Journal of Thermal Analysis and Calorimetry (2018) 134:543–548
https://doi.org/10.1007/s10973-018-7194-y

Comparison of thermal properties of the fast-growing tree species and energy crop species to be used as a renewable and energy-efficient resource

Martin Zachar[1] · Martin Lieskovský[2] · Andrea Majlingová[1] · Iveta Mitterová[1]

Received: 1 November 2017 / Accepted: 11 March 2018 / Published online: 19 March 2018

Abstract

The energy stands of fast-growing tree species and crops are a prospective resource of renewable energy to the future. The paper focuses the assessment and comparison of the thermal properties of selected species of fast-growing trees (*Paulownia tomentosa*, *Salix viminalis* clone Tora, *Populus* × *euramericana* clone MAX 4) and energy crops (*Sida Hermaphrodita*, *Arundo donax*, *Miscanthus* × *giganteus*), as well as ash content (mass%). The following fire and thermal and properties were tested: spontaneous ignition temperature, gross caloric value, heating value. Besides those parameters, the elemental composition and ash content of the samples tested were analyzed. The results showed the energy crops to be much more effective for energy production than the energy trees. It is mostly due to higher yields harvested in a relatively short time, increased share of fiber, as well as higher energy efficiency. The highest heating value (energy potential) in case of energy crops showed *Miscanthus* × *giganteus* (16.29 ± 0.14 MJ kg^{-1}), which had the lowest ash content (2.67 ± 0.08 mass% on average). The highest heating value in case of fast-growing tree species showed Paulownia (16.40 ± 0.18 MJ kg^{-1}), which also had the lowest ash content (0.75 ± 0.05 mass% on average), while the *Populus* had the highest one (2.58 ± 0.24 mass% on average).

Keywords Ash content · Fast-growing tree species · Gross caloric value · Heating value · Spontaneous ignition temperature

Introduction

Global, reliable and environmentally friendly fuel and energy security is the current issue at the present time, of which the countries of the world pay particular attention. The global community needs sustainable and renewable sources of energy as alternatives to finite fossil fuels that are also associated with climate change [1]. The E.U. energy policy is strategically focused on the promotion of renewable energy sources (RES) taking into account regional specificities as well as energy saving and efficient use of energy and heat. In the regions of Central and Eastern Europe, the highest potential is biomass that can be stored and, unlike wind or solar power, is a relatively stable source of energy. The European Community aims to achieve a 20% share of RES in total energy consumption by 2020. The current energy and climate policy proposal for 2030 sets out a strategy to reduce greenhouse gas emissions by 40% and increase the share of RES to 27%. In the surrounding countries, standardized wood-based fuels are already being marketed, as well as alternative phytomass-based fuels from agricultural production.

The energy consumption of the Slovak Republic is ensured mainly by import of primary energy resources and own primary energy resources currently account for only about 10% of total demand. One of the fuel saving options is a more systematic use of renewable energy sources (RES) that represent the solar, wind, geothermal, energy, water and biomass energy source. Renewable energy production is currently highly political priority that has also being shown by the European Union, which goal is targeting 20% of energy from renewable sources by 2020.

✉ Andrea Majlingová
majlingova@tuzvo.sk

[1] Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 53 Zvolen, Slovak Republic

[2] Faculty of Forestry, Technical University in Zvolen, T. G. Masaryka 24, 960 53 Zvolen, Slovak Republic

The establishment of fast-growing tree plantations, energy crops and grassland crops and heat crops and electricity can make a significant contribution to meeting this goal. At the same time, it is possible to consider such a management to be a diversification of agricultural, taking into account and supporting the environmental objectives. Utilization of renewable energy potential sources of energy is nowadays current issues contributing to the environmental protection savings of fossil fuels [2].

Short-rotation plantations of fast-growing species and energy crops provide a promising way to produce heat and electricity from renewable sources [3]. In the Slovak Republic, there exists an extensive set of fast-growing tree species and energy crops. The most preferred are intensive forest plantations and short-rotation systems from selected clones of poplar (*Populus sp.*), willow (*Salix sp.*) and *Paulownia*. The biomass from plantations of fast-growing tree species and energy crops can be an alternative and attractive base not only for energy production, but also for bioethanol production [4].

The paper presents methods and procedures for qualitative (energetic potential) assessment of selected biomass species to determine the suitability of its use as a renewable energy source in the future. Its energy potential was assessed based on the thermal analysis (calorimetry) methods application, especially for the determination of the gross calorific value and ash content. This is the most often applied approach to assess the biomass energy potential. It can be seen from works of many authors, see [3–16]. The methodology for their exact determination is set in the relevant STN ISO standards.

Experimental

The objective of the experiments was the determination of thermal parameters (gross calorific value and heating value) of the selected types of fast-growing trees and energy crop. Besides it, the ash content and elemental analysis of the fast-growing trees and energy crop samples were analyzed. In the following subchapters, the methodological procedures to acquire them all are introduced.

Fast-growing tree species and energy crop species tested

The following fast-growing tree species which are used for energy purposes in Slovakia most often were selected: *Paulownia tomentosa*, *Salix viminalis* clone Tora, *Populus × euroamericana* clone MAX 4. The samples of the fast-growing tree species and energy crops (*Sida Hermaphrodita, Arundo donax, Miscanthus × giganteus*) were taken from the existing plantations of the University Forest Enterprise of the Technical University in Zvolen and Agricultural Co-operative Dolne Saliby.

Paulownia tomentosa has its origin in Asia. For its ultra-fast growth, resistance and adaptability to the climate, it is considered to be the best of all energy plants. The large area of leaves is the reason for the rapid growth of the tree, because they effectively enable the assimilation of solar energy (photosynthesis). They are involved in the storage of CO_2, making a significant contribution to the mitigation of climate change in the global warming (carbon credit). It is characterized by its resistance to diseases and insects, improved wood properties, strong adaptability to natural conditions, higher resistance to droughts and short-term floods, and it produces quality wood. Adult, 7-year-old trees, will reach up to 0.60–0.90 m^{-3}/tree, depending on the soil and climate, which is 67–96% more than other species [17].

There are approximately 600 separate species among the *Salix sp.*, with different site requirements and varying height. *Salix viminalis L.* has registered varieties of Tora, Tordis, Inger, Sven and others, which are planted with a deliberate crossing of other species of Salix shrub forms. Varieties are protected by Weger's breeders' rights. These are high-yield varieties of Swedish and Austrian origin, intended for intense cultivation. During 1 year, they reach a height of 1–2 m. The Tora variety was created by crossing the Siberian willow with the Orm variety. Tora has long shoots, but lower number than other varieties. The stem is slightly shiny, dark gray and is relatively damp in the winter. It achieves the highest yields of all today's varieties. It is resistant to leaves molding and various insect species [2].

Populus sp. is characterized by their rapid growth and high production of dendromass (biomass). For this reason, they are suitable for bioenergy production. For this purpose, various cultivated hybrids, which are among the fastest growing tree species in Slovakia, are grown. Their hardwood is well processable in various forms of fuel, which is also used for paper and veneer production. About 110 species of poplars are known, of which only 3 species are domestic in Slovakia: Populus *tremula*, *Popolus alba* and *Populus nigra*. In addition to the species mentioned, there are also the cross-breeds in Slovakia—*Populus × canadensis* and *Populus × euroamericana*. The assessment of energy potential and yields was realized on *Populus × euroamericana* clone MAX 4, planted on plantations in southern part of the Slovak Republic [2].

The energy crop species were represented by the *Sida Hermaphrodita*, *Arundo donax*, *Miscanthus × giganteus.*

Sida hermaphrodita is a multi-annual crop of the Malvaceae family. It is a permanent crop of a temperate zone that can be grown for 20–25 years in one place. When used for energy purposes, biomass is suited for biogas production in multiple harvests during vegetation period and in one harvest for combustion or processing to biofuel. The biomass yield is significantly influenced by environmental factors, especially weather conditions and the cultivation system.

Arundo donax is originally a wild, long-lived grass with creeping outcrops, which is particularly widespread in the Mediterranean Sea region. The Arundo is one of the most fertile grasses, which in favorable conditions grows up to 5 m. Research of alternative crops for biomass production for energy has included Arundo among species that are well suited to biomass production.

Miscanthus × giganteus—under favorable growing conditions, the *Miscanthus* can provide over 30 t of dry above ground phytomass yield from hectare per year. Genus *Miscanthus* is naturally extended predominantly in tropical and temperate regions. It includes a total of 33 taxons. *Miscanthus* is a perennial grass of high-rise type, which uses solar energy, water, nutrients to make it highly resistant to diseases and pests. It comes from Southeast Asia and was originally brought to Europe as decorative plant. *Miscanthus* is a promising crop intended for non-food uses giving high-quality lignocellulosic material usable in energy or fiber production.

The initial moisture content of the samples tested was as follows: *Paulownia tomentosa* (61.18%), *Salix viminalis L.* (54.80%), *Populus × euroamericana* (56.02%), *Sida hermaphrodita* (32.17%), *Arundo donax* (31.79%), *Miscanthus × giganteus* (39.82%).

Determination of the spontaneous ignition temperature

The testing method is specified in the standard STN ISO 871:2006. Plastics—Determination of ignition temperature using a hot-air furnace [18]. Spontaneous ignition temperature values represent the lowest ambient air temperature that will cause ignition of the material under the conditions of this test. Test values are expected to rank materials (wood, crop) according to ignition susceptibility under actual use conditions.

In test, there were used the samples with mass of 3.0 ± 0.2 g. Before the test, they were conditioned at temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%, for 40 h, according to the STN EN ISO 291 standard [19]. The temperature in the hot-air furnace was set to 430 °C during the test.

Five measurements were taken for each sample. The results show the average value of those measurements.

Determination of the gross caloric value and heating value

The *gross caloric value Qs* (kJ kg^{-1}) is defined as the heat released by the perfect combustion (by the oxidation of the active elements of the fuel) of 1 kg of fuel and cooling of the flue gas and the ash to the initial temperature (i.e., 20 °C), while the water vapor condenses and changes to the water. The gross caloric value is determined by experiments in a calorimeter.

The *heating value Qn* (kJ kg^{-1}) is defined as the heat released by the perfect combustion of 1 kg of fuel, when the combustion is cooled to its original ambient temperature (t = 20 °C), while the water (evaporated from the fuel produced by the oxidation of hydrogen contained in fuel and supplied with humid air) remains in the gaseous state.

To calculate the heating value, it was necessary to determine the gross caloric value from the samples taken. The IKA C200 calorimeter was used to determine the heat of combustion. The procedure was conducted in correspondence with the standard STN ISO 1928:2003-07: Solid fuels—Determination of gross caloric value and calculation of heating value [20]. In the test, the sample is burnt in a calorimetric bomb, filled with oxygen under the pressure of 3–5 MPa.

Before the testing the samples were dried at 103 ± 2 °C to reach the moisture content of 0% and further conditioned in a desiccator at the temperature of 20 ± 1 °C for 24 h.

In the calculations of heating value, the relative moisture content of 10% was used.

Three measurements were taken for each sample. The results show the average value of those measurements.

Determination of the ash content

The procedure for ash determination was based on the requirements of the standard STN ISO 1171: 2003 (44 1378): Solid mineral fuels—Determination of ash [21]. The essence of the method is the incineration of the sample, which is heated in air at a temperature of 815 °C ± 10 °C, specified at a rate and maintained at that constant temperature. The ash content is calculated from the mass of the residue after incineration.

Elemental composition analysis

The elemental composition analysis of the fast-growing trees and energy crop samples was realized in the laboratories of the National Forest Centre, Zvolen, using the FLASH EA 1112 device. Using this device, the content (mass) of carbon (C_{daf}), hydrogen (H_{daf}) and nitrogen (N_{daf}) was analyzed. The oxygen content (%) in the sample was calculated based on the formula: $O_{daf} = 100 - C_{daf} - H_{daf} - Nd_{af}$.

Results

In the following three subchapters, the results of the analyses performed are introduced.

Spontaneous ignition temperature

The spontaneous ignition temperature highest values reached the *Populus* × *euroamericana* clone MAX 4 (424.92 °C) and *Sida hermaphrodita* sample (434.67 °C). The spontaneous ignition temperatures for the other woods and crops are introduced in Table 1.

Gross calorific value and heating value determination results

The highest energy potential expressed in terms of the highest gross calorific values (19.71 ± 0.18 MJ kg^{-1}) and heating values was measured in case of *Paulownia tomentosa* and *Miscanthus* × *giganteus* (19.60 ± 0.14 MJ kg^{-1}), see the values introduced in Table 2. Those values are not unlike. It confirms the suitability of energy crops to be used for energy production purposes together with the fast-growing tree species. Their only disadvantage is the stock which is necessary to plant to get the same yields as the wood of the fast-growing trees.

Ash content results

The highest ash content was achieved by the energy crop samples. The values of ash content were in the range of 2.67 ± 0.08 mass% (*Miscanthus* × *giganteus*)–3.46 ± 0.11 mass% (*Arundo donax)*, see Table 3. Lower values of ash content achieved the samples of wood from the fast-growing tree species; their values were in the range of 0.75–2.58 mass%. The lowest ash content was recorded for the *Paulownia tomentosa* sample (0.75 ± 0.05 mass%).

Elemental composition analysis results

The best elemental composition from the energy potential point of view showed the *Populus* × *euroamericana* from the group of fast-growing species and *Miscanthus* × *giganteus* from the group of energy crop species (see results in Table 4).

Discussion

Perspective of the exhaustion of fossil fuels has accelerated the search for new alternative sources of raw materials for industrial and energy use. Another stimulus is also indicative targets set by the E.U.'s renewable sources of energy (RES) that, among other things, assume that RES will provide 20% of the total energy needs of the E.U. These renewable sources should have irreplaceable share of energy from biomass (fast-growing trees and energy crop).

Forest biomass accounts for about 2% of the total direct energy consumption (TDE) currently, with 20% share of TDE in 2020, with the forest biomass share of 12%. The balance of available forest biomass can realistically increase the potential for energy crops production based on the regionalization of the area suitable for the cultivation of energy forests.

At present, in most Western European countries, the energy crop is mainly used for energy purposes for the production of heat (direct burning or pyrolysis). Nowadays, it is possible to mix it with the coal; they can be burned together. Replacing a part of coal leads to a reduction in CO_2, NOx, SOx emissions, because biomass contains a small amount of nitrogen and sulfur in comparison with coal. If the phytomass is used for energy purposes, it is necessary to know its gross calorific value. The gross calorific value of dry matter of whole plants was of c.a. 19.0 MJ kg^{-1} [22], the experiments and results introduced

Table 1 Spontaneous ignition temperature of the fast-growing tree species and energy crop samples

Group	Sample	Spontaneous ignition temperature/°C	Standard deviation
Fast-growing tree species	*Paulownia tomentosa*	420.10	0.21
	Salix viminalis clone Tora	412.65	0.20
	Populus × *euroamericana* clone MAX 4	424.92	0.14
Energy crops	*Sida hermaphrodita*	434.67	0.18
	Arundo donax	431.67	0.11
	Miscanthus × *giganteus*	426.78	0.09

Table 2 Gross calorific value and heating value of the fast-growing tree species and energy crop samples

Group	Sample	Gross calorific value/MJ kg^{-1}	Heating value/MJ kg^{-1}	Standard deviation
Fast-growing tree species	*Paulownia tomentosa*	19.71	16.40	0.18
	Salix viminalis clone Tora	19.63	16.33	0.11
	Populus × *euroamericana* clone MAX 4	19.47	16.18	0.29
Energy crops	*Sida hermaphrodita*	18.75	15.58	0.36
	Arundo donax	18.85	15.66	0.09
	Miscanthus × *giganteus*	19.60	16.29	0.14

Table 3 Ash content of the fast-growing tree species and energy crop samples

Group	Sample	Ash content/mass%	Standard deviation
Fast-growing tree species	*Paulownia tomentosa*	0.75	0.05
	Salix viminalis clone Tora	1.28	0.08
	Populus × *euroamericana* clone MAX 4	2.58	0.24
Energy crops	*Sida hermaphrodita*	2.93	0.11
	Arundo donax	3.46	0.11
	Miscanthus × *giganteus*	2.67	0.08

Table 4 Carbon (C), hydrogen (H), nitrogen (N) and oxygen (O) content (mass%) in the fast-growing tree species and energy crop samples

Group	Sample	C/mass%	H/mass%	N/mass%	O/mass%
Fast-growing tree species	*Paulownia tomentosa*	48.91	5.91	0.61	44.57
	Salix viminalis clone Tora	49.29	6.41	0.61	43.69
	Populus × *euroamericana* clone MAX 4	50.14	5.97	0.60	43.29
Energy crops	*Sida hermaphrodita*	43.74	5.68	0.77	49.81
	Arundo donax	44.19	5.70	1.29	48.82
	Miscanthus × *giganteus*	45.28	5.74	0.29	48.69

in this paper confirmed this fact, while the gross calorific values of the energy crops tested were in the range of 18.75–19.60 MJ kg^{-1}. This value is more than brown coal commonly used for domestic heating, in which gross calorific values range from 12.00 to 14.00 MJ kg^{-1}. That is why the wood and plant-based biomass sources are valuable not only from the efficiency and economy point of view, but also from environment protection point of view.

Similarly, Moya and Tenorio [4] studied the fuel characteristics (gross calorific value and fuel value index) of 10 fast-growing species in plantations in Costa Rica. The results related to the gross calorific value varied from 16.5 to 20.6 MJ kg^{-1} for sapwood and from 16.3 to 20.1 MJ kg^{-1} for heartwood. No consistency was observed with regard to which type of wood (sapwood or heartwood) had the highest gross calorific value. The gross calorific values of the fast-growing tree species varied in the range of 19.47–19.71.

Yavorov et al. [7] were engaged in the determination of the potential of fast-growing hardwood species from Bulgaria: *Paulownia elongata*, *Populus alba* and *Salix viminalis rubra*. They found the highest cellulose content in *Populus alba*, while the amount of lignin was the lowest in *Paulownia elongata*. They obtained the lowest calorific value for *Paulownia elongate*. This is the fact that they accounted the determined lower content of lignin. The results presented in this paper pointed the *Paulownia* to be the fast-growing tree species with the highest gross calorific (19.71 MJ kg^{-1}) and heating value (16.40 MJ kg^{-1}). The authors also confirmed, based on the calorific value of the fast-growing tree species tested, that the *Populus alba*, *Salix viminalis rubra* and *Paulownia elongata* are perspective and suitable for bioenergy production.

The calorific value and fire risk of selected fast-growing hardwood species, especially of *Populus nigra* × *P.*

maximowiczii, *Salix alba L.* and *Robinia pseudoacacia L.*, were studied by Martinka et al. [14]. The average heat of combustion (gross calorific value) of the wood species tested was of 19.20 ± 0.10 MJ kg^{-1}. This value is similar to results achieved in the framework of this study.

The information on the spontaneous ignition temperature completed with the information on the gross calorific value (energy potential of biomass in dry state) and heating value (energy potential of biomass with relative moisture of 10%) to provide a comprehensive view of the fire and thermal parameters of the biomass species suitable for energy purposes.

Conclusions

In this paper, the issue of energy saving and efficient use of energy produced from the renewable energy source, the dendromass and phytomass (biomass) in this case is briefly introduced. The paper is focusing on the problem of the energy potential of the selected types of fast-growing tree species and energy crops assessment. The energy potential is assessed based on the information on the heating value of the wood and crop samples, which was calculated based on the gross calorific value obtained from experiments with calorimeter and relative moisture content, which was set to 10%. As an additional information for the evaluation of the overall suitability of fast-growing tree species and energy crops, the information on ash content and elemental composition was completed. Those data are further completed with information on the spontaneous ignition temperature. The result presented in this paper would be further used in the design of fast-growing trees and energy crop plantations, especially in the selection of the suitable and energy-efficient plant and woody biomass to be planted to be the further use for bioethanol production and for heating, i.e., energy production.

Acknowledgements This work was supported by the Slovak Research and Development Agency, based on the Agreement Nos. APVV-0057-12, APVV-16-0326 and KEGA 013TU Z-4/2017.

References

1. Dipesh KC, Blazier MA, Pelkki MH, et al. Genotype influences survival and growth of eastern cottonwood (*Populus deltoides* L.) managed as a bioenergy feedstock on retired agricultural sites of the Lower Mississippi Alluvial Valley. New For. 2017;48(1):95–114.
2. Messingerová V, Lieskovský M, Gejdoš M, et al. Technika a technologické postupy pri produkcii biomasy a jej energetickom zhodnotení/Equipment and technological procedures in production of biomass and evaluation of its energetic potential. 1st ed. Zvolen: Technical University in Zvolen; 2016 **(in Slovak)**.
3. Kumar JIN, Patel K, Kumar RN, et al. An evaluation of fuelwood properties of some Aravally mountain tree and shrub species of Western India. Biomass Bioenergy. 2011;35(1):411–4.
4. Moya R, Tenorio C. Fuelwood characteristics and its relation with extractives and chemical properties of ten fast-growth species in Costa Rica. Biomass Bioenergy. 2013;56:14–21.
5. Cardoso MS, Ladio AH, Dutrus SM, et al. Preference and calorific value of fuelwood species in rural populations in northwestern Patagonia. Biomass Bioenergy. 2015;81:514–20.
6. Hnilička F, Hniličková H, Hejnák V. Use of combustion methods for calorimetry in the applied physiology of plants. J Therm Anal Calorim. 2015;120:411–7.
7. Yavorov N, Petrin St, Valchev I, et al. Potential of fast growing poplar, willow and Paulowni for bioenergy production. Bulg Chem Commun. 2015;47(SI:A):5–9.
8. Monedero E, Jose Hernandez J, Canellas I, et al. Thermochemical and physical evaluation of poplar genotypes as short rotation forestry crops for energy use. Energy Convers Manag. 2016;129:131–9.
9. Naidu VS, Aghalayam P, Jayanti S. Evaluation of CO_2 gasification kinetics for low rank Indian coals and biomass fuels. J Therm Anal Calorim. 2016;123:467–78.
10. Bychkov AL, Denkin AI, Tikhova VD, et al. Prediction of higher heating values of plant biomass from ultimate analysis data. J Therm Anal Calorim. 2017;130:1399–405.
11. Kačík F, Luptáková J, Šmíra P, et al. Thermal analysis of heat-treated silver fir wood and larval frass. J Therm Anal Calorim. 2017;130:755–62.
12. Morales L, Garzón E, Martínez-Blanes JM, et al. Thermal study of residues from greenhouse crops plant biomass. J Therm Anal Calorim. 2017;129:1111–20.
13. Bryś A, Bryś J, Ostrowska-Ligęza E, et al. Wood biomass characterization by DSC or FT-IR spectroscopy. J Therm Anal Calorim. 2017;126:27–35.
14. Martinka J, Martinka F, Rantuch P, et al. Calorific value and fire risk of selected fast/growing wood species. J Therm Anal Calorim. 2018;131:899–906.
15. Zhao Z, Liu P, Wang S, et al. Combustion characteristics and kinetics of five tropic oilgal strains using thermogravimetric analysis. J Therm Anal Calorim. 2018;131:1919–31.
16. Kačík F, Ďurkovič J, Kačíková D. Chemical profiles of wood components of poplar clones for their energy utilisation. Energies. 2012;5:5243–56.
17. Paulowni Slovakia. Pawlownia. Paulowni Slovakia—Energetický porast. 2017. https://www.Paulowni-slovakia.eu/. Accessed 1 Nov 2017.
18. STN ISO 871:2006. Plastics—determination of ignition temperature using a hot-air furnace.
19. STN EN ISO 291:2008. Plastics. Standard atmospheres for conditioning and testing.
20. STN ISO 1928:2003-07. Solid fuels. Determination of gross caloric value and calculation of heating value.
21. STN ISO 1171: 2003 (44 1378), Solid mineral fuels. Determination of ash.
22. Strašil Z. Základy pěstování a možnosti využití ozdobnice (Miscanthus)/Introduction to cultivation and possibilities of *Miscanthus* utilisation. Praha: Výzkumný ústav rostlinné výroby, v.v.i; 2009 **(in Czech)**.