



# Energy use of *Jatropha* oil extraction wastes: Pellets from biochar and *Jatropha* shell blends

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## ABSTRACT

The aim of this paper is to evaluate the use of biochar (SCB) produced through the pyrolysis of *Jatropha* seed cake in combination with *Jatropha* shell waste (JSh) to form pellet combustion fuel. Mixtures using different proportions of SCB and JSh (0, 25, 50, 75 and 100% each), were prepared, with each proportion tested using two particle sizes and two different quantities of water added. Combustion characteristics and mechanical durability were analyzed to identify the best blend, for which a thermogravimetric analysis was made. Pellets composed of 50% JSh and 50% SCB, with 25% of additional water and 4 mm particle size, presented the greatest mechanical durability (96.83%), and higher heating value (22.14 MJ kg<sup>-1</sup>). Combustion of pellets made with these characteristics in an industrial burner showed average temperatures ranging from 300 to 350 °C, with a maximum temperature of 460 °C. The production cost of the selected pellet is estimated at 0.11 USD kg<sup>-1</sup>, making the energy cost of the pellet [0.005 USD MJ<sup>-1</sup>] approximately 28% of the energy cost of LPG, demonstrating the commercial viability of the selected pellet as feasible.

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## 1. Introduction

The search for new sources of energy is growing day by day, with biomass representing an attractive alternative, especially in countries with limited economic resources, as properly-managed biomass can provide a sustainable low-cost fuel supply (Cuiping et al., 2004).

Among biomass resources, several types of agro-industrial waste can be used for the benefit of industry and the environment (Hoogwijk et al., 2003). The use of biomass for energy purposes generally involves pretreatment systems that improve the energy characteristics of the feedstocks. These procedures can be physical or chemical depending on the specific need or interest in maximizing the energy content.

Several studies have been carried out on the use of *Jatropha curcas* as an energy resource, either by refining the plant's seed oil into a biodiesel fuel (Koh and Mohd. Ghazi, 2011), or by burning the

oil in a mixture with diesel (Forson et al., 2004). *Jatropha curcas* is a shrub native to the American tropics and is cultivated in tropical and subtropical regions. The plant is most commonly found in Mexico and Central America, but is also widely distributed in wild or semi-cultivated forests throughout Latin America, Africa, India and South-East Asia (Pandey et al., 2012).

In Ecuador *Jatropha curcas* is not used as an energy crop, but is rather employed as live fencing in rural areas, mainly in the coastal province of Manabí. However, as part of the Ecuadorian government's "Renewable Energy for the Galapagos Islands" program, the project "Production of pinion oil for a pilot project of electric power generation in Galapagos" focuses on replacing the diesel fuel commonly used for electric generation with pure *Jatropha curcas* oil. For this project, *Jatropha curcas* fruit is harvested in continental Ecuador and processed to extract the seeds' oil, which then is sent to the Galapagos Islands as a clean electric generation fuel. According to data from the Manabí Provincial Council, in 2008 the province had 7000 km of *Jatropha curcas* live fences, which can produce between one and ten tons of seeds per hectare, depending on the age of the plants, soil conditions, and the use of irrigation. From the extraction of *Jatropha curcas* oil in Manabí alone, approximately 200,000 kg of waste were produced in 2018. This

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residual biomass consists of the *Jatropha* fruit's shell, which is removed in filter presses before oil extraction, and the seed cake, which is the solid fraction of the seed remaining following the oil extraction process. Neither the shell nor seed cake have a current disposal management mechanism, leading to residual waste problems.

*Jatropha* seed cake does not require densification (pelletizing) for the generation of heat (Kratzeisen and Müller, 2013), and can be pyrolyzed in order to produce bio-diesel. This pyrolysis produces biochar that is a "stable, homogeneous, clean, and high-caloric fuel (25–30 MJ kg<sup>-1</sup>)" (Yi et al., 2013). On the other hand, the *Jatropha* shell (fruit peel) represents a high-volume biomass that requires densification to reduce transportation costs and facilitate subsequent combustion, as recommended by (Mobini et al., 2014) for the case of wood pellet production.

In Ecuador, management of the waste (seed cake) from the extraction process of *Jatropha curcas* oil is being piloted using pyrolysis to generate bio-diesel and biochar. The pyrolysis reactor consists of a conveyor screw covered by a jacket of electrical resistors which raise the internal temperature of the biomass (seed cake) circulating through the screw. The temperature reached inside the reactor is 450 °C. At this temperature, gases are generated that displace the air inside the reactor, creating an anoxic atmosphere. The gases generated are transferred by pipes to separators and condensers in which the condensable gases (bio-oil) are retained and the non condensable gases are combusted with a torch. The remaining solids from the process (biochar) are cooled and stored.

This research seeks to explore the opportunity for creating pellets from *Jatropha* shell waste together with the biochar produced in the pyrolysis of seed cake, taking advantage of the lignin content of the shell which acts as a natural binder for the pelletizing process, and the higher heating value of the biochar. Pelletizing increases the energy density of the residual biomass through the compaction of the residues, and can lower transportation and disposal costs if the pellets are used as a fuel source in domestic and industrial boilers (Mobini et al., 2014; Stelte et al., 2011).

Recognizing the benefits available from both materials, research on the effect of mixing biomass and coal on the mechanical durability and combustion characteristics of pellets has been previously conducted (Gil et al., 2010b; Guo and Zhong, 2018). Published results on the combustion behavior of pellets from the blending of biochar and coal (Li et al., 2018) also exist, as do results on the performance of biochar pellets obtained from the pyrolysis of corn straw pellets (Xing et al., 2018), but the use of biochar blended with biomass in pellets has not yet been studied.

In recognition of need to improve waste management in *Jatropha* oil production and the gap in existing publications, the current research demonstrates the feasibility of energy use for two waste products. Various blends of the biochar and *Jatropha* shell were evaluated to obtain the best-performing and most economically-attractive pellet.

## 2. Methodology

### 2.1. Oil extraction plant and pilot pyrolysis plant

The sole *Jatropha* oil extraction plant in Ecuador is located at the INIAP-Portoviejo Experimental Station (Manabí, Ecuador). A pilot plant, built next to the oil extraction facility, uses the *Jatropha* seed cake (waste product from the oil extraction process) to produce bio-oil through pyrolysis. The processing capacity of the oil extraction plant is 200 kg of *Jatropha* seed per hour, obtaining an approximate yield of 30% oil and 70% seed cake.

The process starts with dehulling to obtain the seed, which then

goes through a pressing procedure to extract the oil. This process produces two energy-rich waste products, seed cake and shell waste, of which only seed cake is currently used. The seed cake undergoes a pyrolysis process for the production of synthesis gas and bio oil. The processing capacity of the pyrolyzing furnace is 30 kg h<sup>-1</sup>, converting 70% of the seed cake to biochar and 30% to synthesis gas and bio-oil.

The pyrolysis reactor uses a set of electrical resistance heaters with a total power of 900 W, which are responsible for supplying the heat required for the pyrolysis process. The reactor takes approximately 1 h to reach 450 °C without biomass load (7 °C min<sup>-1</sup>). When the reactor reaches this temperature, the heaters are automatically turned off and a conveyor screw is activated, feeding the biomass through the reactor. The reactor has an automatic control system, which is responsible for turning on and off the resistance heaters to maintain the temperature within ± 10 °C of the set temperature. Once the reactor is loaded with biomass, the resistors can remain off for an approximate time of 2 h. The gases produced in the process of thermal decomposition displace the air inside the reactor, creating an oxygen-free atmosphere and giving rise to pyrolysis. As the volume of the gases increases, they are directed to separators and condensers, which recover the condensable bio-oil in liquid form and transfer non condensable gases to a torch to be burned (See Fig. 1).

### 2.2. Materials

The biomass used in this research was the pyrolyzed residue of the waste resulting from the extraction of *Jatropha curcas* oil, also called seed cake biochar (SCB), and the peel of the fruit of the same plant, called *Jatropha* shell (JSh).

The seedcake was pyrolyzed (at 450 °C for 25 min) in order to remove part of the volatile content and increase its energy potential. The JSh was not processed, with the intention of maintaining the lignin content present to preserve its natural binding function for the pelletizing process. The raw materials were crushed and sieved to create two particle sizes, 4 mm and 2 mm, in order to evaluate the influence of particle size on the pellet compaction (Franke and Rey, 2006).

### 2.3. Blend setup process

The mixing process was carried out in order to evaluate the behavior of the pellets using varying SCB-JSh mixtures (100, 75, 50,

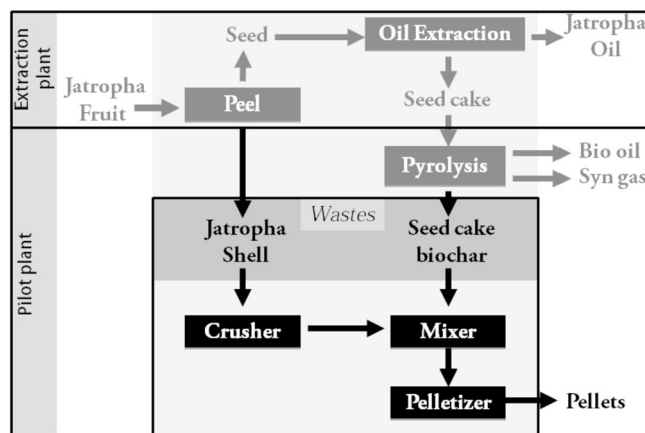


Fig. 1. Schematic of the *Jatropha* oil extraction plant process, and the linked pilot plant waste-to-energy processes. Novel processes under investigation appear in the emboldened box at center.

25 and 0% each), particle size of the solid components (2 and 4 mm) and amount of added water prior to the pelleting process (15% and 25%). The mixtures were carried out in two stages. In stage 1, a dry mixture of 30 kg of SCB-JSh was prepared according to the percentages indicated in Table 1. In stage 2, 10 kg of each resulting SCB-JSh mixture was taken and the indicated quantity of water was added in order to evaluate the effects from the combination of water, lignin (from the Jatropha shell) and heat (produced by the friction of the rollers of the pelletizer) on the mechanical durability of the pellet.

To homogenize the mixture in stage 1, a semi-industrial mixer with a capacity of 120 L was used, while in stage 2 a metal container and a 30 cm spatula were used for manual mixing. In both stages, the mixing time was 1 min.

The details of the 20 different mixtures obtained are presented in Table 1.

#### 2.4. Pelletizing process

The pelletizer used for this process was a semi industrial pelletizer (Chengda Machinery model KL 150B), with a capacity of 120 kg h<sup>-1</sup> and a fixed mold, producing pellets 9 mm in diameter and 2 cm in length. The pelletizer has movable rollers, which exert the necessary pressure for the compaction and formation of the pellet.

Indirect preheating of the pelletizer was necessary prior to beginning pellet production. A mixture of 10% food-grade oil by mass and 90% of the mixture to be pelletized was introduced into the pelletizer and recirculated during 15 min, heated by the friction of the rollers on the matrix, in accordance with the recommendation of the user manual of the pelletizer. Once the preheating procedure was completed, each blend was pelletized.

#### 2.5. Characterization of pellets

To evaluate the durability or mechanical strength of the pellets, the procedure established in “BS EN 15210-1 Determination of mechanical durability of pellets” (British Standard) was applied. For this analysis, a pellet sample of 500 ± 10 g, previously sieved with a 3.15 mm mesh, was taken. The sieved sample was weighed on an

analytical balance (Ohaus model PA214) with an accuracy of 0.0001 g (initial mass). The sample was then introduced into a durabilimeter (Bioenergy model Tumbler 1000), which uses a rotating chamber at 50 ± 2 rpm, and underwent a single 500-rotation cycle. The sample was then sieved (3.15 mm) and the mass of the sample retained by the sieve (final mass) was recorded. The mechanical durability value corresponds to the percentage of the initial mass remaining in the sample after the sieving of the fine particles generated by the collision and friction of the pellets occurring inside the rotating chamber.

The thermal characterization and the higher heating value for both the raw materials and the mixtures were performed by thermogravimetric (TG), derivative thermogravimetric (DTG) and calorimetric analysis. The thermogravimetric analysis was carried out using a thermogravimetric analyzer (Shimadzu model TGA-50), with a flow rate of 50 cm<sup>3</sup> min<sup>-1</sup> at a heating rate of 15 °C min<sup>-1</sup>, ranging from room temperature to 900 °C. Approximately 5 mg of the sample were employed for each measurement. A calorimeter pump (IKA model C2000 basic), was used to measure the higher heating value, and the procedure described in BS-EN-14918 (British Standard) was followed.

#### 2.6. Combustion in a continuous feed burner

The pellet that showed the best characteristics (durability and higher heating value) was tested in a semi-industrial continuous feed biomass burner to evaluate the maximum temperature reached during the combustion and validate the results obtained in the DTG.

The burner used has a horizontal combustion chamber; pellets are fed into a hopper at the top of the device, and the air is supplied by a hole in the side. Three type-k thermocouples were placed in the burner to monitor temperatures, as shown in Fig. 2.

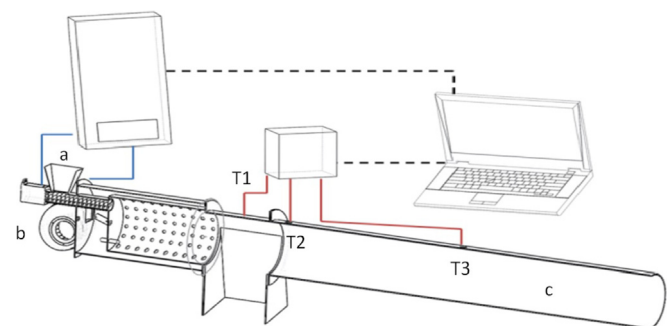
The burner was preheated to maintain stable operation of its mechanical components during pellet testing. An air flow of 208 m<sup>3</sup> h<sup>-1</sup>, and pellet feed rate of 2.6 kg h<sup>-1</sup>, were set to evaluate the temperature reached through the combustion of the pellet. After combustion started, temperatures were recorded for an approximate period of 13 min, with a measurement frequency of 1 s<sup>-1</sup>.

#### 2.7. Economic analysis

The data available from the pilot plant were used to calculate the cost of pellet production, which include capital investment, operation and maintenance services, and expenses for pellet production. The pilot plant is located adjacent to the Jatropha oil extraction plant, so transportation, storage and other raw material costs were

**Table 1**  
Characteristics of the blends employed in the preparation of pellets.

Blends of JSh and SCB + water	Mesh Size	Proportion		Additional water
		%SCB	%JSh	%W
(100SCB) 25 W	4 mm	100	0	25
(25JSh+75SCB) 25 W		75	25	25
(50JSh+50SCB) 25 W		50	50	25
(75JSh+25SCB) 25 W		25	75	25
(100JSh) 25 W		0	100	25
(100SCB) 25 W	2 mm	100	0	25
(25JSh+75SCB) 25 W		75	25	25
(50JSh+50SCB) 25 W		50	50	25
(75JSh+25SCB) 25 W		25	75	25
(100JSh) 25 W		0	100	25
(100SCB) 15 W	4 mm	100	0	15
(25JSh+75SCB) 15 W		75	25	15
(50JSh+50SCB) 15 W		50	50	15
(75JSh+25SCB) 15 W		25	75	15
(100JSh) 15 W		0	100	15
(100SCB) 15 W	2 mm	100	0	15
(25JSh+75SCB) 15 W		75	25	15
(50JSh+50SCB) 15 W		50	50	15
(75JSh+25SCB) 15 W		25	75	15
(100JSh) 15 W		0	100	15



**Fig. 2.** Schematic of the semi industrial burner. a) Power supply/pellet hopper; b) Air intake and c) Combustion chamber. T1, T2 and T3 indicate the position of the type-k thermocouples. The burner has a diameter of 165 mm and a length of 300 mm.

**Table 2**  
Proximate and ultimate analysis, and higher heating values of the raw materials.

Sample	Moisture (%)	Proximate Analysis (% weight, db)			Higher heating value (MJ kg <sup>-1</sup> )		Ultimate Analysis (% weight, db)				
		Volatile matter	Fixed Carbon <sup>a</sup>	Ash			C	H	N	S	O <sup>a</sup>
Jatropha seed cake (SC)	4.08	73.7	19.06	7.24	17.04	52.12	6.91	5.01	0.7	28.02	
Seed cake biochar (SCB)	9.28	40.02	46.62	13.36	28.3	61.31	3.55	3.77	0.38	17.63	
Jatropha Shell (JSh)	10.57	71.52	17.64	10.84	14.37	40.8	5.9	1.53	0.43	40.5	

<sup>a</sup> Calculated by difference; db: dry basis.

not considered. This economic analysis was used to determine the energy cost (USD MJ<sup>-1</sup>) of the pellets, and these data were compared to the corresponding energy cost for Liquefied Petroleum Gas (LPG).

### 3. Results and discussion

#### 3.1. Characteristics of raw materials

Proximate and elemental analysis along with the higher heating values of seed cake (SC), SCB and JSh samples are presented in Table 2. Non-pyrolyzed Jatropha residues (SC and JSh) retain a low ash content (less than 11%), and a fixed carbon level of less than 20%, values that are in the ranges (ash: 1.5–19% and fixed carbon: 11.3–22%), previously reported for these wastes (Kongkasawan et al., 2016; Singh et al., 2008). For SCB the ash content is 13.36%, and fixed carbon content is 47%, higher values than those of the original substrate. This is due to the elimination of 45.45% of the volatile matter through pyrolysis of the Jatropha seed cake, increasing the final concentration of ash and fixed carbon.

The concentration of volatile solids in SC (73.7%) is higher than in SCB (40.02%). Volatile matter favors combustion by facilitating ignition, but an excess of volatile solids also generates large amounts of gases during the combustion process at relatively low temperatures (Jenkins et al., 1998). Excessive gas production as a consequence of combustion can cause negative environmental impacts (Ezzati and Kammen, 2001).

The elemental analysis of SC produced values of C, H, N, O and S, similar to those reported in prior investigations of Jatropha residues (Sharma et al., 2016). In the case of JSh, the H and C content was similar to that observed in other investigations (Pambudi et al., 2017). This is not the case however with the values of N and S, with concentrations up to 50% higher than those presented in other investigations. These concentrations may be explained by variations in the characteristics of the soil where Jatropha was cultivated, and by the application of fertilizer to neighboring crops.

Compared to SCB, the JSh has a higher proportion of oxygen and hydrogen (Table 2). These characteristics reduce the higher heating value of JSh, since the energy contained in the carbon-hydrogen-oxygen and carbon bond is inferior to that of carbon-carbon bond (Gil et al., 2010b). On the other hand, the higher oxygen content of the JSh indicates a higher thermal reactivity than the SCB (Yi et al., 2013). In addition, the sulfur content of the SCB is 0.38%, while the SC contains 0.7%, revealing a reduction in sulfur concentration during the pyrolysis process. Other compounds are formed in the gaseous and liquid fractions during the pyrolysis process, favoring the clean combustion behavior of the selected material pellets.

The higher heating values for SC and JSh were similar, at 17.04 MJ kg<sup>-1</sup> and 14.37 MJ kg<sup>-1</sup> (dry basis) respectively. These values are similar to those reported in other studies (Kongkasawan et al., 2016). The SCB presented a higher heating value of (28.3 MJ kg<sup>-1</sup>), demonstrating it to be an appropriate component for improving the combustion characteristics of the pellets.

It is expected that when mixing JSh and SCB for the production

of a solid biofuel, the SCB will contribute its higher heating value, while the JSh will contribute a high oxygen content, facilitating both the ignition and subsequent combustion of the fuel.

#### 3.2. Mechanical durability

Pellets made with the 4 mm biomass presented the greatest mechanical durability, except for the mixture (50JSh + 50SCB) 15 W, as can be seen in Table 3.

Pellet blends that contained an amount greater than or equal to 75% SCB in the mixture, regardless of particle size and water quantity, did not form pellets due to compaction problems. This implies an upper limit for the amount of SCB in the mixture for pelleting to be viable.

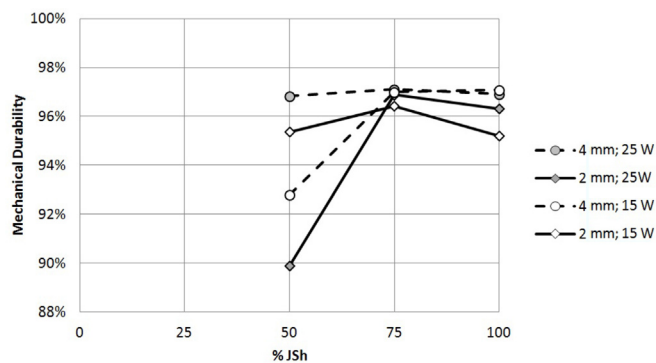
The mechanical durability of the pellets range from 89 to 97%, similar to pellets made from better quality biomass, such as wood (Verma et al., 2012). Other previous research (Gil et al., 2010b) evaluated the addition of coal to other biomass for pelletizing, and also found that an appropriate proportion of anthracite coal (between 5 and 15%) would maintain high durability values, approximately 93% in the best-case scenario. The present research shows similar trends; the higher the biochar proportion, the lower the durability of the pellets. Compared to prior coal-biomass mixtures, the present research shows that more biochar (if equated with coal) can be incorporated while maintaining superior mechanical durability, with values up to 50% of SCB in the blend. BS EN 15210-1 (British Standard) indicates 96% as an acceptable durability value for pellets. This value represents the lower limit when choosing pellets based on quality. Fig. 3 and Table 3 demonstrate that pellet mixtures with 50% SCB present durability values higher than the limit established by the standard, with particle size of 4 mm and an additional water proportion of 25%.

Following selection based on mechanical durability, the next criteria for which pellet selection was based on was higher heating value.

**Table 3**  
Mechanical durability of pellets.

Sample	Mechanical Durability, %	
	Mesh Size: 4 mm	Mesh Size: 2 mm
(100SCB) 25 W <sup>a</sup>	–	–
(25JSh+75SCB) 25 W <sup>a</sup>	–	–
(50JSh+50SCB) 25 W	96.83	89.91
(75JSh+25SCB) 25 W	97.11	96.88
(100JSh) 25 W	96.91	96.31
(100SCB) 15 W <sup>a</sup>	–	–
(25JSh+75SCB) 15 W <sup>a</sup>	–	–
(50JSh+50SCB) 15 W	92.80	95.36
(75JSh+25SCB) 15 W	96.99	96.42
(100JSh) 15 W	97.08	95.20

<sup>a</sup> No values recorded because the blend did not form pellets.



**Fig. 3.** Mechanical durability of pellets made with Seed Cake Biochar (SCB) and Jatropha Shell (JSh) mixtures with 25% and 15% water addition; and 2 mm or 4 mm particle size.

### 3.3. Energy and thermal characteristics

#### 3.3.1. Pellet energy content

In general, pellets with a greater proportion of SCB in the mixture register higher heating values, as can be observed in Table 4.

The energy content of pellet mixtures with equal proportions of JSh and SCB but with different particle sizes does not vary significantly (under 2.2%) when the amount of added water is 25%, and varies up to 5.9% when water content is 15%, as can be seen in Table 4. This stability is expected, because the energy content depends on the composition of the combustion matter and not on the particle diameter. As expected, the greater the SCB content, the greater the higher heating value of the pellet, up to the 50% SCB composition which represents the upper limit for this material in the mixture in order to meet the established mechanical durability parameters. This mixture, 50% SCB 50% JSh, registers values in the range of 19.96–22.14 MJ kg<sup>-1</sup>, which is less than the higher heating value of pure SCB found by the current research (28.3 MJ kg<sup>-1</sup>), or that reported (25–30 MJ kg<sup>-1</sup>) in previous studies (Yi et al., 2013). However, this mixture permits material densification through the pelletization process.

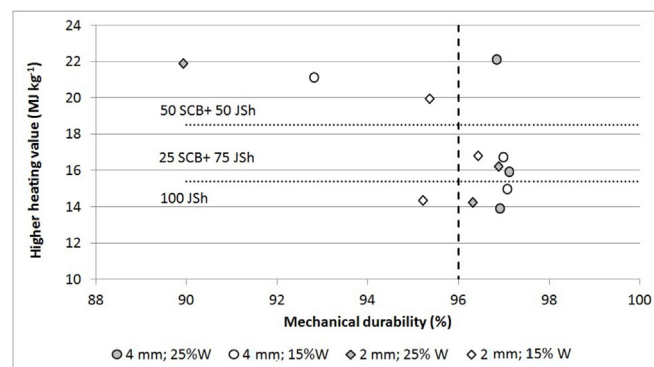
The mechanical durability results (Table 3) and the higher heating values (Table 4) for each pellet mixture are shown simultaneously in Fig. 4. Most of the pellets register a durability between 96 and 98%, which are acceptable values according to the norm BS EN 15210-1 (British Standard). Fig. 4 shows that the pellets elaborated with (50JSh + 50SCB) 25 W and sieved with a mesh size of 4 mm, present the greatest mechanical durability and higher heating value.

**Table 4**

Higher heating values of JSh and SCB pellets.

Sample	Higher heating value (MJ kg <sup>-1</sup> )	
	Mesh Size: 4 mm	Mesh Size: 2 mm
(100SCB) 25 W <sup>a</sup>	—	—
(25JSh+75SCB) 25 W <sup>a</sup>	—	—
(50JSh+50SCB) 25 W	22.14	21.91
(75JSh+25SCB) 25 W	15.94	16.24
(100JSh) 25 W	13.93	14.24
(100SCB) 15 W <sup>a</sup>	—	—
(25JSh+75SCB) 15 W <sup>a</sup>	—	—
(50JSh+50SCB) 15 W	21.12	19.96
(75JSh+25SCB) 15 W	16.74	16.80
(100JSh) 15 W	14.97	14.35

<sup>a</sup> No values recorded because the mixture did not form pellets.



**Fig. 4.** Higher heating value and mechanical durability of pellets using mixtures described in Table 1.

#### 3.3.2. Individual combustion performance of the raw materials (SCB, JSh) and the best-quality pellet [(50JSh + 50SCB) 25 W]

To evaluate the mixture of SCB and JSh in the formation of the pellet during the combustion process, both the selected mixture and its individual components were subjected to a thermogravimetric analysis using an oxidizing atmosphere.

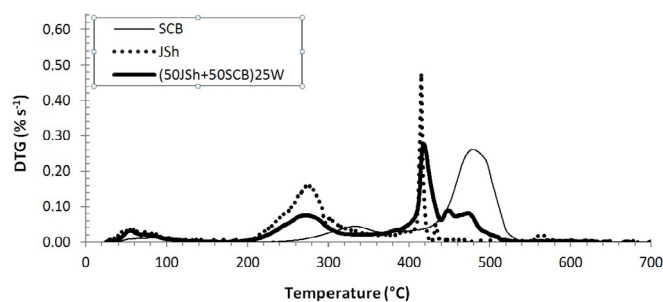
The derivative thermogravimetry (DTG) curves for the samples of JSh, SCB and the mixture (50JSh + 50SCB) 25 W, using an atmosphere of air, are presented in Fig. 5.

The thermogravimetric analysis realized using DTG profiles extends over a temperature range of 25 °C–700 °C. It can be observed that the JSh undergoes three stages of mass loss, while SCB experiences only two.

In the case of the JSh, an initial mass loss (stage A) occurs between temperatures of 25 °C and 105 °C. This loss corresponds to the evaporation of the water contained in the biomass and depends on the moisture content of the sample. Therefore, this stage is prominent in JSh due to its higher moisture content, while SCB shows almost no mass loss over this temperature range.

Two additional stages of mass loss, one occurring with temperatures ranging from 180 °C to 380 °C (stage B), and the other with temperatures from 380 °C to 480 °C (stage C), are observed in the DTG curve of JSh. The loss of mass in stage B is due to the oxidative degradation of the sample, as light organic volatile solids are released and then burned. The loss of mass in stage C is due to combustion of the remaining coal (Gil et al., 2010a; Guo and Zhong, 2018). In the case of SCB, stage B and C take place in the temperature ranges of 220 °C–420 °C and 420 °C–540 °C, respectively.

The temperature ranges for stages B and C in the case of the JSh are similar to those observed for other types of biomass, whereas in the case of SCB, a similarity can be observed in the temperature range of stage C to that of anthracite coal (Gil et al., 2010a). The DTG



**Fig. 5.** DTG curves for pellets elaborated with the mixture (50JSh + 50SCB) 25 W, and their raw materials with an air flow of 50 cm<sup>3</sup> min<sup>-1</sup> and a heating rate of 15 °C min<sup>-1</sup>.

**Table 5**  
Temperature interval, mass loss, residue, peak temperature and maximum rate of mass loss (DTGmax), for the combustion of individual materials (JSh, SCB) and the blend.

Sample	Temperature interval (°C)		Mass loss (%)		Residue (%)	Peak temperature (°C)		DTGmax (% s <sup>-1</sup> )	
	Stage B	Stage C	Stage B	Stage C		Stage B	Stage C	Stage B	Stage C
JSh	180–380	380–480	46.2	20.6	16.5	270	415	0.16	0.44
SCB	220–420	420–540	23.1	61.8	13.7	330	460	0.06	0.28
(50JSh+50SCB)25 W	200–340	340–520	24.3	47.5	14.2	280	413	0.08	0.37

curve of the mix (50JSh + 50SCB) 25 W shares the characteristics of its raw materials. Stage B and C take place in the temperature ranges of 200 °C–340 °C and 340 °C to 520 °C, respectively.

Table 5 shows the combustion temperature range, mass loss, final post-combustion residue, maximum temperature and maximum mass loss rate (DTGmax), corresponding to the two main stages of mass loss (stages B and C). The initial temperature in stage B and the final temperature in stage C were considered as temperature values at which the rate of mass loss was 0.005 s<sup>-1</sup> (Rubiera et al., 1999).

Table 5 shows that JSh experiences a loss of volatile solids (stage B) at a lower temperature (180 °C) than the SCB (220 °C), and registers a higher percentage of mass loss during this stage (46.2%). Thus, combustion of JSh is dominated by stage B processes, occurring between 180 °C and 380 °C. In the case of the SCB, stage C dominated the combustion with a mass loss of 61.8% taking place in the range of 420–540 °C.

The blend (50JSh + 50SCB) 25 W offers advantages from both materials' combustion characteristics, since the loss of mass in stage B (24.3%) is lower than that in stage C (47.5%), allowing the greater mass to be burned at higher temperatures (340–520 °C). This benefit also occurs with SCB, however, as this substrate goes through a previous pyrolysis process, the easily combusted volatile solids are lost, which may impede ignition in the combustion process.

The JSh generated a larger amount of unburned residual material (16.5%) compared to SCB and the blend (50JSh + 50SCB) 25 W. If the combustion residues of JSh and SCB from Table 5 are compared with the ash content detailed in Table 2, the more complete combustion of SCB is evident. The percentage of SCB combustion waste (13.7%) is much closer to the percentage of SCB ash (13.36%, Table 2) when compared to JSh. Therefore, SCB will help to achieve a better combustion of the blend.

As the temperature at the point of maximum rate of mass loss is observed to be inversely proportional to the reactivity (Gil et al., 2010a), SCB proves to be the least reactive material. However, when SCB is combusted in combination with JSh, the mixture's reactivity is not very different from the reactivity of pure JSh, the most reactive material. This behavior is observed for both stages B and C. In general, it can be observed that the reactivity of a mixture decreases with the reduction of JSh levels. Subsequently, the main mass loss stage occurs during a higher range of temperatures, indicating greater thermal efficiency (Liu and Han, 2015).

### 3.4. Combustion in a semi-industrial burner

The combustion of the selected pellet (50JSh + 50SCB) 25 W in a horizontal flow burner reached temperatures above 350 °C during the first 7 min of combustion, and subsequently stabilized at around 300 °C, as shown in Fig. 6. This temperature decrease is due to the design of the burner, which is not optimized for this type of pellet. The accumulation of ash hampers continuous pellet feeding into the combustion chamber. This is because the ash evacuation grid's mesh is too small for this type of pellet ash. If air flow is increased to displace the accumulated ash, it becomes difficult to

properly feed pellets from the vertical hopper. This experience demonstrates that optimizing the design of the burner is necessary to fully exploit the potential of the selected pellet under semi-industrial conditions.

The average and maximum temperatures reached in the burner are in the respective ranges of the peaks of stage B for JSh (270 °C) and C for SCB (460 °C). The maximum temperatures reached in the burner was 460 °C, while the maximum temperature in the DTG for the mixture (50JSh + 50SCB) 25 W was 500 °C (Fig. 5). This implies a difference of 8% comparing the value obtained in the laboratory and the value tested in the semi industrial burner, which can be explained by burner heat losses and the lack of optimization of the burner for the pellet type.

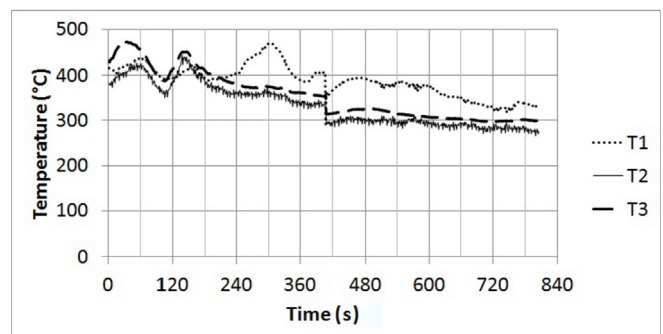
### 3.5. Economic analysis results

In order to estimate the energy cost of the selected pellet, the cost per kg of pellet was first estimated using the annual cost of pilot plant operation (considering credit on investment, labor, electricity and water supply costs) and the plant's annual pellet production. Then, the energy cost of the selected pellet was calculated using the higher heating value and compared to the respective value for LPG.

*Number of pellets per year.* To determine the amount of raw material available, an average value was calculated based on the residual biomass production of the Jatropha oil extraction plant over the last five years. The result obtained was 63,924 kg per year of seed cake biochar (SCB), and 55,910 kg per year of Jatropha Shell (JSh). Also, a 15% mass loss was observed during the pelletization process.

To manufacture pellets with the chosen formulation (50JSh + 50SCB) 25 W, the use of the entire JSh (55,910 kg) and an equivalent amount of SCB (55,910 kg) would be necessary. Thus, taking into account losses during pelletization (15% by mass), the final production of pellets was estimated at 95,047 kg per year.

*Annual operational costs.* The main equipment at the production plant includes: crusher, screw conveyor, mixer and pelletizer, corresponding to an investment of 15,000 USD. Estimating a 10% interest loan paid over 5 years, this translates to an annual cost of



**Fig. 6.** Temperature evolution in the semi-industrial burner when fed with the selected pellet (50JSh + 50SCB) 25 W

3300 USD. The employment of one operator, paid Ecuador's minimum wage (400 USD per month) (Ministerio de Trabajo ECUADOR, 2017), is estimated as sufficient to manage the volume of the existing residual biomass and the processing capacity, leading to an additional 4800 USD per year in expenses.

The electricity cost was estimated based on the total electricity consumption of the pilot plant (5616 kWh per month). The energy consumption was 8.55 kWh h<sup>-1</sup>, considering only the pelletizing process, so operation 8 h d<sup>-1</sup> results in a monthly consumption of 1368 kWh. The electricity cost for the industrial sector in Ecuador is 0.08 USD kWh<sup>-1</sup> (Agencia de Regulación y Control de Electricidad, 2018), which results in 1313 USD per year of expenses from the pelletizing process.

The consumption of water in the pelletizing process is low, but if cleaning activities are also considered, the consumption of water per month at the plant is 67 m<sup>3</sup>. The water cost for the industrial sector in the province of Manabí is 1.50 USD m<sup>-3</sup> (Gobierno Autónomo Descentralizado Municipal del Cantón Portoviejo, 2016), which results in 1206 USD per year of expenses.

*Cost of pellets:* Considering all the expenses mentioned, the yearly cost of producing 95,047 kg of (50JSh + 50SCB) 25 W pellets is estimated to be 10,619 USD, resulting in a production cost of 0.11 USD kg<sup>-1</sup>.

*Energy cost of pellets compared to LPG:* The use of pellets in the industrial sector would displace the consumption of LPG. LPG for the industrial sector in Ecuador costs 0.804950 USD kg<sup>-1</sup> (PetroEcuador, 2018) and presents a higher heating value estimated at 44.3 MJ kg<sup>-1</sup> (OLADE, 2017). Thus, the energy cost of LPG is 0.018 USD MJ<sup>-1</sup>. The (50JSh + 50SCB) 25 W pellet has a cost of 0.11 USD kg<sup>-1</sup>, and a higher heating value of 22.5 MJ kg<sup>-1</sup>, so the energy cost of this pellet is 0.005 USD MJ<sup>-1</sup>. These values demonstrate that the energy cost of (50JSh + 50SCB) 25 W pellets represents only 28% of the energy cost of the LPG heating. This estimation does not consider the final energy delivered by the combustion of the LPG or the pellets, since this depends on the combustion efficiency of the burners and thermal efficiency of other equipment, nor does it consider transportation costs.

As the pellets' energy cost is lower than that of LPG, the profit margin that can be obtained by substitution could be used for pellet promotion, pellet burner facilities for users, or to provide price subsidies, in order to overcome adoption barriers related to users' unfamiliarity with pellets or other issues.

#### 4. Conclusions

Pellets made with a 50/50 mixture of Seed Cake Biochar and Jatropha Shell constitute a biofuel with good combustion characteristics. The Seed Cake Biochar contributes its high energy content, which is reflected in a greater range of combustion temperatures and a lower percentage of unburned material, in comparison with Jatropha shell by itself. The Jatropha shell provides reactivity for the pellet blend with its high content of volatile matter, facilitating the ignition of the pellet. The studied mixture is recommended for industrial use in large burners, as a low percentage of post-combustion residues are generated. The energy cost [USD MJ<sup>-1</sup>] of the selected pellet blend is 60% lower than that of LPG, making it a feasible alternative.

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