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Research article

Hay pellets — The influence of particle size reduction on their physical–mechanical quality and energy demand during production

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ABSTRACT

The densification of hay into pellets will be a complex undertaking, strongly affected by its raw material characteristics as well as the technology used. The physical–mechanical properties of such pellets are most important and highly dependent on grinding, conditioning and the operation of the pellet press. This study tries to evaluate the most efficient way of producing high quality hay pellets by finding the lowest specific energy input while achieving the highest bulk density and durability values of the pellets in accordance with ISO 17225-6. Therefore, the performance of three different grinding techniques was researched: cutting, impact and hammer mill with different influencing parameters (mesh sizes of 2, 4, and 6 mm, with or without additional aspiration). Afterwards, the densification of the ground material in a ring die press was investigated. Eventually, a hammer mill with a 4 mm mesh was found to yield hay pellets with the required bulk density and durability while having the lowest specific energy input ($E_{spec,total}$ 157 Wh/kg).

1. Introduction

CO_2 reduction goals set by governments around the world and the motivation for regional energy self-sufficiency increased the interest in alternative biomass fuels from straw, miscanthus or hay, especially in countries such as Germany. With the international quality standard ISO 17225-6 [1] for non-woody biomass pellets, the foundation for an increasing commercial utilization of a wide range of biomass was laid in 2014.

Generally, during pelletizing loose material is transformed into a bulk cargo with defined physical–mechanical properties. Furthermore, combustion plant can be specifically tailored to these standardized fuel properties so that a high degree of efficiency is reached while minimizing emissions. In Germany targeted research initiatives were undertaken to have boiler systems be certified for such fuels according to 3 para. 1 no. 8 to bring the 1st BImSchV. However, besides the development of appropriate combustion technology, a lot of the feedstock potentials are yet untapped for energetic purposes.

Hay, for instance, is currently produced on 4.6 Mio. ha of permanent grassland in Germany [2] while it additionally occurs a residual material in the landscape conservation and management. Especially in the framework of NATURA 2000 nature protection areas non-woody material may occur as a residue, since these areas need to be cut once or twice a year while the traditional use as animal feed is often obsolete. The fodder quality is low (fiber-rich and protein-poor) due to the late mowing [3].

The higher degree of lignification of the raw material is of advantage for the energetic utilization as it has a positive effect on energy content [4]. Yet, herbaceous biofuels, usually require higher boiler maintenance due to critical ingredients [3,6,7]. The harvest date as well as the procedure for making bales, the soil condition and the plant population has great influence on the chemical composition, in particular the content of nitrogen, sulfur, chlorine and minerals. High ash will not only cause high abrasions during the grinding and pelletizing processes but also increase slagging tendency during combustion. High contents of nitrogen, sulfur and chlorine are often linked to technical problems during the combustion process and increased emissions [6,8]. However, since hay has a low water content (≤12 wt.%) and comparatively high energy content, it is an ideal substrate for pelletizing and an subsequent combustion, especially since no further drying of the raw material is necessary.

The production of pellets with high physical–mechanical qualities is highly dependent on the following two categories and their related parameters: (i) raw material and (ii) process parameters. The particle size distribution, the moisture content and a homogeneously distributed mixture of the ground materials are important raw-material parameters. Mani et al. [9] studied the influence of particle size and moisture content on the pellet density by using a single pellet press (SPP) on wheat and barley straw, corn stover and switchgrass. In their study the corn stover sample yielded the highest pellet density when using a hammer mill with 3.2 mm screen size and a moisture content of 12 wt.%. A little different result for pelletizing of barley straw was found by Serrano et al. [10]. In their study the optimum moisture

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content for barley straw pellet production proved to be in the range of 19–23 wt.% and there was no difference found in pelletizing barley straw ground with either 4 or 7 mm screen size. However, in this study a pilot-scale pellet plant was used. Theerarattananoon et al. [11] studied the pelletizing of corn stover, sorghum stalk and wheat straw by using a ring die pellet-press. A maximum durability was achieved at a moisture content range between 9 and 14 wt.% for corn stover and wheat straw and 14–16 wt.% for sorghum stalk. In their study using a larger hammer mill screen-size (screen opening of 6.5 instead of 3.2 mm) resulted in increased of bulk density, true density and durability of biomass pellets. Other studies investigated the influence of blending different materials e.g. adding pine to barley straw [10], adding miscanthus to wood [12,13], blending hay and digestate [14], pine and rapeseed cake [15] or pine and bark [16].

Important process parameters are the geometry of the die [11,17], the gap between roller and die (compression pressure) [14] and the press capacity (often referred to as flow rate). The process parameters which received most attention were the compression temperature and pressure when using a hydraulic press (SPP) [9,18–23]. Independent of the raw material, a similar trend could be observed in most studies: the temperature had a greater effect on pellet quality than the pressure. Increasing the temperature or the moisture content resulted in a decrease of the pelletizing pressure. Mostly the pelletizing pressure increased with decreasing particle size. However, a flat or ring die press is state of the art for pelletizing biomass and results obtained by SPP can only be used as indications for processes occurring in a full scale pellet press.

In order to produce high quality pellets from herbaceous biomass a few basic principles need to be understood. Fibrous materials, such as hay, are kept together mostly by interlocking bonds [24]. Therefore a suitable wide particle size distribution for closing gaps and holes between the fibers during densification of herbaceous biomasses is necessary. In contrast, for compression of woody biomass (e.g. beech) an area of solid bridges due to lignin softening and inter-diffusion between adjacent wood particles is observed [25]. Further, bindings with material bridges can occur formed by natural binders such as lignin, proteins and starch at the corresponding process temperatures and/or water contents [24–26]. Thereby *van der Waals*-forces and hydrogen bonding are significant. Probably, the particle size distribution had a minor effect on the physical–mechanical characteristics of produced wood pellets. Bergström et al. [27] studied this effect for producing Scots pine sawdust fuel pellets. For reducing the production costs it is mainly important to have particles of below 8 mm or otherwise the raw material should be sieved before. The observance of the standardized physical–mechanical properties of hay pellets and the achievement of an optimal fiber composition can be influenced positively by an optimal grinding and homogenization using a suitable grinding technology. The fine grinding is the first essential process step for the pellet production. As a result of the grinding, a homogeneous material with a uniform fiber degree is produced. For the production of pellets with a diameter of 6 mm, a particle size of the raw material of <4 mm is required (for wood pelletizing [28]), in order to avoid too long fibers and additional grinding effects associated with higher energy inputs during pelletizing. During the grinding process diverse mills with different kinds of stress such as friction, shearing, and cutting or impact are considered for the size reduction of herbaceous biomass [29]. Hammer mills are state of the art and create mainly beating forces. Thus, hammer mills for grinding various biomasses are used in most investigations [9–11,14,16–18,22]. Using thin and more instead large and less hammers the grinding result is higher for herbaceous biomass [17]. For causing a mass flow increase an additional aspiration during the grinding process can be used. Generally, the advantages of an additional aspiration are: continuously transportation of the ground material with simultaneous dust removal, cooling the material and the mill as well as reduction of the specific energy input [30]. The influence of additional aspiration on the particle size distribution has not been studied yet. Most particle size distributions of ground biomass were characterized with a standardized sieving method [9,21,27,31–33]. However, ground biomasses are not spherical particles but rather long fibers. Though, an alternative method for characterizing the hay fibers was used in this study.

Researches with semi-industrial plants are highly complex and time-consuming and the pelletizing characteristics of hay in such plants have not been researched sufficiently until now. In the study presented here focus was put on finding the most suitable combination of raw-material and process parameters. The goal is to achieve highest pellet quality with the least energy consumption during the pelletizing process. Several types of mills were tested for their energy input and influence on pellet quality parameters. The physical and mechanical pellet properties in accordance with ISO 17225-6 [1] were compared and specific energy input for pellet production was measured.

2. Material and methods

2.1. Raw material

In accordance with nature protection and landscape conservation schemes eight different batches of hay were harvested in late summer (between the end of August and early September) from the regions Havelland (Brandenburg, Germany, hay batches A–E) and Meissen (Saxony, Germany, hay batches F–H) (Table 1). Hay batches A–E are from four different locations (H1–H5) while hay batches F–H are from the same location (H6) harvested in three consecutive years. Table 2 summarizes the moisture and ash content as well as the lower heating value of the selected hay batches in comparison with the thresholds provided by ISO 17225-6 [1]. The analyses were performed according to European standards.

In order to further characterize the hay samples and to draw conclusions on possible binding mechanisms common feed analysis [37] were performed on a selection of samples (see Table 3). Crude fiber (CF) can be seen as the sum of the cell wall material including cellulose, hemicellulose and lignin. Crude lignin (CL) was also analyzed as a separate fraction as well as the crude protein (CP) and the non-fiber carbohydrates.

The preparation of the material was carried out after evaluation of the chemical analyses. Grinding and pelletizing experiments were performed for one representative hay batch (C). This batch has the lowest ash content as well as the highest lower heating value at once and is conceivable for further combustion tests.

2.2. Milling and evaluation of ground raw material

The hay was delivered in round bales (diameter 1.2–1.5 m), which were manually disintegrated and crushed with a chopper and sieved with a mesh size of 26 mm (Strohhexe SHE 10 manufactured by Hirlinger Landtechnik). The crushed raw material (see Fig. 1) was

Table 1
Description of the different hay batches, their origin, management type and year of harvest.

Hay batches	Site	Description	Harvest
A	H1	Lowland fen, liquid manure fertilization	2010
B	H2	Lowland fen, extensive management, no fertilization	2010
C	H3	Lowland fen, extensive management, mineral fertilizer without N	2010
D	H4	Lowland fen, no fertilization	2010
E	H5	Permanent grassland, dry location, no fertilization	2010
F	H6	Permanent grassland, humid location, no fertilization, originally grassland land for sheep	2011
G	H6	Permanent grassland, humid location, no fertilization, originally grassland land for sheep	2012
H	H6	Permanent grassland, humid location, no fertilization, originally grassland land for sheep	2013