

Utilization of wood and bark of fast-growing hardwood species in energy production

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Abstract

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In this research, the calorific value and ash content of wood and bark of some fast-growing hardwood species, such as tree-of-heaven, (*Ailanthus altissima* (Miller) Swingle), empress tree (*Paulownia tomentosa* (Thunberg) Steudel), trembling aspen (*Populus tremuloides* Michaux), oriental plane (*Platanus orientalis* Linnaeus) and black locust (*Robinia pseudoacacia* Linnaeus) were investigated in order to comprehend their behaviour during combustion and estimate their utilization potential as solid biofuels (pellets). Beech (*Fagus sylvatica* Linnaeus) wood was used for comparative reasons. Different ratios of all the studied species in mixture were examined in order to investigate the material ratio that provides a satisfactory calorific value, while parallelly meeting the ash content requirements of the pellet production standard (ISO 17225-2:2014). Black locust bark seems to greatly increase the calorific value of the material. Empress tree wood had the lowest ash content, meeting the requirements of the best class (ENplus A1 – residential use), while tree-of-heaven and poplar were classified into ENplus B class (third class of residential use). By using the appropriate proportions, all the materials examined could be utilized in pellet production.

Keywords: ailanthus; ash content; biomass; heating value; paulownia; pellets

Intensive cultivation of fast-growing forest species in short rotation periods could partly solve the problem of wood shortage in the last decades. Lately, interest in many countries has been attracted by the use of wood fuels derived from species not properly utilized so far, wood residues from several uses or logs of small diameter considered not to be appropriate for constructional uses, coming from natural forests or energy plantations (HYTÖNEN, NURMI 2015).

Wood is used in energy production either traditionally in the raw form of firewood or in more

processed forms, compact for easier use, packaging, storage and transportation, such as wood particles, chips, pellets or briquettes, in contemporary combustion equipment, marking great energy yields. The rational use of wood biomass in energy production requires precise knowledge of its physical and chemical properties and combustion characteristics.

In pellet production, the ash content of the material is critical to remain at low levels, in order to meet the requirements of the respective in-

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ternational standards for domestic or industrial uses. Additionally, the high ash content has been proven to decrease the calorific value of biomass (HYTÖNEN, NURMI 2015). Generally, the calorific value and the ash content value vary among different species, even between parts of the same species, and depend on many factors such as soil fertilization, growing density, species type and moisture content of fuel material (HAKKILA, KALAJA 1983). Therefore, the investigation of basic thermal characteristics of several wood species seems to be of great importance for the comprehension of their behaviour during combustion and implementation of their proper utilization as biofuels.

The objective of the present research work is to indicate the suitability of wood and bark material of these five abovementioned fast-growing hardwood species, commonly found in the Mediterranean area, as well as in numerous countries around the world (tree-of-heaven, empress tree, poplar, oriental plane and black locust), to be utilized in biofuel (pellet) production, by examining the most critical for their future utilization thermal characteristics, those of ash content and higher heating value. Wood of European beech was used in this work for comparative reasons. Different ratios of all the studied wood species in mixture were examined in order to investigate the material ratio that would provide the most satisfactory calorific value, meeting parallelly in the best possible way the requirements of the standard (ISO 17225-2:2014, pellet production) referring to ash contents of the wood and bark material of the species studied in the specific research work.

MATERIAL AND METHODS

The raw material of this experiment was wood and bark of stems coming from indigenous species: tree-of-heaven (*Ailanthus altissima* (Miller) Swingle) 11–14 years old, empress tree (*Paulownia tomentosa* (Thunberg) Steudel) 5–7 years old, poplar (*Populus tremuloides* Michaux), oriental plane (*Platanus orientalis* Linnaeus), black locust (*Robinia pseudoacacia* Linnaeus) and beech (*Fagus*

sylvatica Linnaeus) 10–12 years old. Beech wood was included in the experiment for comparative reasons, used as a reference since it is a material traditionally used in pellet production because of its thermal characteristics and behaviour during combustion and it is a raw material of high availability in many European countries, as well as Greece.

For each species, logs of 60 cm in length were randomly selected from 4 trees coming from regions of Central Macedonia (Greece). Specifically, tree-of-heaven logs were obtained from the botanical garden of the Faculty of Forestry and Natural Environment (Aristotle University of Thessaloniki), empress tree wood came from a pilot plantation and the rest of the species were obtained from the University forest of Taxiarchis (North Chalkidiki). Samples were taken at breast height (1.37–1.5 m above the ground) including different annual rings.

Density of the samples was determined as oven-dry weight and volume at a moisture content of 12% (Table 1). For each of the logs, barked diameter, bark thickness and annual ring width were measured at both ends. The proportion of bark was calculated as the ratio of the bark area in a transverse section to the total stem area of the section according to Eq. 1:

$$z = 100 \frac{f(2R - f)}{R^2} \quad (1)$$

where:

z – bark (%),

f – bark thickness (cm),

R – barked stem radius (cm).

For the determination of bark percentage, it was considered that the transverse surfaces were circular. 30 measurements of the diameter of these surfaces were carried out for each species. Consequently, bark and wood were separated and were chipped by means of a portable chipper.

The bulk samples were reduced by coning and quartering to a representative sample of about 0.5 kg. All materials were oven dried until steady mass was achieved and subsequently ground using a rotating-blade Wiley mill with a 0.7 mm sieve.

Table 1. Mean values of density, bark thickness and annual ring width of the studied species

Characteristic	Tree-of-heaven	Empress tree	Oriental plane	Black locust	Poplar	Beech
Density (g·cm ⁻³)	0.55 (0.03)	0.35 (0.01)	0.488 (0.02)	0.762 (0.08)	0.534 (0.02)	0.722 (0.02)
Bark thickness (mm)	3.96 (0.58)	1.93 (0.32)	5.52 (0.57)	6.64 (0.82)	6.76 (0.45)	3.5 (0.34)
Annual ring width (mm)	7.75 (2.71)	27.51 (5.84)	6.47 (2.13)	3.53 (1.42)	5.61 (1.87)	1.26 (0.18)

standard deviation values in parenthesis



Fig. 1. Parr 1261 isoperibol bomb calorimeter (Parr Instrument Company, USA) (a), Parr 1108 oxygen combustion bomb (Parr Instrument Company, USA) (b)

For ash determination, the methodology described in EN 14775:2010 was used in 3 replicates for wood of each species and bark of each species.

The calorific value was expressed by the quantity of higher heating value – HHV (or gross calorific value), which is the absolute value of the specific energy combustion in joules per unit mass of a solid biofuel burned in oxygen in a calorimetric bomb, where all the products of combustion are brought back to the original pre-combustion temperature, and in particular condensing any vapour produced. The HHV was determined in an isoperibol bomb calorimeter (Parr 1261; Parr Instrument Company, USA) (Fig. 1), according to the method described in the European standard EN 14918:2009. The quantity of lower heating value – LHV (net calorific value) is determined by subtracting the heat of vaporization of water from the HHV. This treats any H_2O formed as a vapour, whereas the energy required to vaporize the water is not therefore released as heat. LHV calculations assume that the water component of a combustion process is in a vapour state at the end of combustion, as opposed to the HHV, which assumes that all of the water in a combustion process is in a liquid state after a combustion process.

Afterwards, a theoretical estimation of the fuel characteristics of pellets produced from the selected

species wood and bark was implemented. This was based on the ash content as well as the calorific values of bark and wood that had been determined, taking into account the various barked stem diameters of the raw materials used. Eqs 2 and 3 were used:

$$ASH = a_1 \frac{z}{100} + a_2 \frac{100 - z}{100} \quad (2)$$

where:

ASH – total ash content (%),

a_1 – ash content of bark (%),

a_2 – ash content of wood (%).

$$HHV = b_1 \frac{z}{100} + b_2 \frac{100 - z}{100} \quad (3)$$

where:

HHV – total higher heating value ($J \cdot g^{-1}$),

b_1 – HHV of bark ($J \cdot g^{-1}$),

b_2 – HHV of wood ($J \cdot g^{-1}$).

All the materials separately and several mixtures of them were classified in qualitative categories, based on the requirements (threshold values) for ash content and calorific value parameters of the respective standards (Table 2).

Mean values were compared with ANOVA ($\alpha = 0.95$) using the statistical package SPSS Statistics (Version 22, 2013), while the graphs were created in MATLAB programme (Version 2016a).

Table 2. Threshold values of the most important pellet parameters according to pellet quality requirements of the respective standards (ISO 18122 for ash content, ISO 18125 for calorific value)

Property	ENplus A1	ENplus A2	ENplus B	Industrial I3
Ash content ($w_{\%}$)	≤ 0.7	≤ 1.2	≤ 2.0	≤ 3
Calorific value ($J \cdot g^{-1}$)	$\geq 16,560$			$\geq 16,500$

RESULTS AND DISCUSSION

According to the results (Table 3), all the wood species tested in this research revealed a very satisfactory level of calorific value (HHV and LHV) based on the standard ISO 17225-2:2014 (ISO 18125), concerning the parameters of pellet production material, while no statistically significant differences between these calorific values were found. It should be taken into consideration that, depending on the species, during the first 5–20 years of growth, the wood formed is juvenile and usually has a lower cellulose and a higher lignin content than the mature wood (BARTON 1984), whose presence contributes to a high calorific value of the material (TELMO, LOUSADA 2011).

HHV value of beech wood was found to be higher compared to the rest of the species studied. Specifically, empress tree wood had the 5.72% lower HHV value compared to beech wood, while following an ascending order of difference percentages, poplar, tree-of-heaven, oriental plane and black locust presented 5.82, 6.12, 6.23 and 7.92% lower values than the specific value of beech. As it was expected, the bark material showed a higher heating value compared to the wood material of the respective species, except for oriental plane and beech wood. Although the highest HHV value was recorded by black locust bark, this value was found to be only 3.64% higher compared to empress tree and 3.89% higher than poplar, 5.70% than beech bark, 6.63% than tree-of-heaven and finally 14.83% higher than the oriental plane bark HHV.

The highest ash content among these species was recorded by black locust, which was found quite close to oriental plane ash content, while the rest of

the species recorded quite lower ash contents. The bark material of the species revealed in each case higher ash contents than the wood of the corresponding species, with oriental plane to present the highest and empress tree the lowest ash content.

According to Fig. 2, where HHV and ash content values are related to the barked stem radius of the tested species, beech wood demonstrated a very high HHV percentage value compared to the rest of the species, presenting a slightly increasing tendency as the stem radius increases. It is obvious that HHV of empress tree, tree-of-heaven and poplar species did not particularly alter as the stem radius was increasing, while the oriental plane wood showed an increase, a tendency influenced by the difference between the heating values of wood and bark. Only in the black locust species, the increase of stem radius was accompanied by an intensive decrease of HHV, which can be attributed to the change of the mixture ratio of wood to bark. Higher proportion (%) of wood that has lower HHV, against the bark material, means an HHV reduction in the final material.

As it is evident (Fig. 2, Table 4), the material of empress tree wood in each case could meet the requirements for the best quality class of pellet standard (ENplus A1), referring to ash content, and even branches of small diameter (around 5 cm) could be used without increasing the ash content of the material. This fact is of critical importance, since the energy production obtained from solid biofuels is usually based on short-rotation plantations where smaller stem diameters and higher percentages of bark are usually encountered. Furthermore, in the case of empress tree wood, less material of the whole harvest would be left untapped, contributing

Table 3. Thermal characteristics of wood and bark material of the species studied

Species	Value	Higher heating value ($\text{J}\cdot\text{g}^{-1}$)		Lower heating value ($\text{J}\cdot\text{g}^{-1}$)		Ash (%)	
		wood	bark	wood	bark	wood	bark
Tree-of-heaven	mean	18,040.17	18,437.24	12,387.48	12,882.45	0.69	7.69
	SD	10.76	58.91	10.76	58.91	0.07	0.06
Empress tree	mean	18,118.04	18,968.80	12,465.36	13,414.00	0.33	2.99
	SD	30.94	35.80	30.94	35.80	0.01	0.03
Poplar	mean	18,097.48	18,923.29	12,444.80	13,368.49	0.39	5.58
	SD	21.81	37.93	21.81	37.93	0.05	0.06
Oriental plane	mean	18,019.32	17,120.41	12,366.63	11,565.61	1.26	9.10
	SD	42.45	40.65	42.45	40.65	0.07	0.05
Black locust	mean	17,694.42	19,660.92	12,041.74	14,106.12	1.4	7.03
	SD	51.08	54.89	51.08	54.89	0.04	0.12
Beech	mean	19,216.99	18,600.24	13,564.31	13,045.44	0.50	7.73
	SD	40.28	7.95	40.28	7.95	0.07	0.53

SD – standard deviation

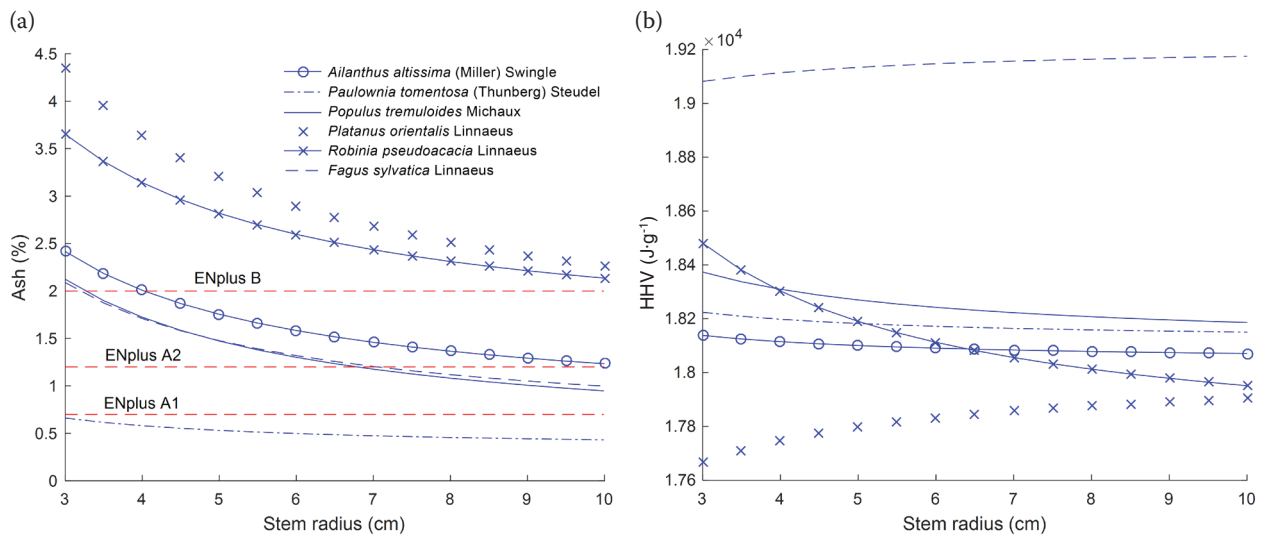


Fig. 2. Configuration of higher heating value (HHV) percentage (a), ash content (b) correlated with the barked stem radius of the tested species

to a sustainable use of resources. For the ENplus B quality class of the standard, which corresponds to the lowest category suitable for the production of pellets of non-industrial use the woody species tree-of-heaven and poplar meet the requirements for ash content, referring to the specific stem diameters used. On the contrary, in the case of oriental plane and black locust material, extremely large stem diameters are required in order to fulfil the ash content requirements of the ENplus B category, which usually corresponds to wood pieces of large dimensions, intended for commercial technical timber for construction/building applications etc. Though, these species of medium or small diameter could be used in pellet production for industrial use (quality class I3) or other sorts of fuel production.

As it is obvious in Table 5, using stems of at least 10 or 15 cm in diameter of the tested species in pellet production could fulfil the requirements of the ENplus B standard class for the ash content, except oriental plane and black locust which should be of larger stem diameters in order to be classified into this category.

The ash content is one of the crucial fuel characteristics, since it is closely related to problems of ash removal, equipment corrosion, slagging and deposit formation in the furnace and depending on

this value, restrictions are put on the use of specific species in fuel production. Although the calorific values of the studied species did not show any remarkable differences, their ash content values revealed statistically significant differences.

In Table 6, the ash content of different mixing proportions of the tested species was estimated so that these selected mixing proportions would approach as much as possible the material mixture that is characterized by the lowest ash content combined with the highest possible calorific value. Referring to the barked stem diameter of 10 cm, very low ash contents (1.002%) would be recorded by the material coming from empress tree and poplar

Table 5. Ash content values that correspond to the barked stem material of the tested species, referring to the diameter of 10 and 15 cm

Wood species	Ash (%)	
	radius = 5 cm	radius = 7.5 cm
Tree-of-heaven	1.75	1.41
Empress tree	0.53	0.46
Poplar	1.47	1.12
Oriental plane	3.20	2.58
Black locust	2.82	2.37
Beech	1.47	1.16

Table 4. Stem radii of the species that could meet the requirements of ISO 17225-2:2014 standard in ash content

Quality class	Ash limit (%)	Stem radius (cm)					
		tree-of-heaven	empress tree	poplar	oriental plane	black locust	beech
ENplus A1	0.7	–	2.67	18.20	–	–	25.13
ENplus A2	1.2	10.67	1.07	6.78	–	–	7.05
ENplus B	2	4.02	0.49	3.26	13.73	12.34	3.18

Table 6. Estimation of ash content in different mixing proportions of the wood species, keeping empress tree constantly at 25 or 50%

Ash (%)	Proportion in mixture (%)					
	tree-of-heaven	empress tree	poplar	oriental plane	black locust	beech
Barked stem diameter = 10 cm						
1.45	75	25	–	–	–	–
1.24	–	25	75	–	–	–
2.53	–	25	–	75	–	–
2.25	–	25	–	–	75	–
1.24	–	25	–	–	–	75
1.74	15	25	15	15	15	15
1.14	50	50	–	–	–	–
1.00	–	50	50	–	–	–
1.87	–	50	–	50	–	–
1.67	–	50	–	–	50	–
1.00	–	50	–	–	–	50
0.26	10	50	10	10	10	10
Barked stem diameter = 15 cm						
1.17	75	25	–	–	–	–
0.96	–	25	75	–	–	–
2.05	–	25	–	75	–	–
1.89	–	25	–	–	75	–
0.98	–	25	–	–	–	75
1.41	15	25	15	15	15	15
0.94	50	50	–	–	–	–
0.79	–	50	50	–	–	–
1.52	–	50	–	50	–	–
1.42	–	50	–	–	50	–
0.81	–	50	–	–	–	50
0.23	10	50	10	10	10	10

wood in mixture at a ratio of 50:50 or empress tree and beech wood (1.004%) at the same ratio, meeting the requirements of the standard class ENplus A2 for the ash content. Using empress tree wood in a percentage of 50% in the mixture of different species seems to ensure lower ash contents in the material, which corresponds to the ENplus B class (for residential use), compared to 25%, which nevertheless offered low ash contents (ENplus B class) except oriental plane and black locust. The material of tree-of-heaven and empress tree wood in mixture at a 50:50 ratio had the ash content lower than 1.2%, which classifies it in the ENplus A2 quality class of the standard.

Using all the woody species of the present research in a mixture with a proportion of 15%, keeping only empress tree wood at 25%, revealed quite a low ash content (1.74%, EN plus B class), while mixing the species at 10%, keeping only empress tree wood at 50% demonstrated the lowest ash content (0.26%), which contributed to the classification of the material in the best category of ENplus A1 quality class for residential use. Generally, all the

examined mixing proportions of this experiment met the ash requirements of the class I3 of the standard (industrial use).

Using wood material of the examined species in mixtures coming from barked stems of 15-cm diameter would result in very low ash contents that correspond to ENplus A1 and ENplus B classes, except the mixture of empress tree with oriental plane wood at a ratio of 25:75, which could be used only in the production of pellets for industrial use (I3 quality class). The case of 15-cm diameter revealed that the mixture of all the wood species at 10%, keeping only empress tree wood at 50%, had the lowest ash content among all the examined proportions (0.23%), classifying the material into the best quality class ENplus A1 for residential use.

Generally, higher heating values and ash contents were recorded in bark than in pure wood, which is in agreement with earlier studies (HAKKILA, KALAJA 1983; HYTÖNEN, NURMI 2015).

Furthermore, all the examined mixing proportions of this work met the requirements for low ash content of the quality class I3 (industrial use of

pellets). Specifically, empress tree wood presented the lowest ash content among the studied species, meeting the requirements of the best category ENplus A1, even using very small diameters of stems (around 5 cm), which is in accordance with the results of other studies (POPOVIĆ, RADOŠEVIĆ 2010). Tree-of-heaven and poplar wood met the requirements of ENplus B class, referring to the specific stem diameters used. Similar ash content (0.9) for tree-of-heaven was reported by FERREIRA et al. (2013). Using stems of at least 10- or 15-cm diameter of the tested species could meet the requirements of the ENplus B class, concerning the ash content, except oriental plane and black locust.

Estimating the ash content of different mixing proportions of the tested species, referring to the barked stem diameter of 10 or 15 cm, very low ash contents would be recorded by the material mixture of empress tree with poplar (50:50) and empress tree with beech wood (50:50) (ENplus A2 class) or by mixtures of empress tree with the other wood species (ENplus B class).

Using material mixtures of barked stems of the examined wood species of 15-cm diameter would provide even lower ash contents (ENplus A1, A2 and ENplus B), except for the mixture of empress tree with oriental plane wood (I3 class). The proportion of all the species amounting to 10% in mixture, keeping only empress tree wood at 50%, revealed the lowest ash content among all the examined proportions, classifying the material into the best quality class ENplus A1.

CONCLUSIONS

Although black locust wood had the lowest calorific value, the proportion of black locust bark in pellet material could greatly increase the calorific value of the solid biofuel. All the mixing proportions met the ash content requirements of class I3 (industrial use of pellets). Empress tree wood showed the lowest ash content, meeting the requirements of the best quality class ENplus A1, providing the opportunity to utilize empress tree stems of very small diameters (around 5 cm). Tree-of-heaven and poplar met the requirements of ENplus B class. Using stems of at least 10- or 15-cm diameter of the tested species could meet the requirements of the standard class ENplus B, except

oriental plane and black locust species. Referring to the barked stem diameter of 10 or 15 cm, very low ash contents could be recorded by the material mixture of empress tree with poplar (50:50) and empress tree with beech (50:50) (ENplus A2 class) or by mixtures of empress tree with the other wood species (ENplus B class). Using material mixtures of 15-cm diameter barked stems would provide even lower ash contents (ENplus A1, A2 and ENplus B), except for the mixture of empress tree with oriental plane wood (class I3). The proportion of all the species amounting to 10% in mixture, keeping only empress tree wood at 50%, revealed the lowest ash content of all the examined proportions, classifying the material in the best class of pellets.

Consequently, the material of bark and wood of common fast-growing hardwood species, usually left so far untapped, could be utilized in pellet production, using each one in the appropriate proportion, in order to achieve the highest possible calorific value with the minimum ash content. In this way, new products of high value added (solid biofuels) and satisfying thermal characteristics can be created, whose use would contribute to sustainable and good management of forest biomass.

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