Pelletization properties of raw and torrefied pine sawdust: Effect of co-pelletization, temperature, moisture content and glycerol addition

Roberto García, M. P. González-Vázquez, Covadonga Pevida*, Fernando Rubiera

Instituto Nacional del Carbón, INCAR-CSIC. c/Francisco Pintado Fe, 26. 33011 Oviedo. Spain.

Abstract

Biomass shows characteristics that makes it a promising feedstock for complementing traditional fossil fuels as main energy source. It is somewhat limited by its generally poor physical properties, but these can be enhanced by densification processes like torrefaction and pelletization.

The aim of the present work is to evaluate the influence of different solid biomass additives (almond shell, cocoa shell, grape pomace, *Miscanthus*, olive pomace and olive stone), and parameters such as temperature, moisture content and glycerol addition upon pine sawdust, PIN, and its torrefied counterpart, PINT, pelletization performance, paying special attention to their abrasion index, higher heating value and energy density.

It was observed that the addition of small quantities of lignin-rich solid additives, like grape pomace, enhances the natural binding properties of both PIN and PINT during pelletization using a bench-scale device.

It was also found that a 13% overall moisture content and a glycerol addition of between 10-20% improve the pelletization properties of PIN and PINT, respectively, and increase their energy density when compared to the raw samples.

Keywords

Biomass; torrefaction; pelletization; combustion; energy density.

1. Introduction

The constant growth in the world's energy demands, which has triggered a 1.9% annual increase in CO₂ emissions during the last three decades [1], could be compensated for by exploiting a diverse range of low carbon energy sources.

Biomass is generally considered a feedstock with promising characteristics for complementing and partially replacing traditional fossil fuels as our main energy source. It will also reduce the energy production impact of the greenhouse effect and global warming due to its CO₂ life-cycle

*Corresponding author. Tel.: +34 985118987; fax: +34 985297662

E-mail address: cpevida@incar.csic.es (C. Pevida).

neutrality [2] and its moderate NO_x and SO₂ emissions [3]. In addition to this, the autonomy of the resource will reduce dependence on imported fossil fuels in countries which lack them and in turn encourage self-consumption, stimulate the economy and energize rural area development [4].

The sustainable market price increase in the most common biomass fuels has shown agro-industrial wastes and fast growth energy crops to be a realistic alternative for use in domestic and industrial combustion systems.

It is widely recognized that raw biomass in general and wastes or energy crops in particular have poor physical properties, specially low energy density and a high physical and compositional heterogeneity that restrict their wider use as a general energy source [5].

However, these drawbacks can be overcome by applying certain pre-treatments, the most common of which are torrefaction and pelletization.

Torrefaction can be defined as thermal pre-treatment under mild conditions, i.e., 200-300 °C during 0.5-3 hours of reaction time [6], under atmospheric pressure [7] and in an inert or low-oxidizing atmosphere [8]. Under these conditions, hemicellulose is partially decomposed to form volatile gases, while structural lignin and cellulose are barely affected, resulting in a hydrophobic product [9] with enhanced grinding and pelletization properties [10]. Due to a relative increase in the mass of carbon in the sample, torrefied biomass displays increased higher heating values (HHV) [11]. However, the bulk density values are even lower than those of raw biomass due to the loss of light volatiles that increases the porosity of the particles. Because of this, it is necessary to densify the torrefied products by means of pelletization that also enhances the energy density.

Several works are found in the literature on the pelletization of pure and blended, raw and torrefied biomass samples at different scales. Thus, Gil et al. [12] used a bench top press unit to test the pelletization properties of several raw biomass samples (pine, chestnut and *Eucalyptus* sawdust, cellulose residue, coffee husk and grape wastes) blended with two different coals (a high volatile bituminous coal and a semi-anthracite), in order to study their combustion behavior and abrasion indexes.

Barbanera et al. [13] focused on determining the physical properties, chemical composition and durability of a densified agro-industrial by-product, olive pomace, mixed with olive tree pruning at different mass ratios.

Li et al. [14] used a single pellet press to co-pelletize three types of raw biomass (fir, camphor sawdust and rice husk) with sewage sludge to study the effect of densification variables like pressure, temperature or moisture and the energy consumption balance on the obtained pellets.

Brady et al. [15] developed a laboratory-scale system to manufacture refuse-derived fuel pellets by adding glycerin, a cheap and plentiful by-product of the biodiesel industry, to sawdust and concluded that it enhances the HHV of the raw biomass.

Rudolfsson et al. [16] also used a single pellet press to study the influence of torrefaction degree, pelletization temperature and moisture content on the densification process of Norway spruce.

Cao et al. [17] torrefied cedar and camphorwood at different temperatures and studied the influence of adding castor bean oilcake on their binding properties when co-pelletized using a bench-scale press.

Finally, Shang et al. [18] compared the effect of die temperature, moisture content, additives and torrefaction degree of raw and torrefied wood chips when pelletized in a single pellet press and a pilot pelletizer, respectively, using their strength, durability, density, HHV and grindability as quality criteria.

The aim of this work is to conduct an ample experimental study on the pelletization of raw (PIN) and torrefied pine (PINT) in a bench-scale device, and to evaluate the influence of different parameters such as temperature, moisture and additives (solid biomass wastes and glycerol) on the quality of the product. The obtained results are especially interesting as PIN is the raw material most commonly used in the local pelletization industry. The knowledge acquired from these tests will be used for scaling up to a pelletizing pilot plant level.

The main quality criterion employed in this work was the durability of the pellets obtained. The energy density and combustion properties of the samples with the highest mechanical resistance were also evaluated.

2. MATERIALS AND METHODS

2.1. Samples, additives and conditions

A softwood sample (pine sawdust –PIN–) and its torrefied counterpart obtained after 1 hour torrefaction at 280 °C (PINT) were selected as reference fuels for this study due to their widespread availability, since this woody biomass is the most commonly used in the Spanish biofuel market. The torrefaction conditions were selected according to the optimum grindability and combustion properties they provide, as described in previous works of this group [19].

Other biomass fuels (almond shell –AS–, cocoa shell –CS–, grape pomace –GP–, *Miscanthus* –MIS–, olive pomace –OP– and olive stone –OS) were also evaluated as possible additives to PIN and PINT, in the search for a synergetic effect that might enhance the pelletization capability of the base fuels. Most of the selected samples are seasonally available in the Spanish biomass

market and cover three of the most important biomass groups: woody, energy-crop herbaceous and agro-waste resources.

The samples were air dried at room temperature to remove external moisture and later ground and sieved between 0.1 and 1 mm; this size range is usually considered as optimum for bench-scale pelletization as particle sizes over 1 mm commonly lead to breakage [12] [20]. Figure 1 shows the cumulative particle size distribution of the samples tested.

The results of proximate and ultimate analyses as well as higher heating value, HHV, of the biomass samples are summarized in Table 1. Fixed carbon and oxygen contents were calculated by difference, as mass percentages on a dry basis by means of equations (1) [21] and (2) [22]:

$$FC (\%) = 100 - (VM + Ash) \quad (1)$$

$$O (\%) = 100 - (Ash + C + N + H + S) \quad (2)$$

The typical lignin contents of the studied samples were obtained from different sources [23] and databases [24]. The reference samples (PIN and PINT) were evaluated separately and also mixed to mass percentages of 50%. Blends with all the other biomass samples were also prepared on the basis of 50/50 mass ratio, to yield 15 raw samples: PIN, PINT, PIN-PINT, PIN-AS, PINT-AS, PIN-CS, PINT-CS, PIN-GP, PINT-GP, PIN-MIS, PINT-MIS, PIN-OP, PINT-OP, PIN-OS and PINT-OS.

After mixing, the effects of temperature (room temperature and the drying temperature of 105 °C), moisture content (0% and 13%) and glycerol addition (0, 10, 20 and 30%) were tested for each raw sample, representing a total of 80 different pelletization conditions.

Room temperature was selected as a testing condition to determine the natural pelletization capability of each sample, which is essential to establish any synergetic effect with PIN and PINT. On the other hand, a stove pre-drying temperature of 105 °C was selected to study the pelletization properties of every sample and to simulate the conditions that are to be encountered in the pelletizing pilot plant, where experience suggests that optimum temperatures are slightly below 105 °C, due to friction between the die and the biomass sample. The selected temperature agrees with previous studies [13] and is within the temperature range studied in most works [9][25].

Water is considered a natural binder and lubricant for biomass pelletization [20]. The value of 13% total moisture was selected as the 10-15% range is commonly reported as being the optimum for this purpose [26][27]. This moisture level is obtained by applying a previous 105 °C pre-drying step, followed by spraying and homogenizing the required amount of distilled water on the sample.

Finally glycerol is tested as an additive since it is reported to be a good lubricant, especially for torrefied biomass, enhancing the resulting fuel's higher heating value and reducing NO_x emissions and ash formation during combustion [28]. The HHV value of the batch of glycerol used for these experiments was recorded as 18.0 MJ/kg. The range of 0-30% was chosen on the basis of previous works [29]. To ensure a homogeneous blend of solid biomass and liquid glycerol, the latter was previously mixed with distilled water in a 50% mass ratio and sprayed over the selected fuel. The wet mixture was then dried at 105 °C for several hours in a stove until the external moisture added with the glycerol was completely removed. In summary, each one of the fifteen raw samples was subjected to six different experimental pelletization conditions: room temperature with no additives, room temperature and 13% moisture, room temperature and X wt.% glycerol addition and pre-drying at 105 °C with X = 0, 10, 20 and 30.

2.2. Pelletization experiments and abrasion index determination

As previously stated durability was considered to be the main quality indicator for the samples prepared under different conditions. The first step in the experimental procedure therefore consisted in making 20 pellets for each sample (6 mm diameter, 3-5 mm height), using a TDP-1.5 single punch tablet press machine, fitted with a 550 W engine that supplied a maximum pressure of 15 kN.

All pellets were subjected to a durability test consisting in 3000 turns at 35 rpm in a specially designed rotating drum described in detail in previous works [30]. The mass of the material remaining after testing was sieved through a 2 mm sieve, so that the abrasion index (A_i), and the durability of the sample (DUR) could be calculated by means of equations (3) and (4) [12][31].

$$A_i = \frac{M_0 - M_R}{M_0} \cdot 100 \quad (3)$$

$$DUR = 100 - A_i \quad (4)$$

where M_0 is the initial sample mass and M_R the mass retained on the 2 mm sieve. The higher the A_i values were, the lower the quality of the resulting pellet was and vice versa for DUR .

2.3. Product analysis

After completion of the pelletization experiments and once the abrasion indexes were determined, samples that showed A_i performances below 10% were studied in more depth. Mixtures and conditions that gave rise to poor densification behavior were discarded for

further experimentation. To that end their HHV was determined following the same procedures outlined for raw biomass. Their bulk density (BD) was determined by measuring the sample's mass and volume in a 250 mL test tube after 300 hits using a tapped density analyzer (Autotap from Quantachrome Instruments). Energy density was also calculated and compared with raw PIN and PINT. In addition to this, thermal behavior was studied by thermogravimetric analysis (TGA) and its derivative (DTG), by subjecting 5 mg of sample to a controlled heating process from room temperature to 900 °C at a 15 °C/min heating ramp in a Setaram TAG 24 under a 50 mL/min flow of air.

3. RESULTS AND DISCUSSION

3.1. Abrasion indexes

The results from the durability tests are shown in Figure 2. As can be seen the experiments performed at room temperature report quite poor durability in most of the cases. All the samples produced at room temperature without additives present abrasion indexes well above 20%, except the mixture PIN-GP that shows a lower value and PIN and PINT-OP results that are only slightly higher. It can be concluded therefore that pure raw pelletization is not the best option and only PIN, GP and OP seem to present acceptable natural conditions for achieving the target in optimal durability.

In the case of the samples prepared at room temperature with 13% total moisture content, when both PIN and PINT are mixed with AS, GP, OP and OS, their natural pelletization properties are greatly improved, but in the case of the OS-blends they are still far from acceptable levels. In contrast, the mixtures PIN-GP, PIN-OP and PINT-OP seem to be promising options that merit more detailed study, as they all have an abrasion index below 10%.

It should also be highlighted that both GP and OP enhance the densification properties of PIN and PINT due to their large lignin contents (53.2 and 42.7, respectively) which reportedly acts as a natural binder [17].

Consequently, additional mixture percentages ranging from 0 to 100% of GP and OP, for both PIN and PINT were tested and their results reported in Figure 3. As can be seen, the binding capacity of PIN and PINT is greatly enhanced even with small GP additions. In the case of PIN, A_i decreases from 30% of the raw sample to 5% when blended with 25% GP. Especially remarkable is the result obtained in the case of PINT: 25% addition of GP reduces the 100% abrasion index value obtained for raw PINT to 18% for the blend PINT-25% GP. Increased percentages of GP in both blends induce a more gradual decrease in the A_i values down to the

2% abrasion index value for raw GP (see Figure 3). As GP is associated with certain environmental issues, e.g., its high sulfur content that militates against its wide use in combustion, the fact that even small additions of this biomass greatly enhances the durability of the blend weighs heavily in its favor.

The OP-blends behavior is very similar to that observed in the GP ones, as even small quantities of it widely decrease the abrasion index of the sample, compared to raw PIN or PINT. This reduction is similar in the case of PIN, from 30% to approximately 10% for a 25% addition of OP, and remains close to this value for the rest of the percentages considered. In the case of PINT the reduction is less pronounced: A_i decreases from 100% for pure PINT to approximately 45% when 25% of OP is added to the blend but further decreases down to values slightly above 10% with the addition of 50% OP. This value remains almost constant for the remaining percentages of OP addition.

PINT blends with both GP and OP led to minimum abrasion indexes but higher than the ones obtained for the corresponding PIN mixtures. This can be attributed to the hydrophobicity of torrefied matter which negatively affects the mixing properties of PINT with GP and OP, their ligand action and thus, the overall pelletization process. This can be particularly observed when 13% moisture addition is evaluated.

Other pelletization options include samples pre-treated at 105 °C in order to dry the fuel before pelletization. To this end, samples were introduced in a stove at 105 °C for several hours and pelletized immediately after. As it can be seen in Figure 2, the best results were obtained with mixtures that include MIS but with abrasion index values just below 60 and 50% for PIN and PINT blends, respectively. All other mixtures and samples presented A_i values over 70%. It can be concluded therefore that heating biomass without additives impoverishes natural binding properties of the studied samples. This can be due to the release of lignin, as this temperature (105 °C) is well above the mean transition temperature of lignin (75 °C) [32].

Another densification condition that was evaluated was the direct addition of 10% glycerol to the blended sample at room temperature, without any previous drying. The results of these tests were not included in Figure 2 as they were extremely poor ($A_i = 100\%$ in every case); the soft pellets generated broke as soon as they were removed from the press. This condition was therefore automatically discarded.

Once direct glycerol addition was ruled out as a suitable option, its combination with the previous drying step was evaluated, in order to simulate the heating conditions of the pilot pelletizer used to scale up this work. The glycerol itself was heated as suggested elsewhere [28][33]. To this end mixtures of glycerol and distilled water in a 50% mass ratio were prepared, to facilitate the spraying of glycerol over the samples and its addition to the raw

fuels to attain 10, 20 and 30 wt.% of glycerol, respectively. Once homogenized, the wet blends were dried at 105 °C to eliminate extrinsic moisture before pelletization. As can be seen in Figure 2, none of the tested mixtures reached suitable durability for glycerol addition of 30wt.%, but all of them showed optimum abrasion indexes within the studied range, in agreement with previous works [28][29]. From the experiments performed not a single glycerol percentage can be proposed as optimum for all the blends, since there is a wide variation from one sample to another. Thus, a careful study and individual optimization procedure for each blend is required before the blending process can be scaled up.

As can be appreciated in Figure 2, PIN and its mixtures with PINT, AS, CS, GP and MIS as well as PINT-MIS and PINT-OP reached an optimum of glycerol addition between 20 and 30 wt.%. This value decreased down to 10-20wt.% in the case of PINT and its mixtures with AS, CS, GP and OS. The PIN blends with both olive wastes –OS, OP- are also included in this last group.

It can be concluded that raw PIN, its mixtures and PINT-MIS admit a higher glycerol quantity without losing their binding properties, whilst PINT and PIN-OS require a lower amount of glycerol. This is probably due to their different degrees of impregnability as a result of their different surface areas and/or particle sizes. For instance, as can be seen in Figure 1, OP is the sample with largest quantity of small sized particles, whilst OS is the fuel with smallest quantity of large-sized.

The combination of torrefied biomass and glycerol is extremely important to increase the energy density of this kind of fuel. Consequently, a more detailed study of the PIN and PINT-Glycerol mixtures was performed to obtain a better understanding of the effect of this additive on particle resistance, the results of which are shown in Figure 4.

As can be seen, the optimum abrasion index for the PINT-Glycerol blends was obtained with the presence of a low glycerol amount in the mixture (close to 5wt.%). For higher loadings of glycerol, A_i rapidly increased to values that made these mixtures unfeasible for the purpose of pelletization.

On the other hand, the PIN-Glycerol mixtures displayed optimum A_i values for amounts of glycerol between 10-20 wt.% in the mixture. It should be noted that A_i in this case was slightly higher than that reached in the case of the PINT blends (A_i values of 20 and 30%, respectively). These values are however far from the target A_i (<10%) obtained for some blends with 13% moisture addition. Therefore, it can be concluded that glycerol addition is not the best option for ensuring good pellet mechanical resistance neither for the PIN nor the PINT blends.

However, since glycerol addition significantly increases the pellet's higher heating value and energy density, a tradeoff between both parameters must be sought with suitable A_i -HHV optimization for each particular case. Moreover, the addition of solid additives, such as GP or

OP, that have been proven to enhance pellet's resistance to abrasion appears to be essential if glycerol is to be added in quantities of more than 10 wt.%.

3.2. Product analysis

Once the abrasion index for the formulation of all the proposed pellets was established, the ones that proved to be more resistant were studied in greater depth to determine their quality as fuel. For that purpose, mixtures with abrasion indexes below 10% (PIN-GP-13% moisture, PINT-GP-10 wt.% glycerol, PIN-MIS-20 wt.% glycerol, PIN-OP-13% moisture, PINT-OP-13% moisture and PINT-OP-20 wt.% glycerol) were selected.

Figure 5 shows images of these pellets; comparison of their sizes with the initial PIN and PINT powdery samples (Figures 5a and 5b) can be easily made by visual inspection. These images were taken 2 weeks after the pellets were manufactured. As can be seen in image 5e, the PIN-MIS-20% glycerol pellets began to swell, suggesting a poor long term storage capability, despite their promising results during the abrasion experiments. For this reason this formulation was discarded for future upgraded experiments. Figures 5d, 5e and 5h clearly show that none of the PIN-Glycerol formulations are promising due to their instability.

Thermogravimetric analysis was performed on the selected samples. The corresponding derivative combustion profiles (DTG) are shown in Figures 6a and 6b. Figure 6a includes raw PIN, for comparison purposes, together with the PIN-based selected samples (PIN-GP-13% moisture, PIN-MIS-20 wt.% glycerol and PIN-OP-13% moisture), while Figure 6b includes the PINT and PINT-based (PINT-GP-10 wt.% glycerol, PINT-OP-13% moisture and PINT-OP-20 wt.% glycerol) densified formulations. Five main peaks were identified in the DTG curves. The first peak that appears in the 90-100 °C region corresponds to water originating from moisture. This peak is especially noticeable for raw samples and samples containing extra moisture amounting to an overall 13%, whilst in the case of the glycerol-rich samples this peak is, as might be expected, much smaller. If just the PINT samples containing glycerol are taken into account, this peak is negligible and smaller than the one obtained in the case PIN-MIS-20 wt.% glycerol. This is due to the hydrophobicity of the torrefied material that impedes moisture to be absorbed during storage, as commonly happens in the case of PIN; this characteristic impoverishes the quality of the prepared samples, as previously mentioned.

The second DTG peak that appears at around 175 °C for PIN-MIS-20 wt.% glycerol, PINT-GP-10 wt.% glycerol and PINT-OP-20 wt.% glycerol corresponds to the volatilization of glycerol.

Two other peaks characteristic of PIN and PINT, corresponding to hemicellulose, cellulose and partial lignin thermal decomposition, appear at approximately 340 and 485 °C. The peak corresponding to the fastest mass loss, due to volatiles release from hemicellulose and

cellulose degradation, referred as peak temperature and commonly used as a measurement of reactivity [34], corresponds to the one that appears at 340 °C.

There is an intermediate peak, at around 450 °C for all blended samples that can be ascribed to the second solid component of the prepared blend (i.e., MIS, GP or OP). The relative height of this peak compared to that of PIN or PINT reflects the relative amount of each component in the blend.

Finally the energy density of these selected samples was evaluated and reported in Table 2. As can be seen the energy density values of some of the pelletized samples are considerably higher than those measured for raw PIN (3850 MJ/m³) and PINT (4078 MJ/m³), reaching a maximum value of 8762 MJ/m³ in the case of the PINT-GP-10 wt.% glycerol sample. The PIN-MIS blend shows the lowest energy density, even after the addition of glycerol, due to the poor physical properties of MIS. If the PINT-OP-13% moisture and PINT-OP-20 wt.% glycerol samples are compared, it can be observed that glycerol addition enhances their HHV but only slightly increases their energy density as it reduces the bulk density of the samples. The three samples prepared with the addition of glycerol then present the lowest bulk density.

From the results presented in this study it can be inferred that the addition of quantities of up to a 15-20 wt.% of solid biomass with high lignin content, such as GP, significantly increases the mechanical properties of PIN and PINT during the pelletization process under specific conditions (i.e., the addition of moisture and glycerol, to PIN and PINT, respectively), without negative impact on their HHV and energy density.

4. CONCLUSIONS

The results obtained from the experiments performed in this study give rise to the following conclusions regarding biomass co-pelletization. Mixtures including solid lignin-rich additives like GP, show highly enhanced binding properties compared to those of raw PIN and PINT. However, because of its higher sulfur content, only small quantities of GP are recommended (maximum between 10 and 20 wt.%). Glycerol can be considered an additive suitable to enhance the HHV of densified fuels and to improve their lubricant properties, especially in the case of torrefied samples. On the other hand, an excessive amount of glycerol decreases the binding properties and durability of these fuels, decreases their bulk density and negatively affects their energy density. The optimum value can be considered to be between 5 and 10 wt.% depending on the fuel selected. Non-torrefied woody fuels, like PIN, show greater durability and better energy properties when the only treatment is external moisture addition. In view of these observations, the mixtures with the most promising properties for scaling up

to a pelletizing pilot plant level are PIN 80 wt.-%-GP 20 wt.-%-13% moisture and PINT-80 wt.-%-GP 20 wt.-%-10 wt.-% glycerol.

5. ACKNOWLEDGEMENTS

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Table 1. Analysis data for the selected biomass samples.

Sample	Ultimate analysis (wt.%, db)					Proximate Analysis (wt.%, db)				HHV _{wb} (MJ/kg)	Lignin Content (wt.%)
	C	N	H	S	O*	Ash	VM	FC*	M		
PIN	51.0	0.3	6.0	0.02	42.3	0.4	85.1	14.5	9.6	18.2	26.0
PINT	53.0	0.4	5.7	0.03	40.6	0.3	80.1	19.6	5.1	20.1	-
AS	49.4	0.3	5.6	0.05	43.3	1.4	78.9	19.6	6.5	18.4	25.6
CS	48.0	2.7	5.9	0.21	35.3	7.9	70.4	21.7	6.7	17.8	34.5
GP	45.5	1.8	5.1	0.17	34.7	12.7	67.6	19.7	11.6	16.7	53.2
MIS	48.0	0.4	5.8	0.11	36.5	9.2	77.6	13.2	5.6	17.6	21.2
OP	49.3	1.6	5.4	0.12	37.4	6.2	72.5	21.3	5.2	19.3	42.7
OS	51.2	0.3	6.0	0.03	41.9	0.6	81.5	17.9	4.3	19.7	30.4

* Oxygen and Fixed Carbon were calculated by difference

VM: Volatile Matter; FC: Fixed Carbon; M: Moisture

All results are presented in dry basis (db) except HHV, which is provided in wet basis (wb).

Moisture content is also provided for HHV comparison.

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Table 2. Energy density values obtained for selected pelletized samples.

Sample	BD (kg/m ³)	HHV _{wb} (kJ/kg)	η _{energy} (MJ/m ³)
PIN	212	18164	3850
PIN-GP 13% moist	499	17286	8627
PIN-MIS 20 wt.% gly	244	18620	4541
PIN-OP 13% moist	455	17254	7850
PINT	203	20082	4078
PINT-GP 10 wt.% gly	429	20442	8762
PINT-OP 13% moist	443	17701	7833
PINT-OP 20 wt.% gly	398	20122	7998

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BD: Bulk Density.

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η_{energy}: Energy Density.

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Figure 1. Cumulative particle size distribution of the solid biomass samples studied.

Figure 2. Results from the abrasion tests.

Figure 3. Evolution of A_i for different GP and OP ratios in the blends with PIN and PINT.

Figure 4. Evolution of the abrasion index for the PIN and PINT-Glycerol mixtures.

Figure 5. Images of the samples with best durability: a) PIN, b) PINT, c) PIN-GP 13% moisture, d) PINT-GP 10 wt.% glycerol, e) PIN-MIS 20 wt.% glycerol, f) PINT-OP 13% moisture, g) PIN-OP 13% moisture and h) PINT-OP 20 wt.% glycerol.

Figure 6. DTG profiles for the tested a) PIN and b) PINT-based pelletized samples, compared with the raw biomasses.