Combustion Characteristics of Fallen Fall Leaves from Ornamental Trees in City and Forest Parks

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Combustion characteristics of leaves fallen off ornamental trees in city and forest parks were evaluated. The moisture content of the leaves at the time of falling was between W_r = 36.1 and 46.9%. The average contents of the individual elements in the combustible material were C^{daf} = 48.1%, H^{daf} = 6.1%, N^{daf} = 1.2%, S^{daf} = 0.1%, and O^{daf} = 44.6%. The resulting ash from the dry leaves varied between A^d = 4.8 and 13.1%. The heat of combustion of the dry leaves was between Q_s = 16,046 and 20,247 kJ.kg^{-1}, and the lower heating value was between Q_n = 13,479 and 19,120 kJ.kg^{-1}. The results were compared with dry firewood of hard deciduous trees. The higher heating value of the dry leaves was 11.7% lower and the lower heating value was also lower by 15.1%. The decline of these basic combustion characteristics is caused mostly by its high ash content and to a smaller extent by the increased nitrogen content.

Keywords: Biofuel; Leaves; Humidity; Elemental analysis of combustible; Higher heating value; Lower heating value; Ash

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INTRODUCTION

In Central Europe, biomass is a significant renewable energy source – one in which energy potential is constantly renewed by natural processes or human activities. Fallen leaves from deciduous trees can be considered a renewable energy source. Leaves that are shed from trees in forests become transformed by a natural biochemical processes into humus, which is a nutrient source for both the trees and other forest vegetation. However, leaves do not contribute to humic development in urban areas, because, in most cases, leaves are shed onto stone, asphalt, concrete, or other impervious surfaces.

Leaves shed on sidewalks and near benches in city parks are an undesirable waste. If cleanliness and order in urban parks are maintained in an effective way, these leaves represent an adequate material for composting, specifically as raw material in the production of heat energy. The combustion characteristics of biofuel – in this case, waste leaves – are dependent on several factors, such as the species of tree, weather conditions prior to collection, leaf collection methods, their storage, and, last but not least, the actual contamination by other impurities (Simanov 1995; Heckman and Kluchinski 1996; Jandačka *et al.* 2007).

This work presents the results of experimental works carried out to determine the basic combustion characteristics of leaves shed in fall off ornamental trees in city and forest parks. The moisture content of the shed leaves, the elemental chemical composition of the combustible substance, the higher heating value, the lower heating value, and the chemical composition of the inorganic share (*i.e.*, ash) were analysed and reported in this work.

EXPERIMENTAL

Materials

To establish the basic combustion characteristics of biofuel, various types of leaves were collected. Leaves were shed in the Fall from ornamental trees in city and forest parks in the district of Zvolen, the Slovak Republic (Central Europe). Leaves of the following deciduous trees: silver birch (*Betula verrucosa* Ehrh.), common hornbeam (*Carpinus betulus* L.), sessile oak (*Quercus petraea* (Matt.) Liebl.), horse-chestnut (*Aesculus hippocastanum* L.), Norway maple (*Acer platanoides* L.), warty birch (*Betula pendula* Roth.), small-leaved lime (*Tilia cordata* Mill.), English oak (*Quercus robur* L.), California walnut (*Juglans regia* L.), sycamore maple (*Acer pseudoplatanus* L.), and European ash (*Fraximus excelsior* L.), which were collected from fabrics placed for this purpose under the trees, in such a way the leaves were not contaminated by dust found on the surface of the pavements.

Methods

Moisture content

Determination of relative moisture content of the leaves of each tree species was carried out according to EN 14774-2 (2010). The sample of biofuel was dried at the temperature t = 103 ± 2 °C for 8 h. The moisture content of the samples was calculated according to Eq. 1,

$$W_r = \frac{m_w - m_0}{m_w} * 100 \tag{1}$$

where W_r is the relative humidity of the sample [%], m_w is the mass of the sample before drying [g], and m_0 is the mass of the sample after drying to constant weight [g].

Elemental analysis

Elemental analysis of the samples of the combustible material was performed on an NCS-FLASH EA 1112 analyzer (Thermo Finnigan, USA). The proportion of oxygen in the combustible matter of the samples was determined by a calculation in accordance with EN 15296 (2011) as follows (Eq. 2),

$$O^{daf} = 100 - C^{daf} - H^{daf} - N^{daf} - S^{daf} \tag{2}$$

where O^{daf} is the oxygen content in the combustible matter [%], C^{daf} is the carbon content [%], H^{daf} is the hydrogen content [%], N^{daf} is the nitrogen content [%], and S^{daf} is the sulfur content [%].

Share of ash

Quantification of ash production from the dry leaves was carried out according to ISO 1171 (2003). The samples of leaves were annealed in a LAC LMH 04/12 muffle furnace at a temperature of 815 ± 10 °C (1499 ± 50 F). The share of ash in the biofuel in the analyzed sample was expressed as a percentage by weight and calculated using Eq. 3,

$$A^d_{fuel} = \frac{m_3 - m_1}{m_2 - m_1} * 100 \tag{3}$$

where A_{fuel}^{d} is the proportion of ash [%], m_3 is the weight of the sample container and the ash [g], m_2 is the weight of the sample container and the sample [g], and m_1 is the weight of the sample container [g].

Chemical composition of ash

The chemical composition of the ash was determined using the ICP-AES (inductively coupled plasma atomic emission spectroscopy) method. The Ca, Mg, K, Mn, P, Zn, and Fe contents in the ash were measured. The principle of the method ICP-AES is based on a measurement of the atomic emission of the individual elements by the optical spectroscopic techniques using an atomic emission spectrometer with inductively coupled plasma (ES 725 VARIAN).

The higher heating value and the lower heating value

The higher heating values of the samples of dry leaves, dried to constant weight (W_r = 0%), were determined. A calorimeter for solid fuels IKA C 200 (Cal Win) was used in accordance with ISO 1928 (2003) for value determination.

The lower limit of the lower heating value of the samples of leaves in the dry state (W_r = 0 %), as well as with the humidity at the time of shedding the leaves W_r, were established using a technical calculation according to the D.I. Mendeleyev equation, adapted from Glijer (1992) and Domansky (2007). The equation is based on the elemental analysis of the combustible matter, the share analysis of ash in the dry matter, and the relative humidity of the biofuel (Eqs. 4 and 5),

$$Q_n^d = [339 * C^{daf} + 1029.8 * H^{daf} + 104 * S^{daf} - 109 * O^{daf}] * \left[\frac{100 - A^d}{100}\right] \quad (4)$$

$$Q_n^r = [339 * C^{daf} + 1029.8 * H^{daf} + 104 * S^{daf} - 109 * O^{daf}] * \left[\frac{100 - A^d - w_r}{100}\right] - 25.12 * W_r \quad (5)$$

where Q_n^d is the lower heating value of the samples at (W_r = 0%) [kJ.kg^{-1}], C^{daf} is the carbon content in the sample of dry leaves [%], H^{daf} is the hydrogen content [%]; S^{daf} is the sulfur content [%], O^{daf} is the oxygen content [%], A^d is the proportion of ash from the dried leaves [%], Q_n^r is the lower heating value of the sample of leaves at humidity W_r [kJ.kg^{-1}], and W_r is the relative humidity of the sample [%].

RESULTS AND DISCUSSION

The moisture content data for the analysed leaves are shown in Fig. 1. The values of moisture content are given in the following form: $x_i = \overline{x_i} \pm u_{Ci}$ and represent the average measured value and the combined standard uncertainty of measurement.

The results of the chemical composition analysis of the combustible mater in the dry leaves (W_r = 0%) are given in Table 1. Table 2 presents the proportions of inorganic residue–ash of the dry leaves–of the particular ornamental trees and the associated higher heating values.

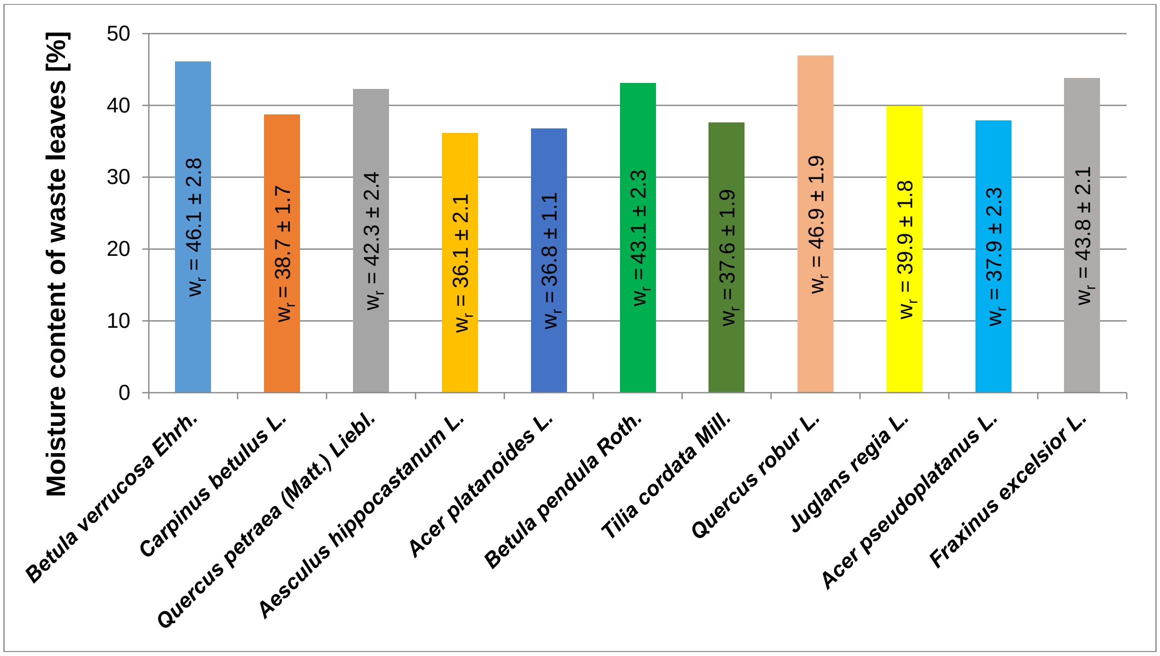

Fig. 1. The average values and combined standard uncertainty of the moisture content of the biofuel – leaves of the analyzed ornamental trees

Table 1. Chemical Composition of the Combustible Matter in the Dried Leaves

Species	C^{daf}[%]	H^{daf}[%]	O^{daf}[%]	N^{daf}[%]	S^{daf}[%]
Betula verrucosa Ehrh.	50.6 ± 0.5	6.1 ± 0.3	42.0 ± 0.4	1.2 ± 0.1	0.1 ± 0.01
Carpinu sbetulus L.	48.2 ± 0.5	5.9 ± 0.3	44.5 ± 0.4	1.3 ± 0.1	0.1 ± 0.01
Quercus petraea (Matt.) Liebl.	50.5 ± 0.5	6.1 ± 0.3	42.2 ± 0.4	1.1 ± 0.1	0.1 ± 0.01
Aesculus hippocastanum L.	45.6 ± 0.5	6.1 ± 0.3	47.1 ± 0.4	1.1 ± 0.1	0.1 ± 0.01
Acer platanoides L.	43.1 ± 0.5	6.1 ± 0.3	49.9 ± 0.4	0.8 ± 0.1	0.1 ± 0.01
Betula pendula Roth.	51.6 ± 0.5	6.2 ± 0.3	41.0 ± 0.4	1.2 ± 0.1	0.2 ± 0.01
Tilia cordata Mill.	44.6 ± 0.5	6.1 ± 0.3	47.6 ± 0.4	1.5 ± 0.1	0.2 ± 0.01
Quercus robur L.	50.6 ± 0.5	6.1 ± 0.3	42.2 ± 0.4	1.1 ± 0.1	0.1 ± 0.01
Juglans regia L.	49.3 ± 0.5	6.0 ± 0.3	43.2 ± 0.4	1.5 ± 0.1	0.1 ± 0.01
Acer pseudoplatanus L.	46.9 ± 0.5	6.0 ± 0.3	46.2 ± 0.4	0.9 ± 0.1	0.2 ± 0.01
Fraxinus excelsior L.	47.9 ± 0.5	6.0 ± 0.3	44.0 ± 0.4	1.1 ± 0.1	0.1 ± 0.01
Avarage ± STDEV	48.1 ± 2.8	6.1 ± 0.1	44.5 ± 2.8	1.2 ± 0.2	0.1 ± 0.05

The higher heating value of the dried leaves was measured as the temperature increased in the calorimeter. Birch (*Betula verrucosa* Ehrh.) had the highest measured value of Q_s = 20,247 kJ.kg^{-1}, as shown in Fig. 2.

Table 2. Proportion of Ash and Higher Heating Values of the Dried Leaves

Species	Combustion Characteristics of the Leaves			
	n	Proportion of Ash [%]	n	Higher Heating Value [kJ.kg^{-1}]
Betula verrucosa Ehrh.	6	5.5 ± 0.3	3	20247 ± 146
Carpinus betulus L.	6	13.1 ± 1.5	3	16278 ± 612
Quercus petraea (Matt.) Liebl.	6	8.1 ± 0.4	3	18912 ± 372
Aes culushippocastanum L.	6	9.5 ± 1.2	3	17908 ± 561
Acer platanoides L.	6	12.8 ± 0.1	3	16787 ± 228
Betula pendula Roth.	6	4.8 ± 1.2	3	19754 ± 342
Tilia cordata Mill.	6	12.5 ± 1.6	3	17396 ± 105
Quercus robur L.	6	8.1 ± 1.8	3	18487 ± 363
Juglans regia L.	6	12.6 ± 1.2	3	16972 ± 510
Acer pseudoplatanus L.	6	12.4 ± 1.4	3	16046 ± 484
Fraxinus excelsior L.	6	11.9 ± 1.3	3	16514 ± 486
Avarage ± STDEV		10.1 ± 2.9		17755 ± 1363

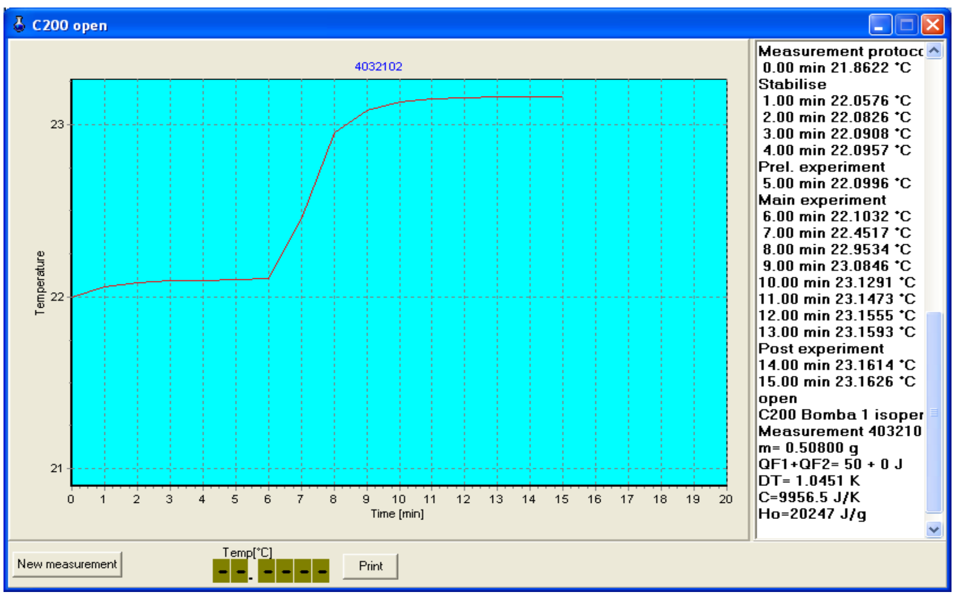

Fig. 2. The higher heating value of the analyzed leaves – at the original moisture and in the dried status (W_r = 0 %)

The lower heating values of the leaves are represented in the form of a bar graph in Fig. 3. The relative humidity at the time of shedding and in the dry state was W_r = 0%. The results of the experimental work and the moisture content of the leaves indicates that the relative humidity of the leaves ranged between W_r = 36.1 and 46.9%. This range of moisture content is acceptable in the composting of green material, especially for biogas production by anaerobic fermentation (Lin and Tanaka 2006; Jandačka *et al.* 2007; Stegelmeier *et al.* 2011). Such a favorable assessment, however, shall not justify the leaves for use of energy in the production of heat by direct combustion. Leaves with such moisture content, as documented in Fig. 3, have a lower heating value of approximately 50% lower than the lower heating value of the same leaves in the dry state. Despite this critical evaluation, for objectivity it is necessary to note that the energy characteristics of the leaves with substantial moisture at the time of shedding are comparable to the energy characteristics of woody biomass with higher moisture content and as an additional biofuel it is burned together with wood chips in heat generator with furnaces adapted to combust wet biomass.

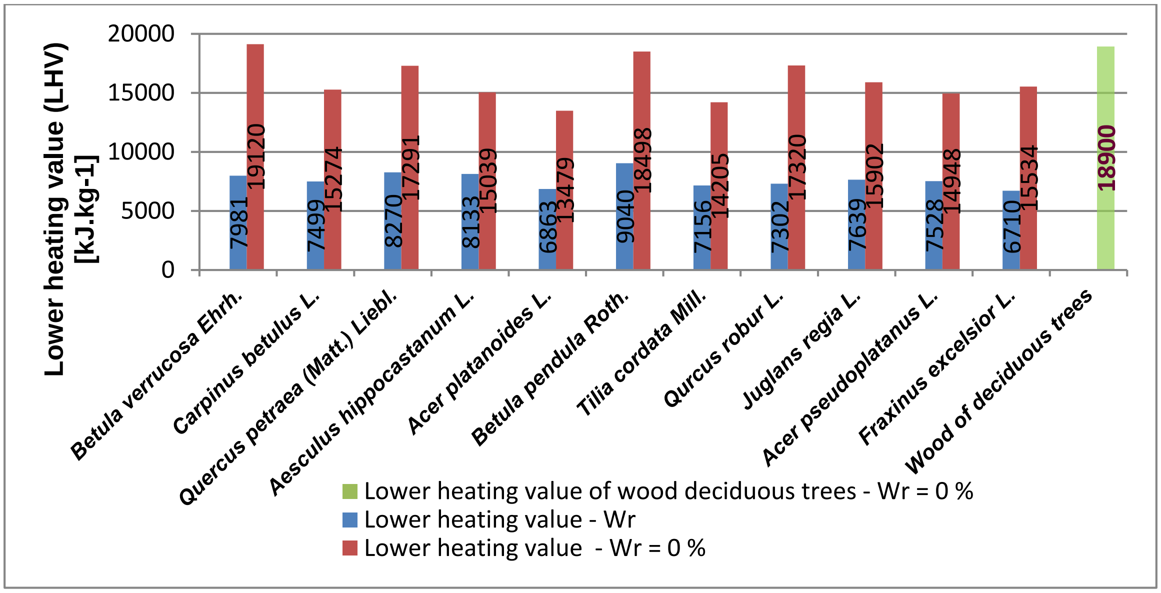

Fig. 3. The lower heating value of leaves shed in the fall from the analyzed species of trees and firewood (reference data), at the original humidity at the time of shedding (W_r = 36.1 ÷ 46.9 %) and in the dried state (W_r = 0 %)

The chemical composition of the combustible mater in dry leaves was compared with the combustible matter of dry wood of deciduous trees stated in EN 14961-1 (2010). The combustible matter of the leaves has a higher nitrogen content–the endothermic component of the biofuel, *i.e.* of the passive component of the biofuel combustible, which in the process of oxidation does not emit heat, but on the contrary this chemical reaction is accompanied by obtaining the heat from the environment. The nitrogen content in the combustible matter of dry leaves is 12 times higher than the nitrogen content in the combustible matter of firewood from deciduous trees. This observation has a negative impact when using the leaves as fuel, as nitrogen oxides are emitted into the air, as mentioned in several previous works (Dzurenda 2004; Stubenberger *et al.* 2007; Čarnogurská *et al.* 2011; Dzurenda *et al.* 2015). The elemental analysis of the other components of combustible matter of leaves indicated a higher dispersion of the proportion of carbon and oxygen in combustible matter of biofuel than it is for firewood of deciduous trees. Similar findings on the combustion characteristics of leaves from fruit trees have also been reported (Garcia *et al.* 2012; Fernandes *et al.* 2013; Martiník *et al.* 2014).

Shares of ash from the dry leaves, which are mentioned in the Table 2, indicate the fact that the leaves are a biofuel with significantly higher production of ash than the ash produced from firewood of deciduous or coniferous trees. According to EN 14961-1 (2010), if the production of ash from firewood is in the range of 0.3 ÷ 0.7%, then the production of ash from leaves of hard deciduous trees (except for the leaves of birch) is generally 20.4 times higher. The finding applies to the non-contaminated leaves by soil and dust from the pavements which normally contaminate the leaves that are collected for the biofuel. The level of contamination of the leaves by dust and soil will depend on the harvesting technique (sweeping, mechanical collecting, vacuuming). According to the analyses performed to determine the level of contamination by dust when collecting the leaves from the city pavements performed by the machine: (cleaning machine) Green Machines 636, the ash content of the samples (a mixture of leaves) increased by A^d = 1.3 to 1.9 %. Since the objective of this paper was the presentation of the characteristics of leaves (biofuels) shed in the fall, proceeding from ornamental trees in city and forest parks, the combustion characteristics of leaves do not include contamination by dust and soil from the pavements.

The average value of the measured higher heating value of the dry leaves was Q_s = 17,755 kJ.kg^{-1} and is 11.7% lower than the average higher heating value of firewood of deciduous trees in the dry state as stated by EN 14961-1 (2010); the average lower heating value calculated using Eq. 5 (D. I. Mendelejev) Q_n = 16,052 kJ.kg^{-1} is 15.1% lower than that of firewood. The lower basic combustion characteristics, *i.e.*, the higher and lower heating values, is predominantly caused by the higher content of inorganic substances (ash) in the leaves and partially also by the higher nitrogen content–the endothermic component in the combustible matter of biofuel. Comparable higher heating values have been found for leaves of fruit trees in previous works (García *et al.* 2012; Fernandes *et al.* 2013).

The results of the chemical analysis of the ash, *i.e.*, the contents of Ca, Mg, K, Mn, Fe, P, and Zn, in the ash of birch, oak, chestnut, maple, and lime leaves using the ICP AES method are presented in Table 3.

Table 3. Chemical Composition of the Ash from Dry Leaves Shed in the Fall

Species	Inorganic Composition of the Ash from Dry Leaves [g.kg^{-1}]						
	Ca	Mg	K	Mn	Fe	P	Zn
Betula verrucosa Ehrh.	290.0	58.9	32.2	14.7	7.9	34.2	2.8
Carpinus betulus L.	219.5	42.7	24.9	15.9	7.6	30.9	1.6
Quercus petraea (Matt.) Liebl.	172.9	19.1	20.1	2.8	12.7	13.6	0.2
Aesculus hippocastanum L.	249.4	46.5	5.17	2.1	7.9	8.1	0.1
Acer platanoides L.	204.0	17.4	8.66	5.0	6.4	5.9	0.1
Betula pendula Roth.	281.3	51.5	31.0	13.9	8.3	32.7	0.9
Tilia cordata Mill.	220.9	26.4	9.19	6.1	18.0	9.6	0.2
Qurcus robur Mill.	187.0	18.0	17.9	3.6	11.9	11.3	0.2
Juglans regia L.	271.1	39.8	28.0	10.5	15.9	36.4	0.5
Acer pseudoplatanus L.	198.4	16.8	7.9	5.3	7.0	6.0	0.2
Fraxinus excelsior L.	176.0	36.2	25.6	12.9	5.7	20.3	0.1
Average ± STDEV	224.6 ± 42.3	33.9 ± 15.2	16.8 ± 8.2	7.0 ± 4.2	10.0 ± 4.1	15.8 ± 9.6	0.7 ± 0.9

The chemical composition of the ash has a direct influence on its thermal characteristics. According to previous works the thermal characteristics of ash from biofuels are critically dependent on the representation of calcium, magnesium, and potassium (Malaťák and Vaculik 2008; Jandačka *et al.* 2011). While calcium and magnesium increase the melting temperature of the ash, potassium with the sintering temperature of 850 °C (1562 °F) contributes to the reduction of thermal characteristics of inorganic residue from the combustion of biofuels. As stated in EN 14961-1 (2010), the proportional representation of K:(Ca + Mg) = 0.57 in the ash of hardwood trees. In the ash of the dry leaves K:(Ca + Mg) = 0.06, so it can be concluded that the ash of the leaves due to lower content of potassium compared with the contents of calcium and magnesium will not stick together and will not affect potassium transport on the furnace grate plates of heat generators.

The ash formed in the combustion process of wood and bark in the form of loose material is suitable as a fertilizer for fertilizing meadows, pastures, and forest plantations (Simanov 1995; Demeyer *et al.* 2001; Pitmann 2006; Kuokkanen *et al.* 2009; Zacharová *et al.* 2012; Dzurenda *et al.* 2014). Fertilization using ash of woody biomass and phytomass is considered to be the path for returning nutrients to the forest ecosystem.

CONCLUSIONS

1. On the basis of an experimental study of the combustion characteristics of leaves shed from ornamental deciduous trees in city and forest parks, it was determined that the moisture content of biofuel leaves is between W_r = 35.2 and 46.9%. This has an adverse effect on the reduction of basic energy values of biofuel, *i.e.*, the higher and lower heating values.
2. The chemical composition of the combustible matter – leaves from deciduous trees – was compared to the chemical composition of firewood from deciduous trees. The only noticeable difference was the nitrogen content. The combustible matter of leaves contains 7.5 times more nitrogen, *i.e.*, the endothermic component, than the combustible matter of firewood from deciduous trees.
3. The average content of ash, *i.e.* inorganic residue, from burned leaves is 20.4 times greater than the ash content of firewood from deciduous trees. The ash production of the analyzed leaves was in the range of A_d = 8.1 to 13.1% and is comparable to the ash production of graded brown coal. Birch leaves were the only exception in which the average value was A_d = 5.2%.
4. The average value of the measured higher heating value of dry leaves from the analyzed trees was Q_s = 17,755 $kJ.kg^{-1}$ and was 11.7% lower than the average higher heating value of firewood of deciduous trees in the dry state as reported in EN 14961-1 (2010). The average lower heating value calculated using Eq. 5 (M. I. Mendelejev) was Q_n = 16,053 $kJ.kg^{-1}$, which was 15.1% lower than that of firewood. The stated decrease in higher and lower heating values is predominantly caused by the greater content of inorganic substances (ash) in the leaves and partially by the greater nitrogen content–the endothermic component of combustible matter in biofuel.

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