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Research article

The use of near infrared hyperspectral imaging for the prediction of processing parameters associated with the pelleting of biomass feedstocks

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ABSTRACT

Near infrared hyperspectral imaging combined with chemometrics was used to assess the potential for the prediction of the moisture content, specific energy and the feed rate of the feedstock into the pellet die. Samples were produced from a diverse set of agricultural products and wood chips, with a range of moisture contents. Image analysis was also utilised to assess the efficient mixing of biomass feedstocks prior to pelleting in a multi biomass stream. The moisture content (%), specific energy (kWh kg^{-1}) and feed rate (kg min^{-1}) were predicted with root mean square errors of prediction of cross validation of 1.11% ($R^2 = 0.94$), 0.12 kWh kg^{-1} ($R^2 = 0.64$) and 0.20 kg min^{-1} ($R^2 = 0.70$), respectively. The results of this study indicate that near infrared hyperspectral imaging has the potential to be incorporated into a biomass pelleting facility to improve the efficiency of the system.

1. Introduction

Biomass for energy production purposes has been attracting greater attention in recent years [1]. Biomass pellets are a potential alternative to fossil fuel sources for both space heating and power generation purposes. Presently, the majority of biomass pellets are produced from either sawdust or wood shavings. Demand for biomass pellets is growing rapidly in many regions including Europe, Northern America and China [2,3]. Sweden has increased its consumption of biomass pellets from 0.49 million tonnes in 1997 to 1.68 million tonnes in 2006 [4], representing an increase of about 240%. Due to this rapid growth in production, countries such as Sweden and Denmark have all but exhausted their supplies of this feedstock [5]. As a result, attention is now turning to the use of alternatives such as cereal straws, short rotational coppices (e.g. *Salix* and poplar), and energy grasses (e.g. switchgrass, *Miscanthus* and reed canary grass) as feedstocks for fuel pellet production [4,6]. These alternatives can either be used as a standalone feedstock or mixed with sawdust to create blended pellets. The primary problems associated with the use of these alternative raw materials as feedstocks are; the expected higher ash contents, lower ash melting points and variable moisture contents (MC) of the samples [2,4,7]. The quality of these parameters is important as it can affect both the combustion efficiencies and the emissions [8].

During densification of biomass, energy is required to complete three main processes [9]. Firstly energy is needed to compress the material into a feed layer between the die and the rollers. Further energy is required to push the compressed material into the openings of the die [9]. Finally, a large portion of the energy is required to overcome the frictional forces generated when forcing the material through the die [9]. These frictional forces include friction between the raw material and the die walls, as well as internal friction between raw material particles [10]. Mani, Tabil and Sokhansanj [11] and Mewes [12] studied the amount of energy required to overcome the frictional forces during compression of straw and hay and found that approximately 40% of the total energy was needed to compress the materials with the remaining 60% used to overcome friction. The specific energy required during biomass densification is influenced by the system used, process variables (temperature, pressure and die geometry), feedstock variables (MC, particle size and initial bulk density), and the biochemical composition of the feedstock (lignocellulosic composition, presence of starch and protein) [13–16]. Variations in the feedstock composition, primarily the MC, cause significant differences in the specific energy required to pellet the raw materials [9]. Therefore, raw materials with different compositions will have varying specific pelleting energies.

Industry demands energy efficient solutions for production of biomass pellets as this not only increases the net energy of the pellets but

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also, more importantly, from a producer's perspective, increases profits [17].

Studies conducted by Larsson [18] and Filbakk [19] used physical parameters of the pelleting process including MC, steam addition, extractives content and pelleting temperature to predict the pelletiser current ($R^2 = 0.93$) and the power consumption ($R^2 = 0.58$), respectively. These studies used single biomass types (reed canary grass and scots pine, respectively) for the development of the models. This is the first study to look at predicting the electrical consumption of a pellet mill based solely on near infrared (NIR) analysis of the feedstocks.

NIR techniques are useful on–line monitoring tools for rapid, non–destructive determination of the thermal properties and chemical composition of biomass samples [20,21]. NIR studies have shown that the gross calorific value (GCV) [20], MC [22] and ash content [23] of biomass samples can be predicted with high accuracy.

The main objectives of this study were to use NIR techniques to firstly predict the specific energy required to pellet a number of agricultural feedstocks, the MC of the agricultural feedstocks and the flow rate of the initial feedstock material into the pelleting chamber across a range of MCs and secondly to classify spectral images to ensure the efficient mixing of biomass streams. This will aid biomass pellet mill operators in maintaining an optimized production of quality pellets while also reducing variability in the electrical energy requirement of the system.

2. Materials and methods

2.1. Biomass pellet production

In this study, pellets were produced from biomass sourced at the Teagasc Crops Research Centre (Oakpark, Co. Carlow, Ireland). The pellets were produced from a number of feedstocks including, pine wood (P; *Pinus sylvestris* L.), wheat straw (W; *Triticum* spp.), Miscanthus (M; *Miscanthus* × *giganteus*) and a Hungarian energy grass (S; *Elymus elongatus* subsp. *Ponticus cv. Szarvasi-1*), which is a tall wheat grass cultivar [24]. A total of 28 pellet samples were produced using a pilot–scale Greenforce MZLP pellet mill (Xuzhou Orient Industry Co. Ltd., Shandong, China) with a rated capacity of 250 kg h^{-1} at UCD's Lyons Estate Research Farm (Newcastle, Co. Dublin, Ireland). The batch size of each pellet blend produced was between 70 and 80 kg. The pelletising process involved the movement of biomass material through a 5 kW hammer mill with an 8 mm screen. The initial MC of the feedstock was determined and water was added to the material to create a set range of MC's for the samples (Table 1). The volume of water to be added to the feedstock was determined on a dry basis. For the blended pellet samples (Table 1) the feedstocks were measured on a mass basis and mixed using a conventional cement mixer. Previous unpublished results determined that this method of adding water to the feedstock resulted in an accurate and evenly distributed MC throughout the feedstock. The material was then forced through a 6 mm die to form cylindrical pellets and allowed to cool to ambient temperature before a sample of the pellets was taken for NIR imaging and analysis in the laboratory.

2.2. Determination of electrical energy consumption

The pellet mill was allowed to reach steady state production of pellets before any measurements were taken. The electrical energy was recorded at the start and end of each run using an OWL monitor (OWL009–051, The OWL Ireland, Malahide, Dublin, Ireland). The mass of the pellets produced was also recorded using a balance with an accuracy of 0.01 kg, and this was used to find the energy consumption per unit mass of material (kWh kg^{-1}) in each feedstock blend. The initial feedstock and pellets were also tested for bulk density, MC, ash content and calorific value using the standard methods [25–28]. The mechanical durability (MD) of the pellets was determined using the formula presented in [29].

2.3. Hyperspectral imaging system

NIR hyperspectral images (HSI) of the initial feedstock were acquired using a push-broom line scanning HSI instrument (DV Optics,

Table 1
Composition and descriptive statistics of biomass pellets.

Sample[a]	Component 1 (g 100 g^{-1})	Component 2 (g 100 g^{-1})	Pelleting energy (kWh kg^{-1})	Feed rate (kg min^{-1})	Feedstock MC (g 100 g^{-1})	Pellet MC (g 100 g^{-1})	MD (%)	Pellet bulk density (kg m^{-3})
$P100_1$	P (100)	–	0.282	1.44	17.27	11.53	96.69	620.41
$P100_2$	P (100)	–	0.293	1.48	20.99	12.04	96.33	624.49
$P100_3$	P (100)	–	0.421	1.01	23.89	13.96	97.18	633.67
$P100_4$	P (100)	–	0.303	1.19	15.53	10.36	95.58	666.33
$P100_5$	P (100)	–	0.517	0.47	14.19	8.34	94.69	656.12
$P100_6$	P (100)	–	0.302	0.76	18.23	9.85	95.36	640.82
$P100_7$	P (100)	–	0.501	0.35	10.43	7.24	94.20	588.78
$P80W20_1$	P (80)	W (20)	0.319	0.98	17.85	14.64	92.33	580.61
$P80W20_2$	P (80)	W (20)	0.331	0.95	22.50	14.86	92.43	551.02
$P80W20_3$	P (80)	W (20)	0.438	0.66	23.40	16.58	93.19	559.18
$P80W20_4$	P (80)	W (20)	0.580	0.48	27.83	17.07	93.41	563.27
$P80W20_5$	P (80)	W (20)	0.762	0.27	29.91	16.29	93.06	587.76
$P60W40_1$	P (60)	W (40)	0.884	0.22	16.95	12.71	92.65	631.63
$P60W40_2$	P (60)	W (40)	0.771	0.22	19.71	11.56	92.14	647.96
$P60W40_3$	P (60)	W (40)	0.885	0.17	21.35	13.70	93.09	662.24
$P60W40_4$	P (60)	W (40)	0.762	0.22	25.52	14.73	93.54	667.35
$W100_1$	W (100)	–	N/A[b]	N/A	16.07	N/A	N/A	N/A
$M100_1$	M (100)	–	0.345	0.59	15.70	8.82	90.50	583.67
$M100_2$	M (100)	–	0.360	0.58	14.92	10.521	91.25	584.69
$P80M20_1$	P (80)	M (20)	0.328	0.59	14.54	8.93	92.14	624.49
$P80M20_2$	P (80)	M (20)	0.267	0.79	17.10	10.45	92.81	559.18
$P80M20_3$	P (80)	M (20)	0.242	1.00	19.55	11.24	93.16	565.31
$P60S40_1$	P (60)	S (40)	0.609	0.30	14.19	10.64	92.21	609.18
$S100_1$	S (100)	–	N/A	N/A	12.97	N/A	N/A	N/A
$S100_2$	S (100)	–	0.300	0.62	15.24	13.53	93.48	565.31
$P80S20_1$	P (80)	S (20)	0.415	0.46	14.63	10.50	94.43	621.43
$P80S20_2$	P (80)	S (20)	0.262	0.75	17.63	11.75	94.98	596.94
$P80S20_3$	P (80)	S (20)	0.266	0.79	19.69	11.74	94.98	590.82

[a] Key for parameters: MC, moisture content; P, Pine wood; W, Wheat straw; M, *Miscanthus*; S, *Szarvasi*.
[b] Not available as the feedstock did not pelletise.