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The effects of sugar beet molasses on wheat straw pelleting and pellet quality. A comparative study of pelleting by using a single pellet press and a pilot-scale pellet press

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ABSTRACT

The main aim of this paper is to investigate the effects of molasses on wheat straw pelleting and physical pellet quality. Molasses was added at weight fractions of 1.5% and 3%, while pure straw served as a control. The effects of molasses were examined by producing pellets in a single pellet press (SPP) and in a pilot-scale pellet press (PSPP). The second aim of this study was to compare the results obtained from the SPP and the PSPP, i.e., to understand how the information from the SPP can be used for the prediction of material behavior, process adjustments, and improvement of pellet quality in an upscale pelleting process. The production and pellet quality parameters were compared and information from the two pelleting methods was combined by response surface modeling. Pellet density was the response variable, while pelleting pressure and temperature were the independent variables. Large differences in pellet quality were observed between the two pelleting methods. These differences are discussed from the perspective of technical differences in the pelleting procedures and different fiber orientations in the pellets. The results indicate that pelleting temperature is a key factor for achieving good pellet quality of all the samples. Exceeding the glass transition temperature of lignin leads to significantly better pellet quality and facilitates pelleting. The results showed that molasses strengthens pellets produced at temperatures below the glass transition of lignin. Addition of molasses at higher pelleting temperature did not significantly affect the pellet quality and processability.

1. Introduction

Cereal straw, an agricultural byproduct, is one of the alternatives to forestry biomass, mainly because it is available in large quantities and is widely accessible. Application of agro-residues as a renewable energy source is particularly important in agricultural regions that lack forests because it can be a significant factor for rural development and sustainable agricultural production.

Straw has very low bulk and energy density; thus, densification by means of baling, cubing, pelleting, or briquetting are techniques to overcome these disadvantages. Wheat straw is a lignocellulose material with a higher amount of ash, proteins, and extractives compared to wood [1]. The chemical composition of wheat straw can vary greatly because of differences in varieties, cultivation conditions, and location [2]. Agro-residues, such as straw and energy grasses, are more challenging to densify than wood because of the lower content and different structure of lignin, the lower bulk density, and the presence of the cuticula (a hydrophobic layer of cutin and waxes on the surface of straw) [3–5]. The compaction characteristics of different agro-residues have been examined in different studies [6–8]. Research on pelleting of agro-residues has been focused on establishing a cost-competitive process without compromising pellet quality. Application of various binders and blending with wood are common ways to reinforce pellets and reduce the energy consumption for densification. Common binders are starch, lignosulphonate, crude glycerin, bentonite, and molasses [9,10]. Molasses can help binding among particles during pelleting [10–12]. Soluble sugars recrystallize after drying and cooling of compacts and form solid bridges. A major challenge and obstacle for wider application of molasses is its high viscosity and sticky nature [13]. Heating and/or dissolving molasses are approaches to facilitate its application and to improve its distribution in powders. The application of molasses as a binder in pellet production is known, but a detailed study investigating the effects of temperature, compacting pressure, and amount of molasses on various pellet quality parameters (e.g., density, strength, hydrophobicity, and water activity) is lacking.

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The single pellet press (SPP) method for testing a material's compacting properties has been widely used in recent years [14–18]. This method can provide information about the material compressibility and estimate some pellet quality properties (strength, density). Information about the processability is limited to properties linked to the die friction (p_{max}) and yield stress of materials [19]. p_{max} represents the minimum pressure required to initiate the motion of a pellet in the compressing channel at a certain speed and density [19–22]. Some studies showed how to estimate the energy consumption in a SPP by calculating the area under the pressure–displacement curve [23,24]. Significant work to understand the information from a SPP has been conducted by Holm et al. [21,25] and Nielsen et al. [15]. These studies focused on analytical and empirical studies of the pelleting process. Holm et al. [25] found that the pelleting pressure increases exponentially with pellet length in a SPP and that it also depends on the process temperature and biomass properties. Nielsen et al. [15] divided the pelleting process into three sections, aiming to estimate the contribution of each section to the overall energy consumption. The first section involves the process of material pre-compaction that occurs in the nip area of a pellet press (compression component). In the following section, located in the die entry, the material is forced to flow into the die holes (flow component). The final section involves friction between the flowing material and the die wall, as well as the energy required to move the compressed material into the die (friction component). The highest portion of energy is needed to force the compressed layer of material to flow into the die (flow component). Nevertheless, there is still a gap in the knowledge and a lack of practical strategies for applying the information from a SPP in a scaled-up pellet press. Two recent studies, by Shang et al. [26] and Puig-Arnavat et al. [27], aimed to extrapolate the results from a SPP to a bench scale pellet mill to find its optimal process parameters. However, finding more information that can aid in the application of SPP data for scale-up and/or optimization of the roller-die pellet press is important as well.

The present study has two objectives: 1) to investigate the effects of sugar beet molasses as a binder on the processability and quality of wheat straw pellets. Pellets were produced by a SPP method at different temperatures and compacting pressures, and in a pilot-scale pellet press (PSPP); and 2) to compare results from SPP and PSPP pelleting, i.e., to understand how the information from a SPP can be used for anticipating material behavior, processing, and product quality in roller-die pellet press pelleting.

2. Material and methods

2.1. Material

The wheat straw (*Triticum aestivum* L. ‘Simonida’) was collected after the summer harvest in 2014 in the Serbian northern province of Vojvodina. Straw bales were placed in dry storage until they were used, for about two months. Before preparing the material for pelleting, the moisture content in the straw was 10.62 ± 0.09%. The moisture content was determined by drying in an oven (Memmert UNB400, Memmert GMBH, Schwabach, Germany) at a temperature of 105 °C in air atmosphere until constant mass is achieved (EN 14774-1) [28].

The sugar beet molasses used in the experiment was obtained from Crvenka Sugar Factory a.d. in Serbia. The dry matter content in the molasses was 84%, as determined refractometrically by an Abbe 5 refractometer (Carl Zeiss Jenna, Switzerland) following the SRPS E.L3.020:1963 standard [29].

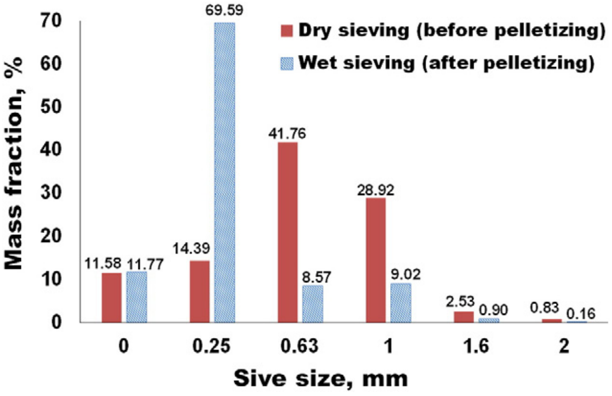

Fig. 1. Particle size distribution of the straw before (dry sieving) and after (wet sieving) PSPP pelleting.

The wheat straw was ground by a hammer mill (Type 11, ABC Inženjering, Pančevo, Serbia) with a screen size of 3 mm. The particle size distribution (PSD) of the ground straw was determined by a sieving test; the results are presented in Fig. 1. The ground material was moisturized to 21% moisture content by spraying water through a nozzle (Düsen-Schlick GmbH, Germany, Model 970) adapted to a double-shaft pedal mixer/vacuum coater (F-6 RVC, Forberg, Norway). The moisturized material served as a control sample (referred to as PS below). Molasses was added in two different amounts, 1.5% (M_1) and 3% (M_2), by spraying previously dissolved molasses over the bulk straw powder in the mixer. The moisture content was the same (≈21%) for all three mixtures. The moisture content was determined by MB45 thermogravimetric moisture analyzer (Ohaus, USA), following the procedure described in the instruction manual [30]. Bulk densities of the raw materials was measured in a bulk density tester (Tonindustrie, West und Goslar, Germany). The bulk density was determined by measuring the mass of 1 l of material that has been loosely poured into the tester's cylinder. The water activity value (a_w) was determined by a Rotronic HygroLab C1 (Switzerland) instrument [31]. The average temperature during a_w measurements was 22.3 ± 0.3 °C. The content of ash and volatile matters was determined in a muffle furnace (Nabertherm D-2804, Germany) according to EN 14775 [32] and EN 15148 [33] standard procedure, respectively. The fixed carbon was calculated by difference between 100 and the sum of the volatile matter and ash content. The higher heating value (HHV) was determined by an adiabatic bomb calorimeter IKA C 200 (Germany), following the EN 14918 standard procedure [34].

2.2. Pellet production

In this study, pelleting of the straw with different molasses levels was tested in a PSPP (Model 14-175, Amandus Kahl GmbH&Co., KG Germany) and a SPP designed and manufactured at the Norwegian University of Life Sciences (Ås, Norway) [14,17,19]. Straw was ground, moisturized, and mixed with molasses just before PSPP pelleting. The same powders were stored in plastic bags at +4 °C until further usage for single pellet production.

1) Cold pelleting (without steam conditioning) was performed in a pilot-scale production facility at the Institute of Food Technology (FINS) in Novi Sad, Serbia. Pellets were produced in a flat die pellet press with a die compression ratio of 3 (die hole diameter 6 mm, die thickness 18 mm). Samples of pellets were taken when steady-state production was achieved. The temperature of the outer surface of the die and the temperature of the pellets exiting the die hole were recorded. The die surface temperature was measured on the outer die wall by using a PT100 resistance thermometer. The pellet temperature was measured by a contact thermometer placed in the bulk of pellets after they exited the die. The production rate was 5.1 kg/h at a steady temperature of about 80 °C. The specific