Fuel 324 (2022) 124435

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Thermal upgrading of hydrochar from anaerobic digestion of municipal solid waste organic fraction

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ARTICLE INFO

Keywords:
Activated carbon
Biowaste
Steam gasification
Hydrochar
Scanning electron microscopy (SEM)
H2-rich syngas

ABSTRACT

Solid fraction obtained from anaerobic digestion of municipal solid waste organic fraction is a waste produced in noticeable amounts, which according to circular economy concept can be upgraded to produce new, value-added products like: hydrogen rich process gas and carbon rich solid material. In this study, thermal upgrading of hydrochar by steam gasification was analysed. Raw material was obtained through hydrothermal carbonization (HTC) of digestate from anaerobic digestion of wet fraction of municipal solid waste at 200 and 230 °C, and residence time of 60 and 120 min. The further gasification step was carried out at 800 °C and the residence time was 10 min under nitrogen with a steam atmosphere. The main objective of hydrochar upgrading through steam gasification was production of carbon-rich material with developed active surface area. The study presented promising results regarding proper management of mixed wastes, which have not yet been analysed in the literature. It was noted that low temperature and residence time are favouring active surface area development. Analysis of the main gaseous products of the gasification process showed that syngas is composed mainly of H_2, CH_4, CO_2, O_2, and CO. The hydrogen concentration was the highest noted for hydrochar obtained at highest temperature and residence time. Analysis of the concentration of each syngas component reveals that combined treatment of digestate from anaerobic digestion through the HTC and gasification process results in H_2-rich syngas products and a high H_2/CO ratio with parallel fair quality activated carbon.

1. Introduction

The demand for energy, both thermal and electrical is increasing. However, to maintain stability, we must move towards eco-friendly solutions and replace fossil fuels with more heterogeneous fuels such as biomass, especially agricultural biomass, municipal waste, and sewage sludge [1]. Another important issue is the efficiency of energy conversion and potential energy accumulation [2]. Therefore, more complex than direct combustion, thermochemical technologies are more suitable for different, even heterogeneous, and very wet feedstocks such as biomass and waste fuel treatment, which gives the possibility of producing valuable and high quality energy carriers in the gaseous, liquid, and solid state [3,4]. Thermochemical treatment of different kinds of waste is a well-known procedure of nonrecyclable waste management, which includes but is not limited to: torrefaction, pyrolysis, liquefaction, gasification, hydrothermal carbonisation, and co-combustion and direct combustion. Due to increasing interest in energy storage techniques and the necessity to introduce the idea of a circular economy, often two or more methods must be combined together to give better results, as not only the efficiency of the process is the main challenge, but waste generation and the continued use of the obtained products to close the material loop are also important issues [5,6]. Another possibility of introducing the concept of circular economy is the direct production of H_2-gas through hydrothermal gasification [7,8] or supercritical water gasification, especially dedicated to wet biomass and waste fuels [9].

Hydrothermal carbonisation (HTC) process allows one to obtain value-added hydrochar from the wet fraction such as municipal solid waste, sewage sludge, or digestate from anaerobic digestion [10,11]. HTC is a thermochemical process that is performed in subcritical conditions in the aquatic environment under elevated temperature and pressure. Water remains in the liquid state under saturation conditions, as a result of the elevated pressure of the process. The temperature range of the process is 180–350° C. The pressure range of 2 to 6 MPa is a direct consequence of a saturation pressure for a selected temperature of the process. The typical residence time for hydrothermal carbonization is 5 to 240 min [12]. HTC enables raw material to be converted in the presence of water into a material containing more carbon and less oxygen than the original material, thus making it similar to lignite or coal.

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https://doi.org/10.1016/j.fuel.2022.124435
Received 4 December 2021; Received in revised form 14 April 2022; Accepted 28 April 2022

Nomenclature

HTC	hydrothermal carbonization
SEM	scaning electrone microscopy
GC	Gas chromatography

Furthermore, there is no need for costly pretreatment of raw feedstock: drying and pelletizing, as the process is carried out in an aqueous environment [13]. During the HTC process, several physicochemical reactions occur, associated with the process of hydrolysis, decarboxylation, and dehydration [14]. The HTC process results in three types of products: gaseous, liquid, and solid hydrochar. The solid carbon-rich material produced might be used as a direct fuel with enhanced properties compared to raw feedstock [10]. Furthermore, hydrothermal carbonization is a waste pretreatment method to obtain high-quality activated carbons [15] and improve the quality of syngas produced during physical activation [16–18].

The gasification process leads to the production of syngas, which is a gaseous mixture with high energetic potential obtained by thermochemical conversion of the feedstock in the presence of a gasifying agent, typically steam, air/oxygen or carbon dioxide [19]. One of the major concerns is the quality of the materials generated through the thermal processing of waste and biomass. Char obtained after the gasification process is currently treated as waste that leads to a certain loss in overall gasification plant management [20]. The urgent need to develop alternative uses for solid residue has prompted scientists to investigate alternative routes for char valorisation, for example, dye adsorption [21], soil fertilization [22], combustion [23] or catalyst preparation [24]. Furthermore, research could be conducted to develop methods for using gasification residues, for example, as active carbon precursors [25]. The global activated carbon market in 2018 was estimated at $ 4.72 billion. Moreover, in the next several years this market will grow due to strict environmental policies related to water resources, air quality control, and the use of clean gas [26].

The combination of hydrothermal carbonization with activation methods such as, for example, gasification is a subject of interest. Several studies on this subject have already been published. Wądrzyk et al. analysed two-stage processing through HTC and CO_2 gasification on the example of cherry pomace [27]. Waste materials were analysed by Lin et al. through steam gasification of hydrochar from polyvinyl chloride and alkali coal [17]. Porous carbon materials from camphor leaves and camellia leaves were produced using hydrothermal carbonization (HTC) and KOH activation and analysed in [28]. Chemical activation was also tested as an activation method of hydrochar produced from textile waste in [29]. All these studies show that there is huge potential in the effective combination of thermal pretreatment and activation, leading to the production of new energy carriers. However, mixed wastes such as municipal solid waste were not yet analysed due to the high heterogeneity of the material. The present study brings new insights into the valorisation of hydrochar from anaerobic digestion of the organic fraction of municipal solid waste, as well as the challenges related to the utilization of postproduction waste generated during the gasification process. It is a mixed waste generated by the industry and needs to be properly and efficiently managed. The main aim of the presented research is to determine the most promising parameters of the HTC process to use this technology as a pretreatment method for further steam gasification and generation of high-quality syngas. The parameters of the hydrothermal carbonization process analysed influenced the composition of the syngas by obtaining a H_2 rich gas with a parallel high H_2/CO ratio, which is expected from a Fischer-Tropsch synthesis point of view. The solid char obtained through steam gasification was analysed as a potential carbon-rich fuel using thermogravimetric analysis and as activated carbon. The morphology of the material produced was analysed using a scanning electron microscope and gas adsorption methods.

2. Materials and methods

2.1. Hydrochar from hydrothermal carbonisation (HTC) process of digestate from anaerobic digestion of wet fraction of municipal solid waste

For the gasification experiment, two types of samples were selected. The first sample was a raw digestate from anaerobic digestion of a wet

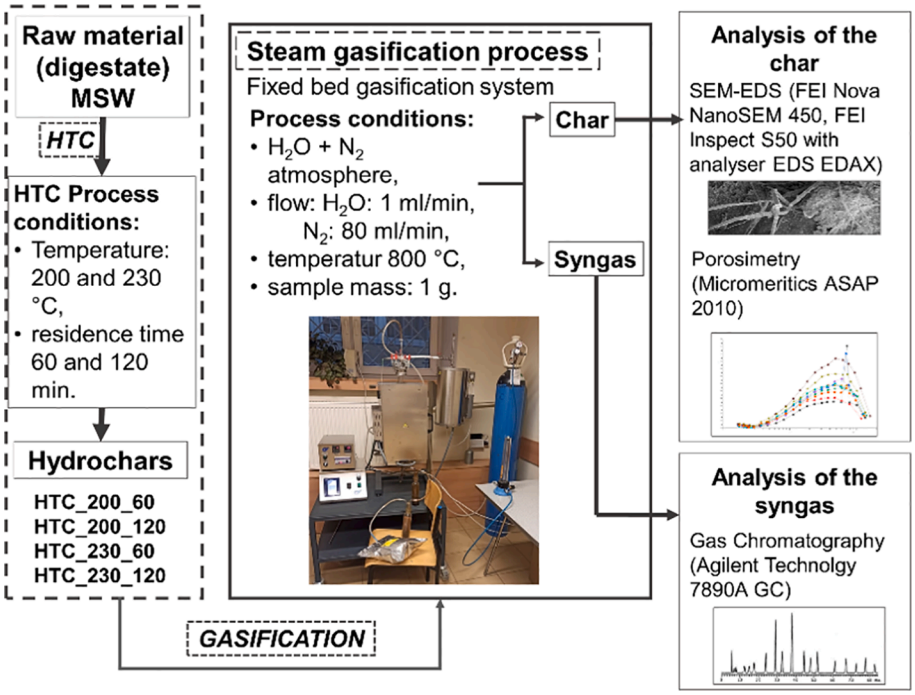

Fig. 1. A layout of analysis flowchart.

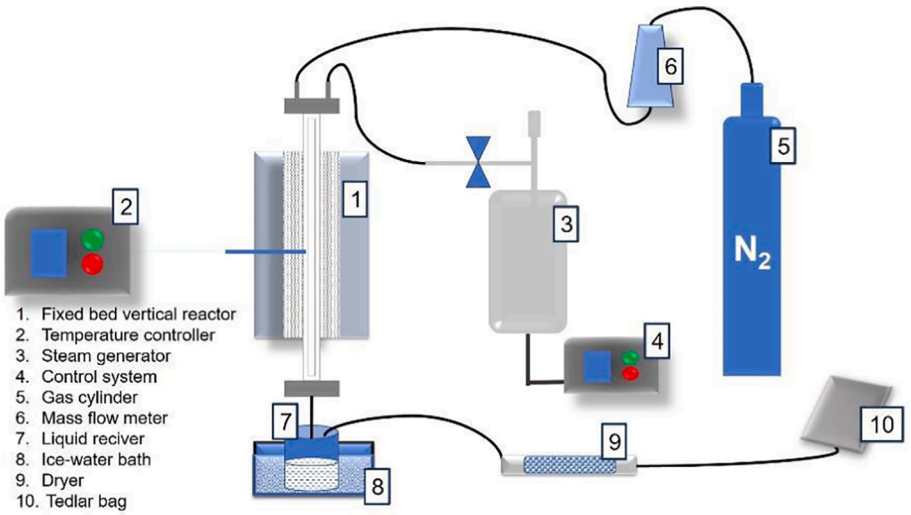

Fig. 2. Semi-batch vertical reactor used for steam activation.

fraction of municipal solid waste, and the second group of samples was hydrochar obtained after the hydrothermal carbonization process of the digestate under four different process conditions. The HTC process was carried out under two residence times of 60 and 120 min and under two temperature of 200 and 230 °C. Both parameters were included in the name of a given sample, e.g.: HTC_200_60 reflects the sample obtained at 200 °C and 60 min of residence time.

The simplified concept of the presented study is shown in Fig. 1. The raw digestate was first subjected to the HTC process, giving four hydrochar samples as a final solid product. Hydrothermal carbonisation tests were performed in a stainless-steel vessel with continuous mechanical stirring with a working capacity of 100 ml at a maximum operating temperature of 230 °C and a maximum working pressure of 35 bar. The temperature inside the reactor is manually controlled and the pressure is measured using a pressure sensor based on the saturation pressure of water at a specific temperature and partial pressure of the gaseous by-products. After the process, hydrochar was dried at 105 °C for 24 h to maintain constant weight. A detailed description of the HTC apparatus and process parameters, together with hydrochar analysis, is presented in [11,12,30]. In the presented study, a raw material and hydrochar gasification process was carried out under a steam atmosphere and a temperature of 800 °C. Fig. 2.

After gasification, the physical and chemical properties of the raw, hydrochar and char samples were determined using the following instrumental methods.

- Simultaneous thermal analysis (STA) was used to define the thermal stability of the material and perform a comparative analysis with hydrochar before activation.

During STA analysis, both hydrochar and samples after steam activation were heated in alumina crucibles (Al_2O_3) from an ambient temperature up to 800° C at a constant rate of 10 °C/min and at a flow of air of 50 ml/min. The mass of the sample was 5 mg. As a result, the TG and DSC curves were obtained.

- When scanning electron microscopy (SEM) was used for determination of the morphology and structure of the chars, the influence of the activation procedure on the material structure was analysed.

Scanning electron microscopy (SEM) with a FEI Inspect S50 microscope was used in structural and morphological investigations. Imaging of the structure was performed using a secondary electron detector under a very high vacuum and a voltage of 1 kV.

- Micromeritics ASAP 2010 analyser for porosity determination.

Porosity was determined using the ASAP 2010 system (Micromeritics, USA). To achieve similar initial experimental conditions, the samples were first degassed at 150 °C. The specific surface area and average pore diameter of each sample were determined using the BET method. The total volume of the pores was determined by applying the Barrett–Joyner–Halenda (BJH) method.

- Gas chromatography (GC) was used for the identification of the chemical composition of the gaseous phase.

The gaseous phase collected during the gasification process was analysed using the gas chromatography system, Agilent Technology 7890A GC. Gases such as CH_4, CO_2, O_2, CO, C_2H_6, C_2H_4, C_2H_2, H_2 were detected at various concentrations. The GC system is equipped with TCD and FIC detectors. The oven program included the following steps: the initial temperature of 40 °C was maintained for 5.5 min, then increased to 180 °C by 4 min with a heating rate of 20 °C/min, the temperature 180 °C was maintained until the end of the analysis run time. The total run time of the program was set to 16.5 min. The TCD detector heater was set at 200 °C with a reference flow set at 30 ml/min and a makeup flow (He) of 1 ml/min. The FID detector heater was set to the same temperature as TCD with H_2 flow of 30 ml/min, air flow of 400 ml/min, and makeup flow (He) of 20 ml/min.

2.2. Steam activation in a semi-batch vertical reactor

Gasification process was conducted in the fixed bed gasification system, presented in Fig. 1. The test rig consists of vertical furnace with power of 1800 W, equipped with quartz reactor, control thermocouple type “K” (NiCr-NiAl), heating and insulation module with an internal diameter 75 mm and total length 420 mm. Inlet of quartz reactor is connected to the gas inlets, the outlet of the reactor is connected to the liquid receiver which is placed in the ice-water bath. Gasification process of raw material and hydrochar was performed under steam atmosphere (mixture of heated to 300 °C H_2O and N_2) at 800 °C. About 1 g of hydrochar was placed on a glass wool in the quartz tube reactor. The gasification process lasted 25 min and consisted of heating stage, which lasted for 15 min and starts from the heating of the system from the ambient temperature to the set temperature and the gasification stage which lasted for 10 min in 800 °C. The flowrates of process gases were: 1 ml/min of water vapour and 80 ml/min of N_2.

Process gases are going through reactor where gasification process

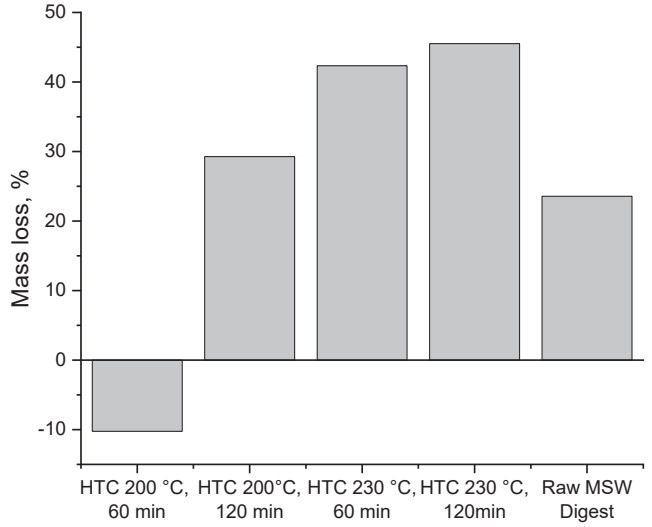

Fig. 3. Mass loss of raw material and hydrochar after the gasification process.

take place, released chemical compounds are moving into the liquid receiver where tars are condensing in the ice-bath. This stage allows to remove liquid phase and separate the gaseous phase which is going through dryer next to be collected in the Tedlar bag which is used to collect syngas the composition of which is analysed with the use of Gas Analyzer.

In the presented study, condensable gases were not collected during gasification process of hydrochar.

3. Results and discussion

3.1. Steam gasification process solid residue yields

In the process of gasification, during and after the experiment, the condensates were not collected in the cooled collecting vessels. It might be concluded that the hydrothermal carbonization process allowed for the effective decomposition of tars and other higher hydrocarbons. After reaching the process temperature, the gases were collected in Tedlar bags and further analysed; the results of the analysis are presented in Fig. 4. The obtained solid residues were cooled down in the reactor in inert atmosphere to be next weighed and prepared for further analysis to define the influence of the gasification process on the porosity of the activated carbons obtained. The results of the change in mass of the solid samples are presented in Fig. 3.

The mass loss increases with the temperature and residence time of the hydrothermal carbonization process. In one case, HTC 200 °C and 60 min, the mass increased, most probably due to water adsorption during the gasification process, as the sample was characterised by a highly macroporous structure (see Fig. 6). Raw samples, which had not been pretreated previously, were characterised by the lowest mass loss, as initially the sample was characterised by the lowest carbon concentration, according to our other studies [12]. The results presented indicate that an increase in the HTC temperature process increases the degradation of the raw material structure and favours the release of volatile parts and tar during the gasification process. The application of chars obtained after the gasification process finds a wide range of capabilities. Not only as a precursor to AC production, but also in the production of biodiesel as a catalyst for tar removal, as an adsorbent in the soil or water enrichment process, as well as in the process of anaerobic digestion or regasification as additives [16].

3.2. Analysis of collected syngas

The results of syngas analysis indicate that the time of the hydrothermal carbonization process is a key element in the case of hydrogen generation in the gasification process. In the case of the HTC sample obtained at 230 °C and 120 min, the share of hydrogen in the process gas was almost 60%. The methane concentration was also the highest in this case and was equal to more than 5.5%. The concentration of higher hydrocarbons was negligible in all cases and did not exceed 1%. The highest concentration of CO and CO_2 was observed for the raw sample, which is typical for samples that had not previously been subjected to thermal treatment. The trend of performance related to the release of H_2 and CO_2 during the gasification process can be observed. This correlation is associated with the water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + 3H_2$) [18] in which the reactants are CO and water vapor which is the environment of the process, while the products are CO_2 and H_2. According to the reaction equation, the amount of hydrogen obtained is

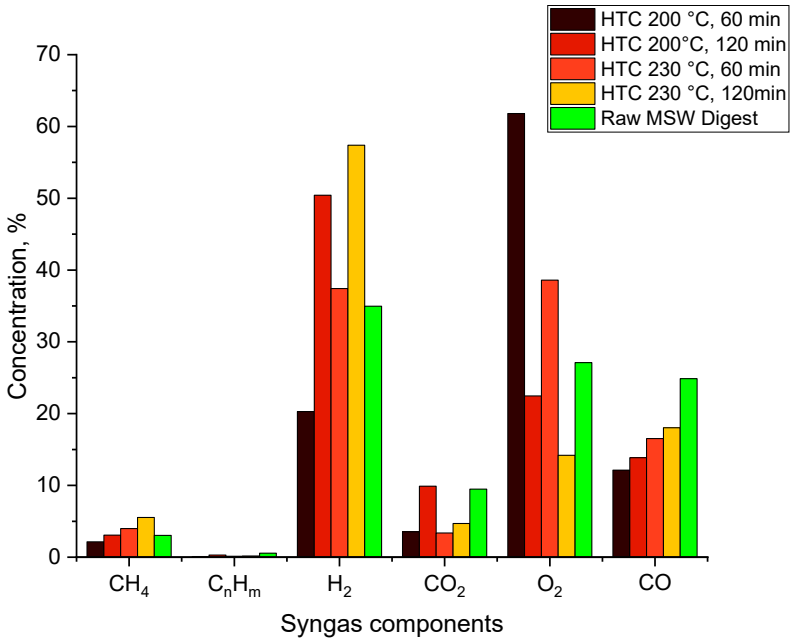

Fig. 4. Analysis of gas from steam gasification of raw material and hydrochar.

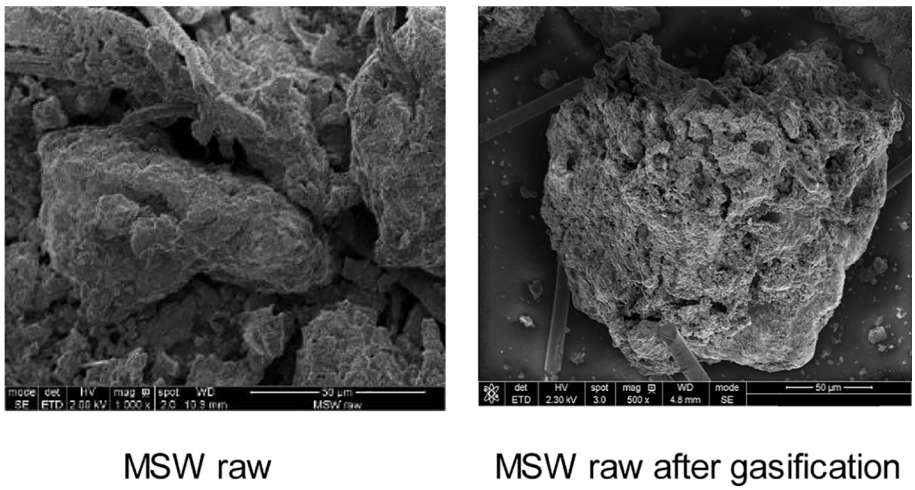

Fig. 5. Microstructural images of the samples before – raw digestate of municipal solid waste organic fraction after anaerobic digestion process (MSW) (left) and after steam gasification of MSW raw material (right).

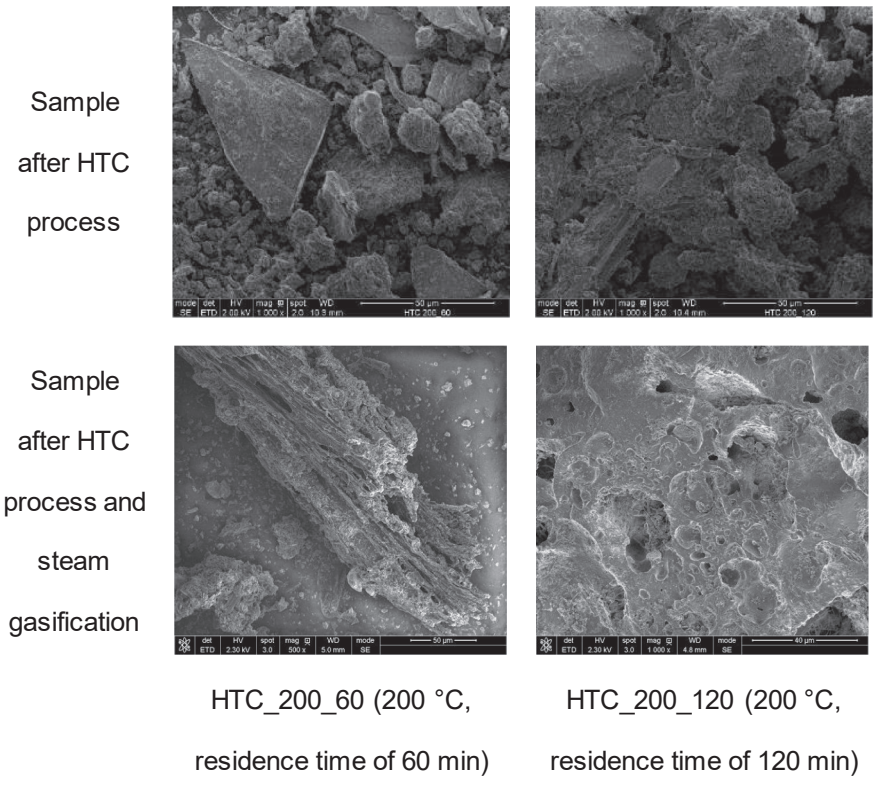

Fig. 6. Microstructural images of the hydrochar obtained at 200 °C and 60 (left) and 120 min of residence time (right).

three times higher than CO_2, which is also reflected in the results presented in Fig. 4.

In previous studies describing co-hydrothermal carbonization with further steam gasification of waste fuel – PVC and alkali coal – it was confirmed that the HTC process improved the performance of hydrogen production [22]. Studies defining gasification performance on biowaste-derived hydrochar confirmed that the temperature of the hydrothermal carbonization process slightly improves the hydrogen generation efficiency of the steam gasification process [16].

It is also worth paying attention to the H_2/CO ratio for studied HTC samples, which ranged from 1.4 for raw material up to 3.6 for the HTC_200_120 sample. In the case of other samples, this ratio is classifying in the following order: 1.7 (HTC_200_60), 2.3 (HTC_230_60) and 3.2 (HTC_230_120). It suggests that increasing the residence time of the HTC process gives better results from the perspective of Fischer-Tropsch synthesis, which demands the H_2/CO ration at a higher level than 2 [31]. Additionally, post-treatment is expected via steam reforming, which is based on the following chemical equation: $CH_4 + H_2O \rightarrow CO + 3H_2$ [32], improve the H_2/CO ratio.

3.3. Structural analysis of produced activated carbons – SEM

The structural analyses of activated carbons produced in this study were presented and compared with hydrochar in Figs. 5-7. More images

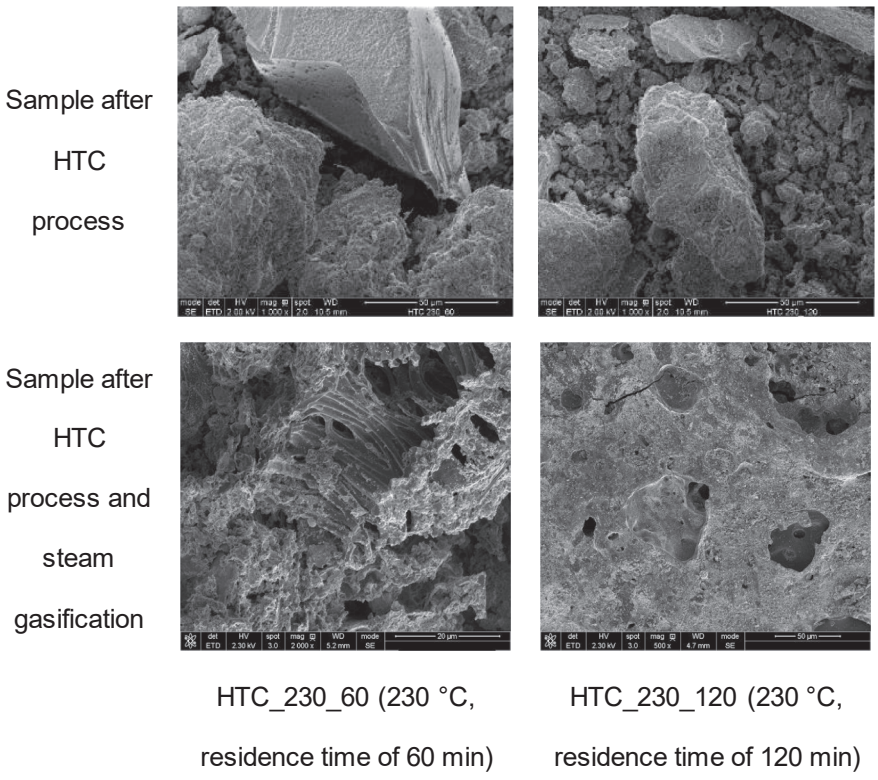

Fig. 7. Microstructural images of the hydrochar obtained at 230 °C and 60 (left) and 120 min of residence time (right).

Table 1
Microstructural parameters of the materials determined using adsorption methods, G – after the activation under H_2O atmosphere.

Sample	Specific surface area (BET), m^2/g	Total pore volume, cm^3/g	Mean pore diameter (BET), μm	Mean pore diameter (BJH), μm
Raw MSW Digest	3.01	0.0198	24.4	21.5
G Raw MSW Digest	**10.22**	**0.0106**	**4.8**	**8.9**
HTC 200_60	6.62	0.0313	19.7	19.4
G HTC 200_60	**77.78**	**0.0696**	**4.5**	**7.3**
HTC 200_120	4.98	0.0304	20.9	21.2
G HTC 200_120	**39.88**	**0.0469**	**4.9**	**8.6**
HTC 230_60	6.76	0.0380	19.5	19.2
G HTC 230_60	**52.02**	**0.0510**	**4.6**	**8.2**
HTC 230_120	4.52	0.0262	20.3	19.6
G HTC 230_120	**50.64**	**0.0603**	**5.3**	**8.9**

of raw material and selected hydrochar samples after the steam gasification process are presented in the Supplementary Material, Figs. A1-A5. The raw material was very heterogeneous and rich in elements of various shapes and sizes. A high heterogeneity of the sample was expected in the case of waste fuel, especially in the case of municipal solid waste which is a mixture of different types of materials, and its composition also varies throughout the year and depends on location as well [33]. The structure of each fraction of the raw material was different as each of them may not undergo a gasification process similarly. The most significant development of the internal area and the highly porous structure was obtained after steam gasification of the hydrochar sample pre-processed at 200 °C for 60 min – see Fig. 6.

The structure of the samples analysed was very complex and depends on the raw material. Some samples of the raw digestate after the HTC process and subsequent gasification showed nonuniform behaviour. The porosity of the samples was enhanced by the steam gasification process, but the pores observed are irregular in shape and size. Some fractions of the material were not modified by steam gasification, most probably due to the low carbon and high ash content. The structure of the activated carbons produced is characterised by many macropores and mesopores. The mesoporous structure is not the most appropriate structure for activated carbons, but the developed structure might result in further development of smaller pores inside the material. The microporous structure was further analysed using gas and mercury sorption methods.

3.4. Porosity of produced activated carbons

The porosity of the samples analysed is presented in Table 1. "G" before the name of the sample denotes the sample after gasification. The results obtained in this study were compared with the properties of the raw material presented in [12]. In all cases, the porosity of the raw material and hydrochar was enhanced, and in some cases, the specific surface area was increased several times. The smallest increase in specific surface area was noted for the raw material. According to the literature, hydrothermal carbonization seems to be a good pretreatment method for the preparation of activated carbon [15]. However, it was noted that the sample residence time in the HTC process did not favour the development of a specific surface area, but only a weak correlation between the HTC process time and porosity might be noticed. The problem with the raw material and hydrochar is its high heterogeneity; therefore, it is hard to precisely define the HTC process parameters on final product properties. However, better results were obtained in the

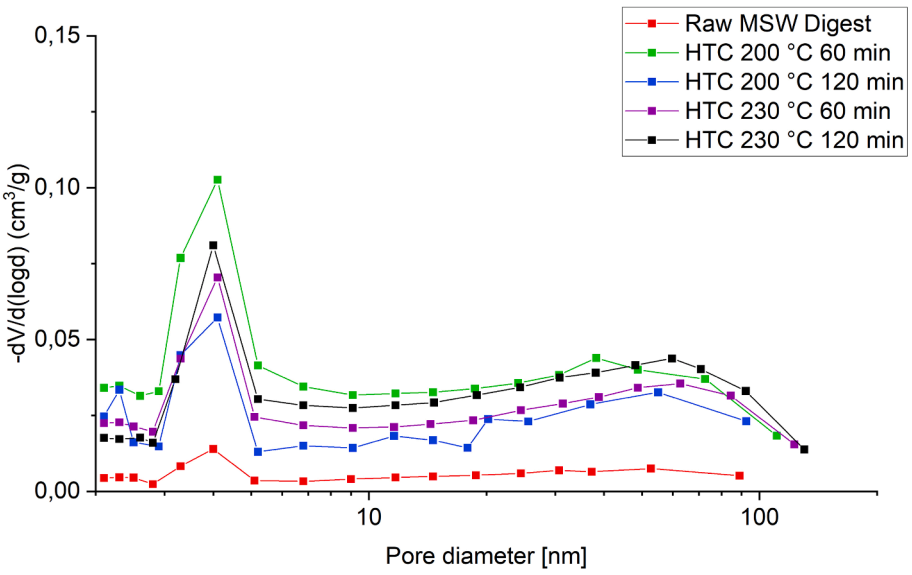

Fig. 8. Pore volume distributions of hydrochar and raw material after steam gasification process.

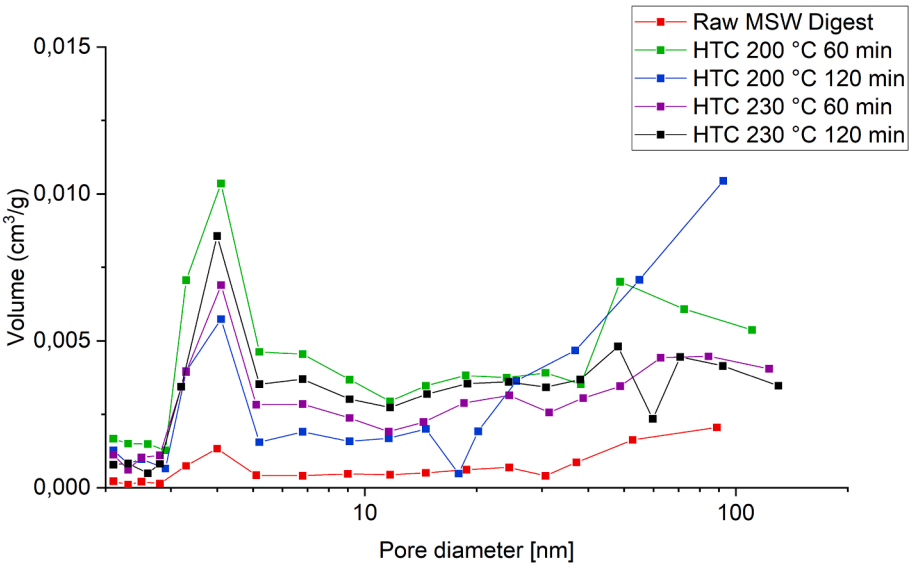

Fig. 9. Pore size distribution of hydrochar and raw material after steam gasification process using mercury intrusion capillary data.

case of material pretreated at 200 °C, which could be directly connected with the presence of closed pores in hydrochar filled with tars produced in the HTC process.

Activation of hydrochar by means of steam gasification leads to a noticeable increase in specific surface area and a decrease in mean pore diameter. It was even possible to enhance the structure of the raw MSW digestate using steam gasification, and the mean pore diameter was similar in all cases (raw material and hydochar). Obtained char have properties similar to those of commercial activated carbons, characterised by a developed microporous structure. The main difference is observed in terms of its active surface area, which is definitely too low to assume this type of material as a potential adsorbent. The surface area of commercial activated carbon BET is in the range of 500 – 3150 m^2/g [34–37]. Steam activation is one of the most frequently used techniques in commercial production of activated carbon from clean fuels such as wood and charcoal. Its main advantage is its minor impact on the environment and small waste generation compared to chemical activation. However, due to the limited performance of the hydrothermal carbonization coupling method with steam activation, as presented in this study, chemical activation is used more frequently in the production of activated carbons from waste fuels such as biomass [38] and waste biomass [6,15,39]. It enables to increase the active porous area of hydrochar derived from waste from fa ew m^2/g to more than 1500 m^2/g [40]. It was also reported in the literature that the reaction time might improve the structural properties of the hydrochar produced from biomass [13], but this was not observed in the case of the hydrochar derived from waste produced in this study.

The activated carbons produced were also analysed using the mercury porosimetry intrusion method, the results are presented in Figs. 8 and 9.

After the gasification process, a structure of hydrochar was developed and the size of pores decreased. In raw samples after the hydrothermal carbonization process, large mesopores and macropores were mostly developed. However, after the upgrading process, smaller pores of about 4 nm were developed. The results of mercury porosimetry intrusion are consistent with those obtained using the nitrogen adsorption method and are presented in Table 1.

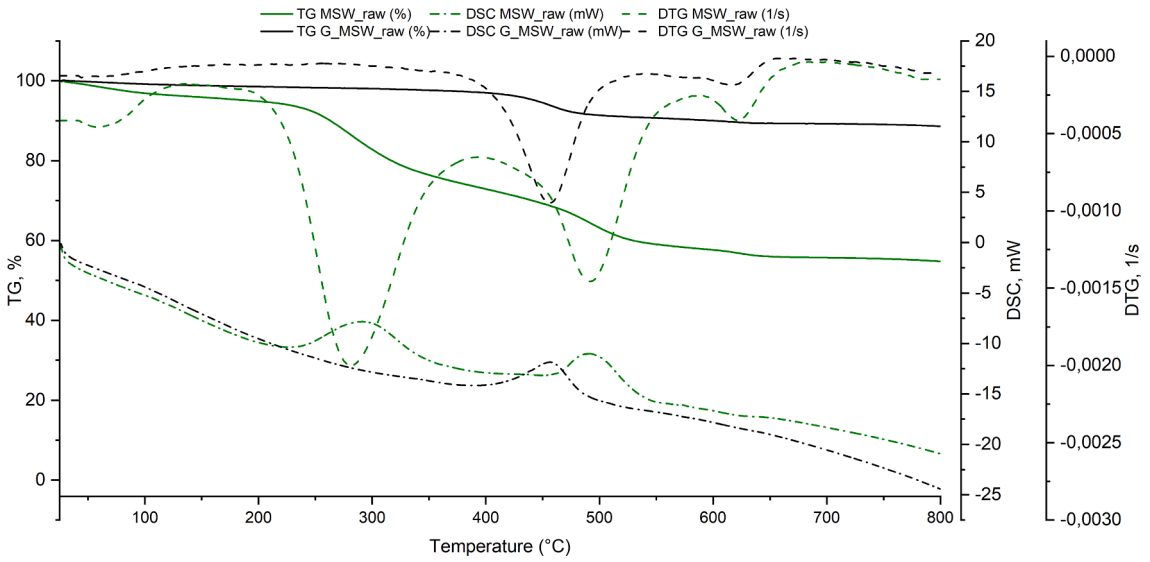

Fig. 10. Thermal behaviour of raw MSW sample and after gasification up to 800 °C under oxidising conditions.

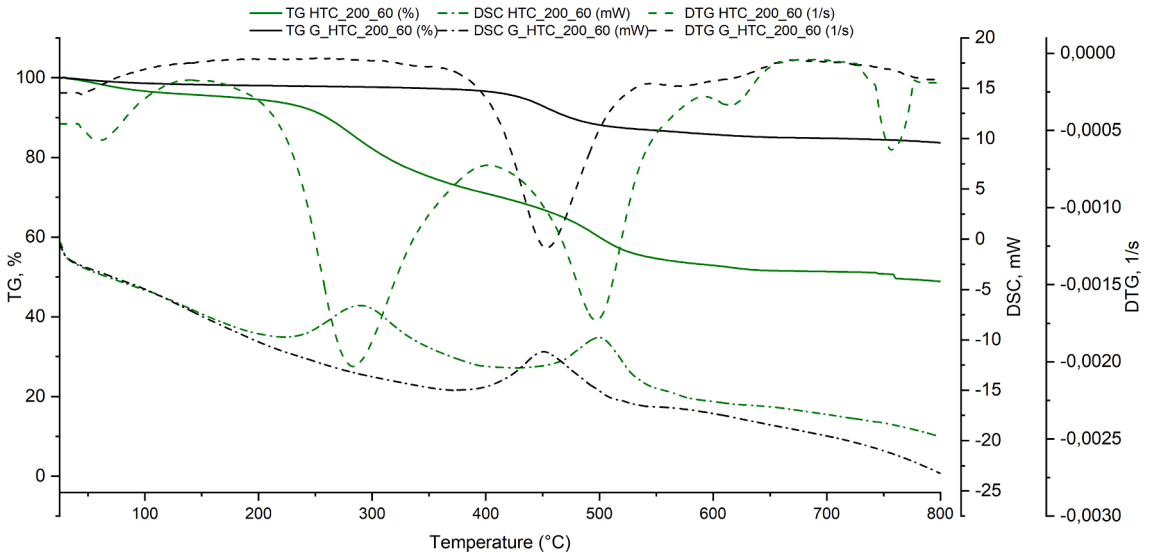

Fig. 11. Thermal behaviour of hydrochar obtained at 200 °C and 60 min residence time and hydrochar after gasification up to 800 °C under oxidising conditions.

3.5. Simultaneous thermal analysis of hydrochar and produced activated carbons

Materials obtained through steam gasification of hydrochar presented enhanced sorption properties and developed surface area. To study the thermal stability and energetic potential of activated carbons compared to hydrochar, thermogravimetric analysis was performed and the thermal behaviour of the materials studied under combustion conditions is presented in Figs. 10–14. On the basis of the obtained TG and DTG curves, the difference between hydrochar and solid residue after gasification is well seen. Analysing Fig. 10, three peaks were observed in raw material DTG, at 285, 493, and 621 °C, respectively. The first can be associated with the decomposition of hemicellulose and cellulose, the second with the decomposition of lignin, and the third (above 600 °C) can be reflected in the decomposition of inorganic matter.

Thermogravimetric analysis for activated carbon after the gasification process confirmed it's stability up to 400 °C.

The evaporation zone in the case of hydrochar occurred up to 150 °C in all the cases analysed. Apart from water evaporation, in the case of hydrochar, three major weight loss steps were noted, whereas after gasification only two at higher temperatures were present. The weight loss step of hemicellulose and cellulose decomposition that occurs at about 300 °C [41] was not present after the steam gasification process. Only steps of lignin and char formation were present for activated carbon, but it should be mentioned that the remaining residue mass was noticeable and about 30 % higher than in the case of hydrochar. Additionally, the thermal decomposition picks in the case of activated carbons shifted toward a lower temperature range and might be associated with the decomposition of lignin and remaining cellulose. Organic matter in the hydrochar was efficiently released during the steam gasification process, and valuable, rich in hydrogen gas, was collected. Therefore, the remaining residue is rather poor in organic matter and the volatile matter in the raw material was completely released during previous thermal processing steps. The results of the remaining residue mass determined using STA analysis are presented in Table 2.

The lower temperature of the HTC process favours carbonisation of the raw material, and at higher temperature a noticeable degradation of organic matter was observed resulting in a higher mass loss than in the case of raw material.

It was observed that HTC process parameters do not influence the

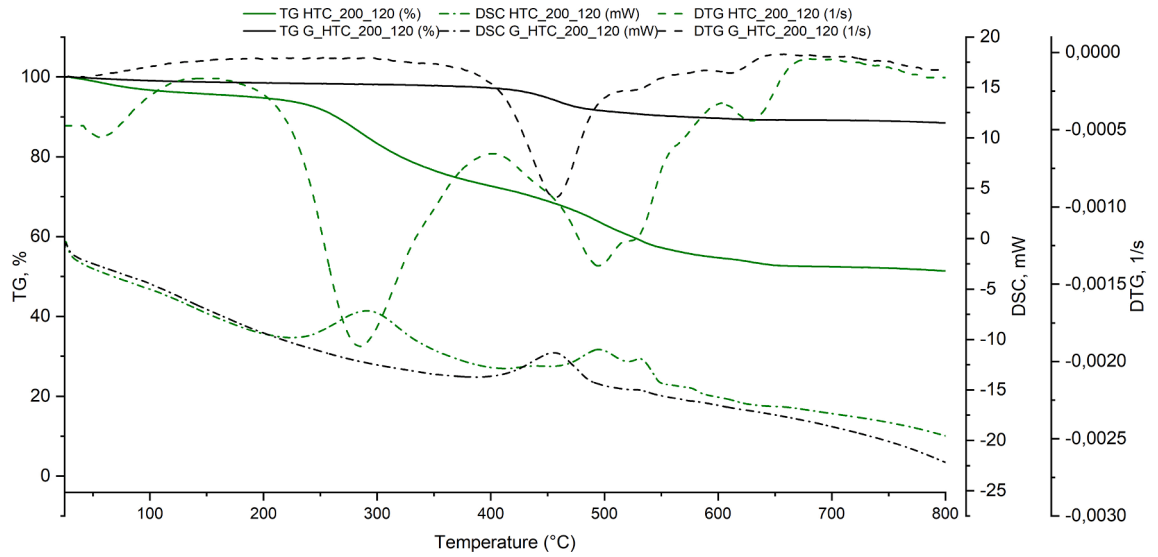

Fig. 12. Thermal behaviour of hydrochar obtained at 200 °C and 120 min residence time and hydrochar after gasification up to 800 °C under oxidising conditions.

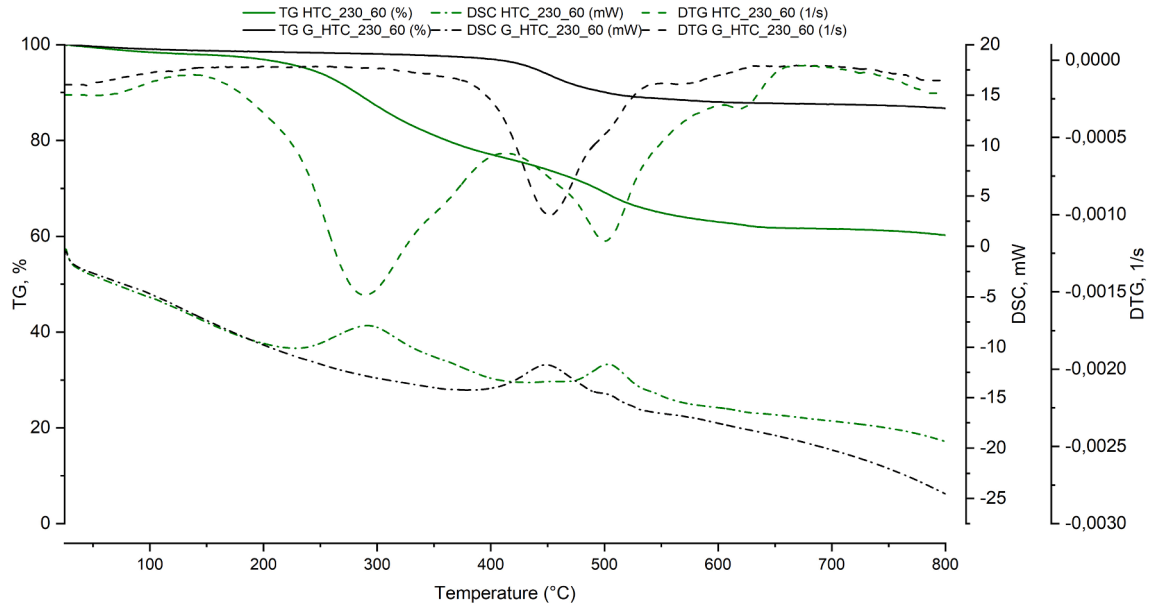

Fig. 13. Thermal behaviour of hydrochar obtained at 230 °C and 60 min residence time and hydrochar after gasification up to 800 °C under oxidising conditions.

thermal properties of activated carbons produced, and similar tendencies and temperature ranges of mass losses were observed in all cases.

4. Conclusions

In this study, the influence of pretreatment of digestate from anaerobic digestion of the wet fraction of municipal solid waste using hydrothermal carbonization on steam activation was analysed. On the basis of the results of this study, the following main conclusions can be briefly drawn:

- The post-gasification mass loss of raw material and hydrochar increases with the increase of the HTC process temperature, due to the promotion of feedstock degradation during the HTC provided at higher temperature and longer residence time.
- During the steam gasification process, no tars were condensed. Collected syngas was characterised by a high concentration of valuable hydrogen, especially after sample pretreatment through the HTC process.
- Syngas was characterised by a wide range of H_2/CO ratio (from 1.4 for raw material, up to 3.6 for HTC_200_120) which is an important factor from the Fischer-Tropsch synthesis perspective, which required obtaining level at least 2.
- Waste material of high organic fraction could be treated as a renewable energy resource, therefore, during the gasification process additional CO_2 capture technology could be considered to achieve negative CO_2 emission.
- The steam gasification process is a good method for upgrading hydrochar and the production of valuable syngas.
- Obtained activated carbon samples are characterised by a higher concentration of smaller mesopores and a higher specific surface area than initial hydrochar samples,
- The specific surface area depends on the initial porosity of the sample, but the mean pore diameter was similar in all cases.

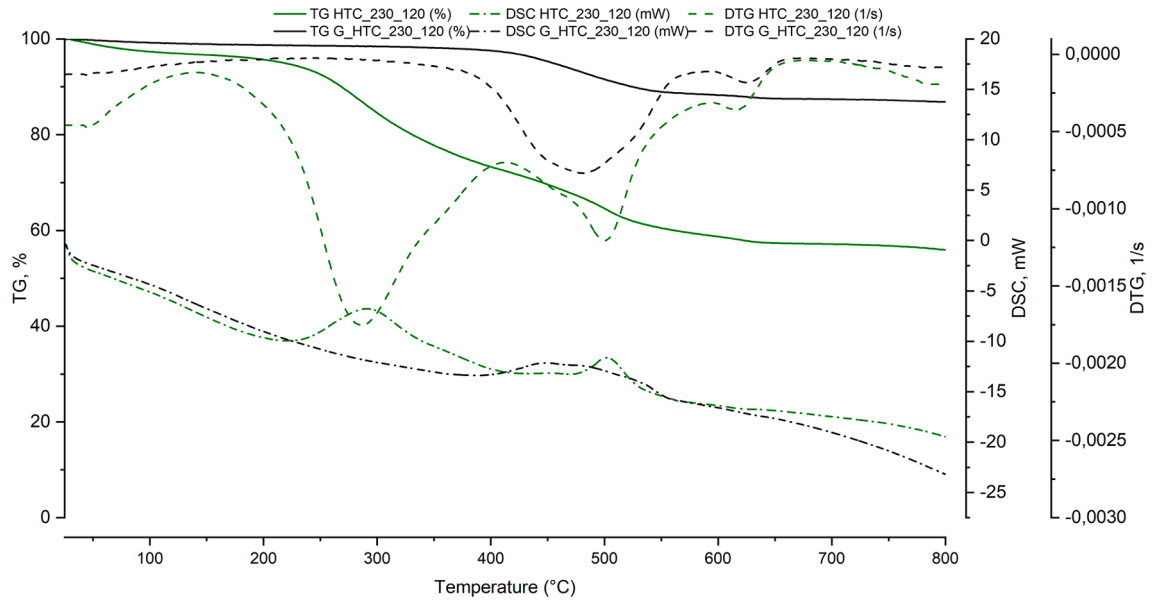

Fig. 14. Thermal behaviour of hydrochar obtained at 230 °C and 120 min residence time and hydrochar after gasification up to 800 °C under oxidising conditions.

Table 2
Residue mass after combustion of hydrochar and activated carbons determined using STA.

Sample	Residue mass, %
Raw MSW Digest	54.77
G Raw MSW Digest	**88.61**
HTC 200_60	48.89
G HTC 200_60	**83.67**
HTC 200_120	51.37
G HTC 200_120	**88.61**
HTC 230_60	60.23
G HTC 230_60	**86.70**
HTC 230_120	55.95
G HTC 230_120	**86.84**

- Produced activated carbons are characterised by high heterogeneity and their properties depend upon the initial composition of the raw material.
- The mercury porosimetry test showed that also mesopores and macropores are present in the samples in the range of 10 up to 100 μm.
- The activated carbons produced were characterised by high stability up to 400 °C, the temperature and the residence time did not influence the thermal properties of the activated carbons produced by steam gasification.
- Better results might be achieved through chemical activation, but in the case of steam gasification, additional high-quality syngas is produced, activated carbon did not show the highest performance, but through process parameters adjustment its quality might be enhanced.
- In this work it was showed that hydrochar obtained under hydrothermal carbonization of municipal solid waste organic fraction are a promising raw material for further conversion in material science filed. As precursors for active carbon production, hydrochar can be used as adsorbent for water purification e.g. in waste water treatment plants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Part of this work was realized within RECOWATDIG consortium financed under the 2018 Joint call of the WaterWorks2017 ERA-NET Cofund, National Centre for Research and Development, grant no. WATERWORKS2017/I/RECOWATDIG/01/2019. Gasification studies were supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 823745.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2022.124435.

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