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SOLAR DRYING ACACIA- INFLUENCE IN PELLETS QUALITY: EXPERIMENTAL RESULTS

Diana Almeida[1]
Tânia Ferreira[2]
Polytechnic of Viseu – Portugal
diana.-almeida@hotmail.com
tania__vanessa@hotmail.com

Edmundo Marques[3]
Oporto University, Porto – Portugal
edmundo@estv.ipv.pt

João Monney Paiva[4]
Polytechnic of Viseu – Portugal
jmonney.e@gmail.com

Abstract. *Acacia spp., an invasive species, was collected and processed to produce pellets and to study the effect of the drying process in the resulting quality.*

One set of samples were dried in a solar kiln, achieving 7, 13, 15 and 20% humidity (wet basis). A second set was dried in a Venticell dryer at 105ºC until approaching complete desiccation. These samples acquired humidity with simple exposure to ambient atmosphere, increasing 1 to 3%, depending on diameter value.

Summer and winter drying cycles were performed. The material was them crushed in a hammer mill, ensuring constant feed mass flow rates and characterized in terms of average size (594-725 μm).

Pelletization was performed at constant level. The quality tests made revealed that pellets with 7 % humidity had the higher index. Otherwise, higher and lower humidity result in lower durability. Particularly, pellets with 3% humidity were extremely frail.

An energy balance of the overall process was performed, revealing an average value of 1300 kJ/kg.

Keywords: *pellets, solar drying, quality, energy balance*

1. INTRODUCTION

Drying is the process of removing the excess water from an industrial or natural product with the objective of obtaining the regular specification moisture content (Belessiotis and Delyannis, 2011).

Direct solar drying refers to a process where material is heated directly by the sun so that moisture is removed by natural air circulation due to density differences. Air relative humidity is a key factor because the lower the relative humidity of the drying air, the more water evaporates from the product, ensuring a lower final product moisture content. Therefore, the drying potential is affected by the air temperature and by the relative humidity (Helwa *et al*., 2004). There are two mechanisms involved in this process: the first one refers to the migration of the mass of water from the inside of the wood cells to the surface; the second one refers to the moisture transfer from the wood surface to the surrounding air, in water vapor form (Khater *et al*., 2004). The rate of water movement differs from one substance to another, depending on the hygroscopic characteristic of the material. Drying non-hygroscopic material achieves zero moisture content. For hygroscopic materials, there is residual moisture content as water becomes trapped into capillaries, a phenomenon that takes place inside green wood (Khater *et al*., 2004).

The amount of energy needed to condensate or evaporate moisture is the latent heat of vaporization and depends on the type of material used, its initial moisture content and temperature. This is the higher percentage of energy needed during the drying process and it represents approximately 2258 kJ/kg at 101.3 kPa (Ekechukwu, 1999).

Moisture content present in a sample is expressed on dry or wet basis and either as a decimal or a percentage. Therefore, the moisture content in wet basis (M_{wb}) is the mass of moisture present in a product per unit of mass of the wet material, as stated in Eq. (1):

$$M_{wb} = \frac{W_0 - W_d}{W_0} \tag{1}$$

Equation (2) refers to the moisture content in the dry basis (M_{db}), that is the mass of moisture existing in the sample per unit of mass of the dry matter:

$$M_{db} = \frac{W_0 - W_d}{W_d} \tag{2}$$

where W_0 represents the initial mass of the wet product and W_d is the mass of the dry matter (Ekechukwu, 1999). All over this paper, moistures are reported to the wet basis (wb).

Producing wood pellets is made by feeding material to a press machine, that will force it to pass into open-ended cylindrical holes (dies) made in the peripheral ring or flat die. For the first kind of machinery, one to three gyratory rolls impulse the sawdust into the dye holes from inside of the ring in the direction of the outside of the ring; flat dies type have rollers over the plate that push the upstream received wooden material into the holes. Inside the holes, those particles accrued are pressed against the wall and with themselves, what increase the attrition forces. When those forces are surpassed, the pellet formed slip from inside to outside of the hole. To obtain ideal lengths, one knife is placed outside the ring or flat die cutting the pellets (Kaliyan and Morey, 2009).

In this process many interactions take place between particles: solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, interfacial forces and capillary pressure. It was observed that water acts as binding agent and a lubricant and, in ideal conditions, helps developing van der Waals' forces by means of augmentation of the contact area between the particles (Kaliyan and Morey, 2009).

Those interactions are affected by variables such as manufacturing temperature, sawdust particle size, moisture, and applied pressure (that defines the static distance between the dye and the rollers). Thus, pellets mechanical properties and resulting density experience changes (Relova *et al*., 2009).

Also, pelletization has to take place at temperatures between 80 and 200°C because at that range of temperatures lignin becomes softer and displays thermoplastic properties, binding loose particles and improving the overall mechanical strength (Yazdanpanah *et al*., 2010; Relova *et al*., 2009).

Another important factor involving this production process is the raw material moisture content. A study presented by Mani *et al.* (2006) revealed that pellet production using sawdust from woody residues with 50% moisture content in wet basis (M_{wb}) was not possible. However, with low moisture content, lignocellulosic materials act as thermal insulation, inhibiting heat transfer and, thus, increasing the temperature, an important factor in the densifying process (Relova, *et al*., 2009). Optimum moisture contents are present in the literature and indicate average values for materials to be processed in pellet mills, in the 8-12% range (Hill and Pulkinen, 1988).

This present work observed how variations in raw material moisture content affected the pelletization process and, consequently, the final quality of the pellets. To assess that influence, a set of samples of *Acaci*a with 0, 7, 13, 15 and 20% M_{wb}, that had been previously shattered, were pelletized and, later on, tested on mechanical durability and water resistance indexes, according to international standards for commercialization.

2. EXPERIMENTAL SETUP

Samples of *Acacia dealbata* were collected and dried in a solar kiln. Raw material moisture content during the drying process was monitored. For that purpose, each day a sample was taken from the solar kiln and dried in a lab Venticelli oven at 105ºC until all water was lost (Samuelsson *et al*., 2006).

Two different drying cycles were carried out: one in the summer and the other one during the winter. Factors involved in the drying process such as irradiance, temperature and air relative humidity were measured, for both (summer and winter) drying cycles.

To obtain data from these processes, the solar kiln was instrumented with Apogee SP215 pyranometers (Fig.1), to allow measurements of solar radiation inside the solar dryer. One pyranometer was placed on the external side of the kiln and another one inside.

Figure 1. Solar kiln: P_1 – external pyranometer; P_2 – internal pyranometer; T_1 – thermocouple, upper part; T_2 – thermocouple, middle; T_3 – thermocouple, lower part; H_1 – air relative humidity sensor, upper part; H_2 – air relative humidity sensor, lower part.

T type thermocouples were used to measure temperatures (one was placed in the upper part of the solar dryer, another one in the middle part and the last one near to the bottom, the lower part of the solar kiln; Honeywell HIH 4000 sensors were used to measure the air relative humidity (one in the upper part, another one in the lower part).

National Instruments NI USB-6008 DAQ, Pico Technology TC-08 USB and ADC-20 data loggers were utilized to connect the sensors. Pico Technology Picolog Recorder and National Instruments Labview 8.6 software were chosen to read and collect data from the drying process. National Instruments Labview 8.6, utilized to collect irradiance values, was programed to save data every one second; every three minutes an average value was calculated. A Pico Technology Recorder, used to measure temperature and air relative humidity, was programed to collect data every one minute.

An Agico wood crusher was used to shatter the raw material. This process was made at constant feed rate. The output product was passed through an internal sieve with 6 mm diameter. The sawdust obtained was then characterized in terms of moisture content and average mean particle sizes were calculated. Using procedures according to ISO 3310-2 1999-01, three samples of each raw material batches were sieved in a Retsch AS 200 device (Fig. 2a), resulting in a total of 15 samples analyzed. Each particle mean diameter was determined using Eq. (3):

$$\overline{d_p} = \frac{1}{\Sigma\left(\frac{x}{dp}\right)} \tag{3}$$

where $\overline{d_p}$ represents the value of the average particle diameter (μm), d_p the sieve mean diameter at a specified interval (μm) and x the retained mass (g) in each sieve.

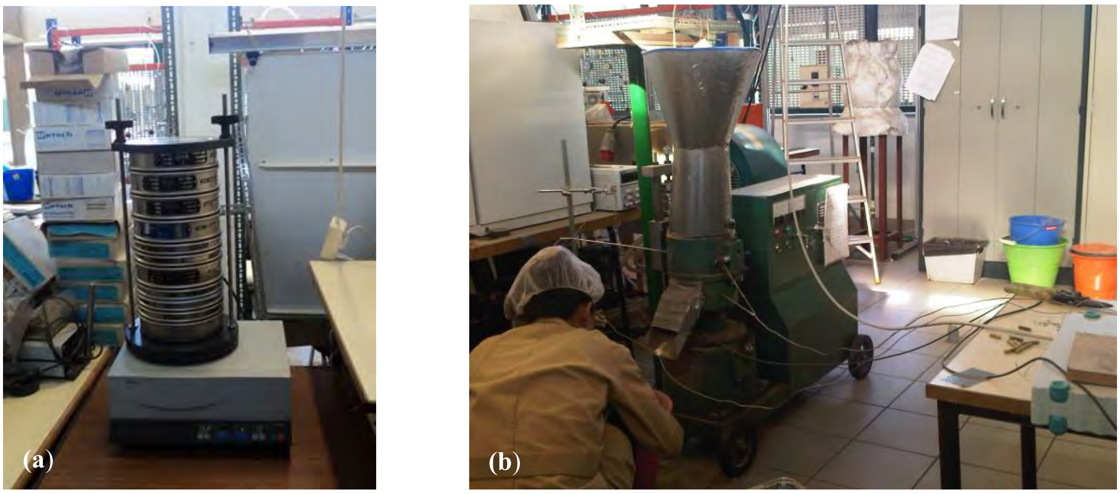

Figure 2. (a) The Retsch AS 200 sieving device and (b) the pelletizing machine.

A pellet mill (Fig. 2b) was instrumented with J and K type thermocouples, externally and internally, respectively, in order to evaluate the temperatures involved in the pelletizing process. A TC-08 USB board was utilized to connect the thermocouples and the Picolog Recorder software was used to read the temperatures. Pellets with 6 mm diameter were produced at an approximate constant mass feed rate. Subsequently, a cooling period was guaranteed (Mani *et al.*, 2004), before they were characterized by means of a set of standard procedures.

Durability and water resistance tests were carried out to evaluate the pellets quality. The durability index, or, simply durability, is obtained simulating the mechanical handling of pellets and aims at predicting the possible amount of fines produced. Pellets were poured into a can and tumbled to abrade and produce fines due to impact and shearing of pellets over each other and over the wall. After tumbling 500 g of pellets for 10 min at 50 rpm, the pellets were sieved. The durability was calculated as the ratio of weight after tumbling over the weight before tumbling (Temmerman *et al.*, 2006).

$$Durability\ (\%) = \frac{Mass\ of\ pellets\ after\ trumbling}{Mass\ of\ pellets\ before\ trumbling} \times 100 \tag{4}$$

For the measurement of the water resistance index, or, simply, water resistance, sets of pellets were immersed in 25 mm of water at 27ºC for 30 seconds. Water resistance is the percentage of water absorbed (Lindley and Vossoughi, 1989; Kaliyan and Morey, 2009).

$$Water\ resistance\ (\%) = \frac{Mass\ of\ pellets\ (after - before)\ absorbing}{Mass\ of\ pellets\ before\ absorbing} \times 100 \tag{5}$$

The energy needed to dry the raw material was estimated using the following equation:

$$S = \frac{I_{av}A_i t}{m_v h_{1g}} \tag{6}$$

where I_{av} is the daily average solar intensity on the kiln surface area, A_i is the effective energy collection area (exposed to solar radiation), t is the time during which the drying process took place, m_v is the mass of moisture evaporated and h_{lg} the latent heat of vaporization (Singh *et al.*, 2006).

3. RESULTS

3.1 Drying processes – summer and winter cicle

Summer drying process took four days to achieve the desired moisture content of 20%. Before entering the kiln, *Acacia dealbata* samples had 28% M_{wb}; when removed, they were at 22.5.

With the winter cycle 16 days were needed to obtain the desired moisture content. Initially *Acacia dealbata* presented a moisture content of 42.2%. After the drying cycle was over, the material had a moisture content of 20%. From the product that was placed in the solar kiln, daily samples were collected and the moisture content evaluated.

Figure 3 represents the irradiance evolution with time during the two drying cycles, summer and winter.

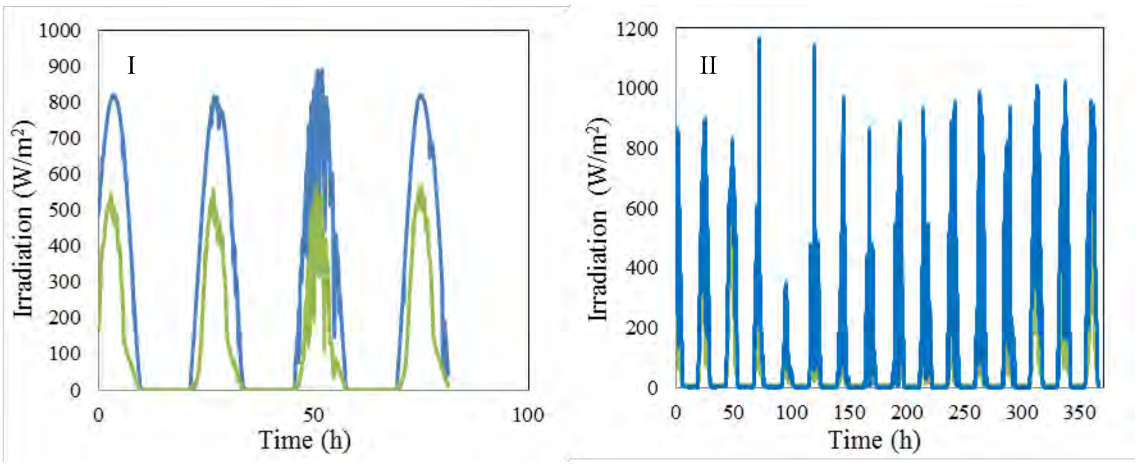

Figure 3. Irradiance data. I. Summer cycle; II. Winter cycle.
(blue – external radiation; green – internal radiation)

Analyzing irradiance data, in summer there are naturally more hours of solar radiation, though last year weather was not as predictably conservative as expected. Still, radiation data revealed pick values for very small periods.

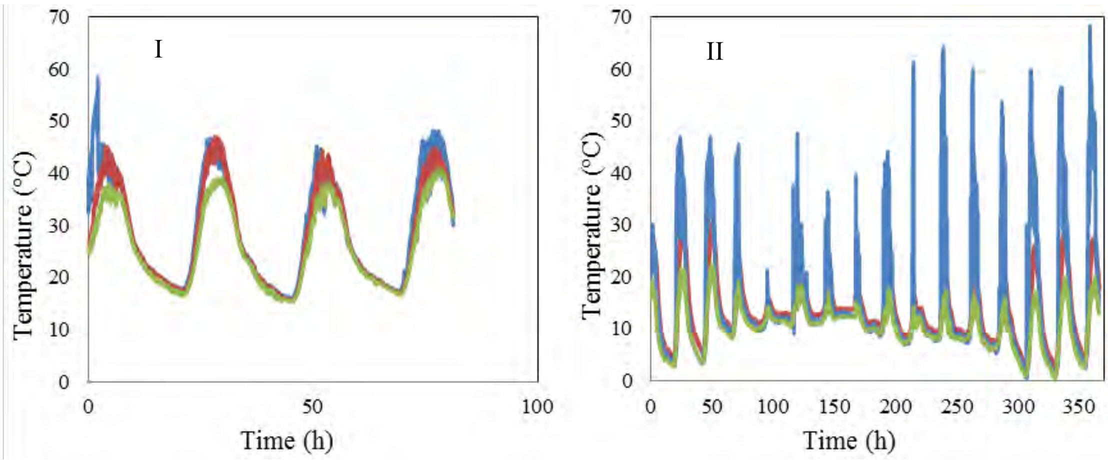

Figure 4. Temperature data. I. Summer cycle; II. Winter cycle.
(blue – upper part; red – middle part; green – lower part)

The air temperature inside the solar dryer was measured. Figure 4 represents that evolution within the period of time during which the drying process took place, for Summer (I) and for Winter (II). To assess air temperatures, three thermocouples were placed inside the solar dryer: one in the upper side, near the cover, one inside the drying cushion composed by the biomass material that was drying, suspended by a plastic net in the middle internal height of the solar dryer, and the third one placed in the lower part, near the bottom.

In Fig. 4, image I, the temperature steep variation resulted of an accidental contact of the thermocouple located on the upper part with the hot surface of the acrylic cover kiln.

Figure 5 represents the air relative humidity evolution with time inside the solar kiln. Two humidity sensors were placed in the solar dryer, one in the upper side, near the transparent cover, and the other in the lower, part close to the bottom.

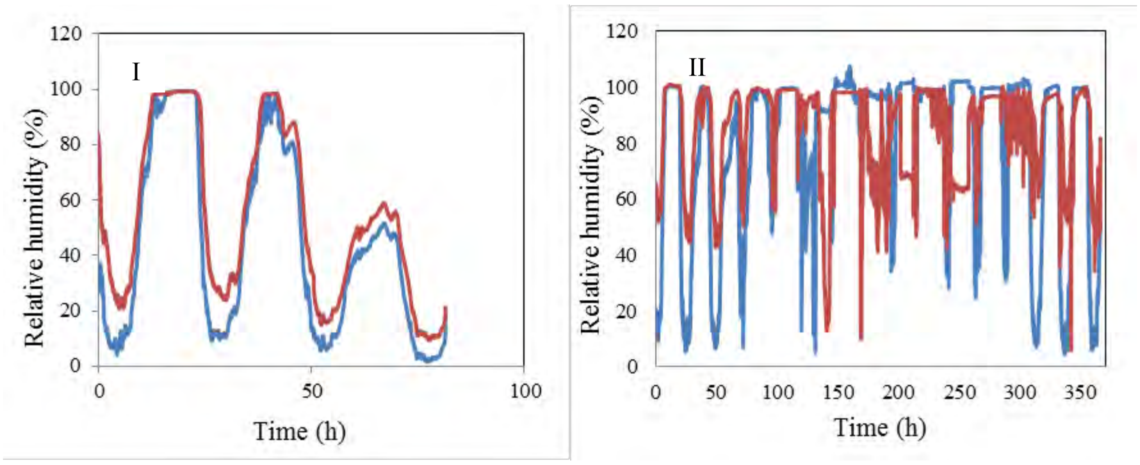

Figure 5. Air relative humidity data. I. Summer cycle solar drying data; II. Winter cycle solar drying data (blue – upper part; red – lower part).

Temperature data in the Summer cycle was higher and air relative humidity was lower, naturally, when compared to the Winter cycle. Temperatures were higher most of the period though, some days, minimum values during the night sometimes recahed 0ºC. Air relative humidity data in the Winter cycle drying process achieved higher values due to the several raining days experienced, which lead air relative humidity to saturation.

Table 1. Solar energy used to dry raw material.

	Acacia dealbata pellets				
	A	B	C	D	E
M_{wb} (%), Eq.(1)	0	7	13	15	20
S (kJ/kg), Eq. (6)	–(1)	1493	1470	1400	980

(1)using a lab Venticelli oven at 104ºC during 24 hours

To achieve the same 20% M_{wb} during the Summer period, fewer days were needed. Analyzing the data obtained, both summer and winter cycles for solar drying, there was an average loss of, approximately, 250 W/m^2, an energy flux that did not passed through the cover of the solar kiln. This value was obtained from data collected with the two pyranometers, one placed just at the outside of the transparent cover and the other one installed inside the solar dryer.

Referring temperature data, in the upper part of the solar kiln higher temperatures were reached, due to the reception of a significant amount of direct radiation. Consistently, higher temperatures induced lower air relative humidities, as reflected in the data collected from relative humidity sensors, as well as measurements of higher values of air relative humidity in the lower part of the solar kiln.

3.2 Milling process and sawdust characterization

After the drying process was over, the raw material was shattered in a hammer mill at an approximate constant feed rate. The moisture content of the resulting sawdust was evaluated and only the material that had the desired moisture content of 20% was taken off. The leftover material returned to the solar kiln and dried until successively 15, 13, and 7 % humidity values were obtained.

All the material at those different humidity contents was sampled to be characterized in terms of particle size distribution and average mean diameter. Figure 6 represents the mass retained in each sieve (x) versus mean diameter (d_p) of *Acacia dealbata* sawdust at 0 and 7% moisture.

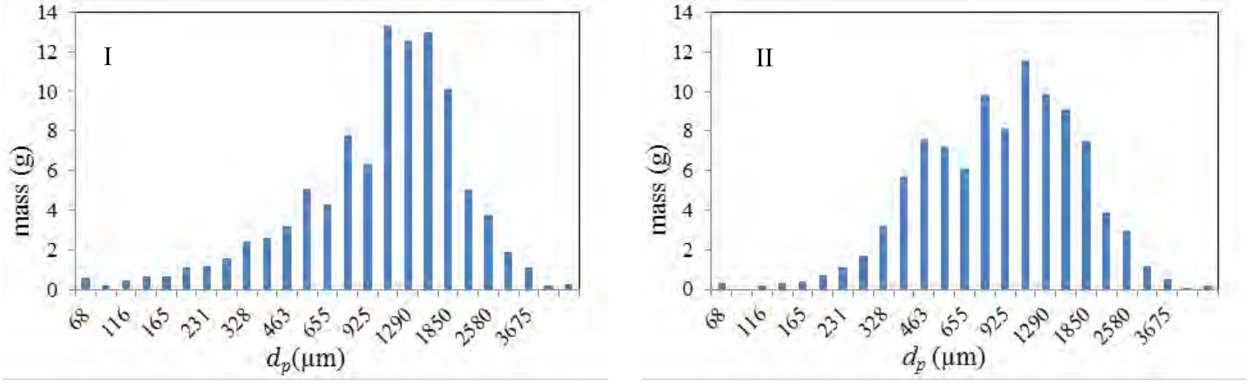

Figure 6. Sieving results - mass *versus* sieve mean diameter, *Acacia dealbata*. I – sawdust at 0% M_{wb}; II – sawdust at 7% M_{wb}.

Characterization in terms of particle size distribution and average mean particle diameter was also performed to 13 and 15% M_{wb} sawdust. As can be observed in Fig.s 6, 7 and 8, the highest mass values were retained between the 1290 and 2580 μm sieves. Figure 7 represents the mass retained in each sieve (x) versus mean diameter (d_p) of *Acacia dealbata* sawdust at 13 and 15% M_{wb}. with the latter displaying an incipient bimodal pattern.

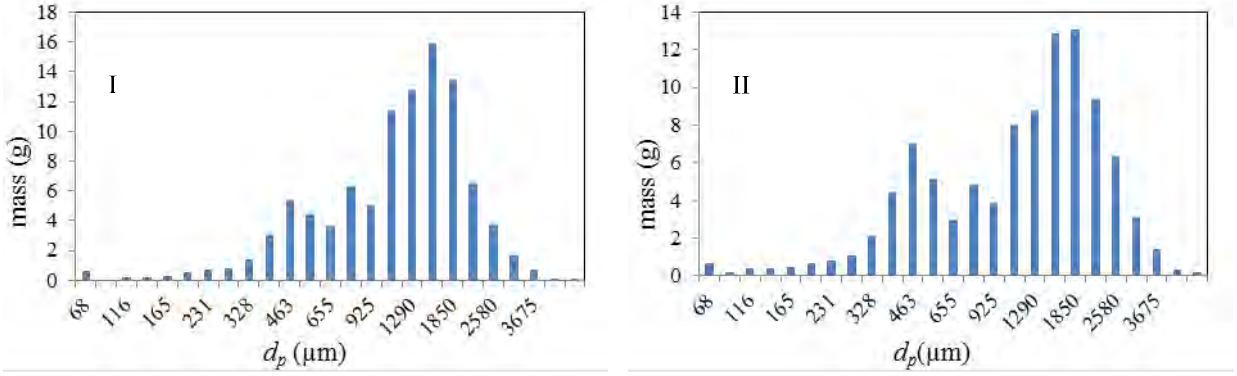

Figure 7. Sieving results - mass *versus* sieve mean diameter, *Acacia dealbata*. I – sawdust at 13% M_{wb}; II – sawdust at 15% M_{wb}.

Figure 8 represents the mass retained in each sieve (x) versus mean diameter (d_p) of *Acacia dealbata* sawdust at 20% M_{wb}, with a similar same incipient bimodal pattern to the 15% M_{wb} samples.

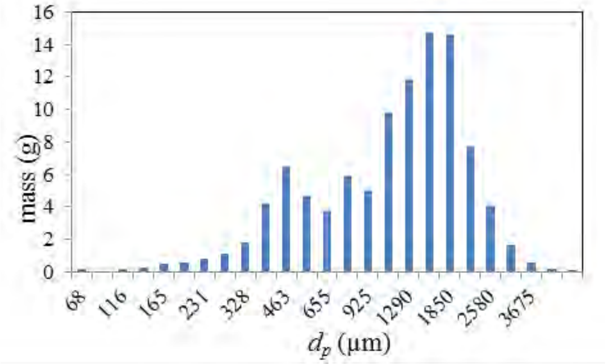

Figure 8. Sieving results - mass *versus* sieve mean diameter, *Acacia dealbata* sawdust 20% M_{wb}.

A comparison between the different particle mean diameters calculated for all the five samples analyzed is presented in Fig. 9.

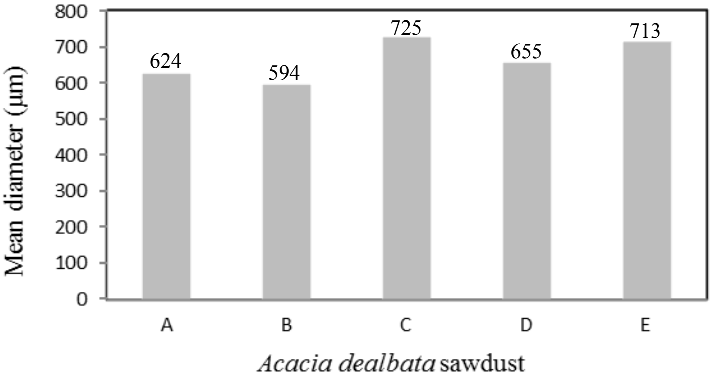

Figure 9. Sieving results - $\overline{d_p}$ *versus Acacia dealbata* sawdust. (A, B, C, D and E represents sawdust at 0, 7, 13, 15 and 20% M_{wb} respectively).

There is no noticeable dispersion either of particle dimensions or calculated average diameters for the five type of samples tested.

3.3 Pelletizing process and pellets characterization

Having obtained sawdust at the different desired moisture content, the material was passed through the pelletizing machine. As a first step, sawdust was well mixed and only then was added to the pelletizing machine at an average constant feed rate. During the pelletizing process, initiated with a tightening torque of 17 Nm for all the cases, temperature was monitored so that samples would be collected after some stabilization was attained. For all the types of pellets produced, the temperature evolution during pelletization presented a similar profile. On average, the temperatures at which the pelletization took place were in the 80-90ºC range.

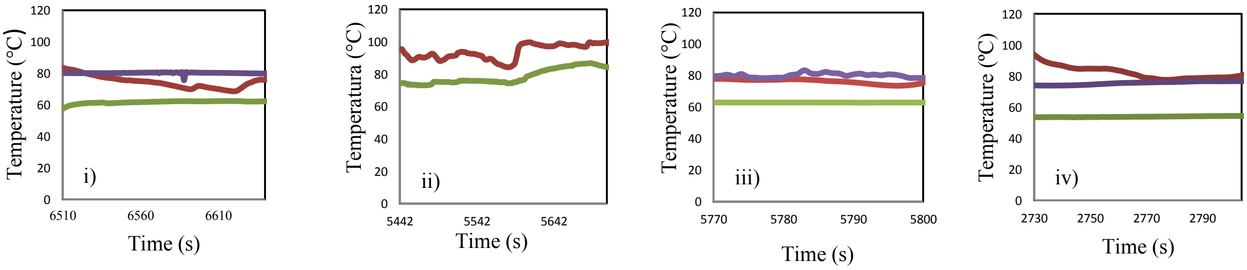

Figure 10. Temperature of pellets manufacturing (i) 7, ii) 13, iii) 15 and iv) 20% M_{wb}).
(red - axis; green - cover upper part; purple - cover lower part)

Samples were then processed and tested. Figure 10 represents the temperature evolution during the pelletization for the different moisture contents. The periods of temperature stabilization were recorded to allow the identification of the corresponding manufactured batches.

For milling and pelletizing processes, energy consumption data was obtained by means of a Hioki Wattmeter Analyzer. This equipment acquires tensions, currents and power factors values of three electrical phases and calculates the respective energy consumption (Ghorbani *et al*, 2008): the overall average values were of 180 kJ/kg for the milling process and 140 kJ/kg for the pelletization, resulting in the final energy values of Tab. 2.

Table 2. Total energy used in drawing, milling and pelletizing.

	Acacia dealbata pellets				
	A	B	C	D	E
M_{wb} (%), Eq.(1)	0	7	13	15	20
E (kJ/kg)	–$^{(1)}$	1813	1790	1720	1300

$^{(1)}$a lab oven was used

Type A pellets were manufactured at a constant feed rate of 160 kg/h, with a corresponding average temperature of 96ºC (Fig. 11).

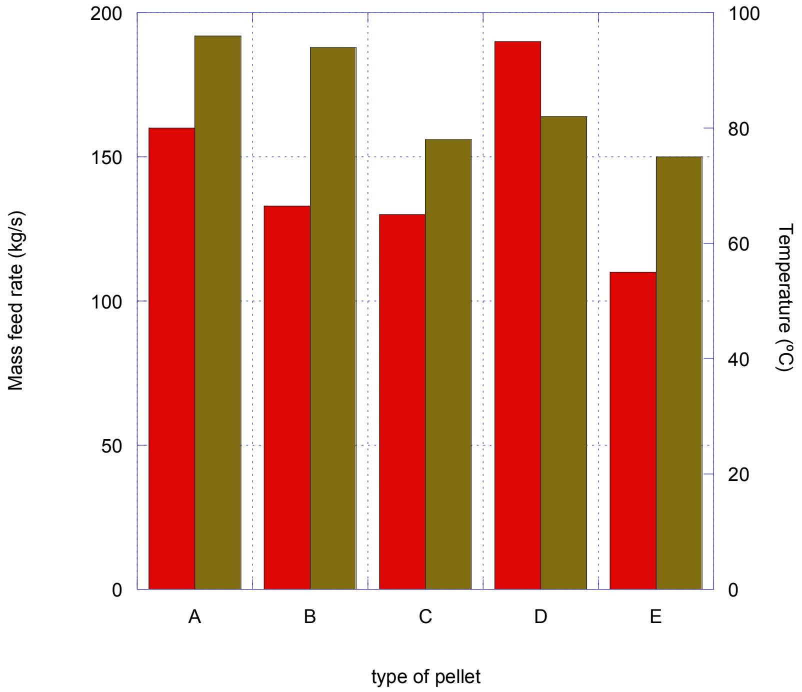

Figure 11. *Acacia dealbata* pellets production conditions: red- average temperature; brown- mass feed rate. (A, B, C, D and E represent pellets made from 0, 7, 13, 15 and 20% M_{wb} sawdust, respectively)

Acacia dealbata B type pellets were produced from sawdust with a moisture content of 7% at a constant feed rate of 133 kg/h with an average temperature of 94ºC.

Pelletizing sawdust with 13% of moisture content, pellets type C, at a constant feed rate of 130 kg/h, an average temperature of 78ºC was achieved. For type D pellets, resulting from adding sawdust with 15 % of moisture content, average temperatures were of 82ºC. Finally, E type pellets were manufactured from sawdust with 20% moisture content at 75ºC with a mass feed rate of 110 kg/h.

Higher moisture content revealed a tendency to diminish the material feed rate due to particle agglomeration. Also, pelletization temperatures were lower when sawdust had higher moisture content because water content makes the material softer and the friction decreases (Kaliyan and Morey, 2009).

The energy used in the water evaporation also contributes to those lower temperature values- this effect was indirectly registered by means of the relative humidity being measured inside the hopper, just above the upper cover.

Table 2. *Acacia dealbata* pellets characterization.

	Type of pellets				
	A	B	C	D	E
Diameter (mm)	5.9	6.1	6.7	6.7	6.4
Length (mm)	20.0	28.7	17.1	15.4	14.0
Weight (g)	0.58	0.9	0.4	0.36	0.31
Fine content (%)	87.1	0.8	9.6	10.1	-⁽¹⁾
Moisture (%, w.b.)	3.0	5.0	9.8	10.4	14.5
Particle density (m^3/kg)	1061	1073	663	663	688

(1) Fine were not collected

D type pellets manufacturing was made at a higher material feed rate of, approximately, 190 kg/h, resulting in a temperature of 82.2ºC during the production process.

For the whole set of experiments, after leaving the pelletizer machine, pellets temperature were in a range of 90 ± 10ºC. They had to be left cooling in ambient air for 6 hours. Only then were the pellets physical characterization done. Table 2 contains some *Acacia dealbata* pellets physical characteristics, where A, B, C, D and E represents, again, 0, 7, 13, 15, and 20% moisture, respectively.

Durability and water resistance tests were performed and the results are presented in Fig. 12.

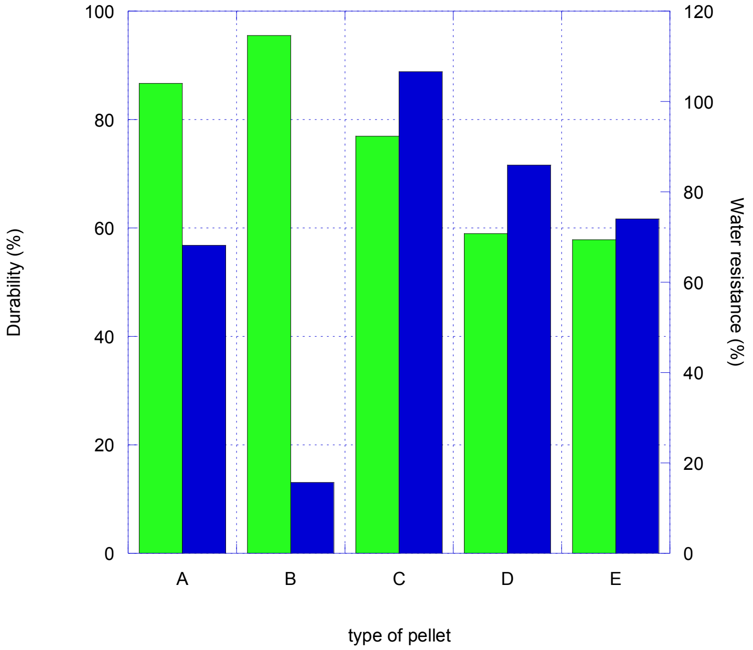

Figure 12. *Acacia dealbata* pellets properties: green- durability; blue- water resistance.
(A, B, C, D and E represent pellets made from 0, 7, 13, 15 and 20% M_{wb} sawdust, respectively)

Pellets type A were produced feeding the pelletizing machine with 0% moisture content sawdust. The resulting durability index was higher than those of type C, D and E pellets, but frailer. The most important issue for this case as the high amount of fine produced, 87.1% (Tab. 2), which makes it a non-alternative option for pelletization.

Better quality pellets were produced with material B, 7% M_{wb} sawdust, achieving 95.5 % durability, a good value though still below international standards.

Pellets produced adding raw material with moisture contents higher than 7%, presented lower durability indexes. The higher the moisture content the lower the durability index.

Pellest type produced with material B revealed a lower percentage of water resistance, comparing to the remaining pellets.

The higher the moisture content of the raw material, the lower the pelletization temperature, the lower the effectiveness of the densification process, the lower the pellets durability and the higher the capability to absorb water, thus confirming the results found in literature (Mani *et al.*, 2006; Relova, *et al.*, 2009)

3.4 Successive pellets entry in pelletizing machine – influence on pellets quality

Pellets manufactured with sawdust at 20% moisture content presented low quality indexes. To reduce the amount of water content, successive pellets processing cycles were done. The influence on the quality of the pellets, Fig. 12, of the change of the moisture content, affects the durability index data of the pellets produced at the end each of each processing cycle in the pelletizing machine.

A loss of moisture content and an increase of durability indexes were, until a critical point was reached. Better durability results were achieved at the fifth processing cycle of pellets into the pelletizing machine, resulting in a very acceptable 98.4% durability index. After the fifth processing cycle an inflection of the trend could be observed, resulting in a progressively decrease on pellets quality, until the seventh processing cycle was done. At that moment, the material had regressed to an almost small dimensions coarse non-aggregative powder. Pellets moisture content decreased successively each time the material was processed, accomplishing a very low 5% moisture content at the tenth and final processing cycle.

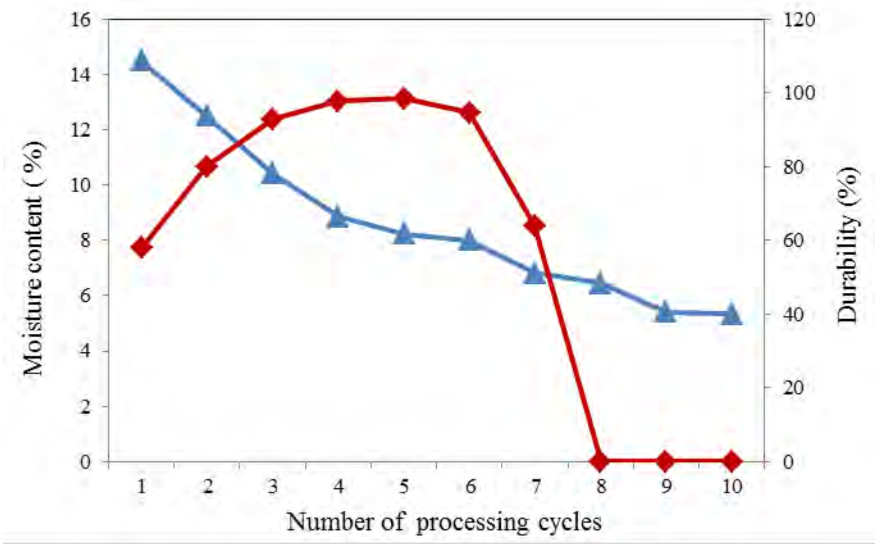

Figure 12. Moisture content and durability indexes data from pellets produced of *Acacia dealbata* (blue – moisture content; red – durability index).

In an initial phase of this process, the dominant factor was the moisture content that decreased due to successive processing cycles leading to an increase of durability index. After de fifth processing cycle, a maximum was attained and, beyond that point the cutting and stripping processes at which the wood fibers had been submitted overcome the benefits of increased temperature and softening of the binding compounds, leading to a decrease on pellets quality caused by irreversible physical and chemical changes.

4. CONCLUSIONS

Sawdust prepared presented particle average mean diameters between 594 and 725 µm and moisture content between 0 and 20 %, intended to evaluate the influence of this range of moisture content in pellets quality.

Pelletizing *Acacia dealbata* revealed that 7% moisture content sawdust produced a better quality pellet, with higher durability values and lower water resistance indexes.

Pellets manufactured adding sawdust at 20% moisture content and reintroducing these pellets into the pelletizing machine revealed an increase in durability indexes and a decrease in moisture content until reaching a critical point. Better conditions were achieved at the fifth processing cycle, with 98.44% durability and 8% moisture content, fulfilling international standards. After the seventh processing cycle, pellet quality degradation was verified leading to powder formation.

5. ACKNOWLEDGEMENTS

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