VALORIZATION OF SUGAR BEET PULP RESIDUE AS A SOLID FUEL VIA TORREFACTION

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Abstract
The potential of torrefaction treatment for upgrading sugar beet pulp residue (SBP) into a high-quality solid bio-fuel was investigated in this work by using a new bench-scale experimental apparatus. In particular, the influence of the main process variable, namely the temperature, on both the torrefaction performance parameters (i.e., mass yield, energy yield and energy densification index of torrefied solids) and the main properties of torrefied SBP (i.e., low heating value, the ratio of fixed carbon to volatile matter, H/C and O/C ratios) was studied. Torrefaction tests were performed at three different temperatures (i.e., 200, 250, and 300 °C) and 30 min reaction time. The torrefaction treatment of SBP resulted in a significant improvements of its fuel properties. It was observed that higher temperatures led to an increase in the calorific value of the torrefied SBP with respect to the parent one. More specifically, the calorific value increased by a factor of 1.4 for the biomass treated at 300 °C and 30 min, changing from 17.2 to 24.5 MJ/kg on a dry basis. Under the same experimental conditions, a 59 % reduction in the O/C elemental ratio was also observed. These positive effects of the torrefaction treatment, however, occurred while returning a mass yield (45 %, daf) and an energy yield of the solid product (61 %, daf) rather low compared to that typically arising from the torrefaction treatment of woody-biomass to get the same energy densification factor. This was mostly a consequence of the low lignin content of SBP compared to woody biomass.

Introduction
Sugar beet is second only to sugar cane as a major source of sugar across the world. In 2009, approximately 20 % of the world's sugar production (153.4 million tons) was obtained from sugar beet [1]. Sugar beet pulp (SBP) is the main solid by-product of the sugar beet industry. It is composed of approximately 75-85%wt.

carbohydrate (cellulose, hemicellulose, pectin, and others), 1-4 %wt. lignin, 7-15%wt. protein, 0.5 %wt. fats, 05-6 %wt. residual sucrose and 7-13 %wt. soluble and insoluble mineral matter on dry basis [2-3]. At present SBP is mostly sold as animal feed at a relatively low price due to its relatively low protein content compared to the requirements of most ruminants. But, alternative uses of such a biogenic residue of sugar industry are currently being investigated in order to enhance its valorization [3]. In this context, the potential valorization of sugar beet pulp as a solid bio-fuel via torrefaction treatment was assessed in this work. Basically, torrefaction is a thermochemical treatment where biomass is heated in an inert environment to a temperature of 200-300 °C. Specifically, the benefits accomplished by torrefaction include: (a) a hydrophobic product that can be stored outdoors; (b) a decrease in biological degradation; (c) an increase in the calorific value with respect to raw biomass; and (e) a feedstock easier to be ground and fed into existing coal plants for co-firing [4] To the best of our knowledge, no works can be found in literature about the valorization of SBP as a solid fuel via torrefaction. Therefore, a systematic study on SBP torrefaction treatment may be of great practical and scientific interest. The primary aim of this work was to study the effect of the key process variable, namely the temperature, on both the torrefaction performance parameters (i.e., mass yield, energy yield and energy densification index of torrefied solids) and the main properties of torrefied SBP as a solid fuel (i.e., low heating value, the ratio of fixed carbon to volatile matter, H/C and O/C elemental ratios).

Material sampling, characterization, and pre-treatments
Sugar beet pulp (SBP) used in this work was collected from a sugar industry located in Bologna (Italy) in November 2016. Prior to use, SBP samples were air-dried down to about 6 %wt. moisture content in a ventilated fume hood, ground in a batch knife mill (Grindomix GM 300 by Retch) and finally manually sieved to select the particle size range required for the specific use, namely: i. 0-400 μm for analyses; and ii. 1-2 mm for torrefaction tests (see Fig. 1c). Torrefaction tests were performed at three different temperatures (i.e., 200, 250, and 300 °C) by keeping the reaction time constant at 30 min. Raw and torrefied biomass samples were analysed in order to investigate the influence of the torrefaction severity on the solid product quality. Proximate analysis was carried out in a TGA 701 LECO thermogravimetric analyser. Carbon, hydrogen, and nitrogen content of samples was determined by using a CHN 2000 LECO analyser. The oxygen content was finally calculated by subtraction of the ash and CHN content from the total. All these tests were made in duplicate at least. Tables 2 reports the results of the above analyses as averaged values. The higher heating value (HHV, kJ/kg, dry basis) of raw and torrefied SBP samples was evaluated based on ultimate analyses data by using the experimental correlation (Eq.1) by Channiwala and Parikh (2002) [5]:

$$HHV = 349.1\ C + 1178.3\ H + 100.5\ S - 103.4\ O - 15.1\ N - 21.1\ ASH \tag{1}$$

$$LHV\ (MJ/kg) = HHV\ (MJ/kg) - 2.442(8.936 \cdot H/100) \tag{2}$$

where C, H, S, O, N and ASH are weight fraction (%) of carbon, hydrogen, sulphur, oxygen, nitrogen, and ash of samples on dry basis. The conversion of higher to lower heating values in MJ/kg was performed according to Eq.(2).

Experimental apparatus and test procedures

Photographs of the bench-scale fixed bed apparatus, which was used for torrefaction tests, are shown in Figs. 1a and 1b. The torrefaction reactor consists of a quartz tube (25 mm inner diameter and 150 mm length) surrounded by an electrical heating tape (FGR-060/240 V-ROPE HEATER 250W by OMEGALUX®). The temperature of the reactor was regulated by means of an electronic PID controller (Gefran 600 PID), which reads the bed temperature by means of a K type thermocouple inserted in the centre of the reactor. The nitrogen supply unit consists of flow meter with 0.15-1.5 NL/min flow range (Asameter by ASA). Specifically, the carrier gas percolated the biomass bed downward leaving the reactor from the bottom. A cold glass tubular trap followed by an impinge bottle was used to condensate torrefaction vapours.
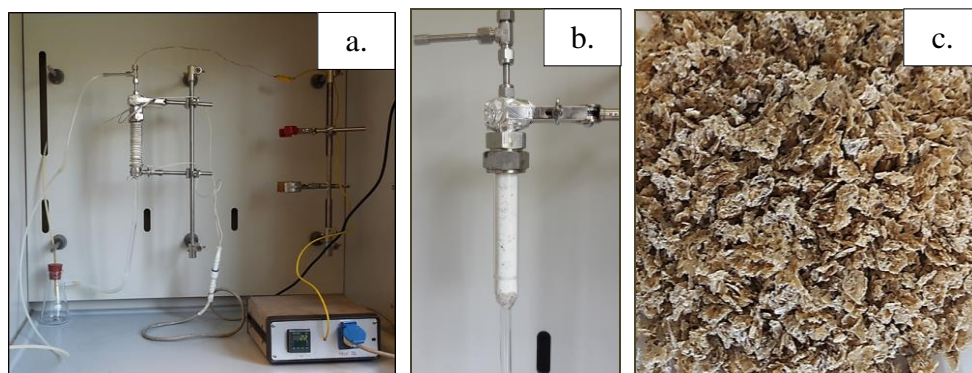

Figure 1 Pictures of: a. the experimental apparatus; b. the fixed bed torrefaction reactor; and c. air-dried sugar beet pulp residue in the size range 1-2 mm.

The reactor was loaded with approximately 3 g of air-dried biomass particles in the size range 1-2 mm (Fig. 1c), which were uniformly mixed with about 28 g of alumina spheres (Fig. 1b) in the size range 400-600 μm (SASOL alumina spheres 0.6/170) to ensure a better temperature control throughout the packed bed and prevent the occurrence of localized hotspots in the reactor [4]. After the evacuation of air from the system by flowing N_2 through the bed at 1.5 NL/min for about 5 min, the reactor was heated up to the target torrefaction temperature with a thermal ramp rate of about 15-20 °C/min. As the prefixed reaction time was passed the system was cooled down to room temperature and solid and liquid products were recovered and weighted. The solid product was separated from the inert bed

component by sieving. Mass yields of solid (MY_S), liquid (MY_L) and gaseous (MY_G) products were evaluated on an as-received basis (ar) through the following Eqs. (3-5). The energy densification index (IED) and the energy yield (EY) of torrefied solids was also evaluated on a dry basis through the following Eqs.(6-7).

$$MY_S\,(\%,\,ar) = m(torrefied\,solid)/m(SBP\,feedstock) \tag{3}$$
$$MY_L\,(\%,\,ar) = m(condensable)/m(SBP\,feedstock) \tag{4}$$
$$MY_G\,(\%,\,ar) = 100 - MY_S\,(\%,\,ar) - MY_L\,(\%,\,ar) \tag{5}$$
$$IED\,(-,\,db) = LHV(torrefied\,solid)/LHV(SBP\,feedstock) \tag{6}$$
$$EY_S\,(\%,\,db) = MY_S\,(\%,\,db) \cdot IED\,(-,\,db) \tag{7}$$

Result and discussion

Table 1 and Table 2 report the main results obtained from the fixed bed torrefaction tests performed on Raw-SBP samples. The same data are also plotted in Figs. 2-3 to comparatively show the influence of torrefaction severity on both the process performance parameters and the properties of solid product.

Table 1. Experimental conditions and results of torrefaction tests.

Sample	Temp. (°C)	MY_S	MY_L	MY_G	I_{ED}	EY_S
		(%wt., as received basis)			(-, daf)	(%, daf)
SBP-200	200	69.5	8.0	22.5	1.2	83.2
SBP-250	250	49.1	16.6	34.4	1.3	63.3
SBP-300	300	44.5	16.4	39.1	1.4	61.2

In more details, Fig. 1a shows the influence of torrefaction temperature on the yields of torrefied solids, condensable volatiles and permanent gas arising from torrefaction tests. It results that, as torrefaction temperature increased from 200 to 300 °C, the yield of the solid product decreased, whereas the yield of volatiles (torgas) consisting of the condensable and the non-condensable fraction, consequently increased. These findings are also consistent with the result of the proximate chemical composition of torrefied SBP samples. As a general trend, volatile matter (VM) decreased with an increase in the torrefaction temperature, while fixed carbon (FC) and ash contents increased. Data also shows that the increase detected in the torgas yield was mainly driven by the release of permanent gases rather than condensable compounds. A probable impact of the presence of alumina on the related yields of liquid and gaseous products is not to be ruled out, but this falls outside the scope of this work. In line with previous research findings [4,], it results that more mass than energy was lost to the gas phase during the torrefaction treatment of SBP, as evinced by the higher values of the energy yields (61-83 %, daf) compared to that of mass yields (45-72 %, daf). The energy gain versus mass loss of torrefied solids is commonly ascribed to the fact that this latter mostly arises from the release of volatiles that are richer in oxygen and hydrogen than in carbon [4].

Table 2. Chemical composition and calorific value of solid products

Sample	Ash Content (%wt., db)	Proximate Analysis (%wt., daf)		Ultimate Analysis (%wt., daf)				Calorific Value (MJ/kg, db)	
		VM	FC	C	H	N	O	LHV	HHV
Raw-SBP	4.2	79.0	16.9	45.7	6.8	1.0	46.7	17.2	18.7
SBP-200	4.3	76.2	23.9	53.7	6.3	2.4	37.7	21.1	19.8
SBP-250	4.8	63.8	36.3	58.6	5.9	2.4	33.1	22.7	21.5
SBP-300	6.7	60.6	39.4	64.7	5.7	2.8	26.9	24.5	23.4
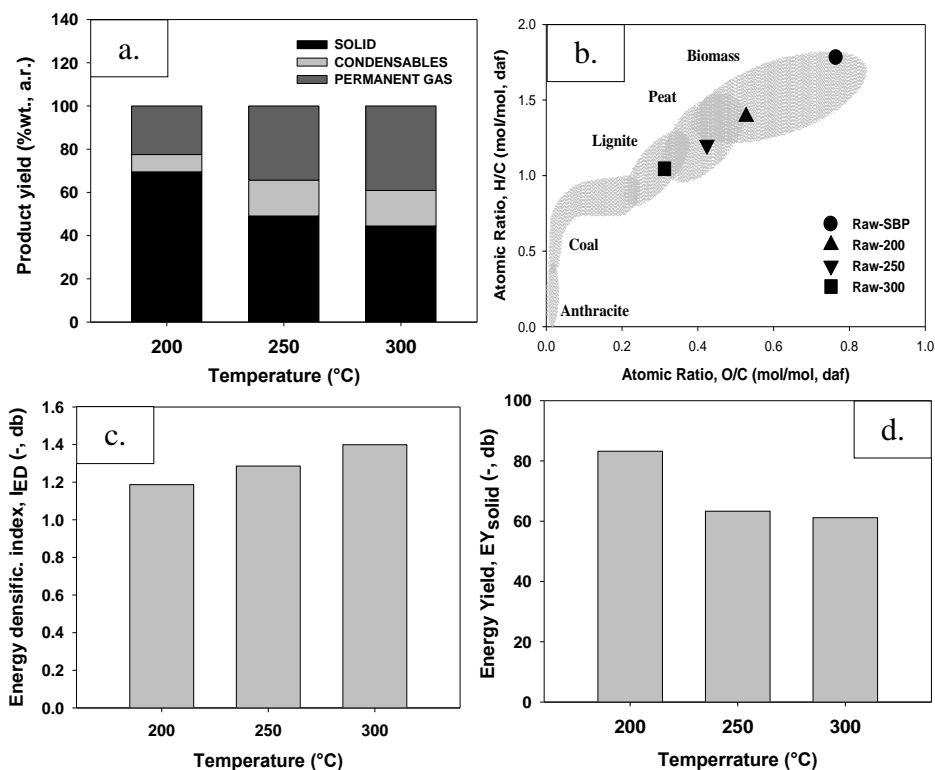
Figure 2 Effect of temperature on: a. the products distribution from torrefaction tests; b. H/C and O/C ratios; c. energy densification index; and d. energy yields.

The decrease of the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios in torrefied solids, which is clearly visible on the Van Krevelen diagram shown in Fig. 2b, provides an evidence of this. Note that the experimental points on this diagram are the elemental composition of raw and torrefied SBP, as expressed in terms of O/C and H/C ratios, on a dry ash free basis (daf). In more details, these data shows that the higher the torrefaction temperature, the more the composition of torrefied SBP moves from the characteristic region of biomass to that typical of

low-rank fossil fuels (peat and lignite). As a matter of fact, the chemical composition changes induced by torrefaction give rise to an increase of the calorific value of torrefied solids with respect to the parent one (Table 1). In particular, the higher the temperature, the higher the energy densification index (IED, db) of the solid product (Fig. 2c). However, by comparing findings of this work with those obtained from a previous study on the torrefaction of tomato peels (TP) [4], it can be noted that the performances of such thermal treatment were better in the case of TP than SBP, as evidenced by the higher mass ad energy yields obtained for torrefied TP (MY: 75-91% and EY= 89-93%, daf) compared to that of torrefied SBP (MY: 46-75%; EY= 67-92%), under similar operating conditions. This was mostly a consequence of the higher lignin content of TPs (25%, db) [4] respect to SBP (1-4%, db) [3], lignin decomposition being slower than that of other biomass components under typical torrefaction conditions.

Conclusion

Outcomes of this work showed that torrefaction is a suitable process for production of high quality solid fuels from sugar beet pulp. More specifically, the calorific value increased by a factor of 1.4 for the biomass treated at 300 °C and 30 min, changing from 17.2 to 24.5 MJ/kg, dry basis. Under the same experimental conditions, a 59% reduction in the O/C elemental ratio was also observed. These positive effects of the torrefaction treatment, however, occurred while returning a mass yield (45 %, daf) and an energy yield of the solid product (61 %, daf) rather low compared to that typically arising from the torrefaction treatment of woody-biomass to get the same energy densification factor.

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