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A comparative study of biomass pellet and biomass-sludge mixed pellet: Energy input and pellet properties

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ABSTRACT

Pelletization has been widely used for mass and energy densification of biomass. As the demand for pellets increases, the conventional raw materials will be insufficient. In this study, the feasibility of sludge mixed with biomass pellets as a solid fuel was researched. Sludge mixed pellets and pure biomass pellets were investigated to evaluate the energy consumption and pellet properties, including proximate analysis, moisture adsorption, pellet density, Meyer hardness, volume expansion, higher heating value and combustion characteristics. The results showed that sludge mixed pellets had reduced energy input, increased hardness, decreased moisture absorption rate and improved combustion characteristics compared with pure biomass pellets. However, the increased ash content of sludge mixed pellets should be noted. These results indicate that there is a balance between an improvement in fuel quality and an increase in ash content. The sludge mixed pellets could be a suitable solid fuel.

1. Introduction

Currently, renewable energy developing has received considerable attention in the world. Among these renewable energies, densified biomass, especially pellets has drawn the global attention due to its advantage over raw biomass such as its physical and combustion characteristics [1]. In China, densified biomass fuel was sought by the government to replace coal in present firing plants without any significant modifications because of the rapid growth of energy demands and the dwindling reserves of fossil fuel [2]. The production capacity of pellets using agriculture wastes in China was 3 million ton in 2010, and aimed to increase to 10 million ton in 2015, furthermore reach to 50 million ton by the year of 2020 [3,4].

The primary biomass materials used for making pellets are not only wood residues, such as sawdust, wood shavings and wood chips, but also agro-residues, such as straw, waste products of the food industry and fuel crops [5,6]. Meanwhile, the pellet markets have developed fast in the past decade. Therefore, the preferred raw materials for wood pellet production, such as cutter shavings and sawdust, are consumed to the maximum extent. This results in the highly competitive raw material market among pellet making, fired power generation, charcoal, and plate industries. The competitive raw material market has been increasing the price of raw material. In recent years, various biomass materials had been used to make pellets, such as tea waste, bamboo, waste paper and wheat straw mixtures, switchgrass, cotton stalk, rapeseed cake, olive cake, palm kernel cake, corn stover, reed canary-grass, peanut hulls and poultry litter [7–10]. However, it is not enough at all with the development of pellets industry. On the other hand, the mechanical strength and hardness of pellets made from the above biomass were always unsatisfactory as mixing unknown biomass for pelleting procedure. The addition of binders can improve the mechanical strength. However, higher price of binder increased the feedstock cost of pelletization.

Sewage sludge (SS) is a complex heterogeneous mixture of microorganisms, inorganic materials, moisture and undigested organics including paper, plant residues, oils, or fecal material. Conventional sludge disposal methods including landfill, incineration, ocean disposal and land application are already facing increasing pressure and protest from environmental authorities and from the public domain [11]. It is known that SS contains a

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significant amount of proteins and carbohydrates, which could serve as a potential natural binder to make it suitable for pelleting [12]. Dospoy et al. [13] firstly managed to produce sludge derived fuel from paper sludge, powder coal, and plastics and realized the industrial application. Currently, several studies have been conducted, focusing on the physical properties and combustion characteristics of sludge refuse-derived fuel (RDF) [14–18]. However, the feasibility of sludge mixed with biomass to produce pellets using a single pellet press and the effect of sludge addition on the energy consumption and pellet properties have never been reported. The results of this study are significant for the feasibility of sludge applying in the current biomass pellet industry.

In this study, three kinds of raw materials (Chinese fir, camphor and rice straw) were applied for pelletization, representing softwood, hardwood and herb, respectively. Sludge mixed pellets and pure biomass pellets were investigated to compare the energy consumption and pellet properties, including proximate analysis, moisture adsorption, pellet density, Meyer hardness, volume expansion, higher heating value and combustion characteristics.

2. Materials and methods

2.1. Materials

The sludge was obtained from an urban sewage plant with aerobic and secondary treatment in Changsha city, Southern China. Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), camphor (*Cinnamomum camphora* (L.) J. Presl) and rice straw (*Oryza sativa* L.) were used to represent the class of softwoods, hardwood and grass, respectively. The elemental and proximate analysis results and some physicochemical parameters of the samples above were shown in Table 1.

2.2. Pelletization and characterization of the pellets

The pellets were prepared using a single pellet press unit which allowed simulation of the pelletizing process in a press channel of a pellet mill [19–22]. Briefly, a cylinder with 7.00 mm in inside diameter and 70.00 mm in height with a piston with 6.90 mm in diameter and 90.00 mm in length was installed for making a single pellet. The cylinder-piston unit was wrapped by a heating tape with a thermocouple and a temperature controller to preheat the inside cylinder to a certain die temperature. In this study, the hole of the cylinder was filled with approximately 0.8 g sample to make a single pellet. The sample was pressed by applying a pressure of 83 MPa and held for 30 s. Pure biomass or biomass-sludge mixtures with a ratio of 50% were used as the samples. The sample with 15% moisture content was prepared at 110 °C with the similar procedure described in a previous publication [23].

The ultimate analysis, proximate analysis, higher heating value, lignocellulose analysis and protein determination have described in a previous paper [20]. Briefly, the ultimate analysis of the raw materials was analyzed by CHNOS Elemental Analyzer Vario EL III (Elementar Analysen systeme GmbH, Germany). Proximate analysis was carried out according to the Standard Practice for the Proximate Analysis of solid biofuels (GB/T28731-2012) using a Jinghong SXL-1002 program control chamber electric furnace (China). The higher heating value (HHV) was determined using an oxygen bomb calorimeter (SUNDY SDACM5000, China) from three replicates. The amounts of cellulose, hemicellulose and lignin were obtained using Van Soest detergent fiber analysis by automated fiber extraction analyzer (Gerhardt fibretherm FT12, Germany). Protein was calculated by multiplying the concentration of organic nitrogen by 6.25. Forces and displacement curves in pelletization were recorded to calculate the energy consumption. The energy consumptions associated with compaction and extrusion were obtained by integrating the curve. Pellet density was determined by calculating the mass, length, and diameter of pellets. The volume expansion was calculated by measuring the length and diameter after storing the pellets inside a sealed bottle at 4 °C for two weeks.

Meyer hardness of pellets was analyzed by the same pellet press unit with a hemisphere-end rod. The Meyer hardness, H_m, defined as the applied force divided by the projected indentation area and was calculated by the following equation [23].

$$H_m = F/[\pi(Dh - h^2)] \tag{1}$$

where h is the indentation depth (mm); F is the maximum force when the pellet is broken (N); and D is the diameter of rod (mm).

The moisture absorption of pellets was measured in a humidity chamber (GT-TH-S-150Z, Gaotian, China) setting at 30 °C and 90% relative humidity. Prior to the moisture uptake test, the pellets were dried in a convection oven at 105 °C for 24 h. The weight of the sample was measured every 10 min at the first hours followed by every 30 min for the next 4 h. Thin-layer drying formulation as below was adapted for the kinetic analysis of moisture uptake [24].

$$\frac{M - M_e}{M_i - M_e} = e^{-kt} \tag{2}$$

where M is the instantaneous moisture content, M_e is the equilibrium moisture content, and M_i is the initial moisture content. The coefficient k is the absorption constant, and t is the exposure time (min).

Combustion characterization of the pellets was carried out by thermogravimetric analysis using a thermo-balance DTG-60 (Shimadzu, Japan). All combustion experiments were conducted from room temperature to 800 °C with a heating rate of 20 °C min^{-1} under an air flux of 100 mL min^{-1}. Approximately 6 mg of sample was used for each experiment.

2.3. SEM and UV-AF

Scanning electron microscopy (SEM) and Ultraviolet auto-fluorescence (UV-AF) were applied to study the bonding

Table 1
Properties of raw sewage sludge and biomass sample.

Analysis	Ultimate analysis (d.b. wt%)				Proximate analysis (r.b. wt%)				Chemical analysis (d.b. wt%)				HHV (MJ kg^{-1})
	C	H	N	S	Moisture	Volatile	Fixed carbon	Ash	Protein	Hemicellulose	Cellulose	Lignin	
Sludge	36.11	5.25	6.50	1.03	5.42	57.22	6.09	31.27	35.5	–[b]	–[b]	–[b]	15.59
Chinese fir	49.08	5.96	0.63	–[a]	7.63	74.49	16.68	1.20	–[b]	12.05	36.22	27.61	18.38
Camphor	48.18	6.09	0.70	–[a]	6.67	79.02	12.53	1.78	–[b]	20.82	38.87	24.40	18.40
Rice straw	45.04	5.05	1.06	–[a]	6.56	64.59	13.51	15.34	–[b]	24.60	41.33	9.22	14.64

d.b. - dry basis, r.b. - received basis.
[a] Below detection limit.
[b] Not measured.