

# Pyrolysis of Food Waste – Solid Carbonaceous Product/Biochar for Material Use

J. Raček<sup>1</sup>, T. Chorazy<sup>1</sup>, M. Vršanská<sup>2</sup>, M. Brtnický<sup>3,4</sup>, L. Mravcová<sup>4</sup>, J. Kučerík<sup>4</sup>, P. Hlavínek<sup>1</sup>

<sup>1</sup> Brno University of Technology, Faculty of Civil Engineering, AdMaS, Purkyňova 651/139, 612 00 Brno, Czech Republic, racek.j@fce.vutbr.cz, chorazy.t@fce.vutbr.cz, hlavinek.p@fce.vutbr.cz

<sup>2</sup> Mendel University in Brno, Department of Chemistry and Biochemistry, Zemedelska 1, 613 00 Brno, Czech Republic, martina.vrsanska@mendelu.cz

<sup>3</sup> Mendel University in Brno, Department of Agrochemistry, Soil Science, Microbiology and Plant Nutrition, Zemědělská 1, 613 00 Brno, Czech Republic, martin.brtnicky@mendelu.cz

<sup>4</sup> Brno University of Technology, Faculty of Chemistry, Institute of Chemistry and Technology of Environmental Protection, Purkyňova 464/118, 612 00 Brno, Czech Republic, mravcova@fch.vut.cz, kucerik@fch.vutbr.cz  
Presenting author email: racek.j@fce.vutbr.cz

## Abstract

Food waste is a biodegradable waste from kitchens, restaurants, and public canteens, which represents a complicated group of wastes, especially from the point of view of microbiological and leaches pollutions and greenhouse gases emission. It is necessary to find a new way for material transformation of such waste into new usable product which would meet the principles of circular economy. The thermal treatment of food waste, which represents one of suitable way of its processing, can be performed by pyrolysis technology with following outputs: solid carbonaceous product/biochar, pyrolysis oil and pyrolysis gas. This paper summarizes the results of food waste mixing with additives, pelletizing process, and thermal pyrolysis process. The thermal pyrolysis tests revealed several variables influencing pyrolysis such as pelletization process, pyrolysis residence time, process temperature, yields and solid carbonaceous product/biochar parameters such as calorific value, organic carbon, surface area, P, Mg, K, Ca, heavy metals, pH, and electrical conductivity.

## Keywords

Thermal treatment, pyrolysis, food waste, solid carbonaceous product, biochar

## 1. Introduction

### 1.1. Food waste – characteristic, present treatment, legal aspects

Food waste (FW), thus biodegradable waste from kitchens, restaurants, canteens and canteens, is a problematic group of waste due to the generation of significant amounts of landfill gases and leachates [1]. These gases, a significant proportion of which are methane and carbon dioxide, make it difficult to FW land, which can also be a source of pathogenic micro-organisms, toxins and other infectious pathogens that pose a potential biological risk to human and animal health [2]. It is also often a source of odour and the presence of insects and rodents, so proper management of this bio-waste is important, especially to prevent the spread of infections [3].

The main chemical components of FW are: carbon, oxygen, nitrogen, lipids, proteins, carbohydrates, hemicellulose, cellulose, lignin, unstructured carbohydrates, starch, sugar, sucrose and glucose. FW consisting of rice and vegetables is rich in carbohydrates, while FW from meat and eggs is high in protein and lipids [4]. Eggshells contain high amounts of calcium carbonate (CaCO<sub>3</sub>), which could be used as an alkaline compound to remove heavy metals (HMs) from wastewater [5].

According to the European Union (EU), it is important to ensure the least burden on the environment and at the same time to make the prevention of dangerous diseases more effective. FW is defined as biodegradable waste from gardens and parks, food and kitchen waste from households, restaurants, catering and retail premises and comparable waste from food processing plants. It does not include forest and agricultural residues, manure, sewage sludge or other biodegradable waste such as natural textiles, paper or processed wood. It also excludes food by-products that never become waste [6]. The European Parliament has called on Member States to take measures to reduce FW. 88 million tonnes of food were discarded in 2014 and should be reduced by 30% by 2025 and halved by 2030 [7]. Preventive measures to reduce FW from restaurants, hotels, catering establishments as well as households are campaigns by various organizations that motivate consumers to reduce FW and sort waste components. We are seeing an initiative to reduce FW and recycling. In EU countries, FW is most often processed by composting, anaerobic digestion or a combination. After the digestion process, the digestate usually becomes part of the compost pellet and the leachate is used as a liquid fertilizer for agriculture [8].

The Food and Agriculture Organization (FAO) supports countries in Asia, the Pacific, the Middle East and other countries to analyse and develop FW reduction strategies according to the specific capabilities and needs of

their regions and countries [9,10]. FW treatment processes using anaerobic digestion and composting predominate in the world today [11].

According to the legislation in the EU, it is no more acceptable to use the FW for animal livestock and there is also other restriction related with FW as a biological degradable waste. FW also cannot be crushed and drained into sewage system, because a lot of wastewater treatment plants are not designed for this biological load. Another way of recycling must be found. One way in which bio-waste can be treated separately is to convert it into energy or fertilizer [12].

Solid carbonaceous product (SCP)/biochar is a product of pyrolysis, thus incineration in the absence of air, waste biomass [13]. A solid is formed that is rich in carbon and other elements. In soil enriched with this solid, some parameters improve, such as higher nutrient and water retention, increased pH in acidic soils, increased cation exchange capacity [14] and better binding of contaminants present in the soil. For this reason, the addition of SCP/biochar to the soil is proposed as a suitable strategy not only to increase soil quality, but also as a means of remediation of contaminated soils.

Carbon capture storage in the form of a SCP/biochar can also be described as one of the ways not to further increase, but on the contrary to reduce the production of carbon dioxide, thus greenhouse gas [15]. According to Woolf et al. [16] the production of biochar and its application to land can help reduce up to 12% of current anthropogenic CO<sub>2</sub> emissions.

In general, biochar is already a traditional universal means of improving soil fertility in developing countries. In recent years, however, biochar has become a major topic in developed countries. New technologies are constantly emerging and usable systems are being sought in order to find a system solution for the "biochar economy" on an industrial scale. The use of biochar is an effective strategy to cope with the ever-declining quality of agricultural land, high requirements for food self-sufficiency, the risk of contaminants in soils and the threat of the greenhouse effect.

### 1.2. Solid carbonaceous product/biochar certification

To produce certified SCP/biochar from FW, the thermochemical reductive treatment process should be defined together with pretreatment procedures of raw FW. The description of analyses includes determination of the solid yield of biochar and other parameters according to the two guidelines: The International Biochar Initiative (IBI) [17] and The European Biochar Certificate (EBC) [18]. Selected parameters for biochar certification according to guidelines IBI [17] and EBC [18] are reported in Table 1, the requirements are divided into biochar of category A/B (IBI) and biochar EBC – Urban/EBC - Agro (EBC). For biochar of category A and premium biochar, the limits of selected parameters are stricter. The selected general parameters in Table 1 are divided into toxicant assessment with their maximum thresholds and other parameters.

Table 1 Selected parameters for biochar certification according to IBI and EBC guidelines [17, 18]

General parameter	Selected parameter	Unit	Guidelines to biochar certification			
			International Biochar Initiative (IBI) [17]		European Biochar Certificate (EBC) [18]	
			Category A	Category B	EBC - Urban	EBC - Agro
Toxicant assessment, maximum allowed thresholds - HMs	As		13	100	13	13
	Cd		1.4	20	1.5	1.5
	Cr		93	100	90	90
	Cu	mg·kg <sup>-1</sup> dry wt-mass	143	6 000	100	100
	Pb		121	300	120	120
	Hg		1	10 <sup>a</sup>	1	1
	Ni		47	400	50	50
Other parameters	Zn		416	7 400	400	400
	C <sub>org</sub>	%	≥60	≥30	≥50	
	pH	pH	Declaration		Declaration	
	Electrical conductivity	dS·m <sup>-1</sup>	Declaration		Declaration	
	SBET	m <sup>2</sup> ·g <sup>-1</sup>	-		≥150	

Notes: C<sub>org</sub> - organic carbon; <sup>a</sup> methyl mercury 10 mg·kg<sup>-1</sup> and inorganic mercury 40 mg·kg<sup>-1</sup>.

Other options for certification of SCP/biochar of pyrolysis is certification as the soil amendment substance (SAS) as substances without a number of nutrients, which biologically, chemically or physically affect the soil, improve its state or increase the efficiency of fertilizers.

### 1.3. Food waste - thermal pyrolysis processing

In general, there exist many thermochemical treatment processes, which can be classified into two main categories such as thermochemical oxidative processes and thermochemical reductive processes. Thermochemical oxidative treatment processes include combustion, thus monoincineration or co-incineration. Thermochemical reductive processes include gasification, hydrothermal carbonization and pyrolysis, in which oxygen is absent or the amount of oxygen is substoichiometric [19].

The classes of thermochemical reductive treatment process are pyrolysis, gasification, and hydrothermal carbonization. Pyrolysis is the thermochemical reductive process of converting biomass, thus also FW, into carbon rich solid product (SCP/biochar), having yield above 10-80% carried out under a wide temperature range 100-1300°C, at wide residence time 0.05s-12h under low or atmospheric pressure [20]. Depending on the process temperature, pyrolysis can be divided into three classes: low-temperature pyrolysis (<500°C), medium-temperature pyrolysis (500-800°C) and high temperature pyrolysis (>800°C) [21]. Based on our previous research, we focused on medium-temperature pyrolysis for this work.

### 1.4. Aims

This paper presents preliminary results from a pilot study on FW processing and introduces a characterization of the produced SCP/biochar after thermal pyrolysis (TP) process for combustion energy and agricultural use. The analyses included determination of the following parameters: mixing FW with additives, pelletization process, pyrolysis residence time, process temperature, yield of biochar/SCP, yield of pyrolysis oil, yield of pyrolysis gas, calorific value, organic carbon ( $C_{org}$ ), Brunauer–Emmett–Teller (BET) surface area ( $S_{BET}$ ), P, Mg, K, Ca, HMs, pH, and electric conductivity (EC).

The overall goal of the paper is to increase the knowledge of the SCP/biochar produced from FW via TP and the conclusions may serve as the basis for biochar certification.

## 2. Material and methods

### 2.1. Pretreatment process

For this paper, the pretreatment of FW samples for TP consists of two consequent steps: mixing dried FW with additives and pelletizing this mixture. FW was mixed in 2 different ratios with the following additives: catalyst or/and organic additive.

The mixtures of dried raw FW with catalyst and organic additives were pelletized by pelletizing press. The additive types, ratio FS : ADD1 : ADD2 (ADD1 – organic additive, ADD2 – catalyst), moisture, and  $C_{org}$  after pelletization process are reported in Table 2. For these experiments, the pelletization process used an extrusion die having 6 mm.

Table 2 Feedstock composition after pelletization process

Additive type	Ratio FW : ADD1 : ADD2 (%)	Moisture (%)	$C_{org}$ (%)	
-	Mix0 (control): Dried and pelletized FW	100 : 0 : 0	10.88	54.78
Organic additive	Mix1: Wooden sawdust	75 : 25 : 0	8.68	50.06
Organic additive + catalyst	Mix2: Wooden sawdust + Zeolite	75 : 20 : 5	8.51	50.32

### 2.2. Thermal treatment process

TP was performed in laboratory, small-scale conditions, in a small-scale TP unit working under 600 °C. This unit works discontinuously, and the maximum capacity is around 5 kg·batch<sup>-1</sup> of feedstock (FS). The glass condenser attached to the pyrolyzer was used for the separation of gaseous products and the pyrolysis oil.

The input weight of FS samples was 3 000 g·batch<sup>-1</sup>. The FS was placed into the TP unit in a stainless-steel cylindrical reactor, During the experiments, the residence time was 340 - 410 minutes, and the temperature did not exceed 600 °C. Selected pellets containing FS and SCP/biochar are shown in Fig. 1.



Fig. 1. Left: pelletized dried food waste as feedstock before TP, right: SCP/biochar after TP.

### 2.3. Analytical procedures

#### Combustion test, determination of $C_{org}$ , and $S_{BET}$

The combustion tests, mean the energy efficiency of samples was measured by the semi-automatic device (IKA C 200) under the standard laboratory conditions. In the first part, the random small doses were determined for combustion tests. The small doses were ground to fine dust by friction dishes. 0.4-0.8 g of fine dust were prepared for calorimetric measurement. The dose was interfaced with the spark plug circuit using a cotton thread. The entire specimen holder assembly was placed in a calorimetric bomb which was sealed and supplemented with pure oxygen at an internal pressure of 34 bar. The calorimetric bomb was input to a calorimetric heat-insulated container with demineralized water. With constant intensive stirring of water in a calorimetric vessel, the water temperature was monitored for 3 minutes until a constant value was established. Subsequently, a bomb sample was ignited by the ignition circuit, and a calorific value was determined from the temperature change in the calorimetric vessel as a result of the combustion tests of the sample. The results were the average of the three calorific values for each mix.

$C_{org}$  determination was performed by Shimadzu TOC-LCSH/CPH analyzer. The evaluation was performed using the TOC-L Sample Table Editor software. The crushed sample was placed in a container and added to analyzer. The input temperature was 900 °C, the sample was analysed at 5-10 minutes depending on the weight and type of sample. The test was performed 3 times and the average was calculated.

$S_{BET}$  was measured by Quantachrome Nova 3200e gas adsorption and using NovaWin software. Nitrogen was used with the setting: adsorption/desorption 0.050/0.050, time equilibrium adsorption/desorption was 240/240 s, time equilibrium output adsorption/desorption was 480/480 s, temperature was -196 °C. Samples were degassed in a vacuum dryer for 24 hours at 50 °C.  $S_{BET}$  was determined at five points using a multi-point BET method. Bipolar junction transistor (BJT) analysis was used for pore size analysis. 24 points were measured for adsorption and 38 points were measured for desorption.

#### Determination of P, Mg, K, Ca

Each sample is first homogenized using a Retsch MM 200 oscillating mill. Aqueous leachate is then prepared for each sample: 5 g of sample were weighed and 50 ml of MiliQ water was added (1:10). The sample was then shaken for 24 hours and then filtered through filtration paper. The digestion is carried out using the ETHOS UP microwave digestion system from ChromSpec. This is acid digestion using aqua regia (1:3 mixture of HNO<sub>3</sub> and HCl). First, 2x0.25 g of sample is weighed into two cartridges. 3 mL of HNO<sub>3</sub> and 9 mL of HCl are added to each of them. The temperature program is described in Table 3. The mixture was then transferred to a 50 mL volumetric flask and made up to the mark with MiliQ water.

Table 3 Microwave decomposition temperature program

Step	Time (min)	T (°C)	Power (W)
1.	15	200	1800
2.	15	200	1800
3. (cooling)	10	-	-

The continuous source of radiation was used Xe lamp. A flame was used as the atomization source for the determination of Mg, Ca and K and electrothermal atomization was used for P. Standard calibration solutions for individual HMs were prepared in the concentration range of 1 g·L<sup>-1</sup>. Samples were diluted before measurement according to the needs and sensitivity of the instrument.

An atomic absorption spectrophotometer with a continuous radiation source ContrAA 800 from Analytik Jena was used for the determination of the above-mentioned elements in aqueous leachate and acid digestion. For K, Mg, and Ca this was flame atomization (using an acetylene-air combination) and for P it was electrothermal atomization using a cuvette with a platform. The measurement conditions are listed in Tables 4 and 5. Firstly, standard solutions were prepared and analyzed. The absorbance of each solution was measured three times. The average values of concentrations were calculated.

Table 4 Conditions for Ca, Mg, and K analysis

Element	Wavelength (nm)	Acetylene-air flow (L·h <sup>-1</sup> )	Burner height (mm)
Ca	422.67	80	5 - 9
Mg	285.21	70	5 - 8
K	766.49	80	5 - 9

Table 5 Conditions for P analysis

Element	Wavelength (nm)	Modifier	Drying T (3 stages) (°C)	T pyrolysis (2 stages) (°C)	T atomization (°C)	Cleaning T (°C)
P	213.62	Pd(NO <sub>3</sub> ) <sub>2</sub>	80, 90, 110	350, 1050	2500	2550

#### Determination of heavy metals

For comparison, the content of HMs in FS and SCP/biochar samples were measured by two optimization methods. For the optimization of the Advanced Mercury Analyzer (AMA) and Atomic Absorption Spectrometer (AAS) methods for determination of selected HMs certified reference materials of calibration standard solutions ASTASOL® with concentration of measured metal 1000±0.002 mg·L<sup>-1</sup> in 5% HNO<sub>3</sub>, from Analytika Ltd., Czech Republic (Czech Metrological Institute), were used. All other used chemicals were of analytical reagent grade.

Extraction in distilled water (water extraction) was performed as follows: 5 grams of the milled sample was weighted to the plastic bottle and 50 mL of water (prepare on Mili-Q Ultrapure Water Systems) was added. The mixture was shaken for 24 hours and then filtered.

Digestion in *Aqua Regia* was performed as follows: 10 grams of the milled sample was transferred to a flask containing 60 mL of *Aqua Regia* (HCl:HNO<sub>3</sub> in a ratio 3:1). The sample thus prepared was boiled under reflux for 2 hours. After cooling, the sample was filtered. For analysis, it was diluted with distilled water in a ratio of 1:8.

Analyses of HMs contents were performed using atomic absorption spectrometer with electrothermal atomization ZEE nit 60 from Analytik Jena (Germany) with Zeeman background correction and selected hollow cathode lamp by Photron (Australia). Optimal measurement parameters and specific temperature programs, reported in Table 6, were used. Other conditions were graphite cuvette with platform, slit width 0.2-0.8 nm, used current was 3-8 mA and injection volume 20 µL. All obtained results are the average of three separate independent determinations, each was measured for atomic absorption spectrometer five times.

Table 6 Thermal programs for the determination of selected HMs: As, Cd, Cr, Cu, Pb, and Zn

Metal	Wavelength (nm)	Drying 1/2/3 (°C)	Pyrolysis (°C)	Atomization (°C)	Cleaning (°C)
As	193.70	90/100/110	1 000	2 200	2 400
Cd	228.80	90/105/110	500	1 500	2 300
Cr	357.90	90/110/120	1 000	2 100	2 400
Cu	324.80	90/110/130	1 000	1 800	2 300
Pb	283.30	90/100/110	1 100	2 000	2 300
Zn	213.90	90/105/120	600	1 800	2 300

Hg was analysed on atomic spectrometer Advanced Mercury Analyzer AMA 254 (Altec, s. r. o., Czech Republic) at wavelength 253.65 nm under conditions reported in Table 7.

Table 7 Temperature mode of the AMA 254, for the determination of Hg

Process	Drying (°C)	Decomposition (°C)	Waiting (s)
Cleaning	60	120	45
Blank	60	60	45
Calibration	60	120	45
Determination	10	200	50

### Determination of pH, electric conductivity, and other parameters

The EC and pH parameters were measured in aqueous extracts. EC was measured on conductometer ECTestr 11+ (Oakton Instruments), and pH values were measured on a Shott pH meter (SI Analytics, GmbH), and calibration was performed on pH 7 buffer. pH was measured using Titrator Scot TitroLine alpha plus equipped with combined glass electrode WTW Sen Tix 81. In principle, 1 g of biochar was milled in laboratory ball mill (steel), then it was dispersed in 10 mL of deionized water. The suspension constantly stirred for 24 hour, filtered and then pH was measured. The reported values are averaged values of three measurements.

## 3. Results and discussion

The characterization of the SCP/biochar of FW was carried out to identify its combustion energy and potential for agricultural use and/or glue-green infrastructure. The results included these parameters: temperature and density of pelletizing process, temperature of TP process, yield of SCP/biochar, yield of pyrolysis oil, yield of pyrolysis gas, calorific value,  $C_{org}$ ,  $S_{BET}$ , P, Mg, K, Ca, HMs, pH, and EC.

### 3.1. Pretreatment and pyrolysis tests

FS composition from FW and SCP/biochar composition after TP is reported in Table 8. The raw FW (Mix0), FW + wooden sawdust (Mix1), and FW + wooden sawdust + zeolite (Mix2) and crushed limestone as one catalyst were used. These selected parameters were measured: moisture, temperature, yield of SCP/biochar, and yield of pyrolysis oil. The highest SCP/biochar yield was achieved with raw dried FS and 25% wooden sawdust (Mix1).

Table 8 SCP/biochar composition after TP: moisture, temperature, and yields

Additive type	Ratio FW:ADD1:ADD2 (%)	Moisture (%)	Maximum temperature (°C)	Yields (%)		
				SCP/biochar	Pyrolysis oil	Pyrolysis gas
Mix0 (control): Dried and pelletized FW	100 : 0 : 0	3.94	600	30.9	41.7	27.4
Mix1: Wooden sawdust	75 : 25 : 0	3.97	600	35.3	43.3	21.3
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5	6.05	600	32.5	43.3	24.2

Notes: FS-feedstock, SCP-solid carbonaceous product, ADD-additive

### 3.2. Characteristic of samples

#### Determination of Calorific value, $C_{org}$ , and $S_{BET}$

SCP/biochar composition after TP is reported in Table 9. The zeolite was used as a catalyst. One organic additive was used: wooden sawdust. These selected parameters were measured: calorific value,  $C_{org}$ , and  $S_{BET}$ .

Table 9 SCP/biochar composition after TP: calorific value,  $C_{org}$ , and  $S_{BET}$

Additive type	Ratio FW:ADD1:ADD2 (%)	Calorific value $MJ \cdot kg^{-1}$	$C_{org}$ (%)	$S_{BET}$ ( $m^2 \cdot g^{-1}$ )
Mix0 (control): Dried and pelletized FW	100 : 0 : 0	23.82	66.51	1.36
Mix1: Wooden sawdust	75 : 25 : 0	26.13	72.45	1.83
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5	22.36	65.30	2.17
Limits according EBC, EBC Urban / Agro [18]		n/d	50	150

Notes: FS-feedstock, SCP-solid carbonaceous product, ADD-additive, n/d-not defined

Calorific value is not a specific evaluated parameter according to IBI [17] or EBC [18] guidelines, however, the results in Table 9 show a high energy potential of FW utilization.

The results in Table 9 show that the  $C_{org}$  of the sample (Mix0) is higher than required by the EBC Urban / Agro [18], thus this parameter respects the guideline. To increase this parameter, additional samples were mixed with organic material, i.e. wood sawdust to increase the  $C_{org}$  content. Testing confirmed that there was a slight increase in the organic carbon content of the Mix1 sample, but the increase is not significant.

Generally, biochar is mainly composed of organic carbon, while the inorganic portion mainly contains minerals such as Ca, Mg, K, P, and inorganic carbonates depending on the FS type of FW. The morphology of surface biochar after TP of FS is illustrated in Figure 2, which shows scanning electron microscopy (SEM) image obtained by using a back scattered electron detector. The light parts in Figure 2 represent parts containing elements with higher atomic numbers than the surrounding area.

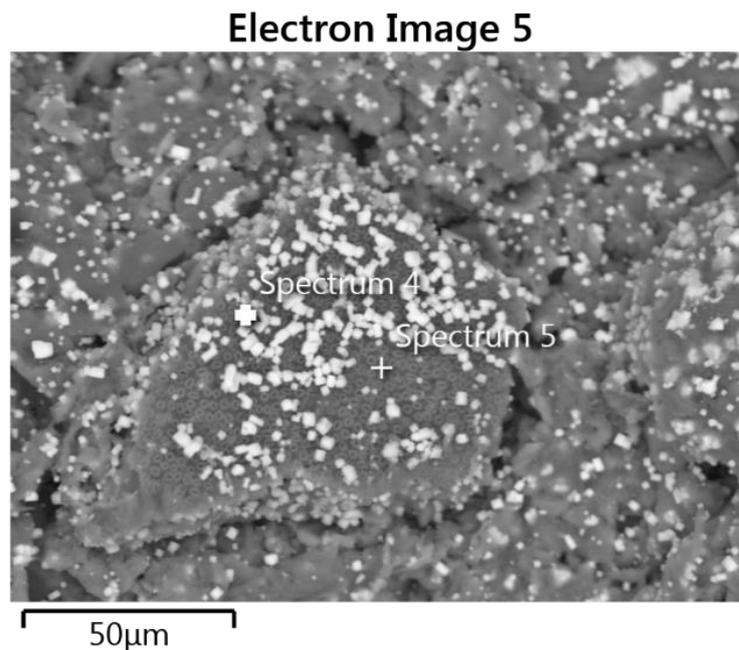


Fig. 2. SEM Surface morphology of FW biochar after TP.

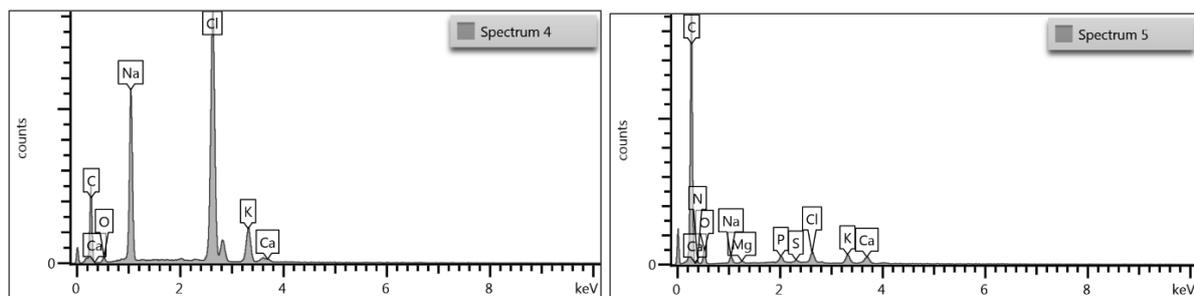


Fig. 3. EDX analysis of FW biochar: spectrum 4 and spectrum 5 according SEM photo in Figure 2.

The results of EDX analysis of these light parts are reported in Figure 3. It can be seen, that the light parts contain predominantly C, N, O, Na, Mg, P, S, Cl, K, and Ca. The dark parts on the photo in Figure 2 represent the carbonaceous part (ash, mineral matter) of biochar. Close inspection of the Figure shows a porous structure. Based on the characteristics of FW and TP process conditions, the biochar may contain non-pyrolyzed residues of the FW and stable condensed aromatic structures resulting from the high temperature transformation of the original organic matter of raw FW. Mineral formation depends on the FS type and if biochar is not fully carbonized and exhibits carbonized and noncarbonized phases.

The morphology of surface biochar is characterized in Table 9 by the parameter  $S_{BET}$  - in this case the limit value was not reached for any of the samples according to the guidelines.

### Determination of P, Mg, K, and Ca

SCP/biochar composition after TP is reported in Table 10 and Table 11. The zeolite was used as a catalyst. One organic additive was used: wooden sawdust. These selected parameters were measured: P, Mg, K, and Ca.

Table 10 SCP/biochar composition after TP: P, Mg, K, and Ca, extraction in water

Additive type	Ratio		P (mg·kg <sup>-1</sup> DS)	Mg (mg·kg <sup>-1</sup> DS)	K (mg·kg <sup>-1</sup> DS)	Ca (mg·kg <sup>-1</sup> DS)	Total (mg·kg <sup>-1</sup> DS)
	FW:ADD1:ADD2	(%)					
Mix0 (control): Dried and pelletized FW	100 : 0 : 0		155	114	24 038	951	<b>25 257</b>
Mix1: Wooden sawdust	75 : 25 : 0		97	100	12 692	734	<b>13 623</b>
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5		540	34	9 463	660	<b>10 698</b>

Table 11 SCP/biochar composition after TP: P, Mg, K, and Ca, extraction in *Aqua Regia*

Additive type	Ratio		P (mg·kg <sup>-1</sup> DS)	Mg (mg·kg <sup>-1</sup> DS)	K (mg·kg <sup>-1</sup> DS)	Ca (mg·kg <sup>-1</sup> DS)	Total (mg·kg <sup>-1</sup> DS)
	FW:ADD1:ADD2	(%)					
Mix0 (control): Dried and pelletized FW	100 : 0 : 0		14 426	4 421	40 186	7 716	<b>66 749</b>
Mix1: Wooden sawdust	75 : 25 : 0		10 315	3 650	29 299	6 892	<b>50 156</b>
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5		10 233	2 650	30 031	4 051	<b>46 966</b>

Two methods of determining the parameters were performed for this work: extraction in water and extraction in *Aqua Regia*. According to the IBI [17] and EBC [18] guidelines as for the Corg parameter, other parameters (nutrients) were monitored: P, Mg, K, and Ca. These parameters are reported in Tables 10 and 11. Based on the results, it was confirmed that the parameters respect the requirements of EBC Urban / Agro, thus, nutrients are contained in the biochar of FW after TP.

### Determination of heavy metals

SCP/biochar composition after TP is reported in Table 12 and Table 13. The zeolite was used as a catalyst. One organic additive was used: wooden sawdust. These selected HMs were measured: As, Hg, Cd, Cr, Cu, Ni, Pb, and Zn.

Table 12 SCP/biochar composition after TP: HMs, extraction in water

Additive type	Repetition number	HMs, extraction in water (mg·kg <sup>-1</sup> DS)								Total
		As	Hg	Cd	Cr	Cu	Ni	Pb	Zn	
Mix0 (control): Dried and pelletized FW	No. 1	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.01	0.16	<b>0.17</b>
	No. 2	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.01	0.01	<b>0.02</b>

Notes: LOD-limit of detection

Table 13 SCP/biochar composition after TP: HMs, extraction in *Aqua Regia*

Additive type	Repetition number	HMs, extraction in <i>Aqua Regia</i> (mg·kg <sup>-1</sup> DS)								Total
		As	Hg	Cd	Cr	Cu	Ni	Pb	Zn	
Mix0 (control): Dried and pelletized FW	No. 1	0.81	0.00	0.10	0.00	<LOD	6.88	2.74	4.14	<b>15</b>
Mix0 (control): Dried and pelletized FW	No. 2	<LOD	0.01	<LOD	0.00	<LOD	9.78	2.30	3.48	<b>16</b>
Limits according EBC, EBC Urban/Agro [18]		13	1	1.5	90	100	50	150	400	<b>806</b>
Limits according IBI, category B [17]		100	10	20	100	6 000	400	300	7 400	<b>14 330</b>

Notes: LOD-limit of detection

Two methods of determining the HMs were performed for this work: extraction in water and extraction in *Aqua Regia*. As expected, the results show (verified only on sample Mix0) that a low level of HMs was detected. Therefore, the tested samples meet the limit values according to the guidelines for the biochar certification.

### Determination of pH, electric conductivity, and other parameters

SCP/biochar composition after TP is reported in Table 14. The zeolite was used as a catalyst. One organic additive was used: wooden sawdust. These selected HMs were measured: pH, EC, concentration of NH<sub>4</sub><sup>+</sup>, PO<sub>4</sub>, NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub>.

Table 14 SCP/biochar composition after TP: pH, EC, concentration of NH<sub>4</sub><sup>+</sup>, PO<sub>4</sub>, NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub>, extraction in water

Additive type	Ratio FW:ADD1:ADD2 (%)	pH (-)	EC (μS·cm <sup>-1</sup> )	c NH <sub>4</sub> <sup>+</sup> -N (mg·L <sup>-1</sup> )	c NH <sub>4</sub> <sup>+</sup> (mg·kg <sup>-1</sup> )	c PO <sub>4</sub> -P (mg·L <sup>-1</sup> )	c PO <sub>4</sub> (mg·kg <sup>-1</sup> )
Mix1: Wooden sawdust	75 : 25 : 0	9.4	898	1.5	19.2	6.0	183.4
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5	10.2	900	1.1	14.4	56.0	1 702.7

Additive type	Ratio FW:ADD1:ADD2 (%)	c NO <sub>3</sub> <sup>-</sup> -N (mg·L <sup>-1</sup> )	c NO <sub>3</sub> <sup>-</sup> (mg·kg <sup>-1</sup> )	c Cl <sup>-</sup> (mg·L <sup>-1</sup> )	c Cl <sup>-</sup> (mg·kg <sup>-1</sup> )	c SO <sub>4</sub> <sup>2-</sup> (mg·L <sup>-1</sup> )	c SO <sub>4</sub> <sup>2-</sup> (mg·kg <sup>-1</sup> )
Mix1: Wooden sawdust	75 : 25 : 0	5.9	260.4	6 600	65 778	38	379
Mix2: Wooden sawdust + Zeolite	75 : 20 : 5	4.5	197.6	6 100	60 483	79	783

Notes: c-concentration, EC-electrical conductivity

The results shown in Tables 14 and 15 confirm the high content of nutrients. However, high EC was found, caused mainly by salt ions - from this point of view, it will be complicated to apply biochar of FW directly to agricultural land without further treatment.

### 3.3. Summarizing discussion

In this research, we present properties of three types of SCP/biochar produced via TP process of FW. Dried FW was mixed in different ratios with the catalyst and organic additive. As follows from the results, the FS and SCP/biochar can find energy or agricultural use / blue-green infrastructure.

The pilot study obtained the characteristics of the SCP/biochar and found the following:

- i) SCP/biochar from FW contains more than the limit, e.g. 50% content of the amount of  $C_{org}$  in comparison with the limit content according to EBC certification; the addition of organic additive increases the  $C_{org}$  content in the resulting biochar only slightly;
- ii) within the  $S_{BET}$  parameter, the performed analyzes did not show sufficient porosity in comparison with the limit content according to the EBC certification, which is  $\geq 150 \text{ m}^2 \cdot \text{g}^{-1}$  (measured only in units of  $\text{m}^2 \cdot \text{g}^{-1}$ );
- iii) SCP/biochar of FW shows high calorific values above  $22 \text{ MJ} \cdot \text{kg}^{-1}$  and confirms high energy potential;
- iv) SCP/biochar samples of FW contain an expected high content of nutrients (P, Mg, K, Ca and N). Within the requirements according to the EBC certification (but also the IBI), the condition of biochar certification for "biochar" is fulfilled from this point of view;
- v) SCP/biochar of FW contains only a minimal load of selected HMs, from this point of view it is again a matter of meeting the conditions of EBC and IBI certification;
- vi) from the point of view of other parameters, high EC is essential, which is related to the salinity of the samples - it turns out that treated FW without other.

#### 4. Conclusion

The aim of this work is to present TP of FW. The data were compared with the biochar certification guidelines. The TP tests were carried out by using full-scale unit, which correspond to real conditions. The aim of this pilot study is to present a full-scale reactor for TP of FW. In addition, we focused on pelletization process, pyrolysis residence time, process temperature and parameters such as yields, calorific value,  $C_{org}$ , pH, EC. SCP/biochar seems to be attractive solution for energy, agriculture use, and glue-green infrastructure - as a substrate for green roofs, walls, and parking lots. However, the high electrical conductivity detected in the samples due to salt in the FW represents a complication for direct use in agriculture. SCP/biochar can retain water and capture pollution. TP represents an eco-friendly way of FW disposal, which belongs among the important strategies of circular economy.

#### Acknowledgment

This paper has been worked with the financial support of TA ČR in the project No. TJ02000262 "Food processing waste into a solid carbon product for material use".

#### References

1. Zamanzadeh, M., et al., Biogas production from food waste via co-digestion and digestion- effects on performance and microbial ecology. *Scientific Reports*, 7(1): p. 17664 (2017)
2. Gerba, C.P. and J.E. Smith, Sources of Pathogenic Microorganisms and Their Fate during Land Application of Wastes The opinions expressed in this article are those of the authors and do not necessarily reflect those of the USEPA. *Journal of Environmental Quality*, 34(1): p. 42-48 (2005)
3. Wang, X., et al., Effects of the feeding ratio of food waste on fed-batch aerobic composting and its microbial community. *Bioresource Technology*, 224: p. 397-404 (2017)
4. Kunwar Paritosh, Sandeep K. Kushwaha, Monika Yadav, Nidhi Pareek, Aakash Chawade, and Vivekanand Vivekanand, "Food Waste to Energy: An Overview of Sustainable Approaches for Food Waste Management and Nutrient Recycling," *BioMed Research International*, vol. 2017, Article ID 2370927, 19 pages. <https://doi.org/10.1155/2017/2370927> (2017)
5. Purabi R. Ghosh, Derek Fawcett, Shashi B. Sharma, and Gerrard Eddy Jai Poinern, "Progress towards Sustainable Utilisation and Management of Food Wastes in the Global Economy," *International Journal of Food Science*, vol. 2016, Article ID 3563478, 22 pages, 2016. <https://doi.org/10.1155/2016/3563478> (2016)
6. European Commission ENVIRONMENT. <http://ec.europa.eu/environment/waste/compost/index.htm> (2019)
7. Nelles, Michael and Grünes, J and Morscheck, Gert. Waste Management in Germany – Development to a Sustainable Circular Economy? *Procedia Environmental Sciences* [online]. *Procedia Environmental Sciences*, 14, [https://www.researchgate.net/publication/305892463\\_Waste\\_Management\\_in\\_Germany\\_-\\_Development\\_to\\_a\\_Sustainable\\_Circular\\_Economy/citation/download](https://www.researchgate.net/publication/305892463_Waste_Management_in_Germany_-_Development_to_a_Sustainable_Circular_Economy/citation/download) (2016)
8. Vološinová, D., Kořínek, R. a Čejka, E. Způsoby nakládání s biodepadem v Praze a ve vybraných hlavních městech států Evropské unie. *Vodohospodářské technicko-ekonomické informace*, 2019, roč. 61, č. 3, str. 31–35. ISSN 0322-8916.
9. Ricci-Jürgense M., Confalonieri A., CIC a Newman D. ANAEROBIC DIGESTION MARKET REPORT in ITALY [online]. In: [www.worldbiogasassociation.org](http://www.worldbiogasassociation.org), <http://www.worldbiogasassociation.org/wp-content/uploads/2018/07/Italy-International-Market-Report.pdf>
10. The Food and Agriculture Organization (FAO). The Food and Agriculture Organization (FAO) [online]. The Food and Agriculture Organization (FAO) <http://www.fao.org/faolex/results/en/?query=food%20waste>

11. Smid J. Waste management studies (Studie nakládání s odpady). Prague, 2013, 82 s. <https://webcache.googleusercontent.com/search?q=cache:iCctcW517CQJ:https://is.cuni.cz/webapps/zzp/download/130115216+&cd=1&hl=cs&ct=clnk&gl=at>.
12. Li, Q., et al., Biochar assisted thermophilic co-digestion of food waste and waste activated sludge under high feedstock to seed sludge ratio in batch experiment. *Bioresource Technology*, 249: p. 1009-1016. (2018)
13. López-Cano, I., et al., Biochar improves N cycling during composting of olive mill wastes and sheep manure. *Waste Management*, 2016. 49: p. 553-559 (2016)
14. Liang, B., et al., Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Science Society of America Journal*, 2006. 70(5): p. 1719-1730 (2006)
15. Randolph, P., et al., Effect of biochars produced from solid organic municipal waste on soil quality parameters. *Journal of Environmental Management*, 2017. 192: p. 271-280 (2017)
16. Woolf, D., et al., Sustainable biochar to mitigate global climate change. *Nature Communications*, 2010. 1: p. 56 (2010)
17. IBI (2015) International Biochar Initiative. Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil. Product Definition and Specification Standards (2015)
18. EBC (2022) European Biochar Certificate - Guidelines for a Sustainable Production of Biochar. European Biochar Foundation (EBC), Arbaz, Switzerland. [https://www.european-biochar.org/media/doc/2/version\\_en\\_10\\_1.pdf](https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf). Version 10.1E of 10th January 2022 (2022)
19. Šejvl, R. Energy gasification and its way to higher efficiency and energy recovery of waste. *Technical Systems Usable for Energy Waste Utilization, Overview of Development Trends Their Way to Achieving Higher Energy Efficiency* (2009)
20. Racek J., Sevcik J., Chorazy T., Kucerik J., Hlavinek P. Biochar – recovery material from pyrolysis of sewage sludge: a review. *Waste and Biomass Valorization*. <https://doi.org/10.1007/s12649-019-00679-w> (2019)
21. Capodaglio, A. G., Callegari, A., Feedstock and process influence on biodiesel produced from waste sewage sludge, *Journal of Environmental Management*, Volume 216. pp 176-182. ISSN 0301-4797. <https://doi.org/10.1016/j.jenvman.2017.03.089> (2018)