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Increasing the Calorific Properties of Sawdust Waste from Pellets by Torrefaction

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Torrefaction, a thermal treatment, was studied as a means to increase calorific properties in sawdust biomass for some wooden species from southeast Europe. Torrefaction of wood material in the form of sawdust waste is known to modify the biomass at the chemical level, especially hemicelluloses. Four wood species, namely beech, spruce, larch, and oak, were thermally treated as sawdust waste at temperatures of 200 °C, 220 °C, 240 °C, 260 °C, 280 °C, and 300 °C for different times of 3 min, 5 min, and 10 min. The results indicated an increase in the calorific value and calorific density with increased torrefaction temperature and time. From the economic point of view, the pellets obtained from torrefied sawdust had better properties than untreated ones. The value-added pellets could compete on the market with traditional fossil fuels.

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INTRODUCTION

Wooden waste is a renewable energy source (RES) that plays an important role in the global energy market. It is a substantial part of biomass and was the first alternative source of energy. By tuning its properties and by optimizing its use as energy material, it can become a promising source of energy (Aghamohammadi *et al.* 2011; Swithenbank *et al.* 2011). Wooden waste is frequently used in rural areas as the main energy source. In the 18th century, when fossil combustibles such as coal, oil, or natural gas were first used at a large scale, solid biomass lost its domination. The evolution of fossil fuel consumption and environmental issues changed the goals of energy production. Combustibles obtained from solid biomass are neutral sources of energy, with lower emissions of CO_2, SO_2, NO_X, volatile organic compounds, and heavy metals compared with combustible fossil fuels (Hu *et al*. 2011). Research into new ways of energy production is necessary because of the global population growth (the population will reach 9 billion people by 2050) and the increase in hazardous emissions from fossil fuels (Pienkos and Zhang 2009; Sarvaramini *et al*. 2014). The amount of energy accumulated in the biomass is estimated at 50 EJ (1EJ = 10^{18}J) from the total primary energy supplied in the world in 2009 (Batidzirai *et al*. 2013). Forest waste, municipal waste, agricultural waste, firewood, and waste from wood processing can be used for bioenergy production through various forms of conversion (thermal, biological, mechanical, and physical) (Phanphanich and Mani 2011; Bridgwater 2012).

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The woodworking industry is an inexhaustible source of wood waste, which must be evaluated to find the most efficient methods of energy capitalization. For example, the amount of produced sawdust differs from one woodworking process to another, with13% for the softwood timber factories of 50000 m^3 timber/year capacity, 9.6% for hardwood timber of 180000 m^3 timber/year capacity, 3% for aesthetic veneer with 4300 m^3 logs/year capacity, 17% to 22% for doors and furniture from solid wood, 3% for parquet plants from strips, 15% for parquet made of timber, *etc*. For example, the large amount of sawdust waste obtained in timber or oriented strand board (OSB) plants leads to problems regarding the efficient use of the available sawdust storage space, in some cases causing a complete shutdown until the sawdust is removed. The sawdust could constitute a raw material for obtaining new value-added products as pellets.

One method for making sawdust more efficient is torrefaction followed by pelletisation. Torrefaction was used for the first time in the thermal treatment of tobacco to intensify its aroma (Lunguleasa *et al.* 2017). It is widely used to improve the mechanical or physical-chemical characteristics of wooden biomass in the form of chips, sawdust, chops, solid wood, briquettes, and pellets (DIN 51731 1996; CEN/TC 335 2004; CTI-R 04/5 2004; EN ISO 17225-1 2014; EN ISO 17225-2 2014; Chen *at al.* 2015). The top 5 producers of pellets at European level in 2016 are presented in Fig. 1, from a total production of 14 million tons (AEBIOM 2017).
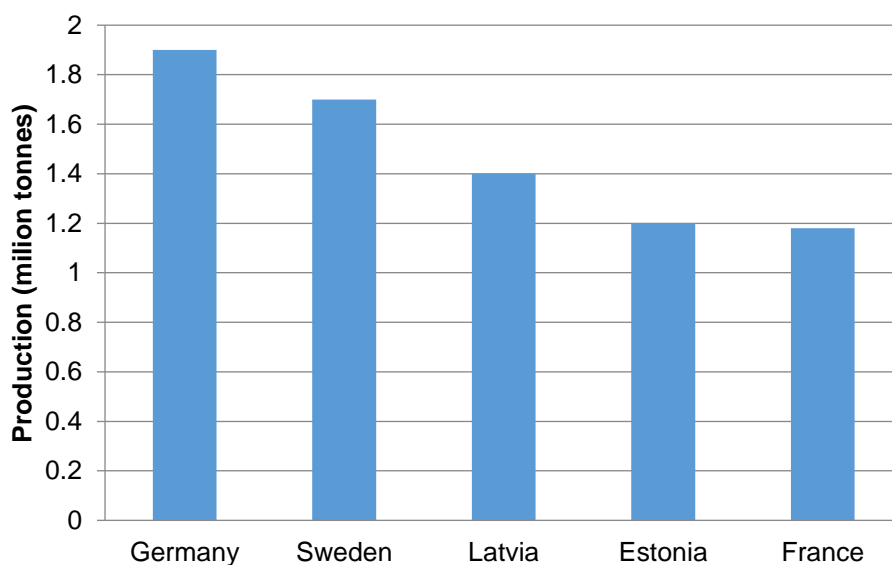

Fig. 1. Top 5 EU-28 producers of pellets in 2016 (AEBIOM 2017)

There are two torrefaction methods: wet (hydrothermal treatment) and dry (torrefaction). The dry thermal treatment takes place at 200 °C to 300 °C with a duration of about 30 min for sawdust (Almeida *et al.* 2010) or about 72 h for timber (Chiaramonti *et al.* 2010). Another type of thermal treatment is quick pyrolysis pretreatment, which can obtain higher energetic characteristics and consists of thermal treatment of the wooden waste at 500 °C, in total absence of oxygen (Bridgwater 2012). The torrefaction process of the quick thermal treatment is the most efficient in increasing the carbon content of wood (Almeida *et al*. 2010; Chen *et al.* 2011a,b; Sarvaramini and Larachi 2014). Torrefaction presents several advantages, such as dimensional stabilization (Pelaez-Samaniego *et al*. 2013) of the wooden product (smaller swelling and shrinkage), reduction of hydrophilicity,

and increase of calorific value in a relatively short period of time. There are torrefaction reactors that can treat any type of lignocellulosic biomass, including algae (Broström *et al.* 2012). The sawdust (pellets) obtained by torrefaction has similar energetic characteristics to conventional fossil fuels such as coal (Ragland *et al.* 1991). Each type of biomass and wood species has some particularities that must be considered during the thermal treatment step (Kok and Özgür 2013; Zhang *et al.* 2018), which necessitates research on the torrefaction of new species and materials.

This paper examined the optimal thermal parameters and conditions for torrefaction of sawdust in a low-oxygenated atmosphere, with the goal of increasing the calorific power of the wood sawdust biomass. The influence of four different wood species was studied. The influence of the chemical elements (carbon, oxygen, and hydrogen) and chemical compounds (lignin, cellulose, and hemicellulose) on the calorific value was considered.

EXPERIMENTAL

Four species of wood sawdust were used in the experiments: beech (*Fagus sylvatica*), oak (*Quercus robur*), spruce (*Picea abies*), and larch (*Larix decidua*). These species are ubiquitous in southeast Europe, particularly Romania, where spruce and other resinous species occupy 24% of forest areas, while beech accounts for 30% and oak for 18%, respectively (Tumuluru *et al.* 2011). These woody species were chosen because they are abundant in the specified area and were not used in the sawdust torrefaction process.

Fig. 2. Spruce sawdust samples used for 5 min torrefaction and temperature of 200 °C to 300 °C

The sawdust taken from a circular machine was sieved (2 mm superior mesh and 0.4 mm inferior mesh) to obtain particles about 0.4 mm to 2.0 mm. Because the degree of torrefaction depends on the size and distribution on dimensional categories of un-torrefied sawdust, the particle size granulometry for each wood species was determined. The measurements were made on special paper with squares of 0.5 mm, under a magnifying glass. All particles had granular form, and their framing was measured in appropriate squares of the half-millimeter paper.

The sawdust was dried at 105 °C for 24 h in a laboratory oven and cooled in desiccators prior to its use. The experimental process involved two parts. In the first phase

the sieved sawdust was thermally treated (torrefied) in a calcination furnace STC 18.26 (Ploiesti, Romania) at successive temperatures of 200 °C, 220 °C, 240 °C, 260 °C, 280 °C, and 300 °C (Fig. 2) in a low oxygenated environment. The heat treatment was performed with the ventilation valve of the oven closed. Due to the oxidative processes produced during torrefaction, the oxygen content in the oven medium decreased by 30 to 44%, the determination being made with the classic method using the glass tube and steel wool. The periods of sawdust torrefaction were 3 min, 5 min, and 10 min, respectively, for each temperature and wood species. During this step some changes of the sawdust sample color occurred, coupled with the appearance of odor and smoke at high temperatures.

The mass loss (ML) of the sawdust was calculated using Eq. 1,

$$ML = \frac{m_i - m_f}{m_i} \cdot 100 [\%]$$ (1)

where m_i is the initial mass of sawdust sample (usually with crucible) (g), and m_f is the final mass of sawdust sample (usually with crucible) (g).

The *ML* values presented in the paper represent an average of 12 measurements, for each thermal treatment time and temperature. In the second step, the torrefied wood sawdust was compressed in cylindrical pellets (about 0.5 g to 0.8 g, 9 mm to11 mm length, and 6 mm diameter) with the help of a Sarras 50 (Brasov, Romania) mechanical press, with a capacity of 50 kg/h, that was designed for such woody remains (Fig. 3). At least 12 valid pellets were obtained and taken in consideration from each thermally-treated wood sawdust batch.

Fig. 3. Mechanical press for pelletisation (Group matrix –roles): 1-main screw; 2-roll; 3-roll support; 4-lubrificat; 5-matrix; 6-motor

Based on the mass and dimensions, the density of the pellets was determined using Eq. 2,

$$\rho_p = \frac{4 \cdot m}{\pi \cdot d^2 \cdot l} \cdot 10^6 \left[\frac{kg}{m^3} \right]$$ (2)

where ρ_ρ is the density of pellets (kg/m^3), m is mass of pellets (g), d is diameter of pellet (mm), and l is length of the pellet(mm).

The bulk density of the pellets was determined using a graduated cylindrical vessel with a known mass in which the pellets were introduced to a certain height corresponding to a given volume. The pellet vessel was weighed and mass was obtained. For determining bulk density of pellets, Eq. 3 was used,

$$\rho_b = \frac{m_{c+p} - m_{ec}}{V} \cdot 10^3 \left[{kg}/{m^3} \right]$$

(3)

where ρ_b is the bulk density of pellets (kg/m^3), m_{c+p} is mass of cylinder with pellets (g), m_{ec} is mass of empty cylinder (g), and V is volume of a certain level of cylinder (cm^3).

The determination of the calorific power of the sample (for control and torrefied wood pellets) was performed with an OXY-1C bomb calorimeter (Shanghai Changji Geological Instrument Co., Shanghai, China), equipped with software for displaying the high and low calorific value (HCV and LCV). An oxygen pressure of 30 bars was used for the experiments, and the methodology parameters were according to DIN 51900-1(2000). For each sample type, 10 measurements were performed, yielding precise results, according to other researchers and European standards (ÖNORM M 7135 2000; SS 187120 1998; Ohliger *et al.* 2013). For comparison, the calorific value of pellets obtained from non-torrefied sawdust was also obtained. For the determination of the calorific value (*CV*, MJ/kg) of the pellets, Eq. 4was used,

$$CV = \frac{C \cdot (t_f - t_i)}{m} - h_c - h_w \quad [MJ/kg]$$

(4)

where C is the calorimeter coefficient obtained by calibration with benzoic acid, t_f is final temperature (ºC), t_i is initial temperature (ºC), h_c is heat obtained by cotton combustion (MJ/kg), and h_w is heat obtained by burning the resistive wire (MJ/kg).

Due to the increase of the calorific power during the torrefaction process, it was necessary to determine its increase coefficient (Eq. 5),

$$IC_{CV} = \frac{CV_{tp} - CV_{cp}}{CV_{cp}} \quad [\%]$$

(5)

where IC_{CV} is coefficient of CV increase(%), CV_{tp} is calorific value of torrefied pellets (MJ/kg), and CV_{cp} is calorific value of control pellets (MJ/kg).

Another two calorific properties were determined, namely the rate of energy release and calorific/energetic density. The rate of energy release was determined as a ratio between amount of energy (as calorific value multiplication by the mass of pellet sample) and time of energy release (Eq. 6),

$$R_{er} = (CV \cdot m)/t_{er} \text{ [MJ/min]}$$

(6)

where R_{er} is rate of energy release (MJ/min), CV is calorific value (MJ/kg), m is mass of sample (g), and t_{er} is time of energy release (min).

During the combustion with the bomb calorimeter, 3 distinct periods were evident: initial period ("before"), principal period ("main"), and final period ("after"). Out of these, only the "main" burning time was taken into consideration, the other two being preparatory. Therefore, the effective combustion time (t_{er}) was obtained from the total period of

combustion from which the sum of initial and final time was subtracted.

Calorific/energetic density (CD) is a more convenient parameter for differential massive wood fuels. If a certain type of fuel links a low moisture content of 10% with a high density of about 1000 kg/m^3, a higher calorific density will be obtained. This case is typical for pellets. Furthermore, if the pellets are torrefied, the calorific value increases, and their storage requires a reduced space. For this purpose, the pellet density was used, and the relationship for *CD* (MJ/m^3) calculation is Eq. 7,

$$CD = CV \cdot \rho_p \left[MJ/m^3 \right]$$
(7)

where *CV* is the calorific value (MJ/kg), and ρ_ρ is pellet density (kg/m^3).

The same sieved sawdust from spruce, larch, beech, and oak were used for ash content tests. Four crucibles resistant to high temperatures were used for tests that were cleaned, dried, and burnt to a constant mass. The ash content was measured based on the ASTM D2866-11 (2011), as well as small requirements from ASTM D1102-84 (2013), and ASTM E1755-01 (2003) standards. A sample of 1.5 g to2 g of sawdust was used from each species and torrefaction regime, placed on crucible, and dried to 105 °C for 2 h to obtain the oven-dry state. The initial mass was obtained by weighing with a high-precision balance. The crucibles with dried sawdust were introduced inside of the same STC 18.26 calciner at 650 °C for 3 h. The complete calcination was visible by the absence of sparks inside of the oven, or when a mass difference between two consecutive values less than ± 0.5% was obtained. After the crucibles were extracted from the oven, they were cooled in desiccators, weighed with the same precision balance, and the final mass was obtained. In order to obtain the ash content, Eq. 8 was used,

$$A_c = \frac{m_i - m_{ec}}{m_f - m_{ec}} \cdot 100 \quad [\%]$$
(8)

where m_i is the initial mass of oven-dried sample with the crucible(g), m_{ec} is the mass of empty crucible(g),and m_f is the final mass of calcined sawdust with the crucible(g).

From each wood species of sawdust, 10 replicates were made. All values were processed in Microsoft Excel™ software to evaluate the differences between species. Trends and variations of the determined parameters as averages, standard deviation, and equations of regression with its Pearson coefficient R^2 were also determined. The same statistical parameters obtained for ash content were found for the other determinations.

RESULTS AND DISCUSSION

Granulometry of Sawdust

The distribution of wood particles with dimensions of 0.4 mm to 2.0 mm on dimensional classes (Fig. 4) was determined to be a Gaussian one, with a slight decentralization to the right. The symmetry of the granulometry data provided a good compaction of the pellets made by placing the small particles in the spaces left by the larger shanks, achieving a strong uniformity of the pellet density below 5%.

The range of wood pellets density was 990 kg/cm^3 to 1040 kg/cm^3, with a median value of 1012±49 kg/m^3. Values of 990 kg/cm^3 to 1010 kg/m3 were obtained for treated pellets, and values of 1010 kg/cm^3 to 1040 kg/m^3 were obtained for untreated wood pellets.

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Lower values of pellet density in torrefied sawdust were attributed to mass loss during heat treatment. During the heat treatment, differences between species, both for sawdust and for pellets, had been greatly reduced.

Density in bulk was 618 kg/cm^3 to 665 kg/m^3 per total, with a lower value for spruce (625 ± 50 kg/m^3) and a higher value for oak (641 ± 52 kg/m^3). This requires a larger volume of about 2.5% for oak *vs.* spruce when pellets are loaded into 15 kg bags.
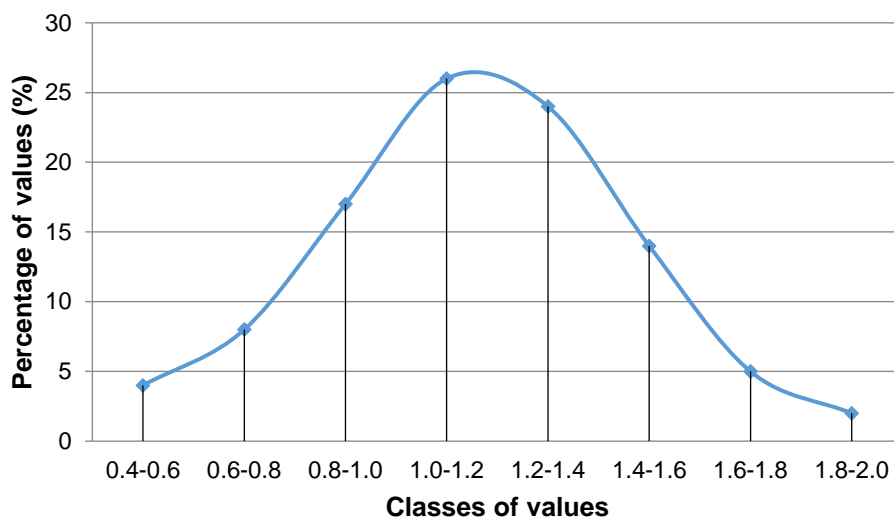

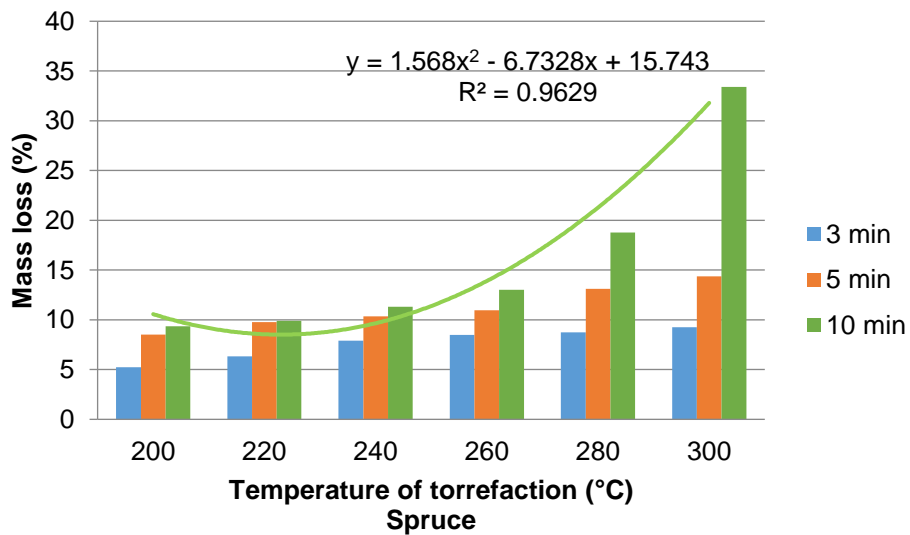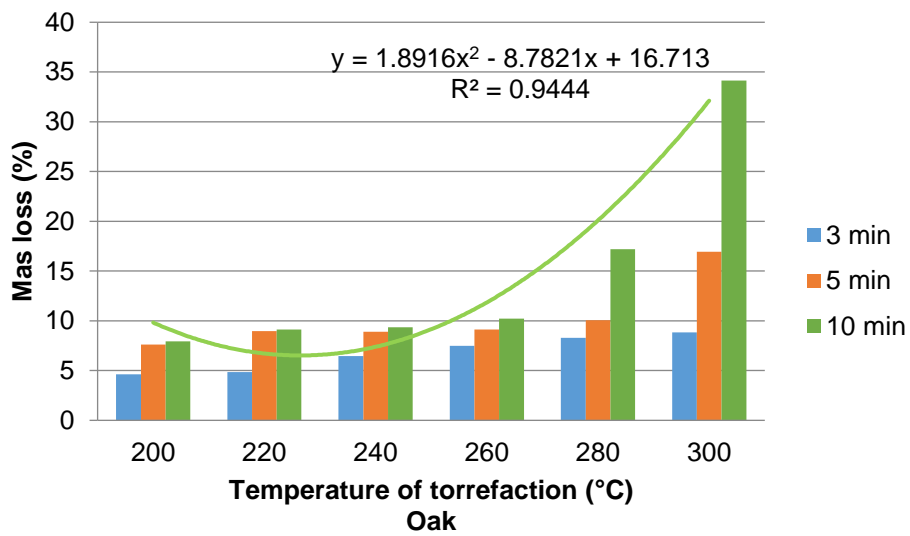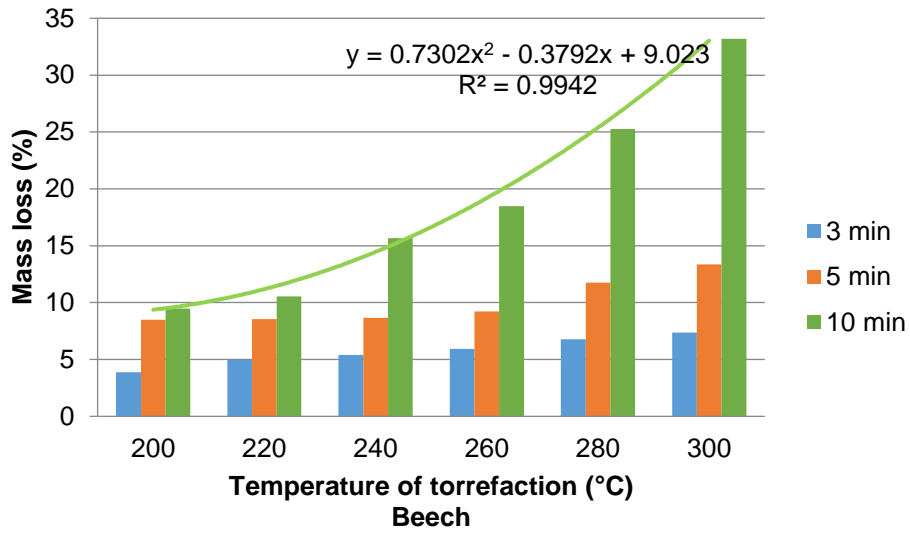**Fig. 4.** Granulometry of spruce sawdust

Mass Losses

Mass losses obtained after thermal treatment were due to decomposition of the main chemical compounds of sawdust: cellulose, hemicellulose, and lignin. Decompositions begin at temperatures of 180 °C (Aghamohammadi *et al.* 2011; Chen *et al.* 2011; Chen *et al.* 2012; Bates and Ghoniem 2013; Serrano *et al.* 2013). Mass loss of torrefied sawdust depends on specie, temperature, dimension of particles, and thermal treatment duration. Small differences existed in the first period of torrefaction up to 5 min and 260 °C. The greatest amount of material was lost in the temperature range of 280 °C to 300 °C and 10 min (Fig. 5). The polynomial regression expresses better the dependency of sawdust percent mass loss on torrefaction temperature (Fig. 2), with correlation factors R^2 higher than 0.944.

Most wood species had maximum values (for 300 °C and 10 min) of 33% to 34%, except for larch, which had a value of less than 18%. The minimum values (for 200 °C and 3 min) usually range around 3% to 5%.

Calorific Value Experiments

The calorific power of non-thermal treated sawdust was 18.02 MJ/kg for spruce, 18.51 MJ/kg for larch, 17.98 MJ/kg for oak, and 17.63 MJ/kg for beech; and this increased continuously during torrefaction up to 20.58 MJ/kg for spruce (14.1% increase), 20.71 MJ/kg for larch (11.8% increase), 20.94 MJ/kg for oak (16.4% increase), and 21.30 MJ/kg for beech (20.7% increase).

$y = 0.7302x^2 - 0.3792x + 9.023$
$R^2 = 0.9942$

Beech

$y = 1.8916x^2 - 8.7821x + 16.713$
$R^2 = 0.9444$

Oak

$y = 1.568x^2 - 6.7328x + 15.743$
$R^2 = 0.9629$

Spruce

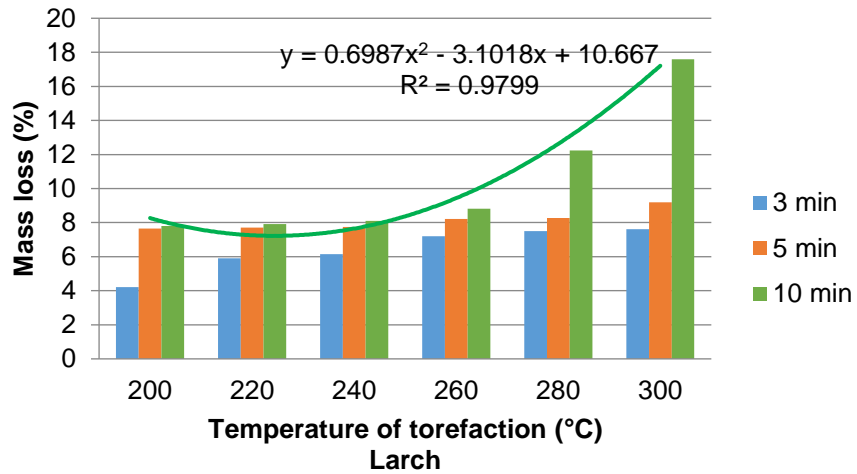$$y = 0.6987x^2 - 3.1018x + 10.667$$
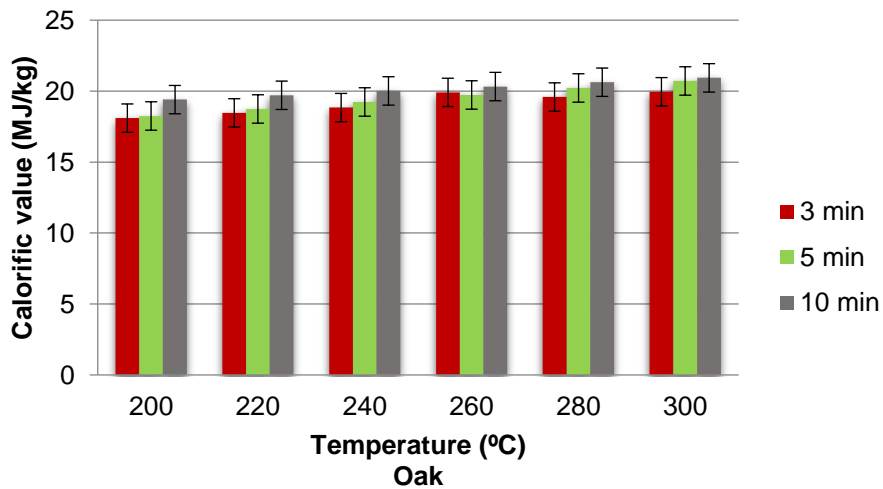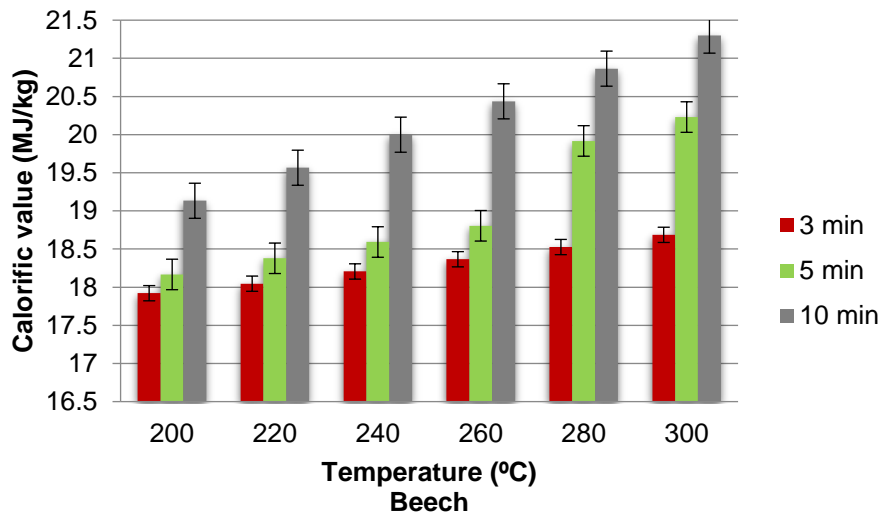$$R^2 = 0.9799$$

Larch

Fig. 5. Dependence of mass losses on torrefaction time and temperature
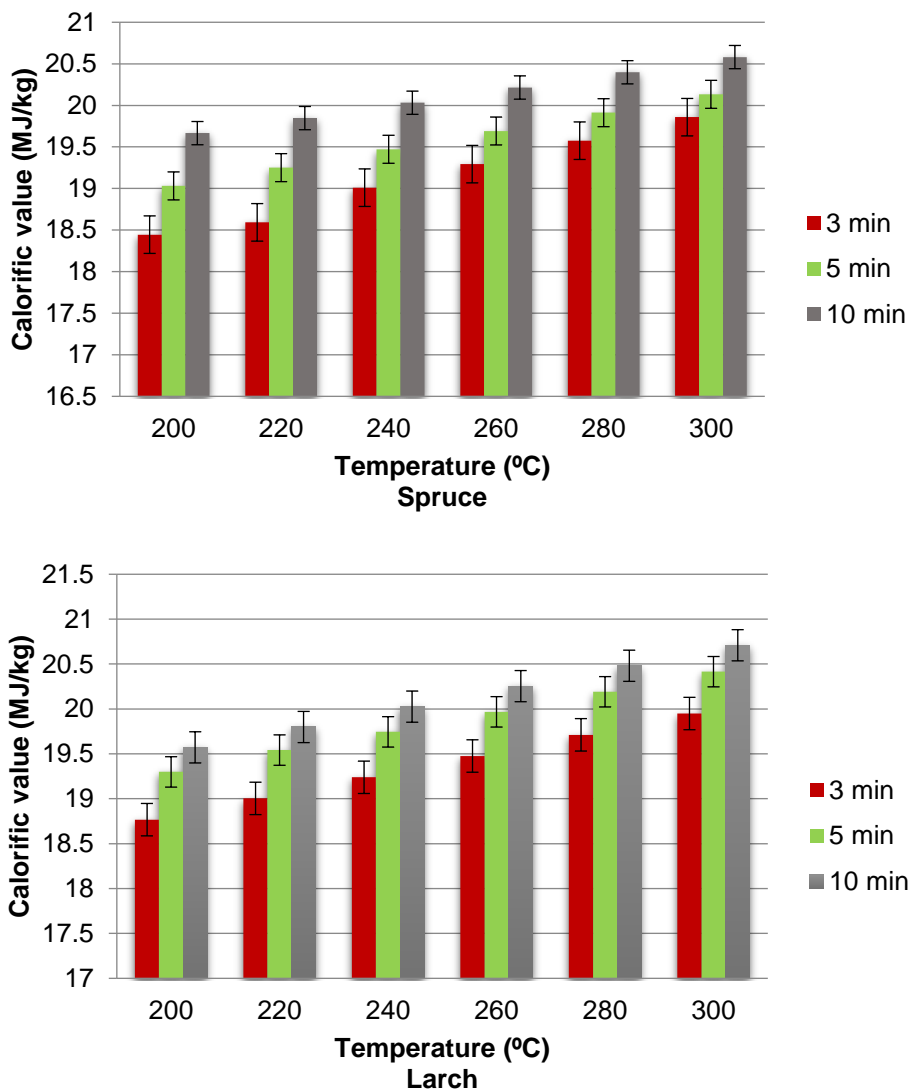
Beech

Oak

Fig. 6. Calorific value of sawdust as a function of torrefaction time and temperatures

Calorific value had a large variation range (Fig. 6), and was high (17.9 MJ/kg to 21.2 MJ/kg) for beech and lower (18.0 MJ/kg to 20.9 MJ/kg) for oak. The increase for each species that was obtained with Eq. 4 was 14.1% for spruce, 11.8% for larch, 16.4% for oak, and 20.7% for beech. The best torrefaction ability was registered for beech, and the worst for larch. The results of the research are comparable to those of other researchers (Chen *et al*. 2012), which found a value of 20.700 MJ/kg for the massive wood torrefied at 220 °C.

Rate of Energy Release

All values for the combustion time ranged between 31 and 47 min. Table 1 presents the value of the "main" time of combustion, determined with the bomb calorimeter software. A slight decrease in torrefaction times was observed, but combined with the increase of the calorific value there was an increased energy release rate from 0.5 kJ/min up to 0.75 kJ/min for spruce, *i.e.* by 50%, and from 0.441 kJ/min to 0.625 kJ/min for beech, *i.e.*, 41.7%.

Table 1. Rate of Energy Release for 10 min Treatment

Species	Temperature (°C)	"Main" Time (min)	Mass (g)	Calorific Value(MJ/kg)	Rate of Energy Release (kJ/min)
Spruce	Control	23	0.6504	18.024	0.509
	200	21	0.6490	19.666	0.607
	220	21	0.7010	19.847	0.662
	240	20	0.6888	20.032	0.689
	260	20	0.6766	20.215	0.683
	280	19	0.7102	20.398	0.762
	300	19	0.6987	20.581	0.754
Beech	Control	28	0.7016	17.634	0.441
	200	27	0.6907	19.133	0.489
	220	26	0.7052	19.566	0.530
	240	23	0.6898	19.999	0.599
	260	27	0.6797	20.436	0.514
	280	24	0.7078	20.865	0.612
	300	24	0.7043	21.298	0.625

The energy release rate shows when a fuel can be used in stoves (when the value is below 0.5 kJ/min) or in high-capacity thermal power plants (when the value is above 0.51 kJ/min). In the latter case (more than 0.65 kJ/min), coal-fired power plants can be used to obtain electricity or steam.

Calorific Density

There were slight differences in density of the pellets. Spruce and larch had 998 kg/m^3, and oak and beech had 1020 kg/m^3. However, during thermal treatment, the calorific density increased due to the increase in calorific values (Table 2).

The value of calorific densities was between 18000 MJ/m^3 and 20500 MJ/m^3 for spruce and 18500 MJ/m^3 to 20700 MJ/m^3 for larch. Value of 14.1% of the calorific density increase due to the torrefaction process was observed at the maximum torrefaction regime 300/3 in the spruce. Similar values of 9.4% in the larch, 16.4% in the oak, and 20.7% in the beech were also found. Values of 11000MJ/m^3 to 12000 MJ/m^3 for firewood were identified by other researchers (Griu and Lunguleasa 2016).

Table 2. Calorific Density of Torrefied Pellets

Species	Temperature	Calorific density (MJ/m^3), for torrefaction time of:		
		3 min	5 min	10 min
Larch	Control	18475		
	200	18638	19210	19532
	220	18965	19502	19759
	240	19200	19705	19985
	260	19437	19928	20213
	280	19672	20150	20440
	300	19909	20174	20667
Oak	Control	18341		
	200	18425	18613	19789
	220	18835	19117	20102
	240	19214	19620	20415
	260	19208	20123	20738
	280	19973	20627	21047
	300	20535	21131	21354

Ash Content Results

Ash content varied from species to another, at 0.2% to 0.6% for hardwood native sawdust (beech and oak) and 0.4% to 1.2% for softwood native sawdust (larch and spruce). As observed before, whitewood/resinous sawdust had a superior ash content related to hardwood species due to its high mineral content. As the torrefaction process enriched the carbon content, the ash content of torrefied sawdust was substantially increased, with a general values range of 22% to 30%. The greater the mass loss of sawdust, the higher the ash content. A maximum value of 29.9% was obtained for beech. These values of ash content were taken into consideration when ashes were evacuated from stoves and central heats, as quantity and dimensions.

Modeling the Variation of Chemical Compounds in Time of Torrefaction

The torrefaction process of wooden pellets increases the calorific properties close to inferior coal (Wang *et al.* 2011). The thermal torrefaction process is a method that contributes to the increasing of the lignin content and degrades hemicelluloses and cellulose in the wooden torrefied pellets (Obernberger and Thek 2004; Chen *et al.* 2012; Moya and Tenorio 2013). It is also known that the calorific power is higher for lignin (25.12 MJ/kg) and much lower for cellulose and hemicellulose (17.37 MJ/kg). If these values are considered, the following dependency relationship of calorific value as a function of wood constituent's content can be found (Eq.8),

$$CV = 25.12 \cdot \frac{L_{ig}}{100} + 17.37 \cdot \frac{C_{el} + H_{em}}{100} \quad [MJ/kg] \tag{8}$$

where L_{ig} is amount of lignin (%), C_{el} is amount of cellulose (%), and H_{em} is amount of hemicelluloses (%).

Modeling the influence of chemical compounds related to the calorific value during the torrefaction process was taken into account, considering that cellulose began to degrade starting from 280 °C, hemicellulose from 200 °C, and lignin at over 300 °C (Fig. 7). The algorithm used in modeling took into consideration the mass loss during torrefaction due to the degradation of hemicellulose and cellulose, percentages of each constituents, and the positive influence of lignin (Wannapeera *et al*. 2011) in Eq. 7.

This modeling shows what happened in the chemical structure of the sawdust during the torrefaction process, in the temperature range of 200 °C to 300 °C. Knowing the regression equations of cellulose, hemicellulose, and lignin variation, it was possible to establish the expansion of the thermal treatment process between 200 and 300 °C, for other values than that were used inside of experiments. For instance, if temperature of 230 ºC is taken in consideration it will obtain for this moment of torrefaction 49.9% cellulose, 37.2% lignin, and 12.9% hemicelluloses.

Modeling the Variation of Chemical Elements in Time of Torrefaction

The torrefaction process enriches the carbon content of the wooden material (Chen *et al.* 2015). The main chemical elements from wooden pellets or sawdust consist of carbon (C), hydrogen (H), oxygen (O), and some secondary elements (usually negligible). These elements are also present in various amounts in all kinds of fossil fuels and renewable resources. The algorithm of modeling considers that the increase in carbon content is offset by the decrease in oxygen and hydrogen content. If the calorific value of carbon (33.91 MJ/kg), oxygen (1.78 MJ/kg), and hydrogen (14.31 MJ/kg) are considered, the relationship

for determining the caloric value of sawdust will become as follows (Eq. 8),

$$CV = 33.91 \cdot \frac{C}{100} + 14.31 \cdot \frac{H}{100} - 1.78 \cdot \frac{O}{100} \quad [MJ/kg]$$

(8)

where *CV* is calorific value of sawdust waste (MJ/kg), *C* is carbon amount (%), *H* is hydrogen amount (%), and *O* is oxygen amount (%).
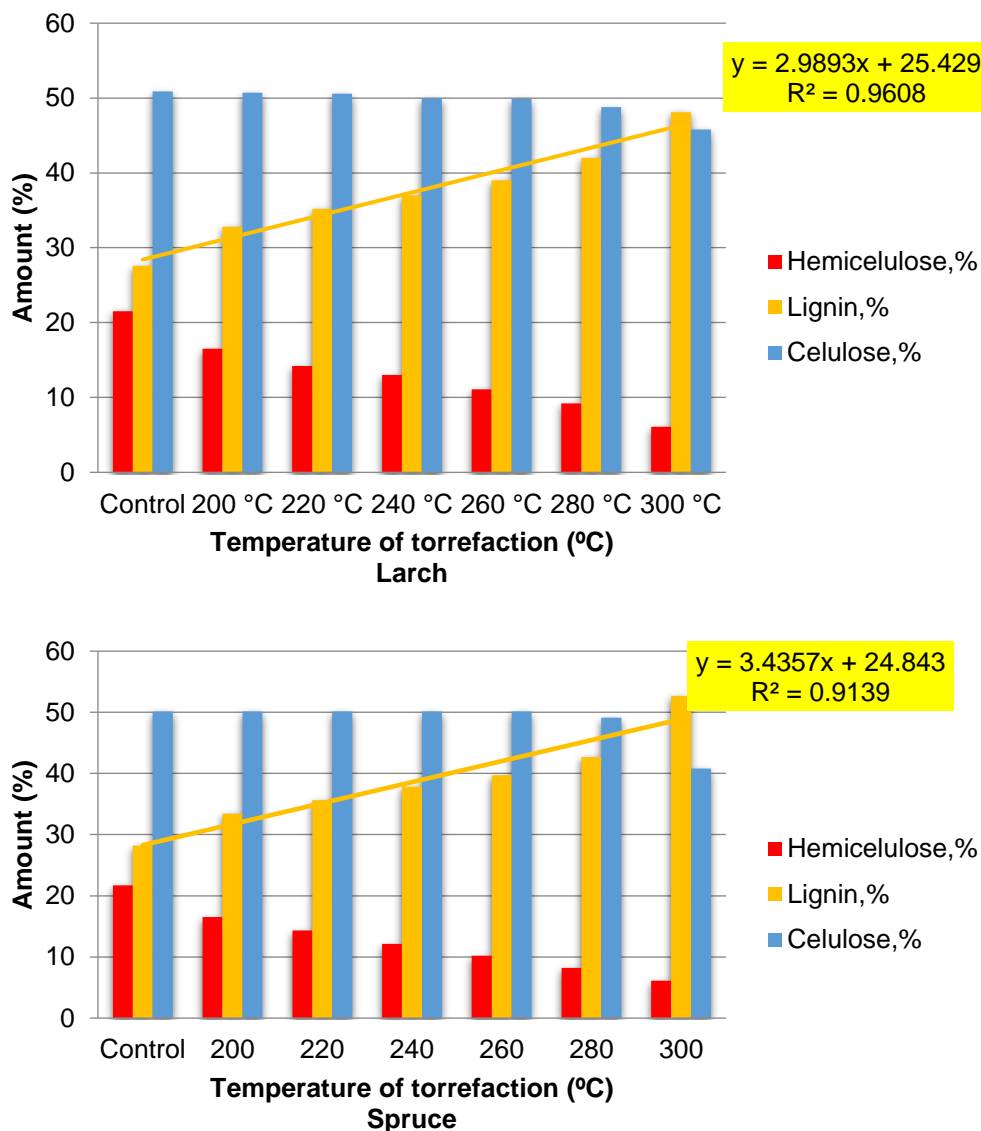

Fig. 7. Variation of chemical compounds as a function of torrefaction temperature

The algorithm for modeling sawdust torrefaction considered the experimental calorific values (related to torrefaction degree) and had finding the percent changes in chemical composition as its aim (Fig. 8).
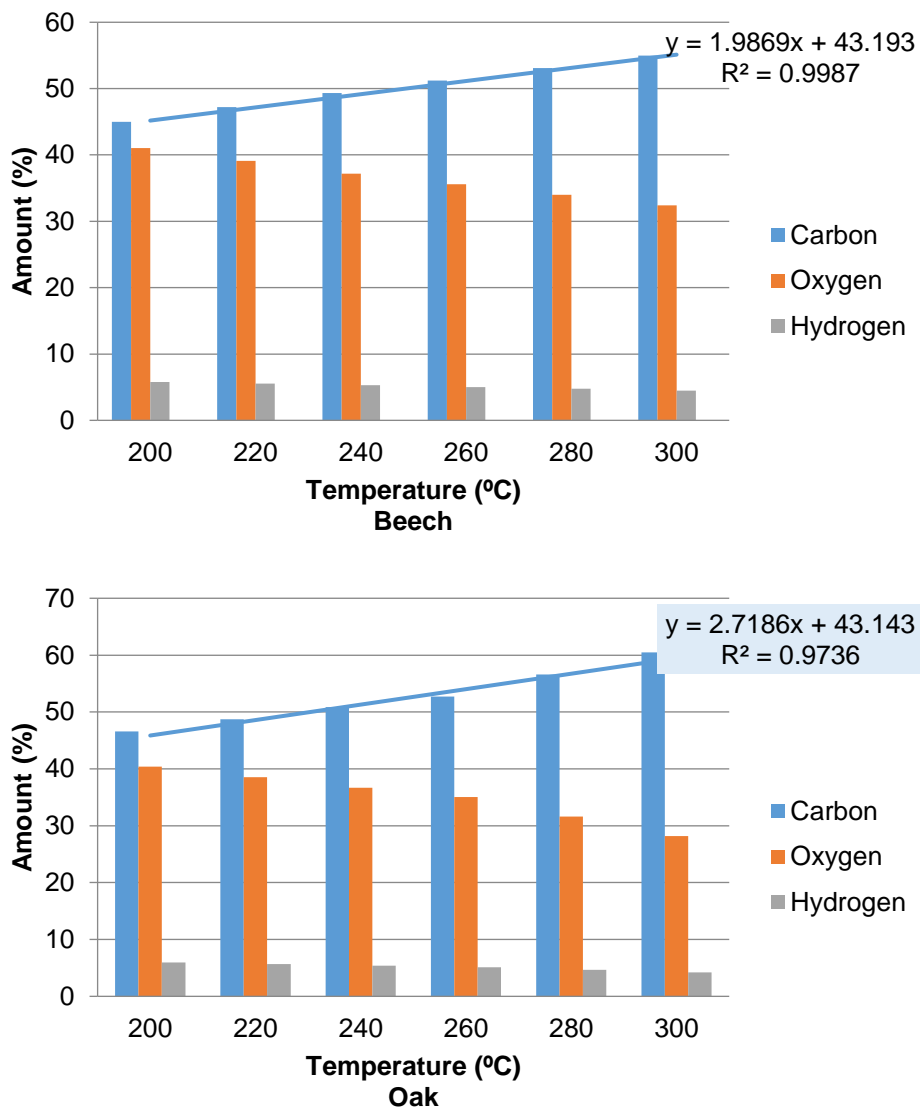
Fig. 8. Variation of chemical elements percentage as a function of torrefaction temperature

The main consideration related to modeling was the prediction of chemical elements, namely the range and trend during torrefaction. For example, at 230 °C, the carbon content was 49%, oxygen content was 46% and hydrogen content was 6%. It was also possible to estimate the carbon content for a temperature above the maximum experiment, such as a carbon content of 52% for 320 °C.

Economical Aspects

The energy market offers many solid combustibles (coal, briquettes/pellets, and firewood) to produce energy. Batidzirai *et al*. (2013) estimates the pellet production costs at 3.0€/GJ to4.3 €/GJ. In Romania, the cost is 4.1 €/GJ for pellets produced from beech, oak, larch, and spruce. Considering all aspects of production (especially operation of sawdust torrefaction), the price of the torrefied pellets obtained in this study was0.43 €/kg (compared with white pellets at 0.4 €/kg).

Table 3. Economical Characteristics of the Treated Pellets *vs.* White Ones

Species	Temperature(°C)	Calorific Value(MJ/kg)	Material Consumption (kg/h)	Unit Price (€/kg)	Price(€/kWh)	Energy Consumption (kWh/season)	Annual Cost (€/season)
Beech pellets	White	16.754	6.88	0.4	0.08		1680
	260/5	18.428	6.25	0.43	0.078		1638
	300/5	19.283	5.97		0.074		1554
	260/10	18.915	5.76		0.072	21000	1512
	300/10	20.339	5.66		0.070		1470
Larch pellets	White	17.256	6.68	0.4	0.082		1722
	260/5	18.266	6.31	0.43	0.078		1638
	300/5	19.172	6.00		0.075		1575
	260/10	19.482	5.91		0.073		1533
	300/10	19.935	5.77		0.072		1512

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The investment in this method is about 15,800 € (Stolarski *et al*. 2013), with a productivity for pellets of about 2.5 t/h to5 t/h. Considering the above features, the annual cost of a residential house (about 200 m^2) in a temperate area, using white and torrefied pellets, can be found (Table 3).

As the sawdust degree of torrefaction increased, the costs for the assessed residential house decreased considerably. For instance, when the larch pellets were used the seasonal costs with torrefied pellets (1512 €) were lower by 12.1% than with white pellets (1722€). If a SWOT (strength-weakness-opportunities-threat) economic analysis was used, the use of pellets obtained from torrefied sawdust was beneficial due to the increased caloric power, mass loss, and lower hydrophilicity (Chen *et al*. 2015). It is also a challenge to obtain and use torrefied pellets in the actual context of a fuel crisis.

CONCLUSIONS

1. The torrefaction treatment on sawdust waste of 4 species less used in the sawdust torrefaction process led to an attractive fuel in torrefied pellets, which are environmentally friendly, inexpensive, and superior to even classical pellets. From this point of view, the torrefied pellets became an alternative to fossil energy sources.

2. The main improved properties of torrefied pellets in a wide range of 200 to 300 °C were calorific power, with a maximum 20.7% increase for beech (regime of treatment with 300 °C and 10 min); calorific density, with a 20.7% increase in the case of beech; and rate of energy release for spruce, with a 50% increase. Increased values were highlighted for caloric density and rate of energy release, less evident in the literature.

3. The two models based on the innovative math relations and algorithms have shown what happened in the torrefaction process from the point of wood constituents or chemical elements degradation and how the thermal process can be extended or shortened. The main observations were the degradation of hemicelluloses and the corresponding increase of lignin, or the increase of carbon content and the decrease of oxygen content.

4. The economical aspect put in evidence the advantages of torrefied pellets and the decrease of seasonal costs with 12.1% favorable to torrefied pellets use.

5. The increase of ash content by torrefaction was compensated by the appropriated mass losses.

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