size has a significant effect ($p < 0.05$) on: (1) D_{50}, (2) bulk density, and (3) particle density. In comparison with ground switchgrass, the particle densities are not significantly different for respective screen size reduced biomass, however, bulk densities are significantly different ($p < 0.05$). Since bulk density depends on the particle size distribution (note that D_{50} for the two materials are different) and particle shape, the bulk densities of ground switchgrass and willow are significantly different ($p < 0.05$). Particle density is the true density of the material, which is measured using ultrapure Helium gas in a pycnometer. Since the basic building block of plant-based materials consist of glucose units that are linked together by glycosidic bonds [14], in the limit as the biomass material is ground to finer and finer particles, the particle density of biomass materials is expected to converge to a unique value.

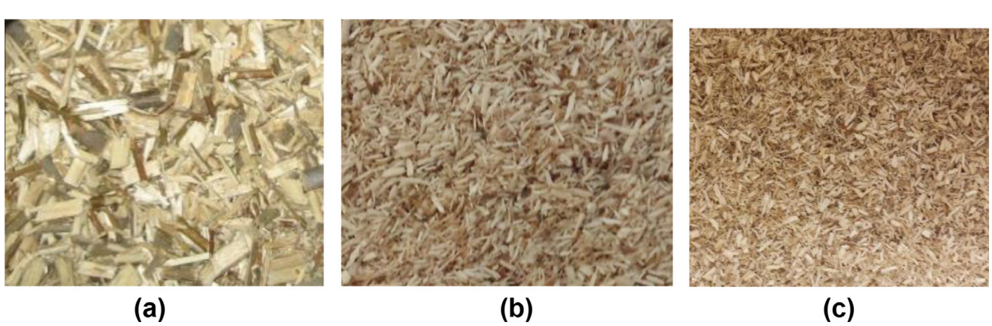

Fig. 1. Photographs of (a) as received willow chips, (b) ground willow with 3.175 mm screen size (5.5 ± 0.3% w.b.), and (c) ground willow with 6.35 mm screen size (5.3 ± 0.4% w.b.).