POPLAR BIOCHAR AS A BRIDGE TO SUSTAINABILITY OF SHORT ROTATION COPPICE PLANTATIONS

Jan VELEBIL[1], Jan MALAŤÁK[1], Barbora TUNKLOVÁ[1], Tomáš KUŠEV[1], Jiří BRADNA[1]

[1]Department of Technological Equipment of Buildings, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká. 129, 165 00 Prague, Czech Republic

Abstract

This article is focused on the fuel evaluation of biochars made from the biomass poplar wood from a short rotation coppice plantation. The biochars were prepared at 250, 300 and 400 °C. Over this temperature range a wide differences dry matter loss after treatment has been noted, from 20 to 65 %. In the lowest temperature setting the conservation of heating value was as high as 91 %, however at the highest temperature it was still 57 %. Through stoichiometric combustion calculation and thermogravimetric analysis it was shown that biochars can be tailored to have a varying fuel properties. Biochar made at 300 °C was the closest in fuel properties to a lignite coal sample.

***Key words:** biochar, short rotation coppice, pyrolysis, poplar, circular economy, biofuel.*

INTRODUCTION

Fast-growing trees, or short rotation coppice (SRC), are grown primarily for the rapid production of high-quality biomass in a relatively short period of time *(Slopiecka et al., 2012)*. These crops could be produced to obtain solid biofuel transformed through combustion (Monedero et al., 2017), pyrolysis *(Sharma et al, 2023)* or gasification *(Malaťáková et al, 2021)* into heat and power in CHP plants. On a European scale, poplars and willows have been the most established *(Don et al., 2012)*. These trees are able to tolerate diverse climates across European countries. The biomass yield is around 7 - 12 tonnes of dry matter/ha/year of cultivation (*Šinkora, 2008*). In young poplar plantations grown for biomass, the rotation period is between 3 and 7 years. Most commonly, the plantation is harvested 4-5 times and the plantation will exist for 20 to 25 years. Between 2004 and 2017, in Czech Republic the area of SRC increased more than 32-fold to 2862 ha. In 2012, fast-growing tree plantations accounted for 2 % of the world's forested area (*Thomas et al., 2021*). Nowadays, in the Czech Republic, the total area of SRC covers around 3000 ha, of which 250 ha are poplars and willows. In Europe, it is estimated that 50,000 hectares of land are fast-growing tree plantations. The most significant areas in Europe are located in Italy, Germany, Sweden, Austria and Poland (*Weger, 2011; Lindegaard, 2016*).

The calorific value of poplar chips without bark content is 19.5 MJ kg^{-1}. For chips with natural bark content, the calorific value is 20.2 MJ kg^{-1} *(Civitarese et al., 2019; Ilari et al., 2021)*. The calorific value of pure poplar wood mass ranges from 18.4 MJ kg^{-1} at a moisture content of 5 % wt. to 6.3 MJ kg^{-1} at a moisture content of 60 % wt. (*Celjak, 2010*). The chemical composition of the biomass plays a significant role in pyrolysis treatment which will strongly affect the yield and quality of the solid product. The cellulose content of poplar wood is reported to be around 40 to 50%, lignin is from 20 to 25% and hemicellulose is 20 to 35% (*Antczak et al., 2023; Rego et al., 2019*) The ash content is reported to be from 1.0 to 2.0 % wt. (*Rego et al., 2019; Stachowicz et al., 2022*). The carbon content in the dry matter of poplar wood is reported to be around 48 % wt., hydrogen 6 % wt. and nitrogen 0.5 % wt. (*Fernandez et al., 2016; Sannigrahi et al., 2010*).

Carbohydrates, including cellulose, hemicellulose and pectins, make up a large portion of the cell walls of poplar wood (45 % wt. cellulose, 20 % wt. hemicellulose and 3 % wt. pectins), while lignin makes up the remaining 25 % wt. (*Mellerowicz et al., 2001; Sannigrahi et al., 2010*).

Of course, a biochar fuel might not always be the best value-added product. Studies show that biochar made from poplar processing residues can be used as a soil substrate additive in tree nurseries, where it promotes rooting and early growth of poplar cuttings (*Fellet et al., 2011*). When applied to soil, poplar biochar or hydrochar improved biomass yields, nutrient cycling and soil carbon sequestration. (*Baronti et al., 2017*). In addition to cultivation, poplar residue biochars was argued to be advantageous in environmental remediation, especially in the adsorption of heavy metals or organic pollutants from wastewater (*Liu et al., 2017*).

The question behind this study was whether poplar wood harvested from SRC plantations could be used to produce a high-quality fuel that could be also tailored to either replace a traditional fuel, such as coal, in places where they are still used, or on the other hand make a high-quality fuel for biomass-fired plants which could be used in times of higher energy demand, i.e. in wintertime.

MATERIALS AND METHODS

Samples of poplar wood logs (*Populus nigra*) were obtained from a SRC plantation. The material contained bark, but was free of any excess dirt. The logs had been air-dried and then milled in a hammer mill to size under 6 mm. Biochar samples were then prepared in a muffle furnace under nitrogen atmosphere. The furnace would be gradually brought to the target temperature according to a temperature probe placed at the centre of the material and then the sample would reside for 1 hour at this temperature. Basic fuel analyses were performed on all samples, i.e. determination of water content, ash content, heat of combustion and elemental composition. Moisture was determined in a LECO TGA701 weighing furnace (thermogravimetric analyser) by drying approximately 1 g of sample at 105 °C to constant weight. Ash content was subsequently determined for the same samples by calcination at 550 °C to constant weight.

Gross calorific value (GCV) was measured in an isoperibolic calorimeter LECO AC600 by combustion in oxygen atmosphere. Net calorific value (NCV) was calculated based on method in ISO 1928.

The elemental representation of the main elements was measured using the LECO CHN628. To determine C, H, N, the sample (approx. 0.1 g) was burned in oxygen at 950 °C. Sulphur was also determined, however, for the poplar samples it was very low (<0.05 % wt.).

Conversions of concentrations to other sample states, especially to dry state and combustible state (dry state without ash) were performed according to EN 15296. Oxygen was determined as a difference of ash and main elements from 100% in a dry sample.

Thermal behaviour of the materials was determined by thermogravimetric analysis (5 K min^{-1}) from 105 °C to 630 °C in LECO TGA701. For each sample, a 1 g load was used in crucibles lined with aluminium foil. During the procedure, the samples were first dried at 105 °C until constant weight. Then, a nitrogen flow of 7.5 l min^{-1} was introduced into the oven and thermal loading was initiated.

The weight loss curves (TG curves) are converted to the dry, ash-free state of the sample, in order to make the results comparable between materials with different ash contents. As a result of this test, the weight loss rate curves (DTG curves) were chosen, which correspond to the negative values of the time derivative of the TG curve and are expressed as a percentage of the loss of the original organic matter per minute.

The measurements were made in triplicates and average values were reported.

RESULTS AND DISCUSSION

The elemental composition (see Tab. 1) shows changes in the fractions of organic elements in poplar wood samples before and after processing at different temperatures. The poplar wood itself may have a relatively wide distribution of composition and calorific parameters (*Sannigrahi et al., 2009*), and in present case it fell well within the reported range. After torrefaction, there was a reduction of oxygen in samples, as it happens in other wood species (*Malaťák et al., 2024; Aniszewska et al., 2020; Olave et al., 2017*). With increasing process temperatures, the mass fraction of oxygen decreased significantly in favour of other elements. This also significantly increases the calorific values, as shown in Tab. 1. Similar decrease was determined for hydrogen. Graphically, the loss of elemental components is visualized in Fig. 1. These processes occur during the processing of other biomass-based fuels (*Jeníček et al., 2025; Chen et al. 2021*). During the combustion of thermally treated biomass materials, problems may arise with ash removal from the combustion device, slag formation in the combustion chamber and increased ash content in the flue gases, as has been shown for other fuels with a higher ash content in the fuel (*Win et al., 2012; van Loo, Koppejan 2012*). The cause is that in dry torrefaction processing the ash present in biomass is left and concentrated in the fuel. However, for biochars produced at 250 and 300 °C, the amount of ash per unit of energy kept at a similar level (around 1.1 g MJ^{-1}). After torrefaction at 400 °C, it then roughly doubled. For comparison with the biochars, a sample of briquetted lignite coal was chosen (see Table 1) which had a similar ash content as the biochars, being most similar in composition to

PW300. At processing temperature of 300 °C and higher, the biochars already had higher calorific values at lower or similar ash content. It needs to be kept in mind that majority of coal-based fuels will have higher ash content than our sample and also relatively high sulphur content (in our case 0.74 % wt. while in the biochars it was negligible). Therefore, quality-wise it is not a problem to make a solid thermally treated fuel with better properties than traditional coal-based fuel. However, if the biochars were to be marketed as thermally treated biofuels according to ISO 17225-8, none would pass the classes of untreated woody biomass, resp. only biochars torrefied at 250 and 300 °C could meet the class TOW2 (<4.2 % wt. of ash).

Tab. 1 Composition and calorimetry of poplar wood and its biochars

Sample	Ash (% wt.)	GCV (MJ kg^{-1})	NCV (MJ kg	Carbon (% wt.)	Hydro-gen	Nitrogen (% wt.)	Oxygen (% wt.)
Poplar wood	1.98	19.57	18.33	51.69	5.72	0.16	*(40.40)*
Poplar wood (250 °C)	2.30	22.07	20.85	57.76	5.56	0.20	*(34.17)*
Poplar wood (300 °C)	3.00	28.23	27.18	71.63	4.84	0.36	*(20.16)*
Poplar wood (400 °C)	6.17	30.61	29.94	82.80	3.10	0.66	*(7.26)*
Lignite coal sample	*5.34*	*24.02*	*23.05*	*64.77*	*4.47*	*0.53*	*(24.15)*

If the main goal of biomass pyrolysis is to gain an optimized solid fuel, then there are two main consideration that go against each other: with higher reaction severity, i.e. mainly with higher temperature, the output will have a higher calorific value and be more resistant to biological decay. On the other hand, the yield of solid matter, and subsequently the yield of leftover NCV will be also lower, although not as significantly. This can be seen easily in Fig. 1, where after torrefaction at 300 °C the yield decreased sharply, there was only around 50 % of dry matter left, however it would still hold close to 80 % of the original net calorific value.

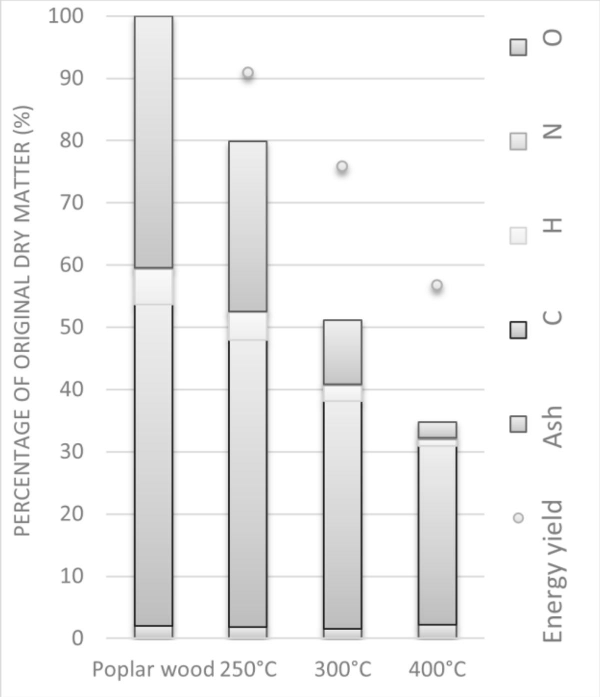

Fig. 1 Mass balance of ash and main organic elements in poplar wood biochars, the height of columns corresponds to fractions of original dry matter. Energy yield is found as the remaining NCV.

Looking further into differences in expected combustion behaviour, stoichiometric calculations give important insight on how a treated material will perform in a combustion designed for a particular feedstock. Some of the most important parameters are the consumption of combustion air and production of flue gas, as these will govern the setup of the combustion device (see Tab. 2). The thermally treated samples are significantly different from the starting biomass which is a general trend (*Malaťák et al., 2023; Malaťák et al., 2024*). In comparison with the lignite coal sample, the most closely comparable were biochars processed at 250 °C and 300 °C. Their values are comparable in both mass or volume of combustion air requirements and flue gas production. Again, the advantage of burning poplar biochar, compared to lignite coal, apart from a possible sustainability perspective, would be practically zero concentrations of sulphur oxides in the flue gas.

Tab. 2 Stoichiometric combustion behaviour of poplar wood and its biochar, values were converted to dry samples and perfect combustion conditions (values in kg kg^{-1})

	Brown coal	Poplar wood	Poplar wood 250 °C	Poplar wood 300 °C	Poplar wood 400 °C
Air consumption for complete combustion	7.98	6.17	7.08	9.03	10.27
Dry flue gas production	8.43	6.55	7.47	9.45	10.80

A Van Krevelen diagram (see Fig. 1) shows the evolution of the three main fuel components – carbon, oxygen and hydrogen – during carbonization. During thermochemical processes, oxygen is released approximately twice as fast as hydrogen until black carbon is formed (*Chen et al., 2021*). Further development to anthracite is usually accompanied by a decrease in the H/C ratio at a practically constant low oxygen content (*Weber, Quicker, 2018*). Figure 1 shows the van Krevelen diagram for biochar produced from poplar wood samples, where it is seen that increasing the process temperatures leads to a decrease in the H/C and O/C ratios. Based on measurements, temperatures in the range of 250 to 300 °C lead to the first two-fold decrease in atomic ratios. Similar trends were reported by Weber and Quicker (*2018*), who observed very similar changes in the O/C and H/C ratios with gradually increasing process temperatures.

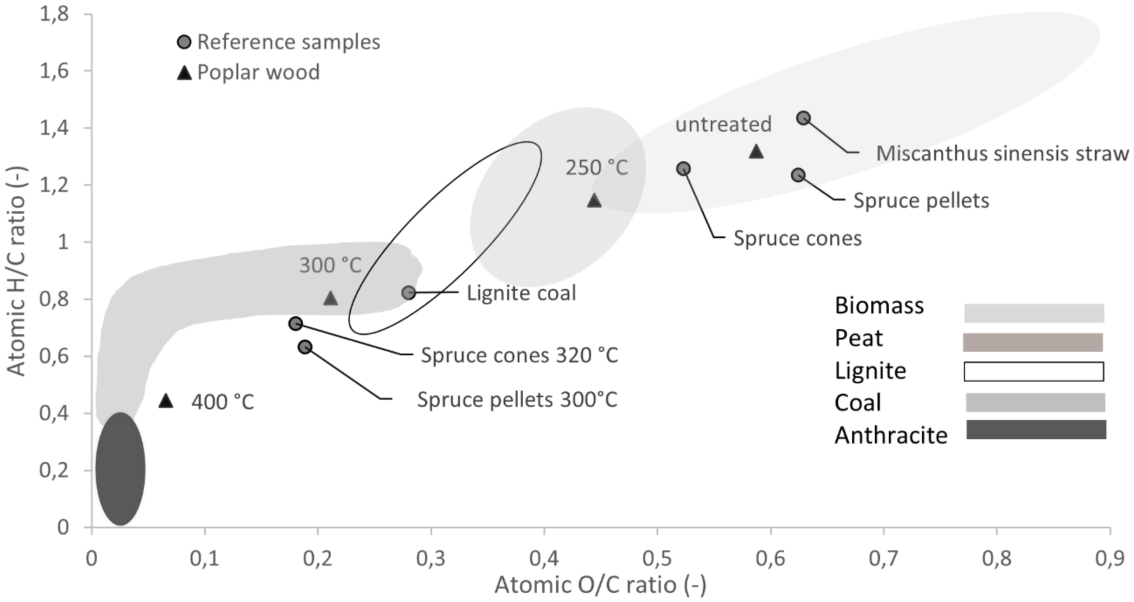

Fig. 2 Van Krevelen diagram for poplar wood and its biochar, with a comparison to other torrefied biomass fuels (adapted from (*van Loo, Koppejan, 2012*)

Reference samples:

- Spruce pellets and Spruce biochar 300 °C (*Malaťák et al., 2024*)
- Spruce cones and Spruce cone biochar 320 °C (*Aniszewska et al., 2020*)
- Lignite coal sample
- Miscanthus sinensis straw (*Malaťák et al., 2022*)

Another look at expected combustion behaviour can be done using thermogravimetric analysis, which compares the evolution of volatile matter during heating (Fig. 3). In general, with biomass the volatile release starts with hemicelluloses below 300 °C, then starts the decomposition of cellulose with a sharp peak around 350 °C while lignin decomposes over a wider range and more slowly. TGA analysis of poplar wood has been reported (Rego et al., 2019) with very similar trend as in present case, showing the two apparent peaks which correspond mainly to hemicellulose and cellulose decomposition. It also confirmed that the curves tend to be similar with different heating rates, which makes them comparable to an extent between different TGA setups. The biochar produced at 250 °C lost the first peak, showing hemicellulose degradation. However, it could still be expected to behave similarly to the original material in a combustion device since there is still a significant peak with high decomposition rate. These fuels (or biomass in general) would be expected to burn with high flame, making it necessary for the combustion chamber to have sufficient dimension to allow the volatile combustible to burn completely, avoiding heat losses due to unburnt fuel (*Johansson et al., 2004 and Malaťák et al., 2020*). On the other hand, poplar wood treated at temperatures of 300 and 400 °C would likely behave similarly to coal, since the release of volatile combustible is much slower and coinciding with that of the lignite coal sample.

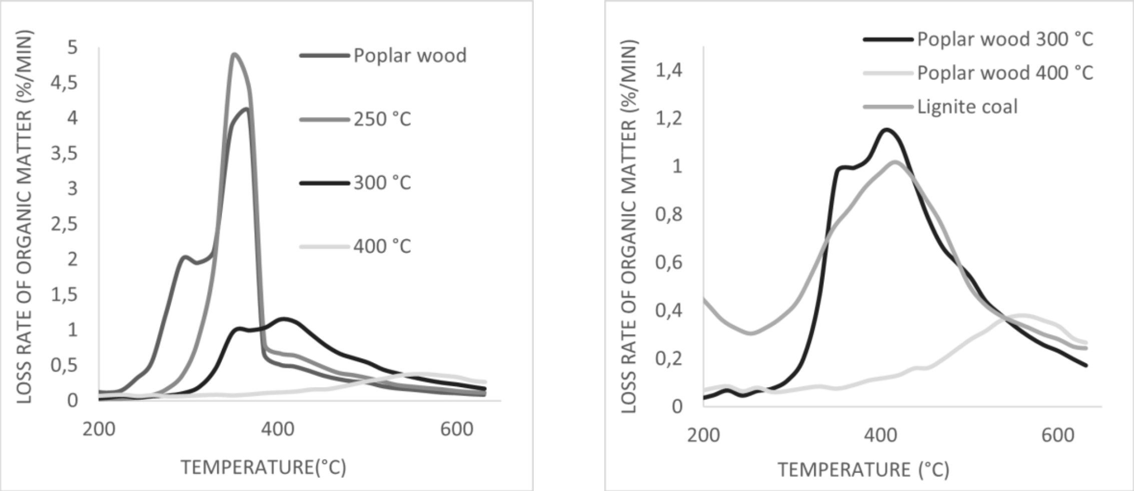

Fig. 3 DTG curves of poplar wood, its biochars and lignite coal in inert atmosphere under 5 K min^{-1} heating rate

Poplar wood can be a promising feedstock not only when focused on biochar production, the pyrolysis process can be optimized for bio-oil or resin production with a biochar side-product which still has very good calorific properties (Sakhakarmy et al., 2024). And indeed, any production system needs to effectively utilize the volatiles released from the biomass, at least to help meet the energy demand of the thermal treatment.

CONCLUSIONS

The results have shown that poplar wood can be a versatile feedstock for biochar production. Varying the thermal treatment process temperature, a wide range of fuel properties could be shown. The biochars achieved high calorific value, with NCV 29.9 MJ kg^{-1} after 400 °C treatment while the yield losses were not exceedingly high, only 43 %. If the biochar were to be used as a replacement for another fuel it could be engineered for a relatively wide range of possibilities. In the case of lignite coal, which was used for comparison in this study, the biochar made at 300 °C would be close both in terms of stoichiometric behaviour, i.e. the throughput of combustion air, as well as in the profile of volatile matter release. Unfortunately, even though the ash content was not particularly high for this type of biomass, the biochars still would not meet the requirements of ISO 17225-8 for thermally treated biofuels from untreated woody biomass.

ACKNOWLEDGMENT

This study was supported by the internal grant agency (IGA) of the Faculty of Engineering at the Czech University of Life Sciences Prague, grant number: 2024:31170/1312/3105.

REFERENCES

Aniszewska, M., Gendek, A., Hýsek, Š., Malaťák, J., Velebil, J., Tamelová, B. (2020). Changes in the composition and surface properties of torrefied conifer cones. *Materials, 13(24)*, 1–14, 5660.

Antczak, A., Szadkowski, J., Radomski, A., Zawadzki, J., Dabkowska-Susfal, K., Walkowiak, M., Witczak, M., & Cichy, W. (2023). The Influence of Selected Physico-Chemical Pretreatment Methods on Chemical Composition and Enzymatic Hydrolysis Yield of Poplar Wood and Corn Stover. *Drewno* , *66* (211).

Baronti, S., et al. (2017). Hydrochar enhances growth of poplar for bioenergy while improving soil carbon sequestration. *Global Change Biology Bioenergy, 9(11),* 1730–1741.

Celjak, I.: Pěstování topolů pro energetické účely – 3. (2010). *Biom.cz* [online]. 2010-09-06 [cit. 2025-09-01]. Available from: https://biom.cz/cz/odborne-clanky/pestovani-topolu-pro-energeticke-ucely-3. ISSN: 1801-2655.

Chen, W. H., Lin, B. J., Lin, Y. Y., Chu, Y. S., Ubando, A. T., Show, P. L., Ong, H. C., Chang, J. S., Ho, S. H., Culaba, A. B., Pétrissans, A., & Pétrissans, M. (2021). Progress in biomass torrefaction: Principles, applications and challenges. *Progress in Energy and Combustion Science*, *82*, 100887.

Civitarese, V., Acampora, A., Sperandio, G., Assirelli, A., Picchio, R. (2019). Production of wood pellets from poplar trees managed as coppices with Different harvesting cycles. *Energies, 12(15)*, 2973.

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M. S., Drewer, J., Flessa, H., Freibauer, A., Hyvönen, N., Jones, M. B., Lanigan, G. J., Mander, Ü., Monti, A., Djomo, S. N., Valentine, J., Walter, K., Zegada-Lizarazu, W., & Zenone, T. (2012). Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy*, *4*(4), 372–391.

Fellet G, Marchiol L, Delle Vedove G, Peressotti A. (2011). Application of biochar on mine tailings: efects and perspectives for land reclamation. *Chemosphere, 83*, 1262–1267.

Ilari, A., Pedretti, E.F., De Francesco, C., Duca, D. (2021). Pellet production from residual biomass of greenery maintenance in a small-scale company to improve sustainability. *Resources, 10(12)*, 122.

Jeníček, L., Malaťák, J., Velebil, J., Neškudla, M. (2025). Pyrolyzed Agro-Food By-Products: A Sustainable Alternative to Coal. *Materials, 18(7)*, 1495.

Johansson, L. S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C., & Potter, A. (2004). Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment*, *38*(25), 4183–4195.

Lindegaard, K. N., Adams, P. W. R., Holley, M., Lamley, A., Henriksson, A., Larsson, S., von Engelbrechten, H. G., Esteban Lopez, G., & Pisarek, M. (2016). Short rotation plantations policy history in Europe: lessons from the past and recommendations for the future. *Food and Energy Security*, *5*(3), 125–152.

Liu, X., et al. (2017). A valuable biochar from poplar catkins with high adsorption capacity for both organic pollutants and inorganic heavy metal ions. *Scientific Reports, 7*, 10033.

van Loo, S.; Koppejan, J. *The Handbook of Biomass Combustion and Co-Firing.* Routledge: London, UK, 2012; 1–442.

Malaťák, J., Jankovský, M., Malaťáková, J., ... Gendek, A., Aniszewska, M. (2023). Substituting Solid Fossil Fuels with Torrefied Timber Products. *Materials, 16(24)*, 7569.

Malaťák, J., Jevič, P., Vaculík, P. (2010). Účinné využití tuhých biopaliv v malých spalovacích zařízeních s ohledem na snižování emisí znečišťujících látek. 2010, Powerprint, Praha, ISBN: 978-80-87415-02-3.

Malaťák, J., Velebil, J., Bradna, J., Gendek, A., Tamelová, B. (2020). Evaluation of CO and NOx Emissions in Real-Life Operating Conditions of Herbaceous Biomass Briquettes Combustion. *Acta Technologica Agriculturae, 23(2)*, 53–59.

Malaťák, J., Velebil, J., Bradna, J., Kučera, M., Gendek, A., Aniszewska, M., Alexiou Ivanova, T. (2024). Comparative Experimental Assessment of Pollutant Emission Behavior in Combustion of Untreated and Thermally Treated Solid Biofuels from Spruce Chips and Rapeseed Straw. *Atmosphere, 15(4)*, 452.

Malaťák, J., Velebil, J., Malaťáková, J., Passian, L., Bradna, J., Tamelová, B., Gendek, A., Aniszewska, M. (2022). Reducing Emissions from Combustion of Grape Residues in Mixtures with Herbaceous Biomass. *Materials, 15(20)*, 7288.

Malaťáková, J., Jankovský, M., Malat'ák, J., Velebil, J., Tamelová, B., Gendek, A., Aniszewska,

M. (2021). Evaluation of small-scale gasification for CHP for wood from salvage logging in the Czech Republic. *Forests, 12(11)*, 1448.

Mellerowicz, E.J., Baucher, M., Sundberg, B., and Boerjan, W. (2001). Unravelling cell wall formation in the woody dicot stem. *Plant Molecular Biology, 47*, 239–274.

Monedero, E., Hernández, J.J., Collado, R. (2017). Combustion-related properties of poplar, willow and black locust to be used as fuels in power plants. *Energies, 10(7)*, 997.

Olave, R.J., Forbes, E.G.A., Johnston, C.R., Relf, J. (2017). Particulate and Gaseous Emissions from Different Wood Fuels during Combustion in a Small-Scale Biomass Heating System. *Atmospheric Environment, 157*, 49–58.

Rego, F., Soares Dias, A. P., Casquilho, M., Rosa, F. C., & Rodrigues, A. (2019). Fast determination of lignocellulosic composition of poplar biomass by thermogravimetry. *Biomass and Bioenergy, 122*, 375–380.

Sakhakarmy, M., Kemp, A., Biswas, B., Kafle, S., & Adhikari, S. (2024). A Comparative Analysis of Bio-Oil Collected Using an Electrostatic Precipitator from the Pyrolysis of Douglas Fir, Eucalyptus, and Poplar Biomass. *Energies, 17(12)*, 2800.

Sannigrahi, P., Ragauskas, A.J., and Tuskan, G.A. (2010). Poplar as a feedstock for biofuels: A review of compositional characteristics. *Biofuels, Bioproducts and Biorefining, 4*, 209–226.

Sharma A., Aravind Kumar A., Mohanty B., Sawarkar A.N. (2023). Critical insights into pyrolysis and co-pyrolysis of poplar and eucalyptus wood sawdust: Physico-chemical characterization, kinetic triplets, reaction mechanism, and thermodynamic analysis. *Renewable Energy, 210*, 321–334.

Slopiecka, K., Bartocci, P., Fantozzi, F. (2012). Thermogravimetric analysis and kinetic study of poplar wood pyrolysis. *Applied Energy, 97*, 491–497.

Stachowicz, P., & Stolarski, M. J. (2023). Thermophysical Properties and Elemental Composition of Black Locust, Poplar and Willow Biomass. *Energies, 16(1)*, 305.

Stolarski, M. J., Warmiński, K., & Krzyżaniak, M. (2020). Energy Value of Yield and Biomass Quality of Poplar Grown in Two Consecutive 4-Year Harvest Rotations in the North-East of Poland. *Energies, 13(6)*, 1495.

Šinkora, Milan: Topoly a vrby pro energetiku. (2008). *Biom.cz* [online]. 2008-02-25 [cit. 2025-08-31]. Available from: https://biom.cz/cz/odborne-clanky/topoly-a-vrby-pro-energetiku. ISSN: 1801-2655.

Thomas, A., Priault, P., Piutti, S., Dallé, E., & Marron, N. (2021). Growth dynamics of fast-growing tree species in mixed forestry and agroforestry plantations. *Forest Ecology and Management, 480*, 1–12.

Weber, K.; Quicker, P. (2018). Properties of Biochar. *Fuel,* 217, 240–261.

Weger, Jan: Výmladkové plantáže topolů a vrb (2011). [online]. *Biom.cz*, 2011 [cit. 2025- 08-31]. ISSN: 1801-2655. Available at: https://biom.cz/cz/odborneclanky/vymladkove-plantaze-topolu-a-vrb

Win, K.M., Persson, T., Bales, C. 2012. Particles and gaseous emissions from realistic operation of residential wood pellet heating systems. *Atmospheric Environment, 59*, 320–327.

Zhang, C., Hu, X., Guo, H., Wei, T., Dong, D., Hu, G., Hu, S., Xiang, J., Liu, Q., & Wang, Y. (2018). Pyrolysis of poplar, cellulose and lignin: Effects of acidity and alkalinity of the metal oxide catalysts. *Journal of Analytical and Applied Pyrolysis*, *134*, 590–605.

Corresponding author:

Ing. Jan Velebil, Department of Technological Equipment of Buildings, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká. 129, 165 00 Prague, Czech Republic, e-mail: velebil@tf.czu.cz