detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

WASTE TO ENERGY: HYDROTHERMAL CARBONIZATION OF AGRO-WASTE FOR THE PRODUCTION OF HIGH VALUABLE SOLID BIOFUEL

Antonio Messineo [1,*], Antonio Picone [1], Chiara Corrado [2], Dario Ticali [1] and Maurizio Volpe [1]

[1] *Department of Engineering and Architecture, Kore University of Enna, Cittadella Universitaria, 94100, Enna, Italy*
[2] *Department of BioMedicine, Neurosciences and Advanced Diagnostics (Bi.N.D), University of Palermo, via Divisi 83, 90133 Palermo, Italy*

Article Info:
Received:
27 November 2025
Revised:
12 January 2026
Accepted:
20 January 2026
Available online:
17 February 2026

Keywords:
Banana peel waste
Hydrochar
Hydrothermal carbonization
Biofuel

ABSTRACT

In the present study, hydrothermal carbonization (HTC) of banana peel waste, showing a moisture content of 85 wt%, was carried out in a 500 mL stirred stainless steel autoclave at a temperature ranging between 180 and 250°C, for a residence time of 0.5 h. The reaction solid residue was recovered via vacuum filtration and washed with distilled water before drying it in a ventilated oven at 105°C, until constant weight, and stored in 50 mL plastic vials, before analytical characterization. Banana hydrochars were characterized in terms of proximate, elemental analysis, FTIR and high calorific value (HHV). Hydrochar mass yield showed a maximum at 220°C (32 wt%), while gas and liquid mass yields increased monotonically with reaction temperature, up to 70 and 2 wt%, respectively. HHV increased with reaction temperature up to 27.13 MJ/kg, corresponding to an energy densification ratio EDR of about 169%. Mass yield and energy properties of banana hydrochar prove that a HTC treatment carried out at 250°C for 0.5 h is able to produce a valuable solid biofuel showing the characteristics of lignite.

1. INTRODUCTION

The urgent need for a sustainable and green production of thermal energy and electricity by renewable sources exploitation, has boosted, in the last few years, the seek for a clean technology to address the climatic challenge and ensure reliable energy solutions (Cotana et al., 2014; Ibarra-Gonzalez and Rong, 2019; Shen, 2020). An adequate thermochemical valorization of waste biomass, globally available in large quantities, may accelerate the transition from fossil fuels to carbon neutral energy systems, reducing both greenhouse gas emissions and waste generation (Lee et al., 2020; Nunes et al., 2020). Between the different technologies investigated in the last decades for the energy exploitation of waste biomass, thermochemical treatments such as pyrolysis and gasification have received high attention due to the possibility of producing energy carriers, either solid (bio-char), liquid (bio-oil) and gaseous (syn-gas), potentially capable to substitute the mineral fuels (R. Volpe et al., 2016). Unfortunately, the majority of waste biomass has high moisture content (often higher than 50% by weight) that limits the use of such dry thermochemical technologies, given the high energy costs associated with the removal of water before the substrate processing (Messineo et al., 2012; Messineo and Panno, 2008).

More recently, hydrothermal carbonization technology (HTC) has shown the high potential for transforming high moisture waste biomass into a carbon and energy dense material, named hydrochar, with energy characteristics close to the pyrochar (Picone et al., 2021). HTC allows to convert wet biomass in closed reactors and in the presence of additional water at subcritical conditions (180-250°C and 10-50 bar), for a residence time from few minutes to several hours, with high energy efficiency (Becker et al., 2019). Compared to the above mentioned dry thermochemical treatments, HTC ensures several advantages, mostly related to the significant energy saving, due the absence of a biomass pre-drying step, the higher conversion degree at milder reaction conditions, and the generation of solid products with a very low ash content (Heidari et al., 2019; Rodríguez Correa et al., 2018). During HTC, subcritical water plays a crucial catalytic role, as it promotes the splitting of the highly heterogeneous lignocellulosic macromolecules by hydrolysis. The generated soluble biomass fragments are then involved into a multiphase and intricate network of competing reactions, with dehydration, decarboxylation, poly-condensation, and aromatization recognized as the main conversion pathways (Wang et al., 2018). Dehydration and decarboxylation lead to a notable

* Corresponding author:
Antonio Messineo
email: antonio.messineo@unikore.it

https://doi.org/10.31025/2611-4135/2026.19566

reduction of oxygenated species in the initial feedstock, substantially increasing the carbon content in the final solid product, while poly-condensation and aromatization govern the hydrochar forming mechanism by liquid-to-solid and solid-solid (pyrolysis-like) reactions (Ischia et al., 2024; Wu et al., 2025).

In the past years, HTC has been successfully employed for the treatment of a wide range of feedstocks, such as food waste, sewage sludge, residues from the agro-inudstrial sector, and plastic substrates, largely showing to be a valid solution within the realm of waste management and the production of valuable bio-derived materials with immense potential in both energy and environmental applications (Volpe et al., 2020). Numerous scholars investigated the potential use of hydrochar for the generation of clean thermal energy by direct combustion, observing promising performances due to the high energy density (higher heating value in the range of 20-28 MJ/kg), higher thermal stability compared to raw feedstock, prevention of fouling and slagging due to the low ash content, and reduced harmful emissions compared to coal combustion (Wang et al., 2018; Wilk et al., 2020). Tunability of hydrochar properties (surface area, pore structure, surface functionality, and chemical composition) by simply adjusting HTC parameters, allowed for the optimization of its electrochemical performances in specific energy storage applications (Zhou et al., 2021). As well documented in literature, hydrochar has been also effectively used for water remediation, by removing heavy metals and organic persistent pollutants, soil amendment, and carbon sequestration (Regmi et al., 2012; Wu et al., 2025).

Until now, extensive work has been dedicated to studying the influence of feedstock nature, in combination with the operating conditions (reaction severity, starting biomass concentration, use of catalysts, etc), on the process outputs, in terms of mass yield and physico-chemical properties, and therefore on their suitability for specifically selected applications (Hedin and Kruse, 2020; Sharma et al., 2020). Nevertheless, further research activity is essential not only for the advancing of scientific knowledge and a complete understanding of the process fundamentals, but also for optimizing and tailoring the conversion toward HTC products with perfectly controlled and desired features (Ischia et al., 2024).

In the present study, we report novel results regarding banana peel waste energy upgrading via HTC at the temperature range of 180-250°C. The produced hydrochars were analytically characterized to measure the energy densification and observe the evolution of proximate, elemental composition, and chemical functionality, after the thermochemical treatment. This work clarly demonstrates the huge potential of HTC to efficiently handle wet agro-waste biomass and convert it into an energy-dense material that might be used as an alternative, carbon neutral solid fuel, contributing to the reduction of fossil fuels exploitation and to the development of a circular bioeconomy.

2. MATERIALS AND METHODS

2.1 Sample preparation and experimental procedure

Banana peel waste (BPW) was used as feedstock for the HTC treatment. BPW represents a typical agro-food waste and was collected as a food residue of kitchen and restaurant. Fresh BPW was ground by using a knife miller to provide completely homogeneous pulp composition with a reproducible size reduction. The so obtained pulp was portioned and stored in sealed plastic bags in a freezer at -20°C, before their use. The sample was slowly left defrosting down to room temperature, before each HTC experiment. A sample of as above prepared feedstock was dried in a ventilated oven at 105°C until constant weight to quantify the moisture content (MC); BPW showed a MC value of 85.0 ± 0.2 wt%.

BPW defrosted wet feedstock, without pre-treatment (Volpe et al., 2022), was hydrothermally carbonized in a 500 mL stainless steel batch reactor with stirring (200 rpm) at the temperatures of 180, 220 and 250°C with a residence time of 0.5 h. For each experiment the reactor was loaded with approximately 300.0 g of wet BPW (corresponding to 45 g of dry sample) and 200.0 g of distilled water (DW), to reach a prefixed biomass to water mass ratio (B/W) of 0.1. After loading the feedstock, the reactor was vented with pure nitrogen (Alphagaz 1, Airliquid™) and the reaction temperature set at the desired temperature. When the conversion time, at set temperature, has passed, the reactor was cooled down to room temperature by a cooling water circulating system, allocated inside the reactor. The gas phase produced was flowed, through an outlet valve, into a graduated cylinder filled with water, and its mass was evaluated applying the ideal gas law, assuming atmospheric pressure, temperature of 30°C and CO_2 as the sole gaseous product. Indeed, it was seen that the typical CO_2 molar fraction in HTC gas is higher than 0.90, with minor traces of other species such as CO, H_2 and CH_4 (Picone et al., 2021). The hydrochar was separated from HTC process water (PW) by vacuum filtration and dried at 105°C until constant weight prior to mass yield determination. All experimental tests were performed at least three times to evaluate the deviation of data and ensure reproducibility (the results were considered valid if standard deviation < 2.0%).

2.2 Analytical methods and calculation

Composition and energy content of raw feedstock and hydrochars were evaluated by proximate analysis and higher heating value (HHV) measurement, respectively. Proximate analysis was carried out by a LECO Thermogravimetric Analyser TGA 701 (following ASTM D7582-15 standard method). Approximately 400 mg of each solid sample was used to quantify volatile matter (VM), ashes (ash) and fixed carbon (FC) as follows: 5°C/min ramp to 105°C in air, held until constant weight (<±0.05%) to remove moisture in open crucibles; 16°C/min ramp from 105 to 900°C, hold time 7 min, in nitrogen and covered crucibles to determine VM as the mass lost; natural cooling down to 500°C in nitrogen; 30°C/min ramp in air to 800°C and isothermal

until constant weight in open crucibles to evaluate ASH as the remaining mass. FC was estimated by subtracting VM and ash percentages from 100%.

Elemental analysis was carried out using a CHN LECO 828 series element analyzer using argon as carrier gas and EDTA as calibration standard.

A calorimeter LECO AC500 was used to measure HHVs according to the CEN/TS 14918 standard. FTIR analysis was carried out on the raw material and corresponding hydrochars samples using a Shimadzu IR Tracer spectrometer in mid-IR mode, equipped with a Universal ATR sampling device containing diamond/ZnSe crystal. The spectra were recorded in the range from 600 to 4000 cm^{-1}, with a resolution of 4 cm^{-1}, by averaging 64 scans, baseline corrected and normalized. The hydrochar mass yield (MY_{HC}) was calculated through Equation 1, where m_{HC} is the mass of hydrochar (d.b.) collected after the conversion and m_{raw} is the mass (d.b.) of solid starting material.

$$MY_{HC} = m_{HC}/m_{raw} \quad (1)$$

Similarly, gas mass yield (MY_{gas}) was evaluated through Equation 2.

$$MY_{gas} = m_{gas}/m_{raw} \quad (2)$$

PW mass yield (MY_{PW}) was calculated by difference through Equation 3.

$$MY_{PW} = 1 - MY_{HC} - MY_{gas} \quad (3)$$

The fuel ratio (FR) was defined as the mass yield ratio of FC to VM to measure the carbonization degree of resulting hydrochar:

$$FR = FC/VM \quad (4)$$

The energy yields (EY) were calculated by Equation 5 to evaluate the energy retention efficiency in the hydrochar after the biomass HTC conversion.

$$EY = (HHV_{HC}/HHV_{raw})\ MY_{HC} \quad (5)$$

3. RESULTS AND DISCUSSION

3.1 Mass yields of BPW HTC residues

Figure 1 shows the mass yields of banana HTC residues. As predictable, gas mass yield slightly increased with HTC reaction temperature, reaching the maximum value of 1.7%, at 250°C. Indeed, since gas formation during the hydrothermal treatment is highly endothermic, it was promoted with the increase of reaction severity, coherently with other studies reported in literature (Wang et al., 2018). Conversely, the hydrochar mass yield did not follow a monotonic behaviour in terms of final mass recovered, with the maximum value (~ 32%) reached at 220°C.

The majority of HTC studies report a monotonic decrease of hydrochar mass yield with the increase of operating temperature, which is ascribed to the dominant hydrolysis and devolatilization of starting feedstock over the formation of stable hydrochar structures (Wang et al., 2020, 2018). However, in some cases, the hydrochar production could be enhanced by increasing the thermal energy supplied to the reactive multiphase mixture inside the reactor. As well known, temperature is the most influential factor in HTC and can indeed significantly affect the conversion pathways leading to solid products (Sharma et al., 2020). HTC relies on a complex and intricate network of both parallel and consecutive reactions that include the formation of solid particles at solid-solid and liquid-solid interfaces (Fu et al., 2025). On the one hand, the so-called primary char is obtained from the unhydrolyzed starting biomass through pyrolysis-like reactions, responsible of the increased carbon content in the recovered solid product (Lucian et al., 2018). On the other hand, the hydrolyzed fraction is involved into competing subreactions, with the formation of highly reactive liquid by-products (Fu et al., 2025). Among these, organic acids, such as acetic, lactic, propionic, levulinic, and formic acids, play a key role in HTC as they lower the pH of reaction medium and spark an autocatalytic process consisting of

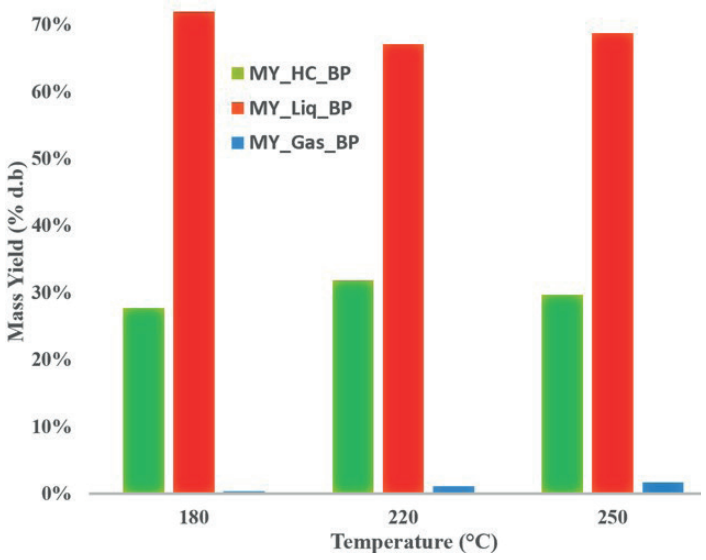

FIGURE 1: Mass yields of banana peel waste HTC residues at different process temperatures (solid, liquid, and gas yields are reported in green, red, and blue, respectively).

a boosted biomass depolymerization. The enhanced PW reactivity may promote the accumulation of hydrochar precursors in the liquid phase, including furans, furfurals, and aldheydes, which could then lead to the endothermic formation of additional solid phases with quasi-spherical structure, named secondary char, via interphase catalyzed reactions. Typically, once formed, the new carbon-based microparticles tend to adhere to the primary char surface and contribute to the increase of hydrochar recovery, especially at severe reaction conditions (Picone et al., 2021; Sevilla and Fuertes, 2009; Wang et al., 2020).

In light of these considerations, the results presented in this section, suggest that the increase of temperature could have promoted the concentration of liquid precursors for secondary char formation and its subsequent deposition of the available primary char sites, leading to a greater hydrochar mass yield at 220 and 250°C, compared to that obtained at 180°C.

It is noteworthy that a fraction between 60 and 70% of the starting feedstock remained in the spent process solvent. Detailed investigations have shown that PW composition can significantly vary according to the feedstock type used for the HTC treatment, however, the most common species detected include organic acids, in high concentration, and other unconverted biomass fragments, heavy metals, nutrients, and organic compounds potentially toxic for the environment (Wang et al., 2020). For this reason, in order achieve the process economic and environmental feasibility, and thus promote HTC upscaling, an adequate valorization of residual PW represents one of the biggest scientific and technical challenges. In the recent past, several scholars demonstrated that PW holds remarkable potential for innovation across energy, agriculture and environmental fields (Ischia et al., 2024), therefore we will focus on the development of effective strategies for PW reuse and/or industrial valorization, in a future study.

3.2 Hydrochars characterization

Table 1 reports the results from the HHV measurement, energy properties (EY, FR) calculation and proximate analysis for BPW raw material and hydrochars obtained at different reaction temperatures.

It can be observed that the energy content of produced hydrochars is substantially higher than that of raw BPW, due to the carbonization reactions. In addition, HHV increased with reaction temperature, up to 27.13 MJ/kg at 250°C, reaching a value approaching that of lignite. The energy yield of hydrochars reached a value of 50.0% at 250°C, with a corresponding EDR of approximately 169%. Proximate analysis data show that, as expected, VM decreased with HTC process temperature, while FC increased up to approximately 31.5%, at 250°C. The ash content was significantly reduced during HTC, from 8.5 for raw BPW to 0.75-1.67% for hydrochars at 180, 220 and 250°C, respectively. This confirms that during the wet thermochemical treatment, most of inorganics are moved to the aqueous phase, thus considerably reducing the risk of slagging and fouling phenomena in the case of combustion (Reza et al., 2013).

Elemental analysis data, shown in Table 2, corroborate the findings of proximate analysis. For hydrochars, the content of elemental carbon increased with increasing temperature, reaching a maximum value of 63.65%, at 250°C. The increase of carbon content with the process severity was accompanied by a drastic reduction of oxygenated species, while, as already reported in HTC literature, hydrogen content is not significantly affected by the reaction, showing stable values between 5.9 and 6.3%.

Thermochemical evolution of BPW undoubtedly prove that coalification occurred during HTC, with a notable densification of carbon and FC contents as the main result (Danon et al., 2014; García-Bordejé et al., 2017). Dehydration and decarboxylation dominate the devolatilization process, leading to the significant decrease of elemental oxygen and VM contents. As both reactions are highly endothermic, they were likely promoted with the increase of reaction temperature, as suggested by the evident reduction of H/C and O/C atomic ratios (Jia et al., 2022; Wang et al., 2022). In this regard, the Van Krevelen diagram reported in Figure 2 clearly shows that dehydration is the main mechanism involved during HTC of BPW. Furthermore, it can be seen that hydrochars progressively assume a fuel behavior resembling that one of peat, at 220°C, and lignite, at 250°C. The carbon densification reflects the higher energy content found for the hydrochars, compared to the parent substrate (raw BPW), definitely proving the effectiveness of HTC technology for the production of solid biofuels with high potential.

Surface chemical functionalities in raw material and hydrochars were studied via ATR-FTIR analysis.

Figure 3 shows the FTIR spectra in ATR mode of raw BPW and corresponding hydrochars obtained at 180, 220 and 250°C.

The spectra show a broad band between 3400 and 3300 associated to the stretching vibration of O-H, involved in hydrogen bonding. It can be seen that this band shifted toward higher wavenumber after the HTC treatment due to the concentration of phenolic compounds in lignin and carboxylic acids groups. The increasing aromatic character in hydrochars with HTC temperature is also

TABLE 1: Energy properties of BPW and correspondig hydrochars.

Sample	HHV* [MJ/kg]	EY [%]	EDR [%]	VM* [%]	FC* [%]	Ash* [%]	FR
BPW_{raw}	16.09 (± 0.18)	100.0	100.0	80.72	10.78	8.50	0.13
BPW_{HC180}	23.48 (± 0.31)	40.5	146.0	75.82	23.43	0.75	0.31
BPW_{HC220}	24.93 (± 0.32)	49.3	155.0	67.59	31.49	0.92	0.47
BPW_{HC250}	27.13 (± 0.26)	50.0	168.6	63.07	35.26	1.67	0.56

** on a dry basis (d.b.)*

TABLE 2: Elemental analysis data, O/C and H/C atomic ratios of BPW and corresponding hydrochars.

Sample	C [%]	H [%]	N [%]	O* [%]	O/C**	H/C**
BPW_{raw}	40.85	5.87	0.84	43.95	1.72	0.81
BPW_{HC180}	54.95	6.59	1.45	36.27	1.44	0.49
BPW_{HC220}	59.55	6.30	1.35	31.89	1.27	0.40
BPW_{HC250}	63.65	6.31	1.33	27.05	1.19	0.32

** O = 100−C−H−N- Ash; ** atomic ratio*

visible with the increase of the aromatic C-H stretching mode at 2950 and 1610 cm^{-1}, together with the bending out of plane vibration at around 720 cm^{-1}. Aliphatic CH_2 and CH_3 vibration modes were also detected in all samples at 2920 and 2850 cm^{-1}, demonstrating that aliphatic character is maintained during HTC due to aromatic structures. C=O stretching vibration at around 1700 cm^{-1} (aldehydic and/or carboxylic compounds) increased with HTC temperature, as visible in the spectra of BPW at 220 and 250°C. The carboxylic C-O stretching mode was revealed by the bands at 1150-1100 cm^{-1}, while the sharp band at 1030 cm^{-1} could be assigned to inorganig C-O vibration. In summary, data from FTIR indicate that HTC strongly promote aromatization and decarboxylation of the BPW sample with temperature.

4. CONCLUSIONS

Hydrothermal carbonization (HTC) is a thermochemical process used for the conversion of high moisture biomass, like agro-industrial wastes, into carbon-dense hydrochars, which could find application as valuable solid biofuels.

In this study, we investigated the thermochemical upgrading of banana peel waste (BPW) via HTC and assessed the effect of reaction temperature on energy properties and composition of the hydrochars produced. Experiments were carried out by using a 50 mL stainless steel batch reactor at the three different temperatures of 180, 220 and 250°C, with a biomass to water mass ratio of 0.1 and keeping a fixed reaction time of 0.5 h. After HTC, the solid products were characterized in terms of higher heating value (HHV), proximate and elemental composition, and surface chemical functionality.

While, as expected, gas production increased with temperature due to the endothermic nature of decarboxylation reactions, differently from the common outcomes reported in HTC literature, solid mass yield did not follow a monotonic decrease, reaching a maximum value of approximately 32%, at 220°C. This peculiar trend might be closely related to the formation of additional solid phases, known as seconary char, at the more severe reaction conditions, with an observable increase of solid mass recovered as the main result. Data from proximate and elemental analyses suggest that dehydration was the main converson pathway and led to a drastic reduction of elemental oxygen content, due to the biomass devolatilization. Correspondingly, a significant carbon and energy densification was found after the BPW thermal treatment, with the hydrochar obtained at 250°C that showed a carbon content of approximately 64%, a fixed carbon of about 35%, and a HHV of 27.1 MJ/kg. HTC also promoted the inorganics removal from the solid phase and

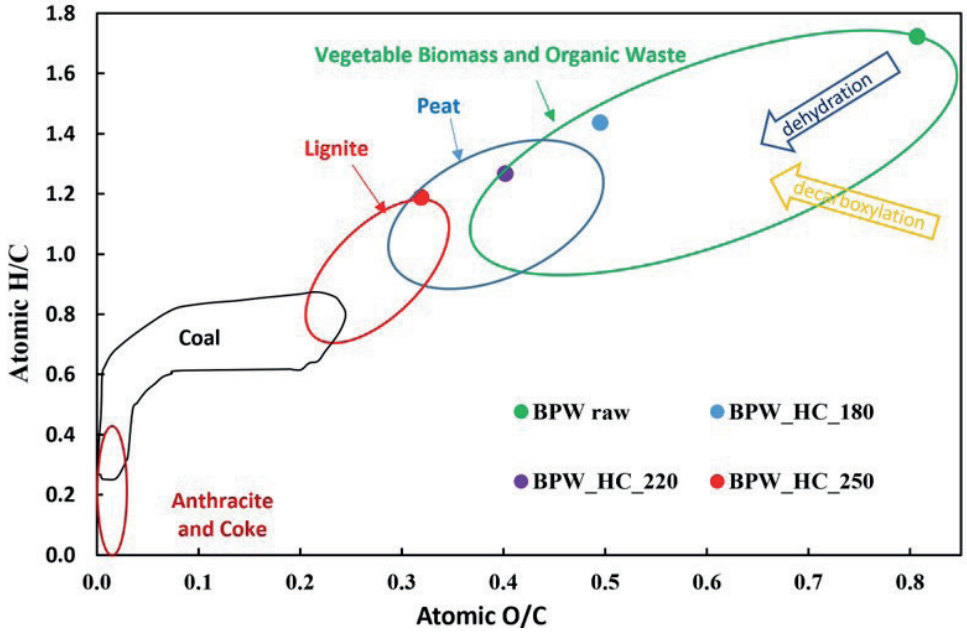

FIGURE 2: Van Krevelen diagram of raw banana peel waste and corresponding hydrochars.

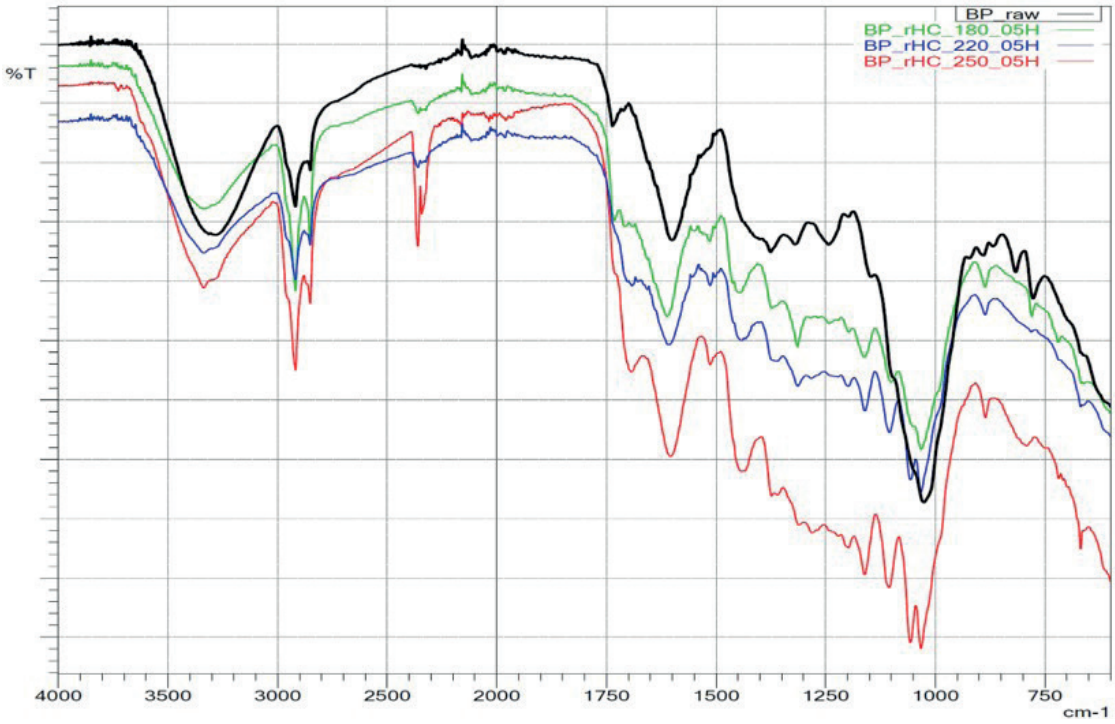

FIGURE 3: FTIR-ATR of raw banana peel waste and corresponding hydrochars.

thus reducing the potential risk of slagging and fouling during combustion.

The obtained results clearly prove that the solid products from BPW HTC should be considered as excellent candidates for co-combustion with mineral coal in existing boilers and for the progressive replacement of fossil fuels. Supplemental hydrochars' characterization, such as the investigation on their chemical composition and structure, would be crucial for a deeper understanding of formation mechanisms and optimization of process conditions, toward tailored target products. A detailed analysis of HTC process water is a lack of our work and will be proposed in a future study to corroborate the experimental findings reported, in terms of chemical reaction pathways, and suggest an adequate valorization method for the residual liquid fraction. Other potential future developments of this study might include the expansion of basic research on unconventional substrates, such plastic waste, investigating the real effects of different substrates interaction during co-HTC, and the implementation of machine learning to assist the process engineering.

ACKNOWLEDGEMENTS

The research was carried out in the framework of the "SiciliAn MicronanOTecH Research And Innovation Center - SAMOTHRACE" project (MUR, PNRR-M4C2, ECS_00000022).

REFERENCES

Becker, G.C., Wüst, D., Köhler, H., Lautenbach, A., Kruse, A., 2019. Novel approach of phosphate-reclamation as struvite from sewage sludge by utilising hydrothermal carbonization. J. Environ. Manage. 238, 119–125. https://doi.org/10.1016/j.jenvman.2019.02.121

Cotana, F., Messineo, A., Petrozzi, A., Coccia, V., Cavalaglio, G., Aquino, A., 2014. Comparison of ORC turbine and stirling engine to produce electricity from gasified poultry waste. Sustain. 6, 5714–5729. https://doi.org/10.3390/su6095714

Danon, B., Hongsiri, W., van der Aa, L., de Jong, W., 2014. Kinetic study on homogeneously catalyzed xylose dehydration to furfural in the presence of arabinose and glucose. Biomass and Bioenergy 66, 364–370. https://doi.org/10.1016/j.biombioe.2014.04.007

Fu, H., Wang, F., Liu, Z., Duan, X., Wang, L., Yi, W., Zhang, D., 2025. Role of secondary char on the fuel properties and pyrolysis behaviors of hydrochars: Effect of temperature and liquid-solid ratio. Fuel Process. Technol. 267, 108167. https://doi.org/10.1016/j.fuproc.2024.108167

García-Bordejé, E., Pires, E., Fraile, J.M., 2017. Parametric study of the hydrothermal carbonization of cellulose and effect of acidic conditions. Carbon N. Y. 123, 421–432. https://doi.org/10.1016/j.carbon.2017.07.085

Hedin, N., Kruse, A., 2020. Assessment of the effects of process water recirculation on the surface chemistry and morphology of hydrochar Renew. Energy 155, 1173-1180. https://doi.org/10.1016/j.renene.2020.04.050

Heidari, M., Dutta, A., Acharya, B., Mahmud, S., 2019. A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion. J. Energy Inst. 92, 1779–1799. https://doi.org/10.1016/j.joei.2018.12.003

Ibarra-Gonzalez, P., Rong, B.G., 2019. A review of the current state of biofuels production from lignocellulosic biomass using thermochemical conversion routes. Chinese J. Chem. Eng. 27, 1523–1535. https://doi.org/10.1016/j.cjche.2018.09.018

Ischia, G., Berge, N.D., Bae, S., Marzban, N., Rom, S., Farru, G., Kulli, B., Fiori, L., 2024. Advances in Research and Technology of Hydrothermal Carbonization : Achievements and Future Directions. Agronomy 14. https://doi.org/10.3390/agronomy14050955

Jia, J., Wang, R., Chen, H., Xue, Q., Yin, Q., Zhao, Z., 2022. Interaction mechanism between cellulose and hemicellulose during the hydrothermal carbonization of lignocellulosic biomass. Energy Sci. Eng. 10, 1–12. https://doi.org/10.1002/ese3.1117

Lee, M., Lin, Y.L., Chiueh, P. Te, Den, W., 2020. Environmental and energy assessment of biomass residues to biochar as fuel: A brief review with recommendations for future bioenergy systems. J. Clean. Prod. 251, 119714. https://doi.org/10.1016/j.jclepro.2019.119714

Lucian, M., Volpe, M., Gao, L., Piro, G., Goldfarb, J.L., Fiori, L., 2018. Impact of hydrothermal carbonization conditions on the formation of hydrochars and secondary chars from the organic fraction of municipal solid waste. Fuel 233, 257–268. https://doi.org/10.1016/j.fuel.2018.06.060

Messineo, A., Panno, D., 2008. Municipal waste management in Sicily: Practices and challenges. Waste Manag. 28, 1201–1208. https://doi.org/10.1016/j.wasman.2007.05.003

Messineo, A., Volpe, R., Asdrubali, F., 2012. Evaluation of net energy obtainable from combustion of stabilised olive mill by-products. Energies 5, 1384–1397. https://doi.org/10.3390/en5051384

Nunes, L.J.R., Causer, T.P., Ciolkosz, D., 2020. Biomass for energy: A review on supply chain management models. Renew. Sustain. Energy Rev. 120, 109658. https://doi.org/10.1016/j.rser.2019.109658

Picone, A., Volpe, M., Giustra, M.G., Bella, G. Di, Messineo, A., 2021. Hydrothermal Carbonization of Lemon Peel Waste : Preliminary Results on the Effects of Temperature during Process Water Recirculation. Appl. Syst. Innov. 4. https://doi.org/10.3390/asi4010019

Regmi, P., Luis, J., Moscoso, G., Kumar, S., Cao, X., Mao, J., Schafran, G., 2012. Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. J. Environ. Manag. 109, 61-69. https://doi.org/10.1016/j.jenvman.2012.04.047

Rodríguez Correa, C., Ngamying, C., Klank, D., Kruse, A., 2018. Investigation of the textural and adsorption properties of activated carbon from HTC and pyrolysis carbonizates. Biomass Convers. Biorefinery 8, 317–328. https://doi.org/10.1007/s13399-017-0280-8

Sevilla, M., Fuertes, A.B., 2009. The production of carbon materials by hydrothermal carbonization of cellulose. Carbon N. Y. 47, 2281–2289. https://doi.org/10.1016/j.carbon.2009.04.026

Sharma, H.B., Sarmah, A.K., Dubey, B., 2020. Hydrothermal carbonization of renewable waste biomass for solid biofuel production: A discussion on process mechanism, the influence of process parameters, environmental performance and fuel properties of hydrochar. Renew. Sustain. Energy Rev. 123, 109761. https://doi.org/10.1016/j.rser.2020.109761

Shen, Y., 2020. A review on hydrothermal carbonization of biomass and plastic wastes to energy products. Biomass and Bioenergy 134, 105479. https://doi.org/10.1016/j.biombioe.2020.105479

Volpe, M., Fiori, L., Merzari, F., Messineo, A., Andreottola, G., 2020. Hydrothermal carbonization as an efficient tool for sewage sludge valorization and phosphorous recovery. Chem. Eng. Trans. 80, 199–204. https://doi.org/10.3303/CET2080034

Volpe, M., Picone, A., Luz, F.C., Mosonik, M.C. at, Volpe, R., Messineo, A., 2022. Potential pitfalls on the scalability of laboratory-based research for hydrothermal carbonization. Fuel 315, 123189. https://doi.org/10.1016/j.fuel.2022.123189

Volpe, R., Messineo, S., Volpe, M., Messineo, A., 2016. Catalytic Effect of Char for Tar Cracking in Pyrolysis of Citrus Wastes , Design of a Novel Experimental Set Up and First Results 50, 181–186. https://doi.org/10.3303/CET1650031

Wang, R., Jia, J., Jin, Q., Chen, H., 2022. Forming mechanism of coke microparticles from polymerization of aqueous organics during hydrothermal carbonization process of biomass. Carbon N. Y. 192, 50–60. https://doi.org/10.1016/j.carbon.2022.02.030

Wang, R., Jin, Q., Ye, X., Lei, H., Jia, J., Zhao, Z., 2020. Effect of process wastewater recycling on the chemical evolution and formation mechanism of hydrochar from herbaceous biomass during hydrothermal carbonization. J. Clean. Prod. 277, 123281. https://doi.org/10.1016/j.jclepro.2020.123281

Wang, T., Zhai, Y., Zhu, Y., Li, C., Zeng, G., 2018. A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. Renew. Sustain. Energy Rev. 90, 223–247. https://doi.org/10.1016/j.rser.2018.03.071

Wilk, M., Magdziarz, A., Kalemba-Rec, I., Szymańska-Chargot, M., 2020. Upgrading of green waste into carbon-rich solid biofuel by hydrothermal carbonization: The effect of process parameters on hydrochar derived from acacia. Energy 202, 117717. https://doi.org/10.1016/j.energy.2020.117717

Wu, S., Wang, Q., Man, H., Wu, D., Lu, Q., Pan, S., Bai, J., Cui, D., Zhang, X., 2025. Recent advances on hydrothermal carbonization of biomass for carbon-negative materials : From mechanistic insights to functional applications. Ind. Crop. Prod. 237, 122142. https://doi.org/10.1016/j.indcrop.2025.122142

Zhou, Y., Shi, W., Engler, N., Nelles, M., 2021. High-value utilization of kitchen waste derived hydrochar in energy storage regulated by circulating process water. Energy Convers. Manag. 229, 113737. https://doi.org/10.1016/j.enconman.2020.113737