Magyar Agrár- és Élettudományi Egyetem

QUALITY BIOCHAR PRODUCTION FOR AGRICULTURAL USE

Doctoral (PhD) theses

by

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1. INTRODUKTION, OBJECTIVES

Biochar is produced from biomass using a technique called pyrolysis. In the process, due to the absence of oxygen - at high temperature - the organic material *turns into cracked carbon with a large surface area* and is present in a solid matrix. Biochar is a biologically stable, black product. Due to the intended use, it can only be made from properly controlled biomass samples.

Its use helps reduce global warming, as the carbon placed in the soil remains unchanged for a long time and does not burden the atmosphere, while helping the soil to be fertile. During the pyrolysis process, renewable energy that can be used in addition to biochar is also generated (heat energy or, by converting it, electricity).

Nowadays, a significant part of international research analyzes the relationship between soil and biochar. The researchers dealing with the production set the goal of aligning the quality of the products with soil nutrition management as a priority task.

The conversion of biomass into biochar mitigates climate change, as it has less influence on the atmospheric GHG concentration compared to traditional biomass decomposition.

My goals:
- *based on international and domestic literature, research into existing biochar production technologies,*
- *producing material containing no harmful substances,*
- *of high quality,*
- *and time-resistant (stable,*
- *creating efficient machinery and technology,*
- *creating the production line of the process,*
- *energetic examination of the system,*
- *analysis of the composition of the obtained biochar.*

The latter is important so that the biochar does not contain components that have a negative effect on the vegetation in the soil (in the growing medium).

Its most important advantages:
- *it retains important substances for plants in the growing medium,*
- *restores the pH value of the soil,*
- *increases soil's water retention and*
- *localizes toxic metals (significantly), etc.*

2. MATERIAL AND METHODS

2.1 The tests and their instruments

Agricultural biomasses and their wastes are very diverse in their physical appearance. According to H. Liang (2016), the raw materials are of great importance for the morphological characteristics of the biochar obtained during the process. Therefore, pyrolysis requires a suitable physical state of the biomass, which is why the very different biomass structures must be brought to a suitable state for use.

Through shredding, materials can be dried more energy-efficiently. Compaction (e.g. pelletizing) results in less space requirement, and the energy density of the material is higher.

Before creating a sample device, which was defined as a goal, the thermal degradation of the materials was investigated in the laboratory, and the results obtained were used in the design.

Important material features:

- moisture content,
- particle size distribution,
- material composition,
- heat of combustion, calorific value,
- gas flow characteristics as a result of the material thickness.

In the decomposition (TGA) experiments, I measured:

- the ash content,
- the amount and composition of the gas produced,
- the burn-through rates at the topmost points of the stacks,
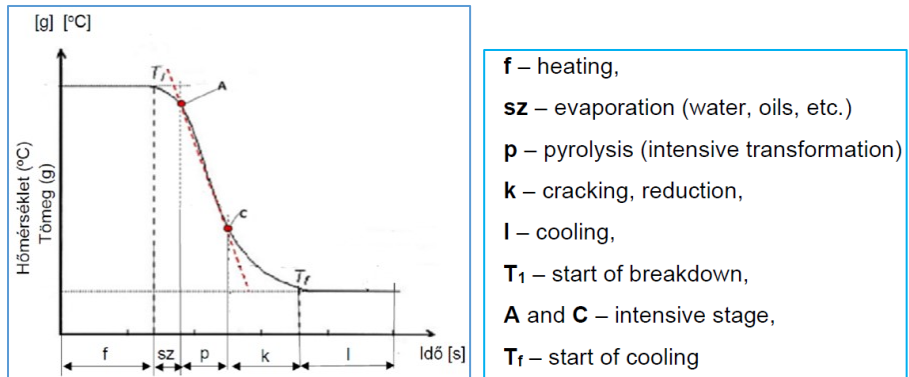- depending on the particle size, the pressure and mass flow required for gas flow.

I measured using the experimental equipment:

- The amount of recirculated gas.
- The (proportion of) ash and carbon content.
- Particle size distribution of the biochar.
- The energy balance of the system (the required and obtained energy).
- We determined the internal material composition of biochar (e.g. heavy metals, PAH content, etc.)
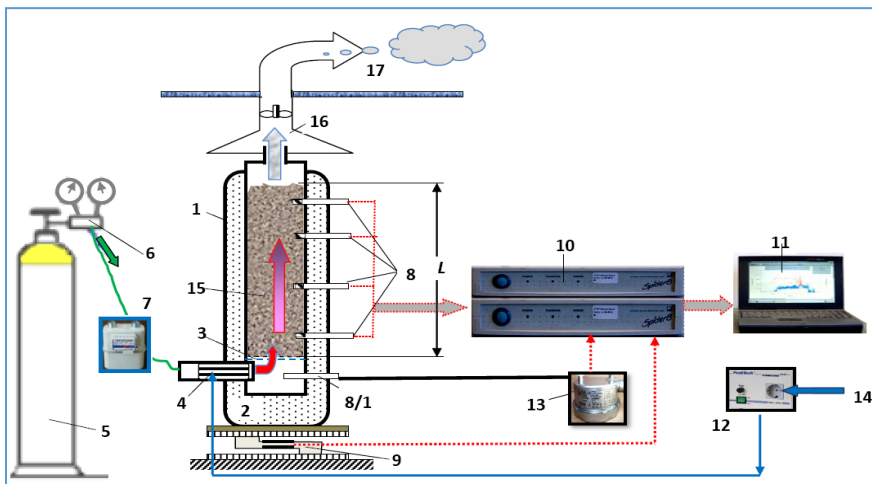
I carried out my tests in the accredited laboratory of NAIK Agricultural Machine Experiment Institute. Most of the instruments were available, but new testing units were also designed and manufactured.

2.2 TGA test methods and instruments

Typical data of TGA values

|	
f – heating,
sz – evaporation (water, oils, etc.)
p – pyrolysis (intensive transformation)
k – cracking, reduction,
l – cooling,
T_1 – start of breakdown,
A and **C** – intensive stage,
T_f – start of cooling

1. Figure TGA diagram characteristic points (for personal evaluation).

2. Figure Lab unit (partially owned design).

Laboratory unit operating with nitrogen gas heating:

1- generator body,
2- insulation,
3- material grid,
4- radiator,
5- N gas cylinder,
6- gas regulator,
7- gas meter,
8- material temperature sensors
8/1- gas temperature sensor,

9- mass sensor (Hottinger),
10- data collector (multi-channel),
11- PC,
12- heating controller,
13- gas pressure sensor,
14- electrical connector,
15- biomass,
16- gas collector,
17- gas outlet.
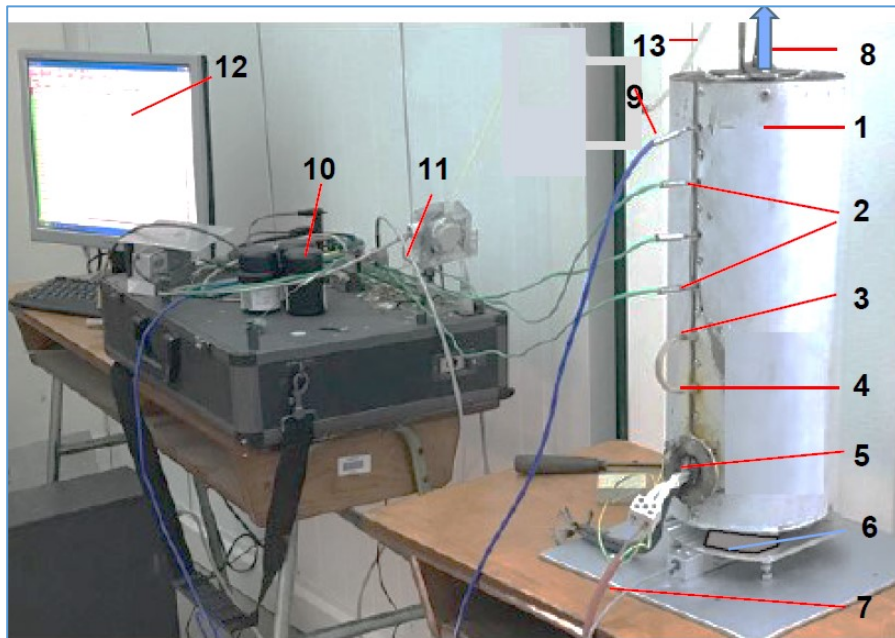
2. Fig. The unit with direct electric heating, suitable for gas recirculation

(can be operated up to 1300oC)

Abbreviations in the figures:

1. Isolated carbonization test 2. temperature gauges 3. gas return 4. air introduction 5. heater 6. metric scale 7. lead from the regulator 8. gas outlet 9. gas discharge to the analyzer 10. electrical signal converter 11. gas pressure sensor 12. record display of data 13. gas hose for returning the gas

This experimental unit was also suitable for demonstrating the effects of our raw gas recirculation.

2.3 Preparation of materials, their characteristics, their effect on processes

We used a laboratory shredder to produce the appropriate particle size. Shredding reduces the size of individual pieces (x_n), but increases the total surface area of the pieces (F_n), which is decisive from the perspective of drying and pyrolysis:

$$F_n = F_0 \frac{x_0}{x_n} (\text{mm}^{2)}$$

The number of grains before (x_o) and after (x_n) shredding.

For the various materials, we determined the percentage of particle distribution by size.

The relative void volume (porosity - ε) is the value of the void volume between the grains relative to the total volume (Ahmed S., 2010):

$$\varepsilon = \frac{V_h}{V + V_h}$$

Where:

- V = the material volume (m^3)
- V_h = the so-called void volume (m^3)

Porosity can also be calculated from the bulk density, in which case, in addition to the volume of the grains, the volume between the grains - filled with air - must also be taken into account:

$$\rho_t = \frac{m}{V+V_h} (\text{kg/m}^{3)}$$

Where:

m = mass of the material (kg).

As such, porosity:

$$\varepsilon = 1 - \frac{\rho_t}{\rho}$$

Where:

ρ = density of the original material (kg/m^3)

During pyrolysis, air or product gas flows through.

The intensity of gas flow is proportional to the pressure gradient of the system *(Darcy - Klinkenberg's law shows gas permeation in rarefied systems, i.e. when the mean free path of the molecules is of the same order of magnitude as the characteristic size of the pore).*

In other words, the homogeneous gradient: the difference in gas pressure at upper (p_o) and lower (p_k) levels, divided by the distance between the measurement points (q_g):

$$q_h = \frac{\Delta p}{h} \qquad (\text{Pa/m})$$

- $\Delta p = (p_k - p_o)$ = gas pressure difference (Pa)
- h = distance of measurement points (m)

The properties of the granular mass and the gas must also be considered when discharging the gas through the grain gaps (κ factor):

$$\kappa = (\varepsilon \cdot \rho q \cdot)/\mu$$

Where:

- ε = porosity of the granular aggregate,
- ρ = density of the gas [kg/m^3],
- μ = dynamic viscosity of the gas [Pa s, kg $\cdot$ m^{-1} $\cdot$ s^{-1}]
- q = the gravitational constant [m^3/kg s^2].

"κ" can also be called the gas conductivity of the set.

In conclusion, the conductivity of various materials depends on the degree of comminution, the strength of the materials, the shape of the particles (e.g. pellets, planer shavings, ground softwood or hardwood, fibrous chips, etc.). Based on these, the set can be coarse- or fine-grained, i.e. containing both large and small particles, as well as hard and soft particles, etc. Hard pellets are considered the best homogenously granulated, where conductivity is almost constant throughout the entire layer thickness. During pyrolysis, the resistance of the lower and upper layers is different for highly inhomogeneous materials. Conductivity deteriorates with strong ash generation.

The yield of mass flowing through a unit cross-section: kg/m^2 (inhomogeneous gradient).

Viewed macroscopically, it gives the value of the average gas velocity (represents a cross-sectional average value). The flows inside the mass of material are ultimately determined by its porosity (ε), as such:

$$v = \frac{q_i}{\varepsilon}$$

Therefore, there is a difference between yield-based intensity and internal intensity.

A distinction must be made between the flow intensity related to the flow rate (yield, $\dot{Q}$) and the speed of the gas flowing through the material (v). The characteristics of the system can be calculated, but several factors must be determined in advance on an experimental basis. The pressure change of the gas flowing through the pile of chips is a dependent of the change in air speed, which can be determined by the following measurements:

$$\Delta p = f\left(v_f\right)$$

Among the factors that create a pressure difference, the most important in pyrolysis systems is the temperature-dependent gas formation intensity in

the case of various material characteristics (energy, moisture content, particle density, bulk density, etc.).

A more accurate model can also be created if the intensity of gas outflow, which is characteristic of individual grains and occurs during temperature changes, is also taken into account, but the obstacles to this are completely random grain shapes.

3. RESULTS AND DISCUSSION

3.1 Weight loss as a dependent of moisture content and temperature

Taking the air-dry material as 100% in the calorimeter, the moisture content was increased to 25%, and 50%. The rate of wood weight loss was measured as a dependent of time at three high temperatures (Figure 4).
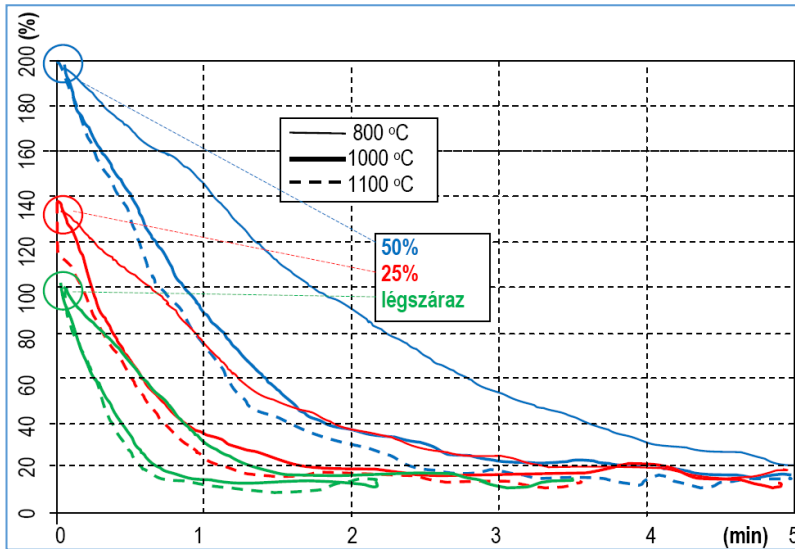

4. Figure Weight decrease by time on different temperatures and moisture contents

We can conclude that regardless of the moisture content, the difference in the amount of remaining material is not significant, but the required time depends on the moisture content of the materials to a large extent, but even more so on the heating temperature.

3.2 Effect of heating temperature on weight loss

Generally, the most basic method, thermo-gravimetric analysis, is used to measure and model some phenomena of pyrolysis (hereafter TGA). The curves recorded in FVM INAIK's laboratory (Figure 5) clearly show the effect of temperature on the level of mass loss.
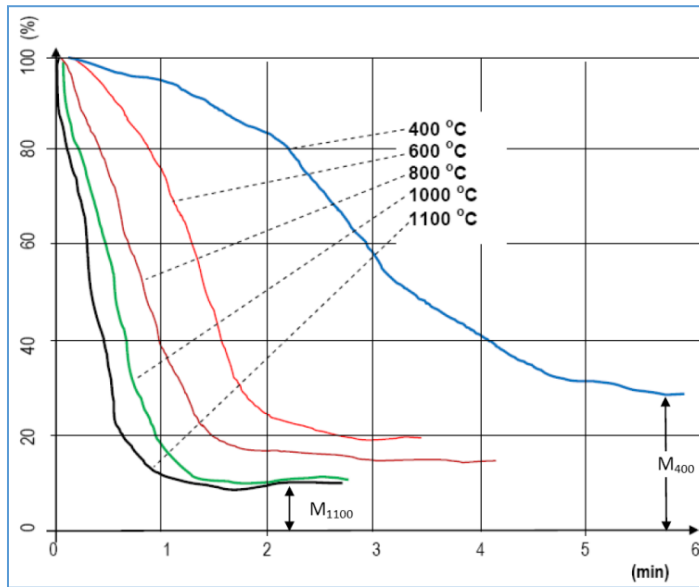
5. Figure TGA curves based on heating time and temperature
(M=excess)

Measurement done with remodeled Nabetherm furnace, MGI.

It is noteworthy that at high temperatures, there is no so-called drying phase, as the material immediately gets rid of moisture due to the sudden heat shock.

The decomposition (heating) temperature ($x = °C$) and the decomposition time:

$$y = -0.0061x + 7.295 \ (min)$$
$$(R^2 = 0.829)$$

Where:

- $x = 400 - 1100 \, °C$.

As such, in the experiment, the relationship between the two factors is approximately linear.

3.3 The effect of the extent of material layers on the decomposition (for TGA characteristic)

For these measurements, we used the self-made experimental unit. 300-500g of material was placed in the cylindrical measuring container.

The measurement was also carried out for materials of several grain sizes in order to determine the air permeability (flow pressure change) of the materials in the different phases of decomposition. During the measurements, the various data were recorded with the directly connected PC. The measurement parameters and the measurement process are detailed below:
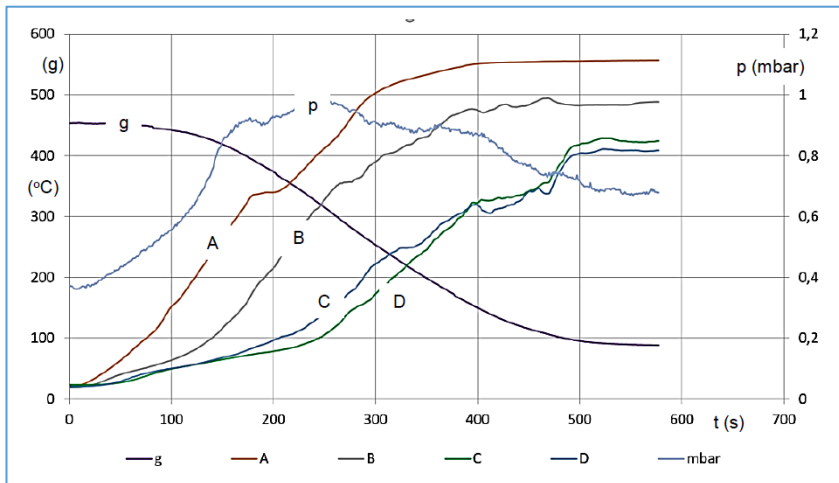
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Measurement characteristics by time:

- the mass change (s - g)
- the temperature change at the measurement points (s - °C)
- the pressure change under the biomass (under the support grid) (s - mbar)
- the gas flow (s - litre/min)

Carbonization of hardwood (sampling density: 1.0 s)
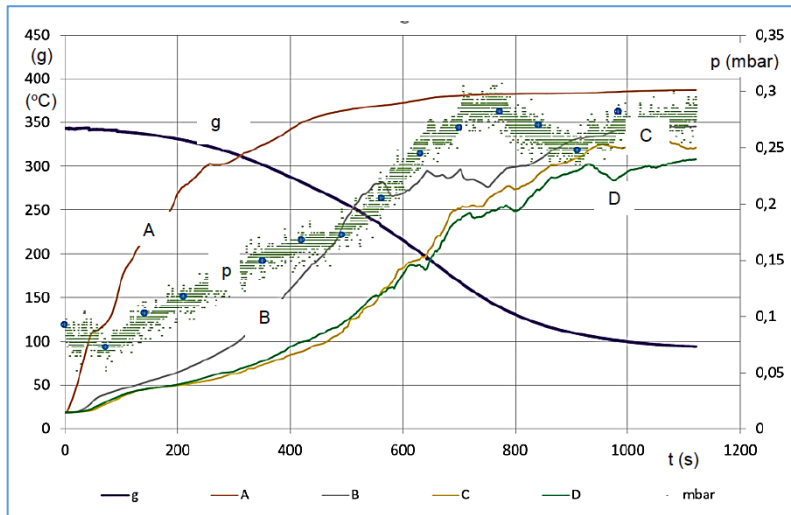
6. Figure Hardwood (G30) carbonization (400 °C).

7. Figure Hardwood (G30) carbonization (600 °C).

Abbreviations in the figures:

g = Mass, $^{\circ}$C = Temperature , A - Upper temperature sensor , B and C = Intermediate sensors, D = Bottom sensor , p = Pressure change measured during the flow

8. Figure Hardwood chips before and after carbonization

If we form a trend between the decomposition intensity (x = g/s) and the percentage ratio of the starting material and the remaining carbon (y) for the entire decomposition stage (including drying and reduction), the typical relationship for hardwood is:

$$y = -36.047x + 44.502 \ (\%)$$
$$R^2 \sim 1.0$$

- x = degradation intensity (g/s) in the 0.2 – 0.9 g/min range.

The typical relationship only for the "intensive" decomposition stage is:

$$y = -28.232x + 65.409 \ (\%)$$
$$R^2 = \sim 1.0$$

At higher temperatures, the residue is ~10% less.

In the case of the G30 material with a smaller grain size, the intensive heating phase begins at a lower temperature and at a ~37% higher peak value (Figure 9). As such, it is advisable to choose a lower heating speed for material with a smaller grain size.
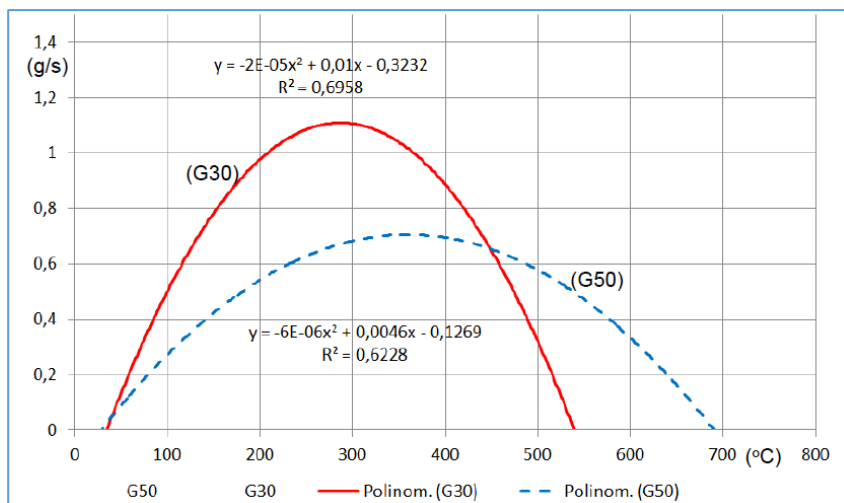
9. Figure Cooling temperature and decomposition speed in the intensive phase

3.4 Heating temperature and coal amount ratio by amount of dry matter

The decomposition took place in airtight conditions (the instrument was perfectly sealed), only the air in the material and the poles of the set provided oxygen for the combustion.
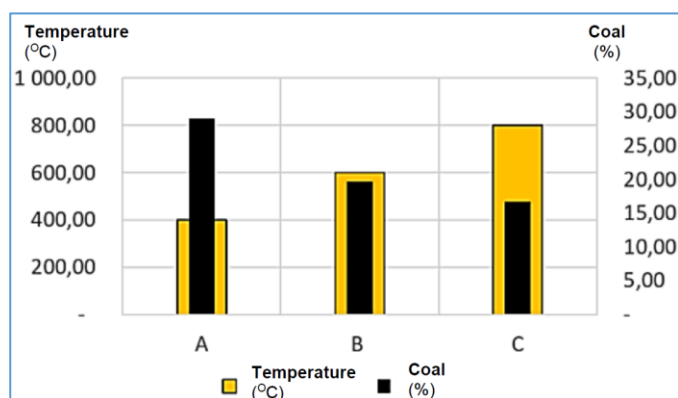
10. Figure Percentage ratio of carbonized material due to temperature, for same material

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It is clear that as the temperature increases, the amount of residual material decreases.

The percentage of charred material depends on the temperature (in the 400-800 °C range), for the same material, according to the following relationship (G30 hardwood chips with 10% moisture content):

$$y = -6.1667x + 34.111, (\%)$$
$$R^2 = 0.9192$$

Where:

- y = the percentage of the carbon content (residue) in relation to the initial dry matter (kg/kg x 100),
- x = the measurement (heating) temperature (°C),

3.5 Gas recirculation

I carried out this experiment with the electric heating device, by directing the produced gas back above the lower combustion zone (by ~10 mm).
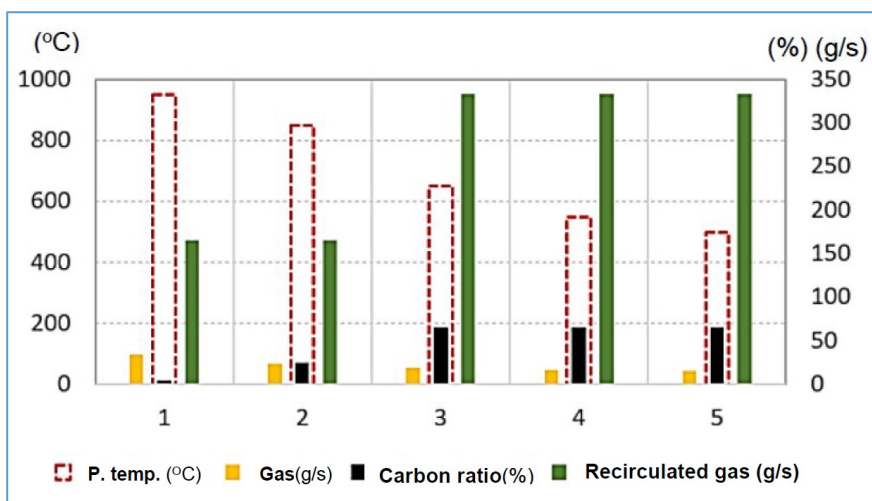
11, Figure Effect of gas recirculation on the coal residue

The trend of factors in the diagram is characterized by the following correlations:

Dependence of the percentage of carbon on the mass flow of recirculated gas, in the x = 166 – 330 g/s range:

$$y = 0.3052x - 35.961$$
$$R^2 = 0.942$$

The percentage of coal is the mass flow of the removed gas in the x = 35 -15.5 g/s range:

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$$y = -0.2612x + 33.907 \ (\%)$$
$$R^2 = 0.8989$$

The proportion of carbon produced depends on the temperature in the x = 500-900 °C range:
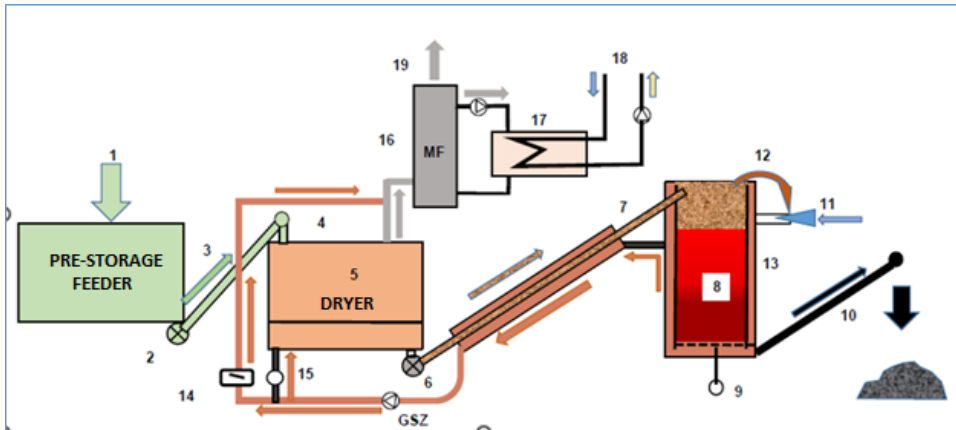
$$y = -0.1425x + 145.03 \ (\%)$$
$$R^2 = 0.9204$$

The mass flow of the discharged gas in the x = 500-900 °C temperature range:

$$y = 0.0386x - 4.9167 \ (g/s)$$
$$R^2 = 0.8884$$

3.6 The sample equipment and the obtained test values

In my company (Pyrowatt Kft.), we prepared the main designs of the **unique gas recirculation** and carbonization equipment, and manufactured the plant-scale equipment (Figure 12)

12. Figure Process flowchart of the system

Markings in the figure:
1. biomass into the pre-storage-feeding hopper, 2. cell dispenser, 3. angled applicator, 4. adding material to the dryer, 5. two-part dryer (paddle mixer and screw discharge unit), 6. cell dispenser, 7. application auger, 8. reactor, 9. moving and scraping structure (with drive motor), 10. biochar storage auger (and accumulated material), 11. air inlet (air jet pump), 12. primary gas outlet and inlet for the jet pump), 13. jacket (inter-wall mixer and combustion chamber), 14. regulator (can be supplemented with a heat exchanger), 15. introduction of air gas mixture into the dryer, 16. introducing the gas flowing out of the dryer into the washing unit, 17. heat exchanger (heat recovery recuperator), 18. extraction of recovered heat, introduction of outside air, 19. purified flue gas, MF. air washer tank GSZ. gas pump

The most important features of the equipment:

- The maximum temperature that can be set is 600-1000 °C.
- Biochar production capacity: 50-100 kg/h.
- Outlet flue gas temperature: 110-130 C°.
- Output biochar temperature: 180 C°.
- Power generated by recovering the heat of the exiting flue gas: ~100 kW
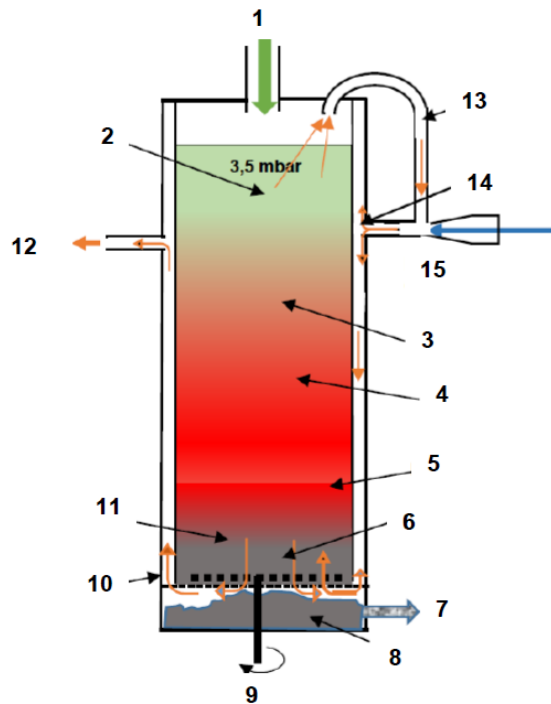
13. Figure Reactor operating schematics

Markings in the figure:

1-Pretreated biomass, 2 - Drying, steam ~ 200oC, 3 - Start of combustion, 4 - Combustion ~1000oC, 5 - Start of cooling, 6 - Two-way flow of gas, 7 - Discharge of carbon, 8 - Coal ~ 300oC, 9 - Scraper unit, 10 - Gas into the mantle, 11 - Cooling of coal 12 - Gas and air mixture (~300oC), 13 – Gas, 14 - Combustion of gas, 15 - Air introduction (air jet pump)
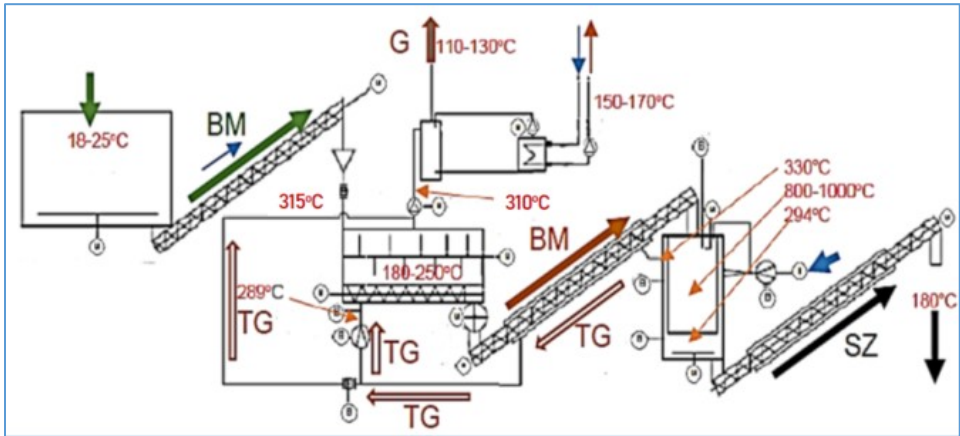
14. Figure Temperature values and mass flow direction during analysis.
Abbreviations: BM – biomass, TG – product gas, SZ – biochar, G – cooled,
cleaned gas
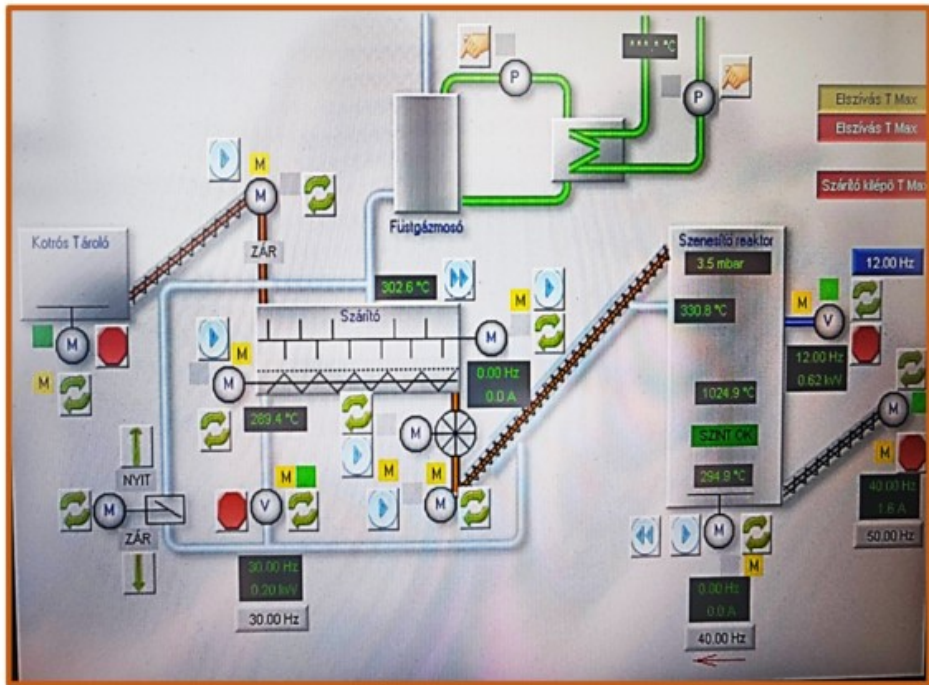
15. Figure Operation panel of the system (implemented).

The total efficiency of the system in terms of biochar:

$$\eta_{ter} = \frac{Q_{BSZ}}{Q_{BM}}100 = 37.03 \ (\%)$$

In practice, it is the quotient of the energy content of generated biochar and the energy content of the input biomass (based on the measurement data). The energetics process is shown in Figure 16.
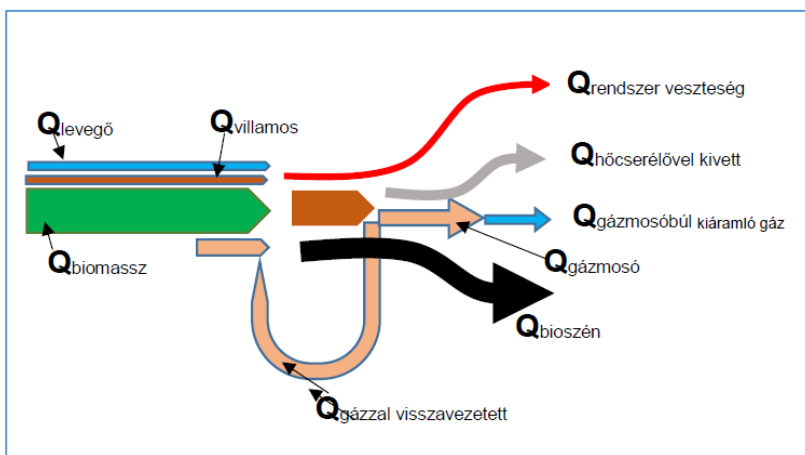
16. Figure Energetics process of the system

3.7 Main characteristics of the obtained biochar

The granularity of the obtained coal after the scraper is shown in Figure 17:

$$y = -1{,}5107x^2 + 13{,}181x - 8{,}3114$$
$$R^2 = 0{,}6161$$
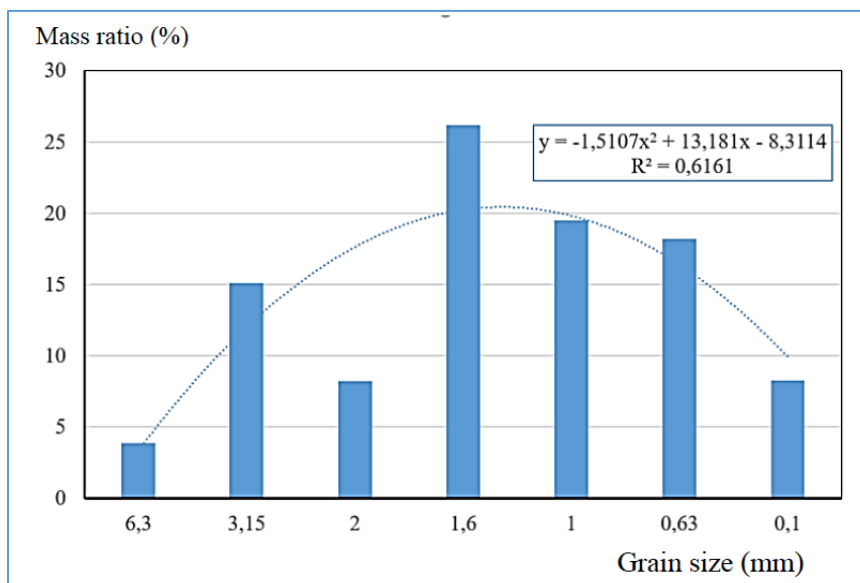
17. Figure Resulting biochar grains by size, classified into a 7-class system

It is important for users to know the internal components of biochar (Table 1), its various mineral contents and the pH value. The permissible limits for heavy metals and the PAH content are particularly important.

Table 1. The most important internal characteristics of the obtained coal.[1]

Tested parameter	Results	
	Unit of measure	Value
pH		10.1
Conductivity at 25 degrees	mS/cm	3980
Nitrite	mg/kg (L/S=10)	<0.5
Chloride *	mg/kg (L/S=10)	3310
TC	m/m% s.a.	50.2
Arsenic	mg/kg n.a.	<1
Phosphorus	mg/kg n.a.	2770
Calcium	mg/kg n.a.	1760
Potassium	mg/kg n.a.	19500
Magnesium	mg/kg n.a.	1540
TOC	m/m% s.a.	44.6
Total PAHs	mg/kg n.a.	<0,12

4. NEW SCIENTIFIC RESULTS

Based on the study of scientific research, I found that biomasses or the processing of their waste through pyrolysis has epoch-defining advantages:

- *compared to natural processes, the transformation carried out in pyrolysis equipment under controlled conditions moderates the emission of harmful substances (gases) into the atmosphere,*
- *pyrolysis is part of circular farming, as the produced biochar, returned to structurally degraded soils, remains part of the soil for a long time and helps regeneration,*
- *waste heat generated during pyrolysis can be used in other technological processes.*

Controlled materials are required for the conversion of biomasses by thermal decomposition. Only precisely controlled and regulated production equipment can be used to produce high-quality biochars and to avoid harmful substances. The design, production and experimental testing of equipment that meets these conditions became possible based on previous research.

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[1] *WESSLING Hungary Kft. Environmental Analytical Laboratory H-1045 Budapest, Anonymus utca 6. H-1325 Budapest, Újpest Pf. 211. Tel.: (+36-1) 872 3600 www.wessling.hu*

1. Temperature dependence of the pyrolysis process

The thermochemical transformation of biomass - pyrolysis - is a multifactorial, complex process. Based on my measurements with the laboratory small sample equipment, I found that depending on the moisture content (~0.0-25%) and the decomposition temperatures (in the 800 - 1100 °C range), the duration of the complete decomposition increases approximately twice. The proportion of carbon and hydrogen in the biomass raw materials remains approximately the same, but there is a significant difference in the Cl and N content.

For the equipment heated with inert gas (in the absence of oxygen), I determined the following relationship between the decomposition (heating) temperature and the heating time in the temperature range of 400 - 1100 °C:

$$y = -0.0061\ x + 7.295,$$
$$R^2 = 0.829$$

Where:

y – the heating time (min)),
x – the heating temperature (°C).

I found that the percentage of charred material by temperature (in the 400 – 800 °C range) follows the following relationship for the same material (G30 hardwood chips, at 10% moisture content):

$$y = -6.1667\ x + 34.111$$
$$R^2 = 0.9192,$$

Where:

- y – percentage of the carbon content (residue) in relation to the starting dry matter (kg/kg x 100%),
- x – the measurement (heating) temperature (°C).

Based on the results, I found that the amount of residual material decreases as the temperature increases.

2. Determining the degradation residue

To determine the amount of decomposition residue (coal, minerals and ash), I performed thermos-gravimetric analysis (TGA), with laboratory measurements in an oxygen-free (or poor) environment, both for inert gas-heated and electric-heated units.

For hardwood between 400 ºC and 600 °C, if we examine the trend between the intensity of decomposition and the ratio between the mass of the starting material and the remaining carbon (y), then for the entire decomposition stage (including drying and reduction as well) the typical relationship is:

$$y = -36.047\,x + 44.502$$
$$R^2 \sim 1.0$$

Where:

   y – the mass of the starting material and the % ratio of the remaining carbon,

   x – degradation intensity (g/s) in the 0.2 – 0.9 g/min range.

The correlation characteristic only for the intensive decomposition phase:

$$y = -28.232x + 65.409$$
$$R^2 = \sim 1.0$$

Based on these, I found that at higher temperatures, the remaining ~10% will have a lower value.

For the G30 material with a smaller grain size, the intensive heating phase begins at a lower temperature and the breakdown intensity (g/s) is ~37% higher at the peak value:

$$y = -6\cdot10^{-6}x^2 + 0.0046\,x - 0.1269.$$

Based on these, I determined that it is advisable to choose a lower heating speed for greater fineness.

3. Effect of primary gas recirculation

The percentage of carbon depending on the mass flow of the recirculated gas in the x = 166 – 330 g/s range:

$$y = 0.3052\,x - 35.961\ (\%)$$
$$R^2 = 0.942$$

The percentage of carbon depending on the mass flow of the returned gas -x (in the range x = 166 – 330 g/s):

$$y = -0.2612x + 33.907\ (\%)$$
$$R^2 = 0.8989$$

The proportion of carbon produced depends on the temperature in the x = 500 – 900 ºC range:

$$y = -0.1425x + 145.03\ (\%)$$
$$R^2 = 0.9204$$

The mass flow of the discharged gas in the x = 500-900 °C temperature range:

$$y = 0.0386\ x - 4.9167\ (g/s)$$
$$R^2 = 0.8884$$

Based on these, I found that gas recirculation is beneficial from the perspective of energetics and product quality.

4. The power requirement of passing the gas

I proposed a new solution, according to which you feed the gas and air mixture (both up and down) into the reduction space.

I found that in the 50 cm thick layer, the mass ratio of the grain sizes within the x = 0.1-6.3 mm (%) range:

$$y = -1.51\ x^2 + 13.18\ x - 8.3$$
$$R^2 = 0.6161$$

For upward flow, the required pressure (between x = 0.05 -and 0.4 m/s) varied in the y = 200 – 2300 Pa range:

$$y = 6508.2\ x - 205.06\ (Pa)$$
$$R^2 = 0.9221$$

With downward flow, the pressure demand was almost 4.5 times this:

$$y = 34977\ x - 1260.8\ (Pa)$$
$$R^2 = 0.9926$$

I proved that these relationships can be used to determine the parameters of the air jet pump. The suction side of the device regulates the upper inflow of gas, and the pressure side determines the mixture of gas and air, thus the combustion temperature in the jacket towards the cracking space ("bed") and the heating pipe.

5. Characteristics of the new machine and the coal received

Based on measurements carried out with a unique gas recirculation device, I found that the percentage distribution of biochar particles classified according to seven sizes is beneficial. The percentage of larger and very small (powder-like) particles is low (x= particle size (min. 0.1 – max. 6.3 mm):

$$y = -1.5107\ x^2 + 13.181\ x - 8.3114\ (\%)$$
$$R^2 = 0.6164$$

The internal characteristics of biochar, important compounds, metal salts and heavy metals were below the limit value. The pH value was favourable (10.1

pH), which can be used to improve acidified soils. I achieved the improvement of the product quality by returning the primary product gas containing still high *polycyclic aromatic hydrocarbons* to the reduction space with air mixing. I used this method for the first time to break down PAH-type constituents. Thus, the total PAH content is 0,01-0,12 mg/kg value, but its components were smaller at the 0.01 mg/kg value. The resulting product also meets international standards (EBC and IBI- 0,5 mg/kg).

Due to the variability of biomasses, the process of the production process can only be implemented with program control (similar to that used in the experimental equipment).

The total efficiency achieved with the system based on the input biomass and the carbon obtained:

$$\eta_{ter} = \frac{Q_{BSZ}}{Q_{BM}}100 = \sim 37.03 \ (\%)$$

Biochar helps soil life through its high porosity and specific surface area, and through the ability of the poles to retain water and filter nutrients. The use of biochar can be beneficial after checking its quality, on soils verified by tests, by calculating the usage dose (kg/ha). The equipment implementing the proposed procedure is of such a size that it can also be placed in a container. Thanks to this, the places producing biomass can be relocated and tracked, so the utility value is high.

4. CONCLUSION AND RECOMMENDATIONS

Biochar is significantly different from coal, which contains many harmful substances, but also differs from coal used in medicine, which is used for cleaning in various processes due to its aggressive properties (drinking water production, pharmaceutical industry, etc.). By breaking down biomass types with a high cellulose content in the material, the so-called I dealt with pyrolysis processes, in which coal, oil and gas are produced depending on the decomposition temperature. The carbon (biochar) obtained during this process can be used to improve soils, to increase the carbon content of the soil, and to use gas and oil as a propellant and to produce mechanical and electrical energy.

With the pyrolysis technology, the biomass was heated at a higher temperature in an oxygen-free environment. As a result, the organic materials are transformed (cracked) and the resulting biochar has a significant absorbent capacity due to its large surface area.

Pyrolysis differs from the incineration (oxidation) process, in that the amount of carbon dioxide produced is at least 40% less, thus "mitigating greenhouse gas emissions that cause global warming".

The amount and quality of biochar that can be obtained is significantly influenced by the temperature conditions of the process, the physical form of the raw material, its chemical composition, and the pyrolysis technology.

According to research, the replacement of biochar in the soil and growing context has many advantages, but its application should only be carried out under controlled conditions. The biochar that enters the soil is beneficial for the soil structure, mediates the absorption of nutrients from the soil for plants, affects the pH value, increases the soil's water-reserving capacity, but also binds toxic substances in the soil, such as heavy metals. The production of biochar by pyrolysis is a closed system that does not significantly affect the environment, **which enables the use of biological waste in the circular nature model.**

Using the data of the literary works, and based on the analysis of several preliminary laboratory experiments, I prepared the plans of the experimental but factory-sized equipment, manufactured it in my own plant, and conducted experiments with various materials. The chemical composition of the obtained biochar was examined in an accredited laboratory, and its physical characteristics were also determined. The material obtained with the system meets the requirements.

Building in a container is advantageous from the perspective of usability of the equipment, since the areas with a significant amount of biomass material (or waste) can be followed by simple relocation.

6. SUMMARY

Biochar is a uniquely well-usable, multi-purpose resource that has significant advantages in solving many environmental problems. It helps to mitigate the harmful soil degradation experienced in recent years (decades), including the restoration of the balance of pollutants, water and gaseous mediums in the soil.

After all, synergistically, with proper use, it can improve soil, water and air quality, carbon dioxide sequestration and moderate greenhouse gas emissions. Compared to other biomass decomposition processes, methane emissions are reduced to almost zero.

I created <u>laboratory and plant equipment</u> for the production of high-quality biochar, and conducted experiments with various biomasses. For the first time, I used the recirculation of primary raw gas mixed with air into the decomposition process, and thereby reduced the PAH content of the biochar to a minimum.

The designed and manufactured equipment is also suitable for smaller plants, and suitable for processing high-quality material (it is still operating under practical conditions).

The quality of biochar depends significantly on the characteristics of the raw material (physical, chemical, etc.) and the pyrolysis conditions. In order to ensure the reliability of the operations, continuous quality tests of the products are justified, but their compatibility with the soils cannot be neglected either. After all, it is an important factor that the biomass to be used meets the pyrolysis requirements.

According to the opinion of international research groups and professional associations, the quantitative use of biochar will increase significantly in the future. There is growing interest in its application: to remove pollutants from soil, water and gas, and its potential to replace expensive commercial activated carbon.

I consider the use of the created equipment to be economical even under the current economic conditions, but with the increase in the use of biochar in the future, its importance is clear.

My prototype equipment that I made is still in operation (it makes suitable material from rice bran).

7. PUBLICATIONS OF THE AUTHOR RELATED TO THE DISSERTATION TOPIC

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