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By-products of wheat milling process as fuel for biomass boilers and stoves

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ABSTRACT

This work aims at experimentally testing wheat milling by-products (bran, fine bran and middlings) as fuel into a biomass fired hot air generator, with the final purpose of demonstrating the advantages of selling these goods to the energy market. The by-products were pelletized and the thermal efficiency of the generator was assessed for each type of pellets including 'EN A1 plus' wood pellets for comparison. Results show a small decrease of performance of the generator using the by-products pellets with respect to wood pellets. In addition, combustion instability given by the clinkering phenomenon was recognized using middlings pellets. ESEM technology was applied to bran pellets ashes in order to evaluate ashes composition and discuss possible application as soil fertilizer. Finally, an economic comparison between by-products sale as fuel and as animal feed demonstrated that it is more convenient to sell these biomasses as fuel considering the actual market situation.

1. INTRODUCTION

Food processing industries consume large quantity of energy in their processes, thus causing massive CO_2 emissions while increasing the final cost of the goods [1]. Energy efficiency and renewable energy production constitute fundamental strategies to pursue a sustainable development [2-6]. Moreover, among the different renewable energy resources, bio-energies are the most suitable to be integrated under a circular economy plan. This approach allows companies to produce considerable earnings while producing value with their by-products [1, 7-8]. The industrial wheat milling sector in Italy represents a significant share of the agro-industrial market. There are 358 milling companies (233 that process common wheat and 125 that process durum wheat) all around the national territory. The wheat supply chain engages more than 300000 farms that cultivate 2 million hectares of land [9]. A study regarding the last 5 years shows that the average wheat production in Italy is about 7.2 million tons of grains per year. This amount corresponds to a 'Base Prices Production' (BPP) of 1.7 billion €, representing 7% BPP of the entire national agricultural cultivations [9]. In 2014, the milling sector gained 3.8 billion €, which represents 3% of the whole industrial food processing economy [9]. To provide for the increasing milled wheat demand, the milling companies require tremendous quantities of electricity. The milling industry consumptions are very relevant when compared with other food industries, because the grinding process requires large, energy-intensive machineries. In the milling process, that involves the refinement of the grains of wheat, there are significant percentages of waste. On average, the efficiency in terms of produced flour reaches 75%wt., while the remaining 25%wt. is bran [10]. The remaining bran is not regular in shape and composition; in fact, milling industries divide the by-products in three sub-categories: bran (20%wt. of the total wheat), fine bran (3%wt. of the total wheat) and middlings (2%wt. of the total wheat) [10]. These by-products, generally named bran, are usually pelletized and sold to the market as feed for animals, while a little part goes back to the human food market as fiber source. The prices of these by-products are not constant over time: they depend on the trend of financial institutions. For example, in the Emilia-Romagna Region (in Northern Italy), the market price of these by-products is monthly set by a government organization called 'Camera di Commercio di Bologna' [11]. An alternative way to make profits from these pelletized by-products consists in selling them as fuel for biomass boilers and stoves. A similar approach was already presented by the authors using spent coffee grounds [1] and digestate from anaerobic biomass power plants [12]. In this paper, different combustion tests were performed using an Ecofaber hot air generator of 29 kWth nominal thermal power. Pelletized bran, fine bran and middlings are investigated as fuel and a comparison of these pellets with standard 'EN plus A1' wood pellets was performed. In addition, an economical comparison between milling by-products sold as feed for animals and as fuel was reported.

2. MATHERIAL AND METHODS

First of all, elemental analyses of the milling by-products were performed in order to evaluate their chemical compositions; then they were used to calculate their heating values. Three kinds of pellets were made using a small scale pelletizer. The pellets were burned in an Ecofaber air furnace to evaluate their behaviors during combustion. Finally, ashes were collected and examined thanks to ESEM (Environmental Scanning Electron Microscope) with the goal of evaluating the ashes composition.

2.1 Elemental analysis

Table 1 sums up the elemental analyses of the 'ENplus A1' wood pellets and of the milling by-products in dry conditions. Table 1 also reports the by-products as-received moistures, the Higher Heating Values in dry conditions (HHVdry) and the Lower Heating Values (LHV) in as-received conditions. Oxygen amount is calculated by difference and HHV and LHV values are determined with the equations suggested by Channiwala and Parikh [13] and Basu [14] respectively:

$$HHV_{dry} = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH \quad (1)$$

where C, H, N, S, O are the weight fractions of the respective elements, ASH is the ash content percentage in the dry sample.

$$LHV = HHV_{dry} - h_g\left(\frac{9H}{100} + \frac{M}{100}\right) \quad (2)$$

where h_g [kJ/kg] is the latent heat of water at ambient pressure and M [%wt.] is the biomass moisture content.

Table 1. Biomasses elemental analysis and properties

Element [%]	Wood pellets [1]	Bran	Fine bran	Middlings
Carbon *C*	46.44	45.65	46.13	46.68
Hydrogen *H*	5.10	6.55	6.68	6.87
Nitrogen *N*	0.03	3.67	3.34	3.47
Sulphur *S*	0	0	0	0
Oxygen *O*	46.25	37.54	38.87	39.2
ASH *ASH*	2.02	6.59	4.98	3.78
Moisture *M*	10	15.42	13.08	11.17
HHVdry [kJ/kg]	17.38	19.58	19.80	20.21
LHV [kJ/kg]	16.12	17.90	18.15	18.01

2.2 Pellets realization

Table 2. Pellets mill technical data [1]

Model	Cissonius PP-200
Max. electrical power consumption	7.5 kW
Max. pellets production rate	150 kg/h
Dimensions	113x48x92 cm

Figure 1. Bran pellets sample

Ten kilograms of pellets derived from each by-product were made. The raw materials have not been further dried because the moisture level was suitable for the pelletization process. However, after their production, pellets were distended on a tarp in order to be cooled and dried in the open air. Table 2 shows the pellet mill technical data and Figure 1 shows a bran pellet sample.

2.3 Combustion tests

The facility used in this work is a commercial hot air generator model AL.PI - GA 35 of 29 kWth nominal power manufactured by Ecofaber [15]. The combustion chamber has a hemispheric geometry and, during combustion tests, it is kept filled with pellets in order to have a constant burning bed height. The hot exhaust gases released by the combustion reactions exchange heat with an air flux through a proper heat exchanger. The hot air flux is carried in a PVC duct where an Extech model HD300 thermo-anemometer [16] is placed. In the meantime, the exhaust gases leave the air furnace through a chimney. The Extech thermo-anemometer measures the velocity in the duct through a calibrated blade rotor. The hot air temperature is measured through an infrared sensor. Temperature of the exhausts chimney, combustion chamber and ambient air are measured through K-type thermocouples connected to a Pico TC-08 datalogger [17]. Experimental tests start with burning wood pellets for 1 hours to reach stable conditions. After that, the four types of pellets start to be used as fuel, and temperature and flux data are recorded. Each type of pellet is burned for about 1 hour. The average thermal efficiency of the hot air generator for each type of biomass fuel is calculated by Equation 3:

$$\eta_{th} = \frac{\rho_{air} c_{p,air} w_{ave} A \Delta T_{ave}}{\dot{m}_{dry,ave} HHV_{dry}} \quad (3)$$

where ρ_{air} = 1.225 [kg m^{-3}] is the density of the ambient air, $c_{p,air}$ = 1.005 [J kg^{-1}K^{-1}] is the specific heat of the ambient air, w_{ave} [m/s] is the average air flow velocity, A = 0.0314 [m^2] is the section of the outlet duct, ΔT_{ave} [K] is the average air temperature increase, $\dot{m}_{dry,ave}$ [kg/h] is the average dry biomass consumption, HHV_{dry} [MJ/kg] is the higher heating value of the pellets.

2.4 Ashes analysis

Normally, from a biomass combustion plant three types of ashes are collected:

- Bottom ashes (heavy materials) produced in the primary combustion zones;
- Cyclone ashes (finer particles), usually removed with a cyclone;
- Fly ashes (ultra-fine particles) that flow away together with the fumes.

In this study, only bottom ashes remained in the combustion zone after the tests were collected and analyzed. Through the ESEM (environmental scanning electron microscope) it is possible to take images of the requested samples. For every sample, several magnification levels can be obtained, and this is useful to explore the morphology in separated zones of the same sample. One of the most interesting thing is the chemical composition of the ashes: thanks to the ESEM distinctive specters, the chemical elements can be detected and a specific use of the ashes can be proposed. The instrument is a FEI Quanta-200 [18]. After the preparation of the sample with 10 nm thick gold layer, a chemical analysis was carried out using a X-EDS Oxford INCA-350 [18]. A SEM analysis was performed on a clinker (melted ashes aggregate) bran sample.

3. RESULTS

3.1 Combustion tests results

Table 3 summarizes the main results of the combustion tests on the milling by-products pellets. All the fuels have been converted into pellets, in order to allow a better flow into the combustion chamber. An initial test with A1 EN Plus certified wood pellets has been performed, to compare the bran-derived fuels with the conventional standard fuel for the stove. The measured average warm air velocity is 12 m/s. The results show different behaviors: the wood pellets exhibit the best performance as expected, but the bran-derived pellets show interesting results. The overall efficiencies are lower than the wood pellet, but still comparable. The flame in the combustion chamber depicted in Figure 2 is vigorous and the biomass consumption is quite low; the thermal power generation is lower. Middlings pellets, even if their LHV was the highest, have shown a problematic trend; probably, the flame could not sustain itself for prolonged periods. However, middlings represent the 2% of the total processed wheat so this by-product is less important with respect to bran (20%) and fine bran (3%). Another thing to consider is that industrial furnaces with big dimensions and sophisticated parameters controls can burn directly the raw material without a pellet transformation.

Table 3. Combustion tests results

	Wood	Bran	Fine bran	Middlings
Average hot air flow [Nm^3/h]	993.60	993.60	993.60	993.60
Average ΔT_{ave} [K]	25.70	10.44	13.12	11.13
Average thermal power P_{th} [kW]	8.73	3.55	4.46	3.78
$\dot{m}_{dry,ave}$ [kg/h]	4.52	2.13	2.80	2.48
Average thermal efficiency η_{th} [%]	39.4	33.5	31.6	30.5

Figure 2. Bran pellets combustion

3.2 Clinker and ashes analysis

Figure 3 shows a clinker sample. This agglomerate was found in the combustion chamber after the combustion tests. The part shown in Figure 3 is oriented in the direction of the flame. Only this part has been studied, be- cause of its direct contact with the fire. The clinker upper part is smooth and glass, solid, without apparent fragility. But using a 2000x zoom (Figure 4), the sample shows a filamentous morphology. Three different regions spectra of these samples have been investigated and then compared. Figure 5 shows the spectra comparison: the spectra are very similar. The more relevant peaks reveal the presence of phosphorus oxides and potassium. Magnesium, calcium and silicon oxides occur, to a lesser extent. Aluminum presence is very low and there is carbon, that reveals the combustion can be optimized. The bran clinker elemental composition is reported in Figure 6. The composition and the spectra comparison reveal some remarkable aspects: the relevant presence of phosphorus and even of potassium indicates that ashes can be used as P-K source for fertilizers [19]. In fact, as suggested by Kompiene et al. [19], ashes produced after the combustion of bio-fuels are often rich in P and in K, valuable nutrients for plants growth. It is therefore possible to imagine an exploitation of the ashes for agricultural uses.

Figure 3. Bran clinker sample

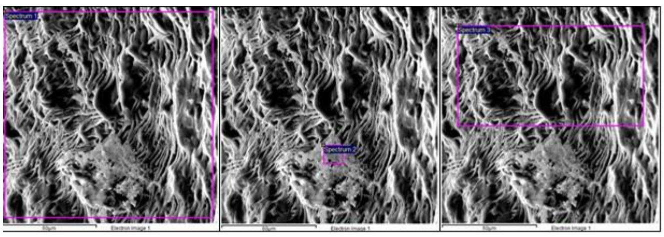

Figure 4. Facing in clinker

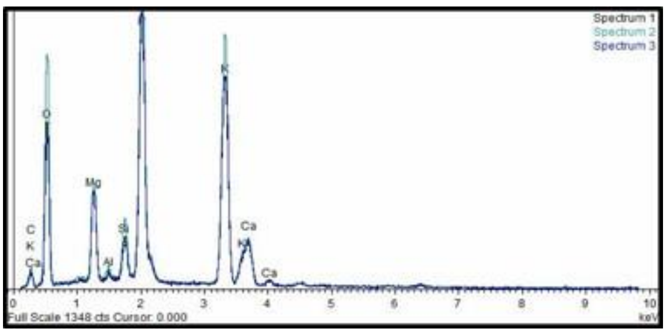

Figure 5. Clinker specters comparison

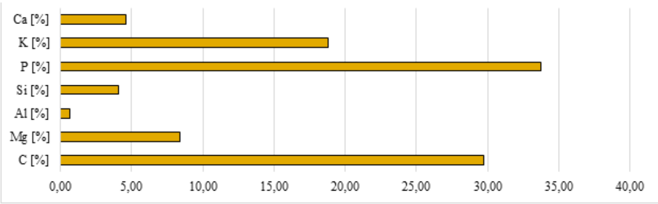

Figure 5. Bran clinker composition

3.3 Economical comparison

Selling of wheat milling by-products as pellets for biomass boilers is a suitable solution that can compete with the market of agri-pellets [20]. These pellets are produced using agricultural residues, in particular straw from wheat, barley and oats cultivation. Sultana et al. [20] evaluate that the cost of these pellets in Western Canada depends on the size of the production plant. In the best case, a production cost of 130 USD/ton was calculated for a production plant with a capacity of 150000 tons per year. In case of industrial wheat milling companies, the production cost is lower because there are no costs typical to agri-pellets production: harvesting, bale wrap, bale collection, bale storage, farmer, nutrient replacement, transport to the production site. These costs represent the 70% of the total production cost of agri-pellets [20]. Starting from that, the production cost for wheat milling by-products pellets is about 40 USD per tons. These by-products are pelletized and sold to the animal-feeding market. The specific cost trends in the Emilia-Romagna Region are reported in Figure 7. However, as highlighted by the combustion tests, these pellets have an acceptable behavior as fuel in biomass boiler, allowing these by-products to exit from the animal feeding niche. It can be assumed that these pellets should be sold to the market as medium quality ’EN plus A2’ pellets for biomass boilers and stoves. The updated price of this fuel is about 194 e per ton [21]. A comparison between bran pellets prices for energy and animal feed purposes is reported in Figure 7, which reports the price trend from 2004 to 2016 regarding animal feed purpose, while the price for energy purposes is constant at the actual cost. It can be noted that the price for energy purpose is higher than the price for animal feed purpose except few months in 2007 and 2013.

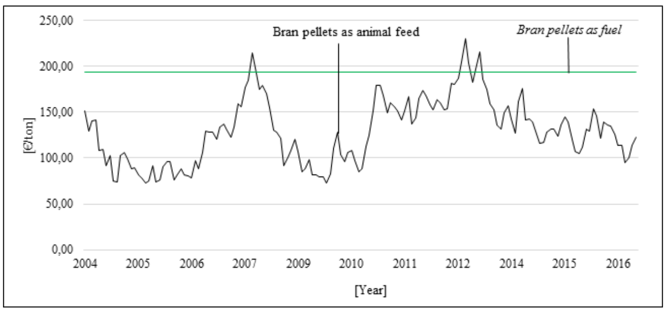

Figure 7. Bran pellets market cost for energy and animal feed purposes

4. CONCLUSIONS

Results show that the use of wheat milling by-products as fuel for biomass boilers is a suitable and possibly profitable solution. In fact, experimental tests using a biomass fired hot air generator proved a low decrease of the thermal efficiency using by-products pellets instead of wood pellets. However, clinkering issues have been observed during the combustion tests, so the use of these pellets is advised in boilers or stoves with moving grate or ash extraction augers able to break clinkers. ESEM analyses show that bran ashes have a high content of phosphorus and potassium and they can be used as P-K source for fertilizers. The economical comparison shows that the sale of by-products pellets as ’EN plus A2’ pellets for energy purpose is more profitable that the conventional sale as animal feed considering the market situation of the last decade. This is a good opportunity for the industrial milling industries because they can choose the more profitable trade between energy and animal feed depending on the market situation.

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REFERENCES

[1] Allesina G, Pedrazzi S, Allegretti F, Tartarini P. (2017). Spent coffee grounds as heat source for coffee roasting plants: Experimental validation and case study. Applied Thermal Engineering 126: 730-736. https://doi.org/10.1016/j.applthermaleng.2017.07.202

[2] Malaguti V, Lodi C, Sassatelli M, Pedrazzi S, Allesina G, Tartarini P. (2017). Dynamic behavior investigation of a micro biomass CHP system for residential use. International Journal of Heat and Technology 35(Special Issue 1): S172-S178. https://doi.org/10.18280/ijht.35Sp0124

[3] Puglia M, Pedrazzi S, Allesina G, Morselli N, Tartarini P. (2017). Vine prunings biomass as fuel in wood stoves for thermal power production. International Journal of Heat and Technology 35(Special Issue 1): S96-S101. https://doi.org/10.18280/ijht.35Sp0113

[4] Allesina G, Pedrazzi S, Cattini C. (2011). Experimental assessment and modeling of energy conversion effectiveness in a gasification power plant. International Journal of Heat and Technology 29(2): 151-156. https://doi.org/10.18280/ijht.2902120

[5] Pedrazzi S, Allesina G, Tartarini P. (2012). Aige conference: A kinetic model for a stratified downdraft gasifier. International Journal of Heat and Technology 30(1): 41-44. https://doi.org/10.18280/ijht.300106

[6] Kautto N, Peck P. (2012). Regional biomass planning: Helping to realise national renewable energy goals? Renewable Energy 46: 23-30. https://doi.org/10.1016/j.renene.2012.03.024

[7] Molina-Moreno V, Leyva-Daz JC, Sanchez-Molina J. (2016). Pellet as a technological nutrient within the circular economy model: Comparative analysis of combustion efficiency and co and NOx emissions for pellets from olive and almond trees. Energies 9(10). https://doi.org/10.3390/en9100777

[8] Kranert M, Gottschall R, Bruns C, Hafner G. (2010). Energy or compost from green waste? a CO_2 based assessment. Waste Management 30(4): 697-701. https://doi.org/10.1016/j.wasman.2009.09.046

[9] ISMEA Istituto di servizi per il mercato agricolo alimentare, from: http://www.ismea.it, accessed in April. 2018.
[10] Tagliavini E. (2017). Audit energetico di un molino da grano tenero e studio di valorizzazione energetica dei sottoprodotti di macinazione. Master’s thesis in Environmental Engineering, University of Modena and Reggio Emilia, Italy.
[11] Camera di Commercio Industria Artigianato e Agricoltura di Bologna, from: http://www.bo.camcom.gov.it, accessed in April. 2018.
[12] Pedrazzi S, Allesina G, Bellò T, Rinaldini CA, Tartarini P. (2015). Digestate as bio-fuel in domestic furnaces. Fuel Processing Technology 130: 172-178. https://doi.org/10.1016/j.fuproc.2014.10.006
[13] Channiwala S, Parikh P. (2002). A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 81(8): 1051-1063. https://doi.org/10.1016/S0016-2361(01)00131-4
[14] Basu P. (2010). Biomass gasification and pyrolysis. Practical Design and Theory 2: 54–59. https://doi.org/10.1016/B978-0-12-374988-8.00001-5
[15] Ecofaber Website, from http://www.ecofaber.com, accessed in April. 2018.
[16] Extech HD300 thermo-anemometer, from: http://www.extech.com/display/?id= 14481, accessed in April 2018.
[17] PICO Technologies, Pico tc-08 data logger, from: https://www.picotech.com/data-logger/tc-08/, accessed in April. 2018.
[18] Ferrari C, Muscio A, Siligardi C, Manfredini T. (2015). Design of a cool color glaze for solar reflective tile application. Ceramics International 41(9 Part A): 11106-11116. https://doi.org/1016/j.ceramint.2015.05.058
[19] Kumpiene J, Brnnvall E, Wolters M, Skoglund N, Čirba S, Česlovas Aksamitauskas V. (2016). Phosphorus and cadmium availability in soil fertilized with biosolids and ashes. Chemosphere 151: 124–132. https://doi.org/10.1016/j.chemosphere.2016.02.069
[20] Sultana A, Kumar A, Harfield D. (2010). Development of agri-pellet production cost and optimum size. Bioresource Technology 101(14): 5609–5621. https://doi.org/10.1016/j.biortech.2010.02.011
[21] AIEL, Mercato e prezzi febbraio combustibili legnosi febbraio 2018, from: http://www.aielenergia.it/public/pubblicazioni/Mercati-Prezzi1-2018.pdf, accessed in April 2018.