Vietnam Journal of Science and Technology
DOI: https://doi.org/10.15625/2525-2518/22022

Effect of hydrothermal carbonization under CO_2 atmosphere during domestic waste gasification

Hong Nam Nguyen, Thu Phuong Nguyen, Phuong Thu Le, Thi Mai Thanh Dinh*

University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet street, Nghia Do Ward, Ha Noi, Viet Nam

*Email: *dinh-thi-mai.thanh@usth.edu.vn*

Received: 30 November 2024; Accepted for publication: 25 September 2025

Abstract. Handling domestic waste with high moisture content and heterogeneity for energy purposes is a challenge that needs to be addressed for sustainable development. This study examines the effect of hydrothermal carbonization (HTC) of waste under a CO_2 atmosphere, followed by high-temperature steam gasification. The waste underwent HTC at 250 °C in a 100 % CO_2 atmosphere, with a waste-to-water ratio of 1:5 and a residence time of 120 minutes. The resulting hydrochar was then used as feedstock for steam gasification at 900 °C under 100 % steam, and the results were compared with that obtained with untreated waste in the same gasification conditions. The findings reveal improvements in bulk density, fixed carbon content, and higher heating value of the hydrochar compared to the original waste. The syngas produced from hydrochar contained higher H_2 and CO concentrations (measured by GC analyzer), exceeding 3 % for conventional HTC and 5 % for HTC under CO_2. Furthermore, the higher stability in syngas composition was also observed for both HTC samples. These results suggest the potential for more efficient and sustainable waste-to-energy conversion.

Keywords: domestic waste, hydrothermal carbonization, gasification.

Classification numbers: 2.8.3, 3.3.2, 3.4.1.

1. INTRODUCTION

In recent years, Viet Nam has witnessed rapid urbanization and economic development, leading to a significant increase in the generation of domestic waste. The country produces over 60,000 tons of solid waste daily, with urban areas accounting for approximately 70 % of this total [1, 2]. Major cities like Ha Noi and Ho Chi Minh City contribute the bulk of the waste, presenting both challenges and opportunities for waste management and sustainable development. Viet Nam's domestic waste stream primarily consists organic materials (food and yard waste), plastics, paper, and other recyclable and non-recyclable components. Typically, around 50-70 % of domestic waste is organic, which makes it highly suitable for composting and energy recovery processes [2]. However, waste management infrastructure in the country is still developing, with landfilling being the most common disposal method, accounting for over 70 % of municipal waste treatment. Most landfills are poorly managed and pose environmental risks, such as water contamination, greenhouse gas emissions, and health hazards for surrounding communities.

UNCORRECTED PROOF

In this context, converting domestic waste into energy offers a promising pathway for sustainable waste management. Energy recovery from waste can reduce the volume of waste sent to landfills, lower greenhouse gas emissions, and provide a renewable source of energy. Viet Nam's high organic waste content makes technologies such as anaerobic digestion particularly attractive, generating biogas that can be used for electricity, heat, or as a transportation fuel [1]. Gasification offers an alternative thermochemical process for converting waste into synthetic gas (syngas) and biochar, which can be further utilized for energy generation or soil amendment. Gasification is a thermochemical process that converts carbon-rich materials, such as wood, agricultural by-products, and different types of biomass, into a gaseous fuel known as synthesis gas, or syngas [3–5]. During this process, biomass is subjected to high temperatures in a low-oxygen environment, resulting in the production of a gas mixture mainly composed of carbon monoxide (CO) and hydrogen (H_2), along with smaller quantities of carbon dioxide (CO_2), methane (CH_4), and other trace gases. Syngas generated from this process can be utilized in numerous applications, including power generation, heat production, and as feedstock for chemicals and biofuels [6, 7].

Researchers are actively developing alternative gasification techniques and innovative process designs to improve the efficiency and effectiveness of waste utilization as feedstock [8]. However, technical challenges of gasifying domestic waste are multifaceted and arise primarily from the complex nature of the waste stream and the requirements for an efficient, consistent, and environmentally friendly process. Domestic waste consists of a wide range of materials, including organic waste, plastics, metals, paper, and other non-biodegradable components. This variability can lead to inconsistent gasification performance, fluctuating syngas quality, and unpredictable process behavior, making it difficult to control and optimize [9]. Organic components and food waste in domestic waste often have high moisture content. This requires significant energy for drying the waste before gasification, which can reduce overall process efficiency and increase operational costs [10]. Moreover, domestic waste may contain various impurities, such as heavy metals, sulfur, chlorine, and silicon compounds. When gasified, these impurities can cause operational issues, such as corrosion and erosion, tar formation, and harmful emissions. The varying composition of domestic waste results in fluctuations in its calorific value (energy content). This inconsistency makes it challenging to maintain a stable gasification process, leading to potential operational instabilities and efficiency losses [11]. High ash content or the presence of silica can lead to slagging (molten ash adhering to reactor surfaces) and handling difficulties, which can reduce efficiency and cause operational disruptions [12, 13].

For effective gasification, domestic waste needs to be pre-treated to homogenize the feedstock, reduce moisture content, remove non-combustibles, and achieve a consistent particle size. Hydrothermal Carbonization (HTC) is an advanced thermochemical process that transforms wet biomass into a carbon-rich solid material, known as hydrochar, under subcritical water conditions [3]. Unlike traditional carbonization methods that require significant drying of biomass, HTC operates with feedstocks containing high moisture content, making it particularly suitable for processing organic waste, sewage sludge, agricultural residues, and other wet materials. The HTC process typically takes place at relatively moderate temperatures (180-250 °C) and elevated pressures (up to 2 MPa) in a water-filled, sealed reactor. During the process, the biomass undergoes a series of hydrolysis, dehydration, decarboxylation, and polymerization reactions. This results in the transformation of the feedstock into a stable hydrochar with improved properties such as enhanced energy density, higher carbon content, and better structural characteristics compared to untreated biomass [14]. HTC offers several advantages over conventional thermal treatments. Since water acts as a reaction medium, there is no need to pre-

UNDER PEER REVIEW

dry wet biomass, saving energy and reducing processing costs. Also, HTC enhances the carbon content of biomass, making it an excellent precursor for biochar production and potential applications in soil amendment, carbon sequestration, and energy production. In addition, HTC can significantly reduce the volume of waste, contributing to more efficient waste management strategies [3]. Moreover, HTC effectiveness can be enhanced with the presence of CO_2 atmosphere. A recent study explored the influence of conducting batch hydrothermal experiments under CO_2 and inert (N_2) atmospheres [15]. The findings demonstrated that the presence of CO_2, as compared to N_2, led to a modest increase in both liquid and gas yields. Furthermore, CO_2 enhanced the crystallinity of the resulting hydrochar. Similarly, another study showed that conducting HTC under a CO_2 atmosphere improved the subsequent gasification of biomass [3]. In summary, HTC pretreatment has proven to be a highly promising approach to improving the effectiveness of domestic waste for gasification. Therefore, this study focused on examining the impact of HTC under a CO_2 atmosphere on the gasification performance of domestic waste.

2. MATERIALS & METHODS

2.1. Domestic waste collection

The domestic waste was collected directly from a landfill site in Ha Noi, following the ISO 18135:2017 solid biofuels sampling method. For analysis, the waste was thoroughly cleaned, inorganic materials (such as stones, metals) were removed, and it was air-dried and homogenized. The composition, nature, and proportions of the domestic waste sample are reported in Table 1. Subsequently, the samples were cut, ground, sieved, and carefully mixed to obtain uniform particles with a diameter of less than 1 mm.

Table 1. Domestic waste composition and its nature.

Number	Composition	Nature	Proportion
1	Grapefruit Peel	Cellulose, hemicellulose, lignin	35 %
2	Nylon	Polyamide polymer	10 %
3	Paper	Cellulose, hemicellulose	25 %
4	Chicken Fat	Triglycerides, which break down into fatty acids, ketones, and aldehydes	10 %
5	Chicken Feathers	Keratin, which breaks down into nitrogen-containing gases such as ammonia and hydrogen sulfide	10 %
6	Styrofoam Box	Polystyrene, which breaks down into styrene monomer and other hydrocarbons	10 %

2.2. HTC treatment

For each HTC treatment, domestic waste was placed into a 500-ml HTC reactor with a waste-to-water ratio of 1:5. The reactor was purged with CO_2 for 10 minutes to displace any air before being sealed and placed into a Nabertherm LT 24/12/P300 muffle furnace. The treatment was conducted at 250 °C with a residence time of 120 minutes, conditions identified as optimal in previous studies [3, 15]. Upon completion of the HTC treatment, the reactor was removed from the furnace and allowed to cool to room temperature. The pretreated solid was then filtered to remove excess water and dried in a Memmert Model 800 Class B Incubator to prepare for further gasification experiments. A control sample was subjected to the same HTC conditions but in an air environment, with the results compared against the CO_2-HTC treated sample. The raw

UNCORRECTED PROOF

domestic waste and HTC samples underwent proximate analysis to measure moisture content (M) according to ASTM D4442, volatile matter (V) based on ASTM D3175, and ash content (A) using ASTM D3174. Fixed carbon content (FC) was calculated by difference. Bulk density was assessed following ASTM D7263. The higher heating value (HHV) was determined using a Parr 6200 Calorimeter, adhering to the NREL protocol. The ultimate analysis was performed to measure C, H, N, O content of the samples. Each measurement was conducted three times to ensure accuracy. The remaining samples were stored in airtight containers for future experiments.

2.4. Gasification treatment

Experiments were conducted using a downdraft gasification reactor, which features a ceramic tube measuring 111 cm in length and 7.5 cm in internal diameter, housed within an electric furnace. Heating was provided by a Carbolite electric heater. A liquid mass flow meter (Brooks 5882/D1A1A3A001) with 1 % full-scale accuracy controlled the water flow. Water was preheated in a 2-meter-long coiled tube located in the reactor's upper heated section, ensuring vaporization before reaching the sample during gasification. Each experiment began by heating the reactor to 900 °C. Approximately 25 g of sample, placed in a holder, was then moved to the desired position within a 100 % steam environment. As gasification progressed, the sample's mass gradually decreased, and this weight loss was continuously tracked by a data acquisition system.

To evaluate the gasification performance of treated and untreated domestic waste, both the conversion rate and syngas quality were analyzed. The conversion X [0:1] of each sample was determined by:

$$X = \frac{m_i - m_t}{m_i - m_{ash}} \quad (1)$$

where m_i, m_t, and m_{ash} are the masses of the initial char, the char at time t, and the ash, respectively.

The syngas analysis was conducted over a 30-minute period, with gas samples collected and filtered at 5-minute intervals throughout the gasification process. The filtered gas samples were then analyzed using an Agilent 990 Micro GC gas chromatograph. Prior to analysis, the gas sampling tubes were purged with argon to eliminate any residual gases. The entire experimental procedure is summarized in Figure 1.

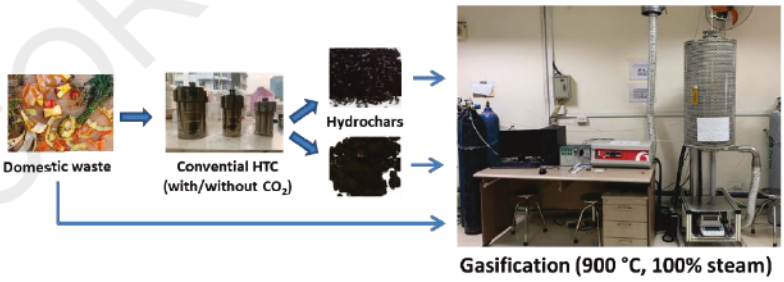

Figure 1. Summary of experimental procedure.

UNCORRECTED PROOF

3. RESULTS & DISCUSSION

3.1. Characteristics of raw waste and HTC samples

Table 2 presents the proximate and ultimate results of the raw domestic waste and the HTC ones.

Table 2. Proximate analysis of raw and CO_2 HTC-treated char.

Characteristics		Raw waste	Conventional HTC	HTC under CO_2
Proximate	M_{as} (%)	24.3 ± 0.5	-	-
	V_{db} (%)	84.6 ± 0.3	81.5 ± 0.3	79.7 ± 0.3
	A_{db} (%)	11.4 ± 0.1	9.2 ± 0.1	8.7 ± 0.1
	FC_{db} (%)	4.1 ± 0.4	9.3 ± 0.4	11.6 ± 0.4
	BD (kg m^{-3})	40.7 ± 5	80.5 ± 5	96.2 ± 5
	HHV (MJ kg^{-1})	19.6 ± 0.5	26.5 ± 0.6	27.9 ± 0.6
Ultimate	C_{daf} (%)	36.2 ± 0.2	44.5 ± 0.2	49.8 ± 0.2
	H_{daf} (%)	15.6 ± 0.1	16.8 ± 0.1	16.9 ± 0.1
	N_{daf} (%)	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
	O_{daf} (%)	48.1 ± 0.4	38.6 ± 0.4	33.2 ± 0.4

M: moisture, V: Volatile, A: Ash, FC: fixed-carbon, as: as-received, db: dry basis, daf: dry-ash-free basis.

The domestic waste exhibits a high moisture content of approximately 24.3 %, primarily due to the moisture in the chicken fat and grapefruit peel. While this moisture level poses challenges for direct utilization in gasification, it offers an advantage for the HTC process [16]. An increase in carbon content is evident from the results of the ultimate analysis.

Following HTC treatment, a marked reduction in both V and A content of the domestic waste is observed. This is attributed to the breakdown of certain weak bonds within the biomass during HTC, as well as the dissolution of some inorganic constituents into the liquid phase. Moreover, when comparing conventional HTC with HTC under a CO_2 atmosphere, the latter shows a more substantial decrease in ash and volatile matter, resulting in an increase in fixed carbon (FC) content. This finding aligns with previous studies on the impact of HTC under CO_2 on biomass properties [3, 17].

Additionally, the BD of the domestic waste after HTC treatment more than doubled. This increase is beneficial for gasification, as it enhances the stability of the material's dynamic flow [12, 13]. Furthermore, the higher heating value (HHV) of the domestic waste significantly improves, increasing from 19.6 MJ kg^{-1} to 26.5 MJ kg^{-1} with conventional HTC and 27.9 MJ kg^{-1} with HTC under CO_2. This increase in HHV can be attributed to the higher carbon content and lower oxygen content in the HTC products, indicating increased energy density. The negligible nitrogen content (< 0.1 %) suggests that using it for gasification will produce a clean and environmentally friendly syngas [4, 5, 18]. The analysis results clearly highlight the potential benefits of the HTC process, particularly HTC under a CO_2 atmosphere, as a pre-treatment for domestic waste intended for gasification.

UNCORRECTED PROOF

3.2. Conversion rate of raw waste and HTC samples

The gasification process can be divided into two distinct stages: the decomposition of volatile content and the char gasification stage. While the initial stage occurs rapidly and shows minimal variation in conversion rates, the char gasification reaction typically proceeds at a significantly slower pace, making it the rate-determining step [6, 19]. Therefore, the char gasification process was further analyzed for both raw waste and HTC-treated samples. Figure 2 shows the conversion rates of the raw and HTC domestic waste throughout the gasification process at 900 °C under 100 % steam.

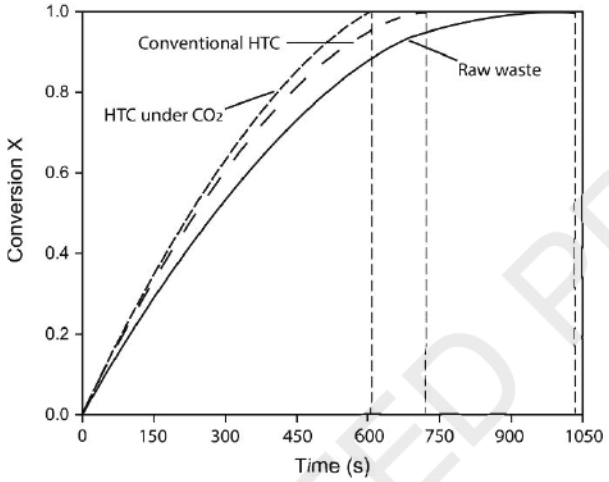

Figure 2. Conversion rate of char and CO_2-hydrochar.

The raw domestic waste was fully converted after 1000 seconds, with a noticeable slowdown within the [0.9-1] conversion range (after 700 seconds). In contrast, hydrochar exhibited faster conversion rates: 725 seconds for conventional HTC and 600 seconds for HTC under CO_2. This increased conversion speed in hydrothermally treated materials can be attributed to enhanced porosity and material fragmentation caused by the high-pressure, superheated steam environment of the HTC process, which improves heat and mass transfer. The difference becomes more pronounced in the latter stages of the transformation process, primarily due to reduced ash content. During HTC, some inorganic compounds dissolve in water, resulting in hydrochar with lower ash content. Previous studies have shown that these inorganic components often inhibit the gasification process [19, 20]. Therefore, hydrochar with reduced ash content exhibits significantly improved conversion rates during gasification. Additionally, the faster conversion of HTC under CO_2, although not drastically different from conventional HTC, can be explained by the greater material uniformity, which enhances heat transfer efficiency throughout the material layer.

3.4. Gas composition and quality

Table 3 presents the distribution of compositional gases in the syngas from all samples under gasification conditions at 900 °C in a 100 % steam environment (Table 2). Since the system was not stable during the first 10 minutes and the produced gas composition fluctuated significantly, results were collected from the 10th to the 30th minute. Additionally, results from five sampling intervals are shown to assess the stability of the produced gas under the same conditions. The overall average across the entire process was calculated to evaluate the syngas quality comprehensively.

UNCORRECTED PROOF

Table 3. Syngas composition from raw and HTC samples (wt%).

	Compositional gas	10th min	15th min	20th min	25th min	30th min	**Average**
Raw domestic waste	H_2	16.3	18.1	19.1	20.3	17.8	**18.3**
	CO	37.5	38.7	39.6	38.3	40.2	**38.9**
	CxHy	3.9	4.5	3.8	3.5	3.1	**3.8**
	CO_2	42.3	38.7	37.5	37.9	38.9	**39.0**
Conventional HTC sample	H_2	20.9	21.3	22.1	21.8	20.8	**21.4**
	CO	39.2	39.2	38.9	37.4	38.5	**38.6**
	CxHy	6.8	6	5.8	5.9	6.7	**6.2**
	CO_2	33.1	33.5	33.2	34.9	34	**33.8**
HTC under CO_2	H_2	22.8	24.5	23.1	23.5	23.1	**23.4**
	CO	39.8	39.4	39.2	40.1	39.5	**39.6**
	CxHy	6.9	5.9	5.8	5.3	5.7	**5.9**
	CO_2	30.5	30.2	31.9	31.1	31.7	**31.1**

For raw domestic waste, the combustible gas components were at their lowest levels, with average values of 18.3 % for H_2, 38.9 % for CO, and 3.8 % for C_xH_y. A significant amount of CO_2 was also produced, resulting from the combination of oxygen from both the water and the waste itself with its carbon content. After hydrothermal carbonization (HTC), the levels of combustible gases increased, while CO_2 content decreased. This can be attributed to HTC breaking down oxygen-containing functional groups in the initial biomass, thereby reducing the overall oxygen content.

A recent study demonstrated this effect: after HTC at 260 °C, the peak strength of O-all decreased by 47.64 %, and that of aro-C increased by 28.62 %, indicating that HTC induces significant dehydroxylation, decarboxylation, and aromatization reactions [21]. The H_2 content increased by approximately 3 % with conventional HTC and by 5 % with HTC under CO_2. Similarly, C_xH_y content rose by about 3 % in both cases. These findings align with previous studies on the effectiveness of HTC and HTC under CO_2 for gasification [3, 22]. Although the improvement in syngas quality due to HTC, especially under CO_2, appears modest at the laboratory scale, it holds significant potential for industrial applications. Moreover, throughout the 30-minute gasification process, the syngas composition from HTC-treated samples remained significantly more stable compared to that from raw domestic waste. This enhanced stability plays a crucial role in maintaining consistent syngas quality, which is essential for downstream applications such as energy generation or chemical synthesis. The steady composition reduces the need for additional gas conditioning and enhances process efficiency, making HTC-treated biomass a more reliable feedstock for industrial gasification systems. This stability, coupled with improved gas yield, underscores the potential of HTC as a transformative step in converting waste into high-quality syngas for sustainable energy solutions.

4. CONCLUSION

The study results highlight several key findings: HTC treatment significantly increased the fixed carbon content and bulk density of domestic waste, doubling their values, while reducing ash content by approximately 3 % and boosting the heating value by 1.5 times. These improvements were even more pronounced under a CO_2 atmosphere during the HTC process.

UNCORRECTED PROOF

Gasification experiments conducted at 900 °C with 100 % steam revealed that hydrochar samples gasified more rapidly, particularly in the final stages, due to their reduced inorganic content. The syngas produced from hydrochar also exhibited higher concentrations of H_2 and CO, with increases of over 3 % for conventional HTC and 5 % for HTC under CO_2. Additionally, both HTC samples demonstrated enhanced stability in syngas composition. These findings underscore the potential for more efficient and sustainable energy production from waste materials through hydrothermal treatment.

Acknowledgment. The authors express their sincere gratitude for the financial support provided by the University of Science and Technology of Hanoi for the Research Group "Sustainable Energy and Environmental Development (SEED)".

CRediT authorship contribution statement. Hong Nam Nguyen: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft. Thu Phuong Nguyen: Investigation, Formal analysis, Validation. Phuong Thu Le: Methodology, Resources, Validation, Writing – review & editing. Thi Mai Thanh Dinh: Conceptualization, Supervision, Project administration, Funding acquisition, Resources, Writing – review & editing.

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.

REFERENCES

1. Tong Y. D., Huynh T. D. X., Khong T. D. – Understanding the role of informal sector for sustainable development of municipal solid waste management system: A case study in Vietnam. Waste Manag., **124** (2021) 118–127. https://doi.org/10.1016/j.wasman.2021.01.033.
2. Nguyen T. K. N. – The determinants of individuals' waste separation intention in an urbanizing city: A case study of Hanoi, Vietnam. Habitat Int., **137** (2023) 102835. https://doi.org/10.1016/j.habitatint.2023.102835.
3. Nguyen H. N. – Integrated CO_2-hydrothermal carbonization and high temperature steam gasification of bamboo feedstock: A comprehensive experimental study. Adv. Bamboo Sci., **6** (2024) 100060. https://doi.org/10.1016/j.bamboo.2024.100060.
4. Nguyen H. N., Tsubota T. – Complete parametric study of bagasse pellets during high-temperature steam gasification. J. Therm. Sci. Eng. Appl., **12** (2019) 041014. https://doi.org/10.1115/1.4045698.
5. Nguyen H. N., Van De Steene L. – Steam gasification of rice husk: Effects of feedstock heterogeneity and heat-mass transfer. Energy Sources Part A Recovery Util. Environ. Eff., **46** (2019) 4229–4243. https://doi.org/10.1080/15567036.2019.1694104.
6. Nguyen H. N., Van De Steene L., Le D. D. – Kinetics of rice husk char gasification in an H_2O or a CO_2 atmosphere. Energy Sources Part A Recovery Util. Environ. Eff., **40** (2018) 1701–1713. https://doi.org/10.1080/15567036.2018.1486900.
7. Nguyen H. N., Nguyen P. L. T., Tran V. B. – Zero-waste biomass gasification: Use of residues after gasification of bagasse pellets as CO_2 adsorbents. Therm. Sci. Eng. Prog., **26** (2021) 101080. https://doi.org/10.1016/j.tsep.2021.101080.
8. Sajid M., Raheem A., Ullah N., Asim M., Ur Rehman M. S., Ali N. – Gasification of municipal solid waste: Progress, challenges, and prospects. Renew. Sustain. Energy Rev., **168** (2022) 112815. https://doi.org/10.1016/j.rser.2022.112815.
9. Liu H., Liu T., Wei G., Zhao H., Li T., Weng F., Guo X., Wang Y., Lin Y. – Environmental and economic assessment of rural domestic waste gasification models in China. Waste Manag., **154** (2022) 160–174. https://doi.org/10.1016/j.wasman.2022.10.001.
10. Qi Y., Muhammad U., Zhang W., Song Y., Zhang M., Wang M., Xu C., Xu Y., Cai S., Han C., et al. – A comprehensive evaluation of recent advancement in municipal solid waste gasification: Research

UNCORRECTED PROOF

status, technical challenges and perspectives. Sep. Purif. Technol., **358** (2025) 130443. https://doi.org/10.1016/j.seppur.2024.130443.

11. Vu N. L., Nguyen N. D., Nguyen V. D., Tran-Nguyen P. L., Nguyen H. V., Dinh T. M. T., Nguyen H. N. – Evolution of properties of macadamia husk throughout gasification: Hints for a zero-waste energy production system. Biomass Bioenergy, **171** (2023) 106735. https://doi.org/10.1016/j.biombioe.2023.106735.
12. Nguyen H. N., Khuong D. A., Vu T. T. H., Mai T. N., Tsubota T., Tran V. B., Blin J., Van De Steene L. – Kinetic and structural changes during gasification of cashew nut shell char particles. Environ. Prog. Sustain. Energy, **40** (2020) e13580. https://doi.org/10.1002/ep.13580.
13. Linh Vu N., Nguyen N. D., Thanh Dinh T. M., Nguyen H. N. – Cascading use of macadamia nutshell for production of energy and adsorbents through biomass gasification. Ind. Crops Prod., **206** (2023) 117662. https://doi.org/10.1016/j.indcrop.2023.117662.
14. Román S., Libra J., Berge N., Sabio E., Ro K., Li L., Ledesma B., Álvarez A., Bae S. – Hydrothermal carbonization: Modeling, final properties design and applications: A review. Energies, **11** (2018) 216. https://doi.org/10.3390/en11010216.
15. Yi W., Zheng D., Wang X., Chen Y., Hu J., Yang H., Shao J., Zhang S., Chen H. – Biomass hydrothermal conversion under CO_2 atmosphere: A way to improve the regulation of hydrothermal products. Sci. Total Environ., **807** (2022) 150900. https://doi.org/10.1016/j.scitotenv.2021.150900.
16. Agarwal N. K., Pattnaik F., Kumar M., Adlak K., Kumari P., Vijay V. K., Kumar V. – Hydrothermal pretreatment of sugarcane bagasse pith for biogas production and digestate valorization to biochar. Ind. Crops Prod., **202** (2023) 116973. https://doi.org/10.1016/j.indcrop.2023.116973.
17. Nizamuddin S., Qureshi S. S., Baloch H. A., Siddiqui M. T. H., Takkalkar P., Mubarak N. M., Dumbre D. K., Griffin G. J., Madapusi S., Tanksale A. – Microwave hydrothermal carbonization of rice straw: Optimization of process parameters and upgrading of chemical, fuel, structural and thermal properties. Materials, **12** (2019) 403. https://doi.org/10.3390/ma12030403.
18. Nguyen H. N., Ha-Duong M., Van de Steene L. – A critical look at rice husk gasification in Cambodia: Technology and sustainability. J. Sci. Technol. (2015) 247–252.
19. Dahou T., Defoort F., Nguyen H. N., Bennici S., Jeguirim M., Dupont C. – Biomass steam gasification kinetics: Relative impact of char physical properties vs. inorganic composition. Biomass Convers. Biorefin., **12** (2020) 3475–3490. https://doi.org/10.1007/s13399-020-00894-9.
20. Dupont C., Jacob S., Marrakchy K. O., Hognon C., Grateau M., Labalette F., Da Silva Perez D. – How inorganic elements of biomass influence char steam gasification kinetics. Energy, **109** (2016) 430–435. https://doi.org/10.1016/j.energy.2016.04.094.
21. Dang H., Xu R., Zhang J., Wang M., Ye L., Jia G. – Removal of oxygen-containing functional groups during hydrothermal carbonization of biomass: Experimental and DFT study. Energy, **276** (2023) 127436. https://doi.org/10.1016/j.energy.2023.127436.
22. Erlach B., Harder B., Tsatsaronis G. – Combined hydrothermal carbonization and gasification of biomass with carbon capture. Energy, **45** (2012) 329–338. https://doi.org/10.1016/j.energy.2012.01.057.

UNCORRECTED PROOF