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## Treatment of biomass using hydrothermal carbonization method

### Introduction

Biomass is an organic material of plant or animal origin, one of the key renewable energy sources. The main types of biomass are forest, agricultural, and waste biomass. Agricultural biomass includes energy crops, such as willow or miscanthus, and crop residues. Waste biomass comes from agri-food waste and sewage sludge (Górnicki et al. 2020; Vaithyanathan and Cabana 2021).

World biomass quantity is estimated at ~280,000 billion t/y, of which about 16% is used. For centuries biomass has been the most popular source of renewable energy.

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Many biological- and plant-origin substances, e.g., wood and agricultural waste, energy plants, and sewage sludge, are determined as biowaste (Energy 2023; FAO 2024; Kowalski et al. 2024; US Energy 2024). Biomass, distinct from fossil fuel, is considered a CO<sub>2</sub>-neutral fuel because of its possibility of absorbing from the air, during photosynthesis, almost an equivalent amount of carbon dioxide released through biomass incineration. This is because the amount of carbon dioxide released during biomass combustion is balanced by the amount absorbed by plants of CO<sub>2</sub> during their growth. Biomass participates in the short carbon cycle because carbon contained in biomass circulates between the atmosphere and the biosphere in a relatively short time, without contributing to the long-term increase in atmospheric CO<sub>2</sub> concentrations. Replacing fossil fuels with biomass can provide significant environmental benefits. It is estimated that the use of biomass can reduce greenhouse gas GHG emissions by up to 80–90% compared to burning coal or oil (Górnicki et al. 2020; Vaithyanathan and Cabana 2021).

Conversion of biomass to high-quality fuels can be realized using technologies, defined as thermal, chemical, or biochemical (Moomaw et al. 2011; Speight and Singh 2014). The energy content in agricultural waste allows the production of about 2 EJ of energy. (Kowalski et al. 2024). The large potential energy of agrarian waste, for utilization of the energy contained in the world quantity of agricultural biowaste, is evaluated as 18–82 EJ/y (Van den Born et al. 2014). The sustainable utilization of agricultural byproducts and waste, economically feasible, could be increasing even to the range of 37–66 EJ by 2030 (Moomaw et al. 2011; Working 2022).

In the energy sector, biomass is a raw material to produce heat, electricity, and biofuels. One of the most promising directions for the use of biomass is biofuel production. Bioethanol and biodiesel are alternatives to traditional fossil fuels in transport. Their use contributes to the reduction of GHG emissions and reduces dependence on imported energy resources. In addition to decreasing GHG, biomass contributes to improved waste management. Organic waste is used as an energy resource, reducing waste amounts going to landfills and decreasing methane emissions from these facilities. Biomass processing includes several processes, such as drying, crushing, pelletizing, and briquetting. These activities aim to increase the energy density of biomass and facilitate its transport and storage. Modern technologies allow for the efficient processing of various types of biomass, adapting them to the needs of specific energy installations. One of the most important aspects of biomass processing is its conversion into more advanced forms of energy. Biomass has a great energy potential, containing, for example, [GJ/t]: in plant fiber 15–18, manure 10–12, plant meal 14–16, energy quantities. The chemical composition, quantity, and properties of biomass wastes determine their use in biochemical, chemical, and thermochemical processes and the production of bioproducts and biomaterials (Kowalski et al. 2022a, 2022b; Danso-Boaseng et al. 2022).

Thermochemical technologies for biomass treatment (Gao et al. 2020) are as follows: incineration, torrefaction, gasification, and pyrolysis. These commonly need the initial pre-drying of biomass with higher water content (>20%). Other types of methods used are

hydrothermal, i.e., liquefaction, gasification, and carbonization (Sharma et al. 2020; Stirling et al. 2018; Suresh et al. 2021; Watson et al. 2018).

Direct incineration of biomass is, for example, technology to produce energy, used for obtaining electricity in steam turbines or heat and power (CHP) cogeneration units (Kowalski et al. 2021a, 2021b, 2022b; Wang and Nakakubo 2022). According to the torrefaction method, the biomass is thermally processed in an oxygen-free atmosphere at 200–300°C, into similar coal products (Arias et al. 2008; Sadaka and Negi 2009; Niu et al. 2021). The pyrolysis method needs temperatures of 300–800°C or more, in an oxygen-free atmosphere, and allows obtaining three products: gas, oil, and pyrolysis residues (Mosko et al. 2021; Huang et al. 2023). The gasification method predicts processing the biomass at 500–1400°C in a gasifier, with a pressure of 33 bar, with the injection of oxygen in the presence of a gasification element and a catalyst, allowing for partial oxidation to produce synthetic gas. Alternatively, the biomass is treated by steam to obtain the greatest quantity of hydrogen and methane (Ahmad et al. 2016; Sansiwal et al. 2017; Stirling et al. 2018). Syngas is applied as a biofuel for heating, diesel engines, and gaseous turbines to produce electricity. Hydrothermal gasification is a thermal process in which the biomass is processed in supercritical state water at 375°C at a pressure of 22 MPa to obtain syngas (Kruse et al. 2010; Matsumara 2015; Alptekin and Celiktas 2022).

The goal of the work was to analyze hydrothermal carbonization (HTC) technology processing biowaste to produce biocarbon pellets. The environmental and economic effectiveness of biocarbon pellet manufacturing from hydrated biomass with the HTC method and the application of the obtained biocarbon pellets are discussed. The first part of the study presents HTC technology-based physicochemical conversion of carbon organic compounds presented in hydrated biomass, under anaerobic parameters, in water as a process environment, creating carbon from biomass. In the last part of the paper, examples of the environmental benefits of hydrothermal carbonization and the possibilities of using the HTC method to manage biomass waste in Poland were discussed.

## 1. Basics of hydrothermal carbonization of hydrated biomass process

Hydrothermal carbonization is a thermal treatment technology of strategic CE actions of bio coal manufacturing from biowaste, needed thermal treatment of hydrated biomass at 160–260°C at a pressure of 20 bar for not many hours (Kruse et al. 2013; Kumar et al. 2015; Marinovic et al. 2015). This method does not result in the emission of harmful gaseous impurities and minimizes GHG emissions. The produced biocarbon could be comprehensively applied, i.e., as biofuel and absorbent, in soil remediation and improvement. The HTC process realizes the thermochemical conversion of biomass at a lower temperature than pyrolysis or gasification. The main product is solid carbonized bio coal, with many uses, mainly as a substitute for natural fossils (Funke and Ziegler 2010; Libra et al. 2011; Cebi et al. 2022).

The hydrothermal carbonization reaction was first investigated by Bergius in 1913 and takes as a model the naturalistic formation of carbon from biomass, over a period of 50,000 to 50 million years. Industrial HTC processing is identical to what appears in nature; however, its parameter is changed to reduce the reaction time to a few hours, conditional on the kind of biomass processed. It is realized in a closed reactor at 180–280°C, and pressure 2–6 MPa, for 5–240 min (Figure 1). The main product of HTC is a coal-like material named biocarbon, and the byproduct, the liquid water phase after hydrothermal conversion AHL, contains fertilizer nutrients.

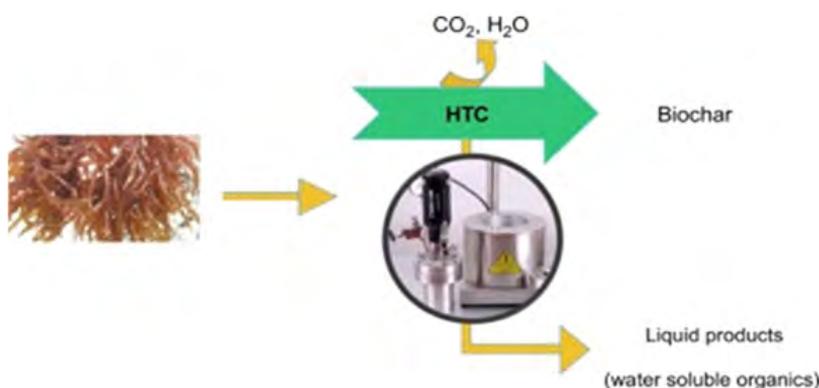


Fig. 1. Conceptual diagram of hydrothermal carbonization HTC

Rys. 1. Schemat koncepcyjny hydrotermalnej karbonizacji HTC

HTC process, as a result of subcritical water action, changes the physical and chemical structure of the biomass feedstock primarily by a hydrolysis reaction; however, aromatization, dehydration, decarboxylation, and recondensation reactions take place too. Eliminating the carboxyl and hydroxyl compounds significantly decreases the O/C ratio, and the final product has a higher energy density (Li et al. 2007; Lu et al. 2012; Nicolae et al. 2020; Djandaj et al. 2021). The HTC of biomass develops CP methods for hydrated organic waste processing. HTC's main advantage is that the direct processing of the hydrated biomass does not need a preliminary pre-drying, thus decreasing energy consumption and process time (Burguette et al. 2016; Owsianik et al. 2016). Hydrothermal carbonization allows hydrated biomass transformation into carbon-accommodated material, a solid biofuel like coal, with an elevated energy density (~35 MJ/kg dry mass), incinerated to produce heat. HTC allows the processing of feedstock with high water content (>80%), such as hydrated biomass. The produced bio-carbons have a much higher carbon content compared to the used raw materials. This is the effect of dehydration and decarboxylation reactions, eliminating H<sub>2</sub>, O<sub>2</sub>, and CO<sub>2</sub> from the hydrated feedstock. Biocarbon contains lower amounts of N<sub>2</sub> and S than the feedstock because these are moved as oxides to the liquid part at treatment. Biocarbon has a low ash content (noncombustible substances), like high-quality coals, because the inorganic

matter accumulating after burning is extracted into the after-hydrothermal carbonization liquid produced in the HTC process (Fuertas et al. 2010; Owsianik et al. 2016; Gonzalez-Arias et al. 2022).

## 2. Technology of treatment of hydrated biomass by hydrothermal carbonization

Hydrothermal carbonization HTC is a method of physical and chemical transformation of organic carbon compounds comprised of hydrated biomass, by anaerobic parameters, in water as a process environment. The HTC is inspired by natural processes occurring in nature imitating the process of carbon formation from biomass, occurring in nature. The HTC method is an example of industrial ecology, establishing an analogy to natural environmental models, which operate in nature in proper connection networks, and build interactive industrial systems. The industrial ecology goal is to decrease the quantity of biowaste generated and completely restructure these large systems (Kowalski et al. 2023b). The concept of the industrial HTC method technology stays similar to that that occurred in nature; however, HTC method parameters (temperature 180–220°C, pressure 20–25 bar) are enhanced to decrease the processing time, which ranges from 1 to 72 hours, depending on the biomass processed. Temperature, pressure, and reaction time determine the progress of the reaction, while the kind of biomass used affects the quality of the manufactured products (Figure 2). The HTC main product, biocarbon pellets, is similar to coal, while the byproducts are the liquid phase, which contains valuable fertilizing components. and the gaseous phase contains small amounts of CO<sub>2</sub>. The water present in the biomass is a very good dissolvent. In a time of HTC reaction, toxic organic compounds and residual micro-contaminations are degraded. As a result, in the HTC process, carbon contents are increased, oxygen and mineral contents are reduced, and the emission of gaseous CO<sub>2</sub> is very low.

Hot compressed water has a favorable reaction environment; it is environmentally safe, cheap, and easily attainable (Titrici 2012). The HTC process is realized in a water environment, since the feedstock does not need drying. Hence, heat-intensive, costly

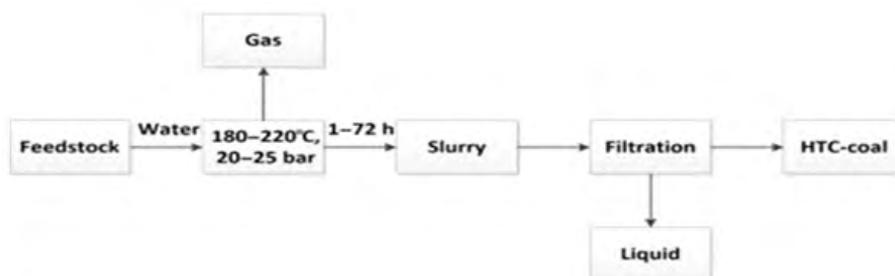


Fig. 2. Diagram of the hydrothermal carbonization process

Rys. 2. Schemat procesu karbonizacji hydrotermalnej

drying used in classical thermal methods (incineration or pyrolysis) is redundant. The HTC technology permits the utilization of raw materials containing higher water content (> 80%), e.g., hydrated biomass. The water's hydrogen bonds are weakened after pressurizing, which leads to a change of dielectric constant, and the reaction is catalyzed by water, which can operate like a basic or acidic liquid at temperatures 200–280°C due to its degree of ionization being enlarged. At these temperature ranges, the dielectric constant of water is reduced, and it operates similarly to a non-polar dissolvent. During the HTC process, hemicellulose and cellulose hydrolyzed into oligomers and monomers, but lignin stayed practically the same. HTC hydrothermal carbonization involves: decarboxylation, dehydration, and polymerization. In the HTC method, no additional catalyst is used, the pressure is fairly mediocre, and manufacturing costs are lower. HTC has some predominance in the process of biomass carbonization. The main advantage of this method is that it is realized in a water medium, and the water contained in the biomass is not a restricting element. In the HTC process, no hazardous waste is produced, and the surplus technological water contains nutrients advantageous to plant cultivation, i.e., N, K, and Fe. Biocarbon accumulates most of the carbon contained in the raw biomass. It has a low concentration of soluble substances (extracted with water), such as S, Cl, and K compounds. Impurity separation stages and biocarbon upgrading are used together with HTC reactors for various market implementations (Danso-Boateng et al. 2015; Hitzl et al. 2015; Burguette et al. 2016; Hernandez et al. 2017, 2018; Picone et al. 2021).

### 3. Ingelia's industrial HTC process

The hydrothermal carbonization (HTC) process efficiently transforms hydrated biowaste – input feedstocks – into high-quality biocarbon. A few HTC industrial installations work in Europe. Ingelia, an HTC process developer, has operated its own manufacturing HTC unit in Valencia since 2010, CPL Industries Ltd exploited an HTC unit in England since 2018, and a third installation in Belgium, implemented in 2021 (Ciceri et al. 2021). This Spanish company worked out of hydrothermal carbonization technology of biomass, enabling recovery of the carbon from the organic waste streams independently of water content in feedstock and heterogeneity to obtain a solid biomaterial containing biocarbon. Presented below industrial Ingelia's process (Figure 3) is an example of the most promising HTC technologies (Titrici et al. 2008; Ingelia 2023).

Biocarbon could be used as a biofuel, an industrial feedstock substituting natural fossils with a high calorific value, a small water content, higher efficiency on combustion, and no CO<sub>2</sub> emission. This solid biofuel can be produced from different types of organic substances. In 2010, Ingelia realized the start-up of its first unit for hydrothermal carbonization of hydrated biomass, according to Ingelia's project and construction. This was the first manufacturing HTC installation worldwide, enabling carbonization of biomass in a continuous HTC hydrothermal technology. Since 2012, Ingelia has exploited this

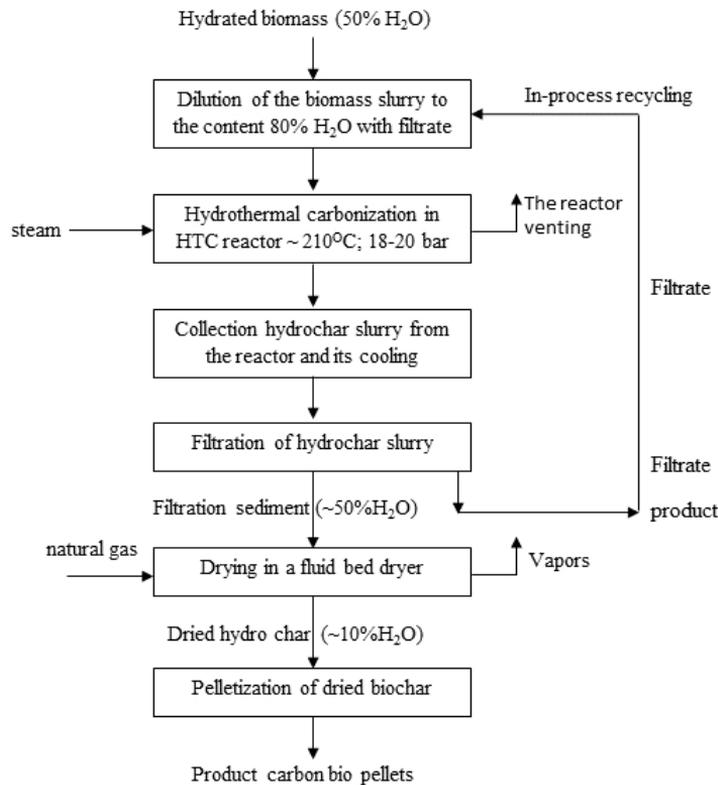


Fig. 3. Flow sheet of the conversion process of hydrated biomass by hydrothermal carbonization HTC technology

Rys. 3. Schemat blokowy procesu konwersji uwodnionej biomasy poprzez hydrotermalną karbonizację w technologii HTC

industrial original unit, showing that its patented HTC method can produce continuous bio coal (hydrochar). Development of patented Ingelia HTC technology is based on their temperature and control system, and the design and construction of their reactor. Ingelia has designed and built a hydrothermal carbonization installation of biomass, enabling the economic and environmental effectiveness of implementation in industry. The HTC process recovers carbon and bio-fertilizers from all types of organic waste. The process begins with the introduction of biomass into the reactor. A piston pressure pump doses biomass-water suspension through heated pipelines to the reactor. In the reactor, the carbonization process of the water suspension lasts ~5 hours, at a temperature of ~200°C, and a pressure of ~20 bar. The reactor is heated by diaphragm steam. Heat is recovered in the form of condensate. It should be emphasized that no additional catalyst is used in the reaction; the role of the catalyst is played only by organic acids formed in the process. Then, through a system of outlet pipelines, the biochar sludge (mixed slurry of biochar and technological water) from the HTC process is cooled and expanded before it is treated in the final processing phase.

At this stage, inert contaminants are removed from it. To pump, the biochar suspension is ground and directed to the separation stage. If there is no contamination with inappropriate materials such as sand, there is no necessity for gravity separation in the hydro classifier; then, only a spiral gravity chute is used. Next, the biochar slurry is filtered in the frame filtration press. The post-filtration sediment contained 45–50% water. Next, the filter cake from the filter press is crushed and dried to decrease the water content. The dried biochar is pelletized without any binder (Hitzl et al. 2015; Hernandez et al. 2017, 2018; Ingelia 2023).

### 3.1. Strengths of Ingelia's technology

HTC is a continuous and modular process, easily scaled and established on a constructed pumping arrangement set for a mixed slurry waste and water improving process performance. Using vertical inverted flow reactors that don't include any mobile elements or heat exchangers allows for reducing investment and operation costs. The developed temperature and pressure control scheme assures stable parameters in the HTC process zone during the entire retention time. Extraction of biochemicals, preventing the content of hydrocarbon compounds in the technological water. Recovery of excess heat from the output tubes to preheat the input (biomass and process water) allows reducing energy costs. Posttreatment equipment from the coal industry (coal washing) allows for the separation of inert matter and impurities and reduces the content of ashes. Hydrothermal carbonization is a waste-free method, the technology is low in energy consumption, and the production cost is low. The process and equipment used are not composite, and the developed units are automatic and easy to operate. The investment costs related to the construction of the installation are relatively low. Hydrothermal carbonization technology enabled the treatment of all kinds of biomass.

Ingelia's HTC process is sustainable. Allows for recycling > 98% carbon and nutrients, there's no process emission – no bad odors. It is characterized by low energy consumption. It is an easy design stable, simple process with modular scalability without process-moving parts. It's made for efficient, fast, and continuous operation and needs little space. The integrated process control systems are very significant too.

### 3.2. Certified products of HTC process

Biomass is transformed into biocarbon products known as “hydrochar”, and liquid byproducts (1–5% amount produced is hydrochar. Biocarbon is a higher-quality biofuel. The byproduct is a fertilizer liquid containing ingredients and nutrients with fertilizing values (N, K, and P). HTC enables high heat recovery compared to other applied valorization methods in both economic and ecological terms. Simple and easily scalable HTC reactors having low energy consumption were designed and constructed. Post-treatment of the

byproduct fertilizer solutions reduces the ash content in the produced biocarbon. The biocarbon pellets produced with the HTC technology have: high C contents, due to the dehydration and decarboxylation reactions removing hydrogen and oxygen from the feedstock (biomass) forming water and carbon dioxide; reduced nitrogen and sulfur contents compared to the input feedstock, due to their soluble constituents are passing into the solution during treatment; decreased ash contents in comparison to other kinds of coal, because the inorganic materials forming ash after combustion are extracted into the liquid phase in time of the HTC production. Characteristics of the biocarbon pellet produced by HTC technology (Figure 4) and fertilizer solutions after hydrothermal carbonization AHL (Figure 5) are presented in Tables 1 and 2.

Bio coal pellets

C > 50% LHV: 20–24 MJ/kg

Fertilized water AHL

Solids 2–4%; N 1–4%, in dry mass



Fig. 4. Fertilized water AHL

Rys. 4. Woda nawożona AHL



Fig. 5. Bio coal pellets

Rys. 5. Pellety biowęglowe

Table 1. Characteristic of carbon bio-pellets produced by hydrothermal carbonization technology HTC

Tabela 1. Charakterystyka biopelletów węglowych wytwarzanych w technologii hydrotermalnej karbonizacji HTC

| Specification                            | Units             | Values/contents* |
|--|-------------------|------------------|
| Calorific value                          | GJ/t              | >23              |
| Bulk density                             | kg/m <sup>3</sup> | 700              |
| Ash                                      | %                 | 4–12             |
| Water                                    |                   | <10              |
| C <sub>total</sub>                       |                   | >58              |
| C <sub>solid</sub>                       |                   | 25               |
| H  |                   | 5.8–6.4          |
| N  |                   | 0.6–2            |
| S  |                   | <0.2             |
| Cl                                       |                   | <0.2             |
| Volatile substances                      |                   | 65               |
| Ash melting point                        |                   | °C               |
| Abrasion (Hardgrove index ISO 5074-1980) |                   | 44–52            |
| Strength                                 | %                 | 95–98            |

\* Value referred to dry ash-free matter DAF.

Below are the characteristics of fertilizer solutions from the HTC process. The advantage of such fertilizers is the meaningful contents of nitrogen and potassium, the basic bio-nutrients of fertilizers.

Biocarbon pellets produced by HTC from hydrated biomass are mainly solid biofuel. Biocarbon pellets having higher energy density (>35 GJ/t of dry mass). Compared to the feedstock (biomass) used, the produced hydrochar has a much-increased carbon content. These, resulting from dehydration and decarboxylation processes, allow the removal of hydrogen and oxygen from the hydrochar slurry (mixture of biomass and water) and carbon dioxide. Biocarbon has low nitrogen and sulfur concentrations, compared to the raw materials, as these are transported, in the form of oxides, to the liquid phase during reactions. Biocarbon pellets have lower ash contents, like that of other coals, because the inorganic materials accumulating after combustion are extracted into after-carbonization fertilizer liquid AHL (Renz et al. 2013; Owsianik et al. 2016; Gonzalez-Arias et al. 2022).

Table 2. Characteristics of fertilizer solutions after hydrothermal carbonization AHL

Tabela 2. Charakterystyka roztworów nawozowych po karbonizacji hydrotermalnej AHL

| Parameter                              | Unit  | Values  |
|--|-------|---------|
| Water content                          | %     | 96.5    |
| Dry mass at 105°C                      |       | 3.50    |
| Total organic matter                   |       | 2.40    |
| Total organic C                        |       | 1.39    |
| pH                                     |       | 5.80    |
| N <sub>total</sub>                     | g/kg  | 1.307   |
| Ammonium nitrogen (N-NH <sub>4</sub> ) |       | 0.277   |
| N nitrate (N-NO <sub>3</sub> )         |       | 0.007   |
| P <sub>2</sub> O <sub>5</sub>          |       | 0.043   |
| K <sub>2</sub> O                       |       | 2.4     |
| CaO                                    |       | 1.8     |
| MgO                                    |       | 0.827   |
| Na <sub>2</sub> O                      |       | 1.109   |
| B                                      | mg/kg | 3.20    |
| Fe                                     |       | 24.5    |
| Cu                                     |       | 0.07    |
| Mn                                     |       | 2.79    |
| Zn                                     |       | 1.54    |
| Ni                                     |       | 0.26    |
| Pb                                     |       | 0.45    |
| Cd                                     |       | 0.004   |
| Cr                                     |       | 0.086   |
| Cl                                     |       | 1,523.0 |

\* Value referred to ash-free dry matter DAF.

## 4. Possibilities of using the HTC method for biomass waste management in Poland

The estimated amount of biomass, a potential raw material for the HTC method, may amount to up to 100 million t/y in Poland. The HTC method may allow for the utilization of whole quantities of sewage sludge produced in Poland in over 3,300 municipal sewage treatment plants. Currently, approximately 40% of the sewage sludge from the largest treatment plants in Poland is burned in fluidized bed furnaces, and an estimated 5% in rotary kilns (medium sewage treatment plants). Several % are collected and burned in cement plants. The price of their disposal in 2021 was PLN 300/t. The largest number (approximately 80%) in Poland are rather slight sewage processing installations (for 10,000–30,000 people), each producing about 2,500 t/y sewage sludges. They have a serious problem with the utilization of sewage sludge. A similar problem is the post-fermentation sludge problem from 128 Polish biogas plants. The solution to this problem is important because, from 2026, there will be a ban on agricultural use of sewage sludge. It is also possible to process using the HTC method all other types of post-fermentation and green waste, the organic part of municipal solid waste, various types of biomass from agri-food production, such as manure, distillery residue, slurry, straw, hay, leaves, and cut branches of fruit trees, sawdust, bark, leaves, beetroots, green corn, pomace from fruit juice production, rotten fruit, etc. (Przydatek and Wota 2020; Kowalski et al. 2024).

Table 3 presents the estimated effects of implementing HTC technology for processing sewage sludge into carbon bio pellets for the processing scale (t/y): 10,000; 100,000; and 1,000,000, respectively. The prices of carbon bio pellets were evaluated according to data from the Polish and European markets. Table 4 presents the production of after hydrothermal carbonization liquid fertilizer AHL. The price of the fertilizer solution was calculated using data based on the prices of firms that produced nitrogen and potassium fertilizers. Operating costs and revenue were calculated based on our data. All calculations should be treated relatively cautiously. A revenue period lower than 5 years is favorable for this kind of investment and indicates its effectiveness.

The amount of AHL solutions produced is relatively small. At a processing scale of 1 million t/y of sewage sludge, 8,300 ha of arable fields can be fertilized with AHL. This confirms the possibility of relatively easy management of such a large amount of AHL fertilizing liquid.

The HTC technology is in line with the CE concept of recycling and reusing the carbon contained in biomass, which could be used as a solid biofuel, according to (PN-EN ISO 2023), and the byproduct, a solution containing bio-nutrients for fertilizers. Hydrochar, due to its wide use in agriculture, water treatment, and as a biofuel, could have a significant market value. HTC could be treated as a hydrated biomass processing technology developing CE strategic activities in the waste management area (Kowalski et al. 2023a). Successful implementation of HTC for recovering value-added products from hydrated biomass developed the possibility of handling higher hydrated waste while bringing environmental and socioeconomic profits in line with the CE concept.

Table 3. Production incomes and revenues of processing hydrated biomass by hydrothermal carbonization technology

Tabela 3. Przychody i dochody z produkcji przy przetwarzaniu uwodnionej biomasy technologią karbonizacji hydrotermalnej

| Specification  | Units       | Variant of capacity/values |         |           |
|--|-------------|----------------------------|---------|-----------|
|  |             | 1                          | 2       | 3         |
| Quantity of biomass processed (30% DM)                                     | t/y         | 10,000                     | 100,000 | 1,000,000 |
| Biocarbon pellet production  | t/y         | 3300                       | 33,000  | 330,000   |
| Biocarbon pellet price   | €/t         | 465.0                      | 465.0   | 465.0     |
| Biocarbon pellets produce value  | million €/y | 1,534                      | 15,34   | 153,4     |
| Estimated operation cost   |             | 0,512                      | 5,12    | 51,2      |
| Gross profit   |             | 1,022                      | 10,22   | 102,2     |
| Investment expenditures  | million €   | 4,88                       | 48,8    | 488       |
| Revenue  | years       | 4.8                        | 4.8     | 4.8       |
| Energy obtained from the incineration of biocarbon pellets (LHV = 23 GJ/t) | GJ/y        | 75,9                       | 759     | 7590      |
| Decreased fee for CO <sub>2</sub> emissions (60 €/t of CO <sub>2</sub> )   | million €/y | 0.78                       | 7.8     | 78        |

Table 4. Annual production of after hydrothermal carbonization liquid fertilizer AHL

Tabela 4. Roczna produkcja płynnego nawozu AHL po hydrotermalnej karbonizacji

| Specification                          | Units | Capacities |         |           |
|--|-------|------------|---------|-----------|
| Quantity of biomass processed (30% DM) | t/y   | 10,000     | 100,000 | 1,000,000 |
| Production of fertilizer solution AHL  | t/y   | 4,000      | 40,000  | 400,000   |
| (N + K)*                               |       | 16.6       | 166.0   | 99.6      |
| AHL fertilizer price                   | €/t   | 7.7        | 7.7     | 7.7       |
| AHL produce value                      | €/y   | 30,698     | 306,980 | 3,069,800 |
| Area of crops field fertilized**       | ha/y  | 83         | 830     | 8,300     |

\* N and K price = 10 PLN/kg; Concentration in AHL (%): N – 0.13, K – 0.2.

\*\* N + K dose 200 kg/ha.

## Conclusions

The analysis confirms that hydrothermal carbonization (HTC) technology successfully converts hydrated biomass into high-quality hydrochar and biocarbon pellets. These make possible the valorization of biomass waste by manufacturing a solid renewable biocarbon material, hydrochar, which could be used as an energy feedstock and soil improver. Water contained in the raw materials during the HTC process solubilizes ingredients as N, P, and K compounds. These nutrients constitute a soluble bio-fertilizer used as a substitute for artificial fertilizers.

The HTC process has many advantages, such as increased efficiency of recycling bio-waste, decreased GHG emissions, connected with landfilling of biomass, and using natural fossil materials. It is also very effective due to the transformation of almost all the biomass's carbon into biocarbon. These aspects make hydrothermal carbonization technology attractive for sustainable waste management and energy production. Implementation of innovative hydrothermal processes of biomass waste management, as HTC promotes CE strategic actions. HTC could be seen as a hydrated biomass processing method to develop CE strategic goals in the waste management area. The rising attractiveness of HTC hydrothermal carbonization technology results in the minimization of biomass waste amounts and the manufacturing of environmentally friendly materials.

The estimated amount of biomass, a potential raw material for the HTC method, may amount to up to 100 million t/y in Poland. It was demonstrated that it is currently possible to process approximately 50 million t/y of biomass using the HTC method and thus produce approximately 16.5 million tons of carbon bio pellets. These should be confirmed by further research.

*The Authors have no conflict of interest to declare.*

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## TREATMENT OF BIOMASS USING HYDROTHERMAL CARBONIZATION METHOD

### Keywords

biofuel, hydrochar, biocarbon, hydrothermal carbonization, hydrated biomass

### Abstract

The analysis of hydrothermal carbonization technology processing showed that this technology effectively transforms hydrated biomass into high-quality hydrated and biocarbon pellets used as biofuels. One of the key advantages of hydrothermal carbonization (HTC) is its ability to enhance the efficiency of bio-waste recycling, leading to increased productivity in waste management. It also decreases reliance on fossil fuels by providing a sustainable alternative energy source while lowering greenhouse gas emissions associated with conventional waste disposal. The process is highly efficient, converting a significant part of biowaste carbon into biocarbon. Hydrothermal carbonization is an exothermic process operating with low energy consumption. The hydrochar produced can be utilized as a soil amendment, enriching soil and sequestering carbon. Investing in innovative technologies like HTC strengthens sustainable waste management strategies, fostering the circular economy concept. By increased use of hydrothermal carbonization, the volume of untreated biowaste can be reduced while simultaneously producing environmentally friendly materials. The development of this technology holds great potential for transforming organic waste into valuable resources, offering a sustainable alternative to traditional disposal. The assessment showed that it is possible to process approximately 50 million tons of biomass per year in Poland using the HTC method and thus produce about 16.5 million tons of carbon bio pellets.

**PRZETWARZANIE BIOMASY METODĄ HYDROTHERMICZNEJ KARBONIZACJI****Słowa kluczowe**

biopaliwo, hydrowęgiel, biowęgiel, karbonizacja hydrotermalna, uwodniona biomasa

**Streszczenie**

Analiza procesu hydrotermalnej karbonizacji wykazała, że technologia ta skutecznie przekształca uwodnioną biomasę w wysokiej jakości uwodnione peletki biowęglowe, wykorzystywane jako biopaliwa. Jedną z kluczowych zalet hydrotermalnej karbonizacji (HTC) jest jej zdolność do zwiększenia efektywności recyklingu bioodpadów, co prowadzi do wzrostu produktywności w gospodarce odpadami. Zmniejsza ona również zależność od paliw kopalnych, zapewniając zrównoważone, alternatywne źródło energii, jednocześnie obniżając emisję gazów cieplarnianych związaną z konwencjonalną utylizacją odpadów. Proces ten jest wysoce wydajny, przekształcając znaczną część węgla z bioodpadów w biowęgiel. Hydrotermalna karbonizacja to proces egzotermiczny o niskim zużyciu energii. Wytworzony hydrowęgiel może być wykorzystany jako dodatek do gleby, wzbogacając ją i wiążąc dwutlenek węgla. Inwestowanie w innowacyjne technologie, takie jak HTC, wzmacnia strategię zrównoważonego gospodarowania odpadami, wspierając koncepcję gospodarki o obiegu zamkniętym. Dzięki zwiększonemu wykorzystaniu hydrotermalnej karbonizacji można zmniejszyć ilość nieprzetworzonych bioodpadów, jednocześnie produkując materiały przyjazne środowisku. Rozwój tej technologii niesie ze sobą ogromny potencjał w zakresie przekształcania odpadów organicznych w cenne zasoby, oferując zrównoważoną alternatywę dla tradycyjnego składowania. Analiza wykazała, że w Polsce metodą HTC możliwe jest przetworzenie około 50 milionów ton biomasy rocznie, a tym samym wyprodukowanie około 16,5 miliona ton biopelletu węglowego.

