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**INFLUENCE OF TORREFACTION PRETREATMENT ON THE  
COMPOSITION AND DECOMPOSITION OF  
LIGNOCELLULOSIC MATERIALS**

**THESIS BOOK**

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## **1. INTRODUCTION AND AIMS**

Recognizing the environmental impacts of fossil fuels has initiated research and development of products, which can be produced from sustainable raw materials. The Paris Agreement aims to involve all nations to fight climate change and to keep the global temperature rise this century well below 2 °C above the pre-industrial levels. Several promising technologies exist, which can at least partially replace the coal and oil products, thus reducing the environmental impact of fossil fuels. However, the development and competitiveness of these new technologies that use renewable raw materials are a major challenge, and further efforts are needed in research and development. The price and location of raw materials appear to be a dominant factor in the pricing of the commodity products. Lignocellulosic biomass is abundant, available at low cost and largely unused; therefore it can be a promising energy feedstock in the future. In energetic applications the properties of raw biomass materials, such as the high oxygen content, low calorific value, low energy density, hydrophilic nature and high moisture content create challenges for their efficient utilization. Pretreatment of biomass is necessary prior to the thermochemical conversion processes to improve the aforementioned disadvantages of biomass; which can be mechanical, thermal, and chemical treatments and various combinations of these methods. Each pretreatment has its own effect; therefore it is not possible to define the best pretreatment method as it depends on many factors, such as the type of lignocellulose and the desired products. Among many pretreatment technologies, torrefaction, a thermal treatment of biomass in the temperature range of 200 °C to 300 °C in the absence of oxygen has gained continuous interests in the past decade. A major goal of torrefaction is to upgrade the quality of the solid product by decreasing the moisture content and increasing the hydrophobicity, grindability, and energy density of biomass. In order to maximize the effectiveness of the energy extraction, we need to characterize the biomass materials as much as possible.

The general aim of my work was to get new information about the composition and thermal decomposition of torrefied hardwood, softwood, and herbaceous biomass materials. The characterization of the samples was carried out by both carbohydrate and lignin content determination and thermal decomposition techniques to get more knowledge about the structural changes taking place during torrefaction in the main biomass components.

The present work contains the results of the following studies:

- Comprehensive compositional analysis was carried out on untreated and torrefied herbaceous materials (rape straw and wheat straw) and hardwood (black locust wood) samples. The impact of the reduction of inorganic ion contents on the thermal degradation process during torrefaction was investigated in detail. Furthermore, the effect of torrefaction on the biomass chlorine content was studied.
- A comparative study was performed on the composition and decomposition of untreated and various torrefied bark, stem wood, and stump samples of softwood (Norway spruce). Additionally, the effect of torrefaction on physiochemical characteristics of the stem wood, stump, and bark samples was investigated.

## 2. BACKGROUND

Lignocelluloses are complex materials consisting of cellulose (linear glucose homopolymer), hemicellulose (branched sugar heteropolymer), lignin (cross-linked polymer of phenyl propane units), extractives, and inorganic components [1].

Biomass can be converted into various energy products via different conversion routes. The three main processes within the thermochemical conversions are: fast pyrolysis, slow pyrolysis (carbonization), and gasification. Pretreatment of lignocellulose is necessary prior to the thermochemical conversion processes; which can be mechanical, thermal, chemical treatments, and various combinations of these methods. The volumetric energy density of biomass can be further increased by a pelletizing process [2].

In the last decades, an increasing interest can be observed for torrefaction, which is a mild thermal pretreatment method between 200 and 300 °C in an inert atmosphere. A major goal of torrefaction is to upgrade the quality of the solid biomass by decreasing the moisture content and increasing the hydrophobicity, grindability, and energy density of biomass (Table 1). Torrefied biomass with unique properties is more suitable for logistics and further conversion to energy [3].

The basic schematic overview of the torrefaction and densification (pelletization) process is illustrated in Figure 1 [4]. The key torrefaction process parameters include temperature and residence time. During torrefaction, besides the solid product, liquid and gaseous (mainly carbon monoxide and carbon dioxide) by-products are also formed. The purpose of the mild heat treatment from a chemical point of view is the removal of water and the acidic groups of hemicelluloses or the whole hemicellulose fraction with minor degradation of cellulose and lignin in the biomass [5].

The thermal properties of lignocelluloses are influenced by the chemical composition of its major components, including cellulose, hemicelluloses, and lignin, and their minor components, such as extractives and inorganic materials. Several complex, competing and consecutive reactions occur during the pyrolysis of biomass materials and provides various products [6]. In order to estimate the feasibility of a commercial torrefaction system in a particular region, local, cheap and abundant lignocellulosic resources, such as agricultural and forest residues should be investigated.

[1] Tumuluru JS, Sokhansanj S, Hess JR, Wright CT, Boardman RD (2011) A review on biomass torrefaction process and product properties for energy applications. *Ind. Biotechnol.*, 7(5): 384-401.

[2] Gent S, Twedt M, Gerometta C, Almberg E (2017) Theoretical and applied aspects of biomass torrefaction for biofuels and value-added products. Butterworth-Heinemann. pp: 1-224.

[3] Bergman PCA, Boersma AR, Zwart RWH, Kiel JHA (2005) Torrefaction for biomass co-firing in existing coal-fired power stations. Report E CN-C--05-013.

[4] Acharya B, Dutta A, Minaret J (2015) Review on comparative study of dry and wet torrefaction. *Sustain. Energy Technol. Assess.*, 12: 26-37.

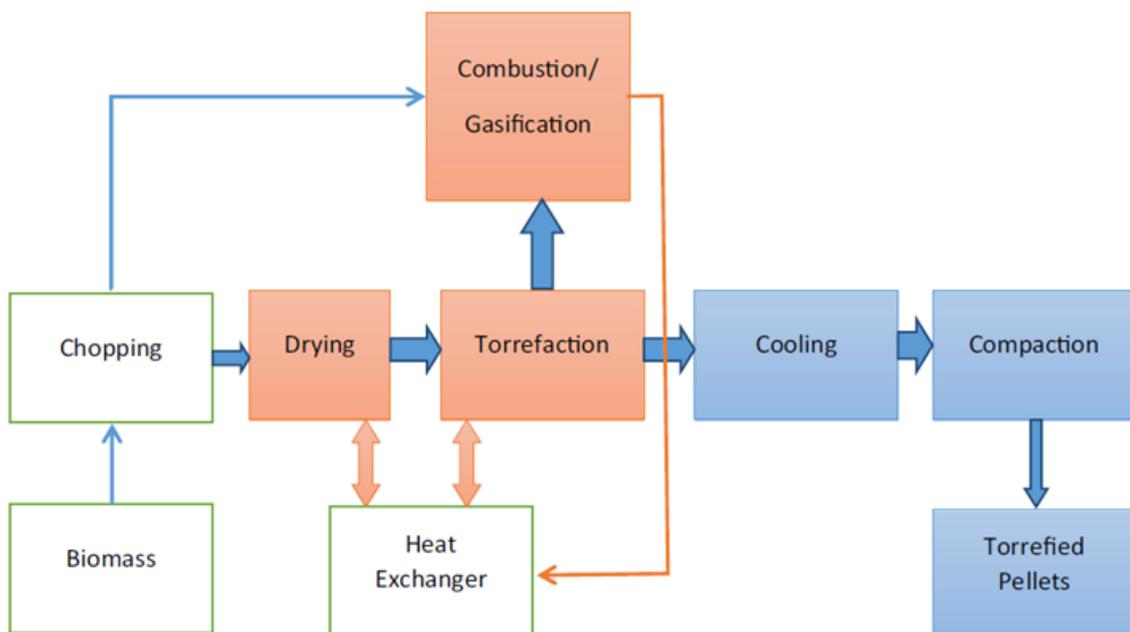
[5] Jakab E (2015) Analytical Techniques as a tool to understand the reaction mechanism. In: *Recent advances in thermo-chemical conversion of biomass*. Elsevier, Amsterdam, Eds: Pandey A, Bhaskar T, Stocker M, Sukumaran RK, pp: 73-106.

[6] Shafizadeh F (1982) Review - Introduction to pyrolysis of biomass. *J. Anal. Appl. Pyrol.*, 3: 283-305.

Forestry residues and agricultural by-products, available in large amounts in Hungary, could be a proper feedstock for bioenergy utilization. The area of black locust forests is representing almost 24% of the total forest area in Hungary; this wood can be a promising biomass for future energy production because of its high growth rate and promising fuel characteristics, such as high heating value and low ash content. During tree harvesting, stem wood is the main product, while the other parts of the tree (including bark and stump) are considered as by-products. These forest residues represent an abundant and underutilized source of renewable energy. Other lignocellulosic residues, studied in my thesis are rape straw and wheat straw materials. Straw is a low-value byproduct of the agricultural industry, and it is available in large amounts, at low cost and largely unused.

**Table 1** Fuel properties of wood, wood pellets, torrefied pellets, charcoal and coal [7].

	Wood	Wood pellets	Torrefaction pellets	Charcoal	Coal
Moisture content (% wt)	30 – 45	7 – 10	1 – 5	1 – 5	10 – 15
Lower heating value (MJ/kg)	9 – 12	15 - 18	20 – 24	30 – 32	23 – 28
Volatile matter (% db)	70 – 75	70 – 75	55 – 65	10 – 12	15 – 30
Fixed carbon (% db)	20 – 25	20 – 25	28 – 35	85 – 87	50 – 55
Density (kg/l) Bulk	0.2 – 0.25	0.55 – 0.75	0.75 – 0.85	~ 0.20	0.8 – 0.85
Energy density (GJ/m <sup>3</sup> ) (bulk)	2.0 – 3.0	7.5 – 10.4	15.0 – 18.7	6 – 6.4	18.4 – 23.8
Dust	Average	Limited	Limited	High	Limited
Hydroscopic properties	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological degradation	Yes	Yes	No	No	No
Grindability	Poor	Poor	Good	Good	Good
Handling	Special	Special	Good	Good	Good



**Figure 1** Process diagram of torrefaction [4]

[7] Koppejan J, Sokhansanj S, Melin S, Madrali S (2012) Status overview of torrefaction technologies. IEA Bioenergy Task 32, Final report.

### 3. MATERIALS AND METHODS

#### Raw materials

In the experimental work, wheat straw and rape straw were used as herbaceous materials; while black locust wood and Norway spruce were selected as hardwood and softwood, respectively.

#### Torrefaction experiments

The torrefaction experiments of wheat and rape straw and black locust wood were performed at 200, 225, 250, 275, and 300 °C temperatures using an isothermal period of 1 h. The torrefaction experiments of different parts of Norway spruce were completed at three different temperatures (225, 275 and 300 °C) using 30 and 60 min isothermal period. The raw and variously torrefied samples can be seen in Figure 2.



**Figure 2** Raw and torrefied wheat and rape straw, black locust and spruce

#### General characterization of the studied samples

Inductively coupled plasma-optical emission spectrometry (ICP-OES) measurements were applied to determine the inorganic contents of the raw samples. The higher heating value of the untreated and torrefied samples was determined using an automatic IKA C 5000 bomb calorimeter. Measurement of moisture and volatile, ash, and fixed carbon contents of the studied samples were performed by gravimetric method. The carbon and hydrogen contents of the untreated and torrefied biomass samples were measured by an elemental analyzer. The oxygen content was determined by difference.

#### Carbohydrate and lignin content determination

The milled (<1mm) and dried samples were treated in a two-step acid hydrolysis with 72% H<sub>2</sub>SO<sub>4</sub> for 2 h at room temperature, and then with 4% H<sub>2</sub>SO<sub>4</sub> for 1 h at 121 °C. The obtained suspensions were filtered and washed with distilled water through G4 glass filter crucibles. The sugar concentrations of the filtered supernatants were analyzed with high-performance liquid chromatography (HPLC). The Klason lignin content was determined by gravimetric method. The solid residues obtained after washing were dried at 105 °C until a constant weight. The amounts of total ash and acid-insoluble ash were determined by ashing the sample at 550 °C for 5 h until the sample weight was constant. The Klason lignin content was calculated by subtracting the acid-insoluble ash content from the acid-insoluble residue content.

### **Thermogravimetry-Mass spectrometry (TG/MS)**

Approximately 4 mg samples were analyzed in argon atmosphere from 25 to 900 °C at a rate of 20 °C min<sup>-1</sup> in a platinum sample pan. The evolved products were led through a glass-lined metal capillary heated at 300 °C using argon carrier gas at a flow rate of 140 mL min<sup>-1</sup>. The ion source of the mass spectrometer was operated at 70eV electron energy. The mass range of 2-150 Da was scanned.

### **Pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS)**

Approximately 0.6 mg samples were pyrolyzed at 600 °C for 20 s in a quartz tube using helium carrier gas. The pyrolysis products were separated on an Agilent DB-1701 capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). The pyrolysis interface and the GC injector were held at 280 °C. The GC oven was programmed to hold at 40 °C for 4 min and then increase to 280 °C at a rate of 6 °C min<sup>-1</sup>. The mass range of m/z 14-500 was scanned by the mass spectrometer in electron impact mode at 70eV.

### **Grinding and particle size distribution**

The raw and torrefied biomass samples was ground in two stages (pre-grinding and fine grinding) in a cutting mill (IKA MF 10.1). The powder samples produced in the fine grinding stage were sieved by a vibrating sieving machine (Fritsch Analysette 3 Pro) with the following mesh sizes: 1 mm, 0.5 mm, 0.3 mm, 0.2 mm, 0.1 mm and 0.063 mm.

### **Principal component analysis**

Due to the large number of samples and experimental data, principal component analysis (PCA) using the Statistica 12 software (StatSoft, Inc. Tulsa, Oklahoma, USA), was employed. The main purposes of a PCA analysis are to identify patterns in data and finding patterns to decrease the data dimensionality with minimal loss of information.

## 4. RESULTS AND DISCUSSION

The aim of my thesis was to study the thermal degradation process of torrefied hardwood, softwood, and herbaceous biomass materials with the goal of understanding deeper the structural changes of the main biomass components taking place during torrefaction. The results of the different methods (proximate and ultimate analyses, high heating values, compositional analysis data, TG/MS experiments and principal component analysis) all clearly demonstrate the progress of the thermal decomposition during torrefaction in the temperature range of 200-300 °C. The joint evaluation of the results obtained by different analytical methods revealed new information about the thermal degradation of the investigated lignocellulose materials.

### **Compositional study of raw and torrefied hardwood and herbaceous materials**

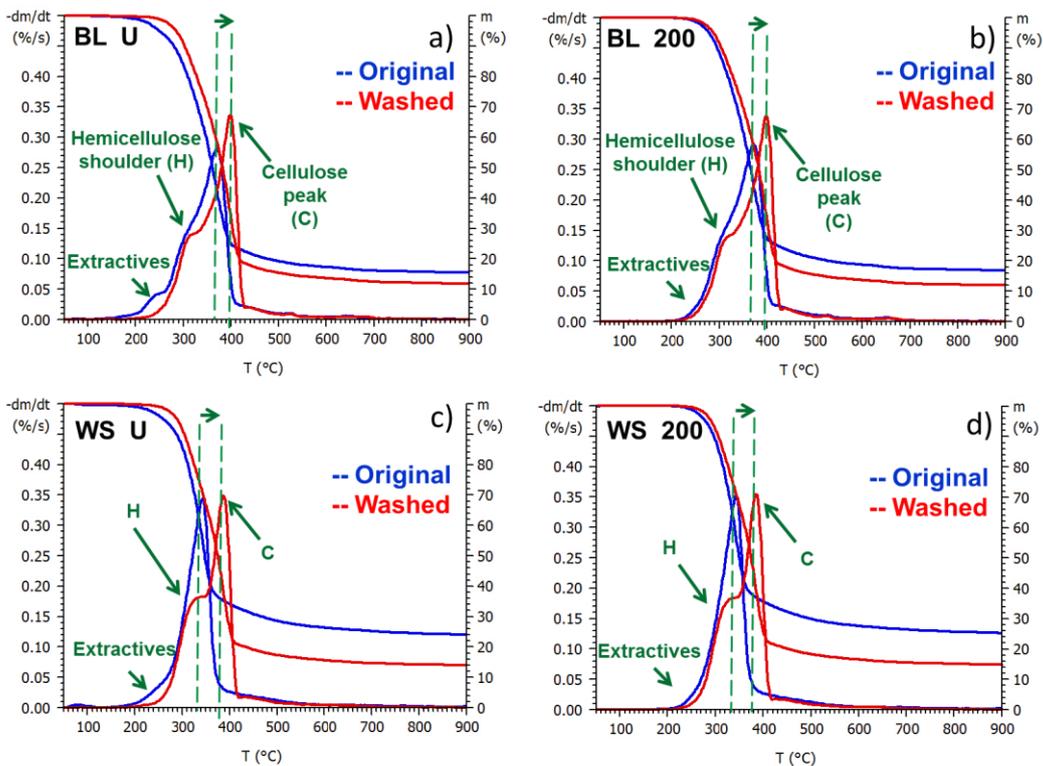
The purpose of this work was to compare the thermal behavior of black locust wood, rape straw, and wheat straw and reveal the chemical changes taking place during torrefaction at different temperatures. We found that the thermal decomposition of the hemicellulose component after torrefaction at 225 °C shifted to a higher temperature, indicating the modified structure of torrefied hemicellulose. Nevertheless, the main mass of the hemicellulose content of each sample was thermally stable during 1 h of torrefaction at 225 °C. These results were explained by the partial split off of the acidic side groups of hemicellulose at 225 °C torrefaction temperature. Significant difference was not found in the thermal stability of the hemicellulose content of straw and wood samples, despite the large difference in the contents of inorganic materials. Therefore, we may conclude that the thermal decomposition of hemicelluloses does not depend measurably on the amount of alkaline ions in the given concentration range contrary to cellulose, where the significant catalytic effect of the alkali ions on the thermal decomposition is a well-known phenomenon.

We found that after torrefaction at 275 °C, the hemicellulose content of each sample is strongly reduced. The degree of cellulose decomposition at 275 °C torrefaction temperature is significant only for straw samples, while cellulose is not degraded in the black locust wood sample at this temperature. The gradual increase in the amount of the acid insoluble materials indicates that the scission of the functional groups is accompanied by the enhanced formation of the crosslinked carbonaceous residues with an increasing torrefaction temperature.

Two sets of PCA calculations were undertaken using different types of data, which resulted in consistent results; the untreated and mildly torrefied samples were separated from the severely torrefied samples. The calculations revealed that the chemical composition and, therefore, the thermal properties have changed to a much greater extent in the temperature range of 275–300 °C than at lower temperatures.

In order to study the effect of inorganic content during the low-temperature thermal treatment (torrefaction), we washed the raw samples with hot water to remove the majority of the water soluble inorganic components. We compared the composition and the thermal stability of the original and the washed samples. We found that the thermal stability of cellulose in the hot water washed wood sample is raised by about 30 °C, while in case of the washed straw samples it is raised by about 50 °C compared to the original samples (Figure 3). The char yield of the raw and torrefied hot water washed samples is significantly lower for the three studied samples than that of the original samples. We also concluded that the effect of washing is more pronounced at higher torrefaction temperatures. These observations confirm that alkali ions have catalytic effects on the decomposition mechanism of cellulose and lignin even at mild thermal conditions.

The formation of methyl chloride was detected by thermogravimetry/mass-spectrometry during thermal decomposition that we explained by the reaction of chlorine with the methyl groups of lignin. We concluded that most of the methoxy groups of straw lignins were probably cleaved during torrefaction at 275 and 300 °C, and at the same time the initial chlorine content of the straw samples decreased. Therefore, the severely torrefied straw samples produced only small amount of methyl chloride during thermal decomposition.

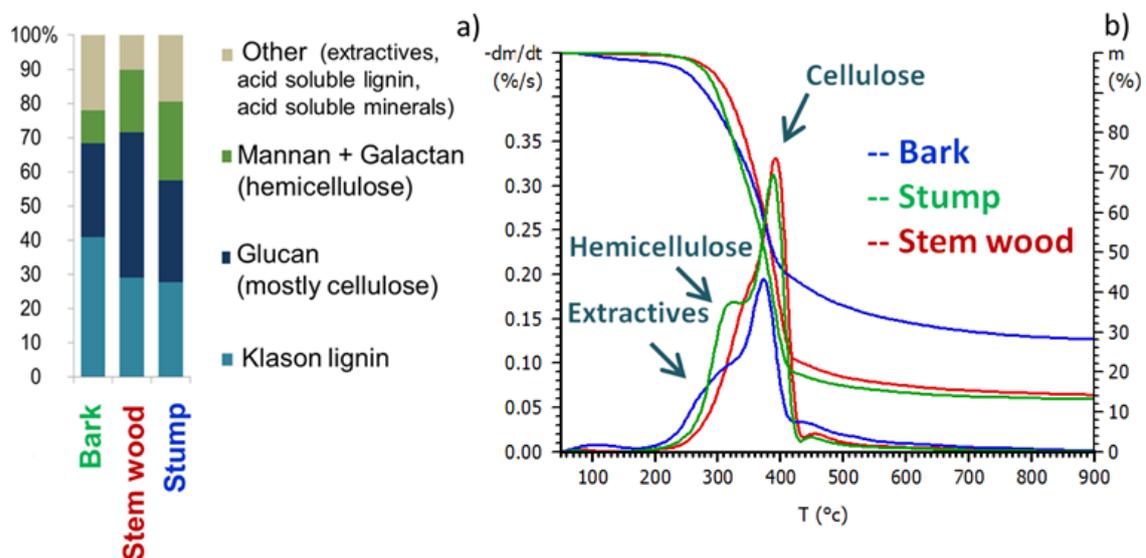


**Figure 3** TG and DTG curves of (a, c) untreated and (b, d) lightly (200 °C) torrefied black locust (BL) and wheat straw (WS) samples.

## Comparative study on the thermal behavior of torrefied stem wood, stump, and bark of Norway spruce

The aim of this work was to gain information about the thermal behaviors and physicochemical properties of stem wood, stump and bark of Norway spruce. The main differences between the thermal decomposition of the studied samples are interpreted in terms of the chemical composition (Figure 4) with the goal of understanding the mechanisms of the decomposition of biomass components during torrefaction. We found that the decomposition of hemicellulose starts with the cleavage of the functional groups at 225 °C. We concluded that the thermally less stable acidic side groups are cleaved at this temperature, increasing the hydrophobicity of the product in this way, which is an important goal during the practical application of torrefaction.

Significant decomposition of cellulose started as low as at 275 °C torrefaction temperature for the bark sample, while it was found to be stable for stem wood and stump, which can be explained by the high alkali ion content of bark. Therefore, we concluded that lower torrefaction temperature should be applied for bark, than for stem wood and stump to obtain products degraded to a similar degree. The torrefaction residence time did not have significant influence up to 275 °C on the thermal behavior of the samples. However, at 300 °C the composition of the torrefied samples changed substantially with the torrefaction residence time due to the intensive decomposition of cellulose. Torrefaction at 300 °C temperature induced severe changes in all biomass components, resulting in significant mass and energy losses; hence this temperature is too high for most of the applications. We found that the treated stem wood and stump behaved similarly during torrefaction; therefore they can be utilized together during thermochemical conversion. From the results of this work, it can be concluded that a mild torrefaction can considerably improve physicochemical properties of spruce stem wood and stump as solid fuel. Therefore, the utilization and conversion of them for energy production can be improved markedly.



**Figure 4** (a) Composition and (b) TG and DTG curves of untreated bark, stem wood, and stump.

## 5. NEW SCIENTIFIC FINDINGS

1. I demonstrated that the combined application of carbohydrate and lignin content determination and thermal decomposition techniques (e.g. TG/MS) provides complementary information on the structural changes in the complex biomass samples during torrefaction. The acidic hydrolysis followed by HPLC analysis of the sugars gives quantitative data on the composition of the carbohydrate backbone; while pyrolytic methods are suitable for the characterization of the functional groups, as well. (Paper I. and Paper II.)
2. Although the chemical composition of hemicelluloses and alkali ion content of herbaceous plants, deciduous and coniferous trees are different, the stabilities of these hemicelluloses do not differ during thermal treatments. (Paper I. and Paper II.)
3. I established by chemical analysis that the hemicellulose backbone of woody and herbaceous plants does not alter essentially during torrefaction at 225 °C; however, the acidic side groups of hemicelluloses are split off as detected by thermal decomposition methods. (Paper I. and Paper II.)
4. I observed that the thermal stability of cellulose in the washed black locust wood sample is raised by about 30 °C, while it is raised by about 50 °C in the hot water washed rape and wheat straw samples compared to the original samples. I found that the effect of washing is more pronounced at 275 and 300 °C torrefaction temperatures. (Paper VI.)
5. Lower torrefaction temperature is suggested to be applied for the samples of high potassium content (wheat straw, rape straw and wood bark) because the high alkali ion content of the herbaceous plants and bark significantly catalyzes the thermal decomposition of cellulose and lignin even at low (200-300 °C) temperatures. Furthermore, I observed that the thermal decomposition of hemicelluloses depended on the amounts of alkaline ions in the low concentration range, but differences were not measurable at higher concentrations. (Paper I.-V.)
6. I established that during thermal decomposition, the relative intensity of methyl chloride decreased by half between the straw samples torrefied at 250 and 275 °C, while after torrefaction at 300 °C, methyl chloride almost totally ceased to be released from the straw samples. The reduced methyl chloride formation was explained by the demethylation of the methoxy groups of straw lignin and the decreased chloride ion content of the torrefied straw samples. (Paper VI.)
7. The low temperature thermal treatment of various parts of Norway spruce (stem wood, stump, bark) was compared. I proved that the treated stem wood and stump behaved similarly during torrefaction; therefore, they can be utilized together during thermochemical conversion. However, bark requires by about 25 °C lower torrefaction temperature than stem wood and stump. (Paper II., Paper III. and Paper V.)
8. Performing principal component analyses, I proved that the thermal treatment of higher temperature (275-300 °C) resulted in significant changes in the composition and the thermal behavior of the samples. In the cases of torrefaction at 225 and 275 °C, the duration of the thermal treatment does not affect the composition of the samples significantly, whereas at 300 °C the residence time has a major effect on the composition manifested in the strong decomposition of cellulose. I concluded that this temperature is too high for most of the applications (Paper II., Paper III. and Paper V.)

## 6. CONCLUSION, POTENTIAL APPLICATIONS

Due to the natural features of Hungary, the utilization of biomass as a source of renewable energy is important for the future energy production. Energy wood plantations and agricultural by-products are available in large quantities. Currently, direct combustion is the most commonly used technology for converting biomass to heat. Black locust wood is a dominant tree species in Hungary; which is a promising biomass for future energy production because of its high growth rate and promising fuel characteristics, such as high heating value and low ash content. During tree harvesting, stem wood is the main product, while the other parts of the tree (including bark and stump) are considered as by-products. These forest residues represent an abundant and underutilized source of renewable energy. Straws are low-value by-products of the agricultural industry, and they are also available in large amounts, at low cost and largely unused.

Hungary aims to raise the amount of renewable energy to 14.65% of total consumption by 2020 in its Renewable Energy Utilization Action Plan. This is above the obligatory 13% prescribed for Hungary as a national overall target in the European Union Renewable Energy Directive. The ratio of renewables in the gross final energy consumption was 9.6% in 2014; and this ratio did not change considerably during the last few years. The share of energy generated from renewable sources in Hungary will have to increase further in the next few years.

The first industrial-scale heat treatment (torrefaction) plant was completed in Canada (Airex Energy, Bécancour, Quebec), which is primarily dedicated to the production of torrefied biomass pellets for coal-fired power plants, moreover, biochar and torrefied wood flour are also produced in this plant. This technology transforms sawmill by-products, logging residues and forestland biomass into value-added biocarbon products. This heat treatment system could solve several problems within one factory: it can produce biocoal for power plants, biochar for soil remediation, and lightly torrefied wood flour for wood-plastic composites.

## PUBLICATIONS

### Papers on which the thesis was based

- I. **E. Barta-Rajnai**, E. Jakab, Z. Sebestyén, Z. May, Zs. Barta, L. Wang, Ø. Skreiberg, M. Grønli, J. Bozi, Zs. Czégény. Comprehensive compositional study of torrefied wood and herbaceous materials by chemical analysis and thermoanalytical methods. *Energy Fuels*, 2016; 30: 8019–8030. (IF: 3.091, I:2)
- II. **E. Barta-Rajnai**, L. Wang, Z. Sebestyén, Zs. Barta, R. Khalil, Ø. Skreiberg, M. Grønli, E. Jakab, Zs. Czégény. Comparative study on the thermal behavior of untreated and various torrefied bark, stem wood and stump of Norway spruce. *Applied Energy*, 2017, 204: 1043-1054. (IF: 7.182)
- III. L. Wang, **E. Barta-Rajnai**, Ø. Skreiberg, R. Khalil, Zs. Czégény, E. Jakab, Zs. Barta, M. Grønli. Effect of torrefaction on physicochemical characteristics and grindability of stem wood, stump and bark. *Applied Energy*, <http://dx.doi.org/10.1016/j.apenergy.2017.07.024>, In press, (IF: 7.182, I:1)
- IV. **E. Barta-Rajnai**, L. Wang, Z. Sebestyén, Zs. Barta, R. Khalil, Ø. Skreiberg, M. Grønli, E. Jakab, Zs. Czégény. Effect of temperature and duration of torrefaction on the thermal behavior of stem wood, bark, and stump of spruce. *Energy Procedia*, 2017, 105: 551 – 556. (Open Access, IF:-, I:1)
- V. L. Wang, **E. Barta-Rajnai**, Ø. Skreiberg, R. Khalil, Zs. Czégény, E. Jakab, Zs. Barta, M. Grønli. Impact of Torrefaction on Woody Biomass Properties. *Energy Procedia*, 2017, 105: 1149 – 1154. (Open Access, IF:-, I:3)
- VI. **E. Barta-Rajnai**, B. Babinszki, E. Jakab, Z. Sebestyén, Zs. Czégény: On the significance of chlorine and potassium content of lignocellulose during torrefaction. Manuscript

### Other related papers

- VII. **E. Barta-Rajnai**, G. Várhegyi, L. Wang, Ø. Skreiberg, M. Grønli, Zs. Czégény. Thermal decomposition kinetics of wood and bark and their torrefied products. *Energy Fuels*, 2017, 31 (4): 4024-4034. (IF: 3.091)
- VIII. **E. Barta-Rajnai** Torrefied coffee bean and biomass materials. *Természet Világa*, 2017; 148 (2): 76-79.

### Other papers

- IX. Z. Sebestyén, **E. Barta-Rajnai**, J. Bozi, M. Blazsó, E. Jakab, N. Miskolczi, J. Sója, Zs. Czégény. Thermo-catalytic pyrolysis of biomass and plastic mixtures using HZSM-5. *Applied Energy*; 2017; 207: 114-122. (IF: 7.182)
- X. L. Wang, **E. Barta-Rajnai**, K. Hu, C. Higashi, Ø. Skreiberg, M. Grønli, Zs. Czégény, E. Jakab, V. Myrvagnes, G. Várhegyi, M. J. Antal, Jr. Biomass charcoal properties changes during storage. *Energy Procedia*; 2017; 105: 830-835. (Open Access, IF:-)
- XI. Z. Sebestyén, **E. Barta-Rajnai**, J. Bozi, M. Blazsó, E. Jakab, N. Miskolczi and Zs. Czégény. Catalytic pyrolysis of biomass and plastic mixtures using HZSM-5 zeolite. *Energy Procedia*; 2017, 105: 718- 723. (Open Access, IF:-)

- XII. Z. Sebestyén, N. Miskolczi, **E. Barta-Rajnai**, E. Jakab, Zs. Czégény. Thermocatalytic studies on municipal solid waste. *Energy Procedia*; 2017; 105: 706- 711. (Open Access, IF:-)
- XIII. Z. Sebestyén, **E. Barta-Rajnai**, Zs. Czégény, T. Bhaskar, B. B. Krishna, Z. May, J. Bozi, Zs. Barta, R. Singh, E. Jakab. Thermoanalytical characterization and catalytic conversion of deoiled micro algae and jatropha seed cake. *Energy Fuels*, 2016; 30: 7982-7993. (IF: 3.091, I:1)
- XIV. Zs. Czégény, J. Bozi, Z. Sebestyén, M. Blazsó, E. Jakab, **E. Barta-Rajnai**, M. Forster, J. Nicol, K.G. McAdam, C. Liu. Thermal behaviour of selected flavour ingredients and additives under simulated cigarette combustion and tobacco heating conditions. *J. Anal. Appl. Pyrol.*, 2016; 121: 190-204. (IF: 3.471)
- XV. Z. Sebestyén, Zs. Czégény, E. Badea, C. Carsote, C. Sendrea, **E. Barta-Rajnai**, J. Bozi, L. Miu, E. Jakab. Thermal characterization of new, artificially aged and historical leather and parchment. *J. Anal. Appl. Pyrol.*, 2015; 115: 419-427. (IF: 3.652, I:1)

### Oral presentations

- I. **E. Barta-Rajnai**, E. Jakab., B. Babinszki, Z. Sebestyén, Zs. Czégény. Szervetlen ionok szerepe növényi anyagok alacsony hőmérsékletű hőbomlása során. MKE Termoanalitikai Szakcsoport és az MTA Termoanalitikai Munkabizottság közös szervezésében rendezett ülése. Budapest, Hungary, 13.12.2017.
- II. **E. Barta-Rajnai**, E. Jakab, L. Wang, G. Várhegyi, R. Khalil, Ø. Skreiberg, M. Grønli, Zs. Czégény. Effect of torrefaction on properties and thermal behaviors of stem wood, stump and bark, 21th International Symposium on Analytical and Applied Pyrolysis, Nancy, France, 09.05.2016. -12.05.2016.
- III. **E. Barta-Rajnai**. Pörkölt kávébab és hőkezelt biomassza. A Magyar Tudományos Akadémia Természettudományi Kutatóközpontja és a Tudományos Ismeretterjesztő Társulat (TIT) közös cikkpályázatának díjátadó ünnepsége, Budapest, Hungary, 15.11.2016.
- IV. **E. Barta-Rajnai**, L. Wang, Zs. Czégény, E. Jakab, G. Várhegyi, R. Khalil, Ø. Skreiberg, M. Grønli. Alacsony hőmérsékletű hőkezelés hatása fa, tönk és kéreg tulajdonságaira, valamint termikus viselkedésére. MKE Termoanalitikai Szakcsoport és az MTA Termoanalitikai Munkabizottság közös szervezésében rendezett ülése, Budapest, Hungary, 26.05.2016.
- V. **E. Barta-Rajnai**. Természetes és mesterséges polimerek hőbomlása, AKT Matematikai és Természettudományi Szakbizottsági meghallgatás, Budapest, Hungary, 04.12.2015.
- VI. **E. Barta-Rajnai**. A növényi biomassza komponenseinek hőbomlása torrefaction során. „A megújuló energiaforrások újszerű felhasználására és korszerű energiatárolási eszközök fejlesztésére alkalmas innovatív eljárások tudományos megalapozása” című KTIA-AIK projekt 4. és 5. munkaszakaszának záró szimpóziuma, MTA Természettudományi Kutatóközpont, Budapest, Hungary, 27.11.2015.

- VII. **E. Barta-Rajnai.** A növényi biomassza komponenseinek hőbomlása torrefaction során. „A megújuló energiaforrások újszerű felhasználására és korszerű energiátárolási eszközök fejlesztésére alkalmas innovatív eljárások tudományos megalapozása” című KTIA-AIK projekt 3. munkaszakaszának záró szimpóziuma, MTA Természettudományi Kutatóközpont, Budapest, Hungary, 31.10.2014.

#### Poster presentations

- I. **E. Barta-Rajnai,** Z. Sebestyén, E. Jakab, Z. Czégény. Torrefaction study of three typical Hungarian biomass materials. 1st Journal of Thermal Analysis and Calorimetry Conference and 6th V4 (Joint Czech-Hungarian-Polish-Slovakian) Thermoanalytical Conference. Budapest, Hungary, 06.06.2017.-09.06.2017.
- II. B. Babinszki, **E. Barta-Rajnai,** E. Jakab, Z. Czégény. Effect of inorganic ions during torrefaction of biomass materials. 1st Journal of Thermal Analysis and Calorimetry Conference and 6th V4 (Joint Czech-Hungarian-Polish-Slovakian) Thermoanalytical Conference. Budapest, Hungary, 06.06.2017.-09.06.2017.
- III. **E. Barta-Rajnai,** L. Wang, Z. Sebestyén, Zs. Barta, Ø. Skreiberg, M. Grønli, E. Jakab, Z. Czégény. Effect of torrefaction on the thermal behavior of stem wood, bark, and stump of Norway spruce, McDonnell International Scholars Academy 6th International Symposium. Brisbane, Australia, 22.09.2016.-25.09.2016.
- IV. Z. Sebestyén, **E. Barta-Rajnai,** J. Bozi, B. B. Krishna, T. Bhaskar, Z. May, Zs. Czégény, E. Jakab. Thermal and catalytic decomposition studies of microalgal residue using Pyrolysis-GC/MS and TG/MS, Mini-conference on biomass, waste and renewable energy. Budapest, Hungary, 06.06.2016.
- V. **E. Barta-Rajnai,** Z. Sebestyén, E. Jakab, Zs. Czégény, J. Bozi. Characterization of the liquid by-products obtained during torrefaction of typical Hungarian biomass waste materials, Mini-conference on biomass, waste and renewable energy. Budapest, Hungary, 06.06.2016.
- VI. **E. Barta-Rajnai,** Z. Sebestyén, J. Bozi, E. Jakab, M. Blazsó, N. Miskolczi, Zs. Czégény. Pyrolysis of mixtures modeling municipal waste in the presence of catalysts, Mini-conference on biomass, waste and renewable energy. Budapest, Hungary, 06.06.2016.
- VII. **E. Barta-Rajnai,** Zs. Czégény, Z. Sebestyén, Z. May, J. Bozi, E. Jakab. Torrefaction study of two typical Hungarian biomass materials, Mini-conference on biomass, waste and renewable energy. Budapest, Hungary, 06.06.2016.
- VIII. **E. Barta-Rajnai,** E. Jakab, Z. Sebestyén, Zs. Czégény. Characterization of the liquid by-products obtained during torrefaction of typical Hungarian biomass waste materials, 21th International Symposium on Analytical and Applied Pyrolysis. Nancy, France, 09.05.2016.-12.05.2016.
- IX. J. Bozi, G. Bakos, Zs. Czégény, E. Jakab, **E. Barta-Rajnai,** Z. Sebestyén, N. Miskolczi, M. Blazsó. Pyrolysis of multicomponent plastic waste derived from end-of-life vehicles, 21th International Symposium on Analytical and Applied Pyrolysis. Nancy, France, 09.05.2016.-12.05.2016.

- X. **E. Barta-Rajnai**, E. Jakab, Sebestyén Z., Bozi J., Czégény Zs.: Mezőgazdasági hulladékok hasznosításának lehetősége alacsony hőmérsékletű pirolízissel, PhD Hallgatók 2. Környezettudományi Konferenciája - Korunk kihívásai a környezettudományok gyakorlati alkalmazásában. Budapest, Hungary, 26.04.2016.
- XI. **E. Barta-Rajnai**, Z. Sebestyén, J. Bozi, E. Jakab, M. Blazsó, N. Miskolczi, Zs. Czégény. Modell háztartási hulladék pirolízisének vizsgálata katalizátorok jelenlétében, XIII. Oláh György Doktori Iskola PhD konferencia, Hungary, 11.02.2016.
- XII. **E. Barta-Rajnai**, Zs. Czégény, Z. Sebestyén, Z. May, J. Bozi, E. Jakab. Jellegzetes magyarországi mezőgazdasági melléktermékek hőkezelése, XIII. Oláh György Doktori Iskola PhD konferencia, Budapest, Hungary, 11.02.2016.
- XIII. **E. Barta-Rajnai**, Z. Sebestyén, J. Bozi, E. Jakab, N. Miskolczi, Zs. Czégény: Pyrolysis of mixtures modeling municipal waste in the presence of catalysts, Athene's chemistry conference, Budapest, Hungary, 27.11.2015.
- XIV. **E. Barta-Rajnai**, Zs. Czégény, Z. Sebestyén, Z. May, J. Bozi, E. Jakab: Thermal decomposition of black locust and wheat straw under torrefaction, 8th International Symposium on Feedstock Recycling of Polymeric Materials, Leoben, Austria, 07.09.2015.-10.09.2015.
- XV. Z. Sebestyén, **E. Barta-Rajnai**, J. Bozi, Z. Sebestyén, M. Blazsó, E. Jakab, N. Miskolczi, Zs. Czégény. Catalytic pyrolysis of mixtures modeling municipal waste, 8th International Symposium on Feedstock Recycling of Polymeric Materials, Leoben, Austria, 07.09.2015.-10.09.2015.
- XVI. Z. Sebestyén, **E. Barta-Rajnai**, J. Bozi, B. Bhavya, T. Bhaskar, Z. May, Zs. Czégény, E. Jakab. Thermal and catalytic decomposition studies of microalgal residue using pyrolysis-GC/MS and TG/MS, 8th International Symposium on Feedstock Recycling of Polymeric Materials, Leoben, Austria, 07.09.2015.-10.09.2015.
- XVII. **E. Barta-Rajnai**, Zs. Czégény, Z. Sebestyén, E. Jakab, J. Bozi, Zs. Barta. Investigation of the enzymatic hydrolysis of torrefied biomass samples, 37th Symposium on Biotechnology for Fuels and Chemicals. San Diego, California, 27.04.2015.-30.04.2015.
- XVIII. **E. Barta-Rajnai**, J. Bozi, M. Blazsó, N. Miskolczi, E. Jakab, Zs. Czégény. Biomassza – műanyag keverékek hőbomlása HZSM-5 és Ni-Mo katalizátorok jelenlétében, XII. Oláh György Doktori Iskola PhD konferencia, Budapest, Hungary, 2015.02.05.
- XIX. Z. Sebestyén, C. Carsote, C. Sendrea, E. Badea, Zs. Czégény, L. Miu, M. Blazsó, J. Madarász, Gy. Pokol, **E. Rajnai**, J. Bozi, E. Jakab. The role of pyrolysis and thermal analysis in the protection of cultural heritage, 20th International Symposium on Analytical and Applied Pyrolysis, Birmingham, United Kingdom, 19.05.2014.-23.05.2014.
- XX. **E. Rajnai**, J. Bozi, M. Blazsó, N. Miskolczi, E. Jakab, Zs. Czégény. Thermal decomposition of synthetic polymer – biomass mixtures in the presence of HZSM-5 and Ni-Mo catalysts, 20th International Symposium on Analytical and Applied Pyrolysis, Birmingham, United Kingdom, 19.05.2014.-23.05.2014.

- XXI. Zs. Czégény, **E. Rajnai**, Z. Sebestyén, G. Bakos, E. Jakab. Torrefaction study of some typical Hungarian biomass waste materials, 20th International Symposium on Analytical and Applied Pyrolysis, Birmingham, United Kingdom, 19.05.2014.-23.05.2014.
- XXII. Z. Sebestyén, J. Bozi, **E. Rajnai**, T. Bhaskar, Z. May, I. Borbáth, E. Jakab. Thermoanalytical and chemical characterization of solid byproduct of biodiesel production from algae and jatropa seeds using mesoporous silica catalysts, 20th International Symposium on Analytical and Applied Pyrolysis, Birmingham, United Kingdom, 19.05.2014.-23.05.2014.

### Conference proceedings

- I. **E. Barta-Rajnai**, Zs. Czégény, Z. Sebestyén, Z. May, J. Bozi, E. Jakab. Thermal decomposition of biomass components under torrefaction: Thermal decomposition of black locust and wheat straw under torrefaction. ISFR 2015: Book of abstracts. 8th International Symposium on Feedstock Recycling of Polymeric Materials. Leoben, Austria, 07.09.2015.-10.09.2015. (ISBN 9783200041431).
- II. **E. Barta-Rajnai**, J. Bozi, Z. Sebestyén, M. Blazsó, E. Jakab, N. Miskolczi, Zs. Czégény. Catalytic pyrolysis of mixtures modeling municipal waste. 8th International Symposium on Feedstock Recycling of Polymeric Materials. ISFR 2015: Book of abstracts. Leoben, Austria, 07.09.2015.-10.09.2015. (ISBN 9783200041431).
- III. Z. Sebestyén, **E. Barta-Rajnai**, J. Bozi, B. Bhavya, T. Bhaskar, Z. May, Zs. Czégény, E. Jakab. Thermal and catalytic decomposition studies of microalgal residue using pyrolysis-GC/MS and TG/MS. 8th International Symposium on Feedstock Recycling of Polymeric Materials. ISFR 2015: Book of abstracts. Leoben, Austria, 07.09.2015.-10.09.2015. (ISBN 9783200041431).
- IV. Z. Sebestyén, Zs. Czégény, C. Sendrea, C. Carsote, **E. Barta-Rajnai**, L. Miu, E. Badea, E. Jakab. Thermal characterization of new, artificially and naturally aged leather and parchment samples; 3rd International Seminar and Workshop on Emerging Technology and Innovation for Cultural Heritage, Sibiu, Romania, 16.10.2014.-18.10.2014. (ISBN 9789731716855sek).