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Research paper

Study on the quality of oat hull fuel pellets using bio-additives

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A B S T R A C T

Fuel pellets made from compressed biomass represent an important product for energy sector as they are used as a fuel for power generation and for residential heating appliances such as boilers and furnaces. As an available agricultural residues in Saskatchewan, Canada, oat hull was considered as a feedstock for the fuel pellets. In this study, the effect of bio-additives, such as lignin and amino acids, on the quality of the oat hull pellets was investigated using single pelleting unit. The oat hull feedstock was characterized using different methods including FI-IR, XRD, TGA, solid state NMR, and Raman spectroscopy. Proline was found to be the best amino acids to be used as an additive with lignin. Results have shown that pellets with lignin content $\geq$15% and proline content $\geq$5% had the highest density, durability, and hardness. In addition, ash content and HHV of the pellets increased with increasing lignin content. Increasing die temperature and compression force enhanced the quality of the pellets, whereas compression time did not have a significant effect. Even though microwave torrefaction increased the hydrophobicity and HHV of the pellets, it negatively impacted the density, durability, and hardness of the pellets. Computed tomography (CT) analysis was performed in the Canadian Light Source Inc. to visualize the internal structure of the pellets. CT analysis showed that the porosity of the pellets increased with decrease in additives content, pelletization temperature, and compression force. Microwave torrefied pellets showed higher porosity compared to that of untreated pellets.

1. Introduction

Over the last decades there have been increasing demands for energy. According to the U.S. energy information administration (EIA), the demand for energy worldwide will increase by 56% between 2010 and 2040 [1]. As an alternative for fossil fuel, agricultural residues provide a clean, renewable, and sustainable source of energy. Agricultural residues have a great potential to replace fossil fuel and to reduce greenhouse gas emission in electricity generation sector. In addition, using agricultural residues as fuel in power plants will increase the profitability of agriculture industry by adding value to the abundant low value agricultural waste. From 2001 to 2010, the average agricultural residue generated was 82.35 million dry ton/yr in Canada, in which Saskatchewan recorded the highest [2]. Oat is one of the major agricultural products in Canada. In 2015, oat production increased by 15.1% to 3.4 million tonnes in Canada [3]. Using agricultural waste as a fuel in its original form is difficult due to its irregular shape, low bulk density (<150 kg/m^3), and high cost of transportation and storage [4–6]; therefore, densification of biomass into pellets was considered to overcome these problems.

The quality of the pellets produced using pelletization method depends on several factors such as moisture content, particle size, compressive force, die temperature, chemical composition of feedstock, pre-treatment conditions, and additives. Moisture content in biomass is important ingredient in pellet formulation as it acts as a natural binding agent and lubricant [7]. In general, the pellet density of biomass increases as the moisture content decreases [8]; however, the optimum moisture content varies based on the type of biomass. According to Obernberger and Thek, high quality pellets were produced when the moisture content of the biomass was between 8 and 12% [9]. In addition, many studies have shown that finer particles produced more compact pellets [7,10]. Furthermore, pelletization at higher temperature and compression forces have a positive effect of the density and durability of the pellets [8,11]. Adapa et al., who investigated the effects of grind size, applied pressure, pretreatment, and biomass type, including canola, barely, oat, and wheat straw, on the quality of pellets, found that applied pressure and biomass type were the most significant factors affecting the density and durability of the pellets, respectively [12].

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A number of pretreatment methods have been used to enhance the mechanical strength, and moisture resistance of the pellets. Steam explosion and torrefaction are efficient methods to preheat biomass prior to pelletization. In steam explosion process, biomass is heated under steam pressure in order to make the biomass polymer more accessible to pelletization. Steam explosion was found to increase heating value, pelletization properties, and moisture resistance of various biomass pellets [13–16]. Torrefaction is a thermal pretreatment method that is based on removal of volatiles to upgrade biomass quality. Torrefaction, which is considered as a mild pyrolysis, was utilized to improve the hydrophobicity and heating value of the pellets [17,18]. Microwave torrefaction is an alternative method for conventional torrefaction that is based on conduction or conviction heating under inert atmosphere. The use of microwave pretreatment for lignocellulosic materials was initially reported by Ooshima et al. [19] and Azuma et al. [20]. Since then many researchers have used microwave torrefaction as a pretreatment for biomass [21–25].

Another important factor that affects the quality of the pellets is the additives or bindering agents. In the presence of moisture and heat, additives were used with some feedstocks to produce quality fuel pellets by positively affecting the compressibility, mechanical strength, hydrophobicity, heating value and ash content. Appropriate additives can play a key role in improvement of the physical and thermal characteristics of fuel pellets [13]. Utilizing bio-additives that are byproducts in milling and pulping industries, such as amino acids and lignin, is attractive because they can produce sustainable and environmentally friendly pellets from non-toxic and cheap materials. Kuokkanen et al. [13], who studied the effects of several bio-additives on pelletization process, found that lignosulphonate and starch additives enhanced the mechanical durability of the wood pellets. Ahn et al. have used several green additives from commercial food wastes and organic byproduct from paper and pulp industries to increase the durability and heating value of wood pellets [26].

The physical, chemical, and thermal properties of raw materials and pellets are examined to evaluate the quality of the fuel pellets. For combustion or gasification efficiency, the chemical and thermal properties, such as ash content, moisture content, heating value, and elemental composition of the raw material and pellets are important parameters to determine the quality of fuel pellets. In addition, mechanical strength, such as durability and hardness, and moisture uptake of the pellets are crucial for transportation and storage. Most of the works in the literature have focused on the physical and mechanical characteristics of the pellets such as density, durability, hardness, and moisture uptake. Scanning electron microscopy (SEM) have been used to show the bonding between different particles of various biomass pellets [27–29]. In addition, Ghiasi et al. have used TGA to analyze the thermal decomposition of wood pellets and chips during torrefaction [18]. Bryś et al. utilized scanning calorimetry (DSC) and FTIR spectroscopy to characterize different wood biomass before and after drying [30]. Studying the chemical and physical properties of the biomass raw material by different characterization techniques can help in understanding the effects of pretreatment, additives, and pelletization conditions on the quality of the pellets.

Several agricultural and wood wastes were considered for densification such as sawdust [21,27], canola meal [28], and wheat strew [29]. However, the increase demand for biomass pellets and the availability of oat hull in Saskatchewan have created interest in utilizing oat hull as a feedstock for fuel pellets. Therefore, there is a need to broaden feedstock base of the fuel pellets to meet the increase demands for fuel pellets. Few studies in the literature have considered oat hull as a feedstock for fuel pellets [15,31,32]. For residential combustion applications, Perzon found that oat pellets are environmentally friendly biofuel with relatively low emissions that is similar to that of softwood pellets [31]. Adapa et al. have studied the compression characteristics and factors affecting the densification of several biomass feedstocks including oat straw [12,14,15,32]. They found that the maximum compacting density of oat straw without binding agent was achieved at applied force of 4400 N and die temperature of 95 °C [32]. Furthermore, steam-exploded treatment of oat straw feedstock increased the density of the pellets by 19% compared to that of non-treated straw [15].

The objective of this work is to develop high-quality fuel pellets using the abundant oat hull in Saskatchewan as a raw material and bio-based additives. The effects of different bio-additives in the compressibility and mechanical strength (durability and hardness), as well as moisture uptake were investigated. The impacts of microwave torrefaction and pelletization conditions on the quality of the oat hull pellets were also examined. The oat hull feedstock was characterized using different techniques to compare the physical, chemical, and thermal properties of the raw material before and after microwave pretreatment. Furthermore, computed tomography (CT) analysis was used to examine effects of pretreatment and bio-additives on the porosity of produced pellets.

2. Materials and methods

2.1. Materials

Oat hulls used as a feedstock were obtained from Richardson Milling Limited (Saskatchewan, Canada). Additives used were purchased from Sigma-Aldrich, Oakville, Canada: L-Phenylalanine (reagent grade, $\geq$98%), L-Alanine ($\geq$98%), L-Proline (reagent plus $\geq$ 99%), and alkali-Lignin. In addition, commercial sunflower oil were used as a lubricant.

2.2. Methods

The moisture content of the ground oat hull was determined, before and after adding water, using ASTM 3173-87 method in triplicates. The ash content and volatile matter of the samples were determined by the procedure in ASTM 3174-04 and ASTMD 3175-07 methods, respectively. The oat hull was analyzed for lignin, cellulose, and hemicellulose compositions using Association of American Feed Control Officials (AAFCO) standards. CHNS elemental analysis was determined using a Perkin-Elmer Elementar CHNS analyzer (Vario EL III, Elementar Americas Inc., NJ). Sulfanilic acid was used as a standards to calibrate the analyzer, then 4–6 mg of the sample was combusted for analysis. Based on ASTM D5865 method, the high heating value (HHV) of the oat hull pellets (HHV) were determined using oxygen bomb calorimeter (Parr 6400 Calorimeter, IL, USA). Benzoic acid pellets were used for standardization of the calorimeter. The weight of the sample was measured to 0.0001 g, then it was placed into the capsule holder. The sample was attached to 10 cm of ignition thread that was connected to the ignition wire. Foureir Transform Infrared (FT-IR) spectra were recorded using a Vertex 70 (Bruker, Germany) spectrometer in the range of 400–4000 cm^{-1}. The X-ray diffraction (XRD) analysis was performed using a Bruker D8 Advance Powder diffractometer (Bruker, Germany) with a Ge monochromator CuKα radiation. The generator was operated at 40 kV and 40 mA, and the scans were recorded from 10° to 90° with a 2θ step size of 0.04. Raman spectroscopy was performed using a Renishaw Invia Reflex Raman microscope (Renishaw, Gloucestershire, UK) equipped with 785 nm laser. Each spectrum was recorded in the range of 800–2000 cm^{-1} at a resolution of 4 cm^{-1} with an average of 32 acquisitions. Thermogravimetric analysis (TGA) was carried out using TGA Q500 model instrument (TA instruments, DE, USA).