



Research Article

Sustainable Conversion of Urban Tree Waste Into High Energy Hydrochar via Hydrothermal Carbonization and Process Water Recirculation

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Abstract

The growing demand for renewable energy and sustainable waste management highlights the need for efficient biomass-to-energy technologies. This study investigated the production of solid biofuel from urban tree waste (UTW) in Hanoi, Vietnam, using hydrothermal carbonization (HTC) coupled with process water (PW) recirculation. HTC was optimized at 240 °C for 3 h, yielding hydrochar with a higher heating value (HHV) of 22.95 MJ kg⁻¹ and an energy yield of ~90%. The PW was recirculated for up to ten cycles at a fixed PW-to-freshwater ratio of 1:1. The fifth recirculation cycle resulted in the highest hydrochar quality (HHV: 22.18 MJ kg⁻¹; energy yield: 77.15%), after which further recirculation resulted in a decrease in the HHV. PW analysis revealed that total organic carbon (TOC) and organic acids (acetic and formic acids) significantly influenced hydrochar yield and energy densification through secondary carbon deposition. A predictive model for HHV based on fixed carbon content was developed and validated with independent datasets. The produced hydrochar met or exceeded Vietnamese solid fuel standards regarding HHV, ash, and sulfur content. Overall, HTC combined with PW recirculation is an effective and sustainable approach for valorizing UTW as a high-quality solid biofuel, reducing freshwater consumption, and minimizing wastewater discharge in the environment.

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Introduction

The global energy sector is under increasing pressure from two converging challenges: the depletion of fossil fuel reserves and the intensification of climate change. According to the International Energy Agency (IEA, 2023), global energy demand is expected to increase by more than 50% by 2050, while fossil fuels, which are currently the dominant energy source, face rising extraction costs and geopolitical instability. Given that governments and industries seek alternatives to ensure long-term energy security, solid biofuels are emerging as a promising solution. These fuels, which are derived from biomass, offer carbon-neutral combustion, compatibility with coal-fired infrastructure, and the potential

to support decentralized energy systems (Demirbas, 2004).

Hydrothermal carbonization (HTC) is increasingly recognized as an efficient thermochemical process for converting high-moisture biomass into hydrochar. Unlike conventional drying and combustion, HTC operates at moderate temperatures (180–250 °C) under autogenous pressure, eliminating the need for energy-intensive predrying. The resulting hydrochar typically has high calorific value, hydrophobicity, and grindability, making it suitable for co-firing with coal or replacing low-grade coal in energy applications (Funke and Ziegler, 2010). Depending on the feedstock category and operating severity, HTC can achieve energy yields of up to 80% (Kambo and Dutta, 2014).

Research on HTC has focused mainly on agricultural residues, sewage sludge, and food waste as feedstocks, while urban tree waste (UTW) remains underexplored. UTW, generated from the pruning and clearance of urban greenery, is typically disposed of by landfilling or open dumping, causing methane emissions, land pressure, and resource underutilization (Lan et al., 2022; Maison et al., 2024). Owing to its rich lignocellulosic composition and high moisture content, UTW is poorly suited for composting or incineration but is an ideal candidate for HTC processing.

The main limitation of HTC is the formation of nutrient- and organic-rich process water (PW). At biomass-to-water ratios of 1:5–1:10, large volumes are produced, necessitating treatment before discharge. Recent studies have proposed recirculating PW into the HTC process as a solution to reduce water consumption and enhance energy recovery. Processing water recirculation has emerged as a sustainable approach that simultaneously addresses waste management and enhances product quality. Studies have demonstrated that compared with conventional HTC using fresh water, the recycling of process water can increase hydrochar mass yield by 5–6% and energy recovery efficiency by 5–8% (Picone et al., 2024). Most studies thus far have investigated only 1–3 cycles and have employed mainly agricultural feedstocks. Hence, the potential of PW reuse for the HTC of UTW has not yet been well explored.

To address this research gap, this study explores the HTC of UTW in Hanoi, Vietnam, with a specific focus on the effects of process water recirculation over multiple cycles. The objectives of this study are (i) to identify optimal HTC conditions for producing hydrochar from UTW with maximum energy yield; (ii) to evaluate the impact of PW recirculation on hydrochar quality, including mass yield, higher heating value (HHV), and proximate composition across up to ten cycles; (iii) to characterize PW evolution (e.g., total organic carbon - TOC, organic acids) and link its composition to hydrochar properties; (iv) to develop an HHV predictive model on the basis of proximate analysis data; and (v) to evaluate the applicability of the fabricated UTW-derived hydrochar.

The novelty of this research lies in its application of PW recirculation in the HTC of urban lignocellulosic biomass over an extended number of cycles, filling a critical gap in the literature. Furthermore, it provides practical opportunities for UTW valorization and promotes a circular economy by closing water and carbon loops. The findings are expected to apply to developing countries, where waste management infrastructure and water resources are constrained. By transforming UTW into high-energy hydrochar, this study contributes to a more sustainable urban bioenergy transition.

Materials and methods

1) Feedstock and chemicals

The UTW was collected in February 2025 from a routine pruning event in Hanoi, Vietnam. The biomass included leaves, small branches, and large branches of *Khaya senegalensis* (African mahogany). After manual separation, each fraction was dried at 40 °C and stored for further use. The dry-basis UTW consisted of 25.6% leaves, 33.3% small branches, and 41.1% large branches. To ensure the consistency of the UTW in each 16 g of the feedstock used in the experiments, 4.1 g of leaves, 5.3 g of small branches, and 6.6 g of large branches were weighed using an electronic balance and mixed for every test. The proximate analysis of the UTW showed that the ash content, volatile matter, and fixed carbon content of the UTW were 6.51% and 61.66%, respectively, and 31.83%. Ultimate analysis of the UTW revealed that it consisted of 43.27% C, 5.63% H, 44.47% O, 0.12% N, and 0% S. The HHV of the UTW was 17.3 MJ kg⁻¹.

2) Apparatus

Hydrochar was produced using custom-made 100 mL Teflon-lined stainless steel batch reactors (internal diameter of 3.5 cm and height of 10 cm). Heating was conducted in a laboratory furnace (Nabertherm L15, Germany). The temperature was monitored using the built-in temperature sensor and automatically controlled via a preprogrammed setting. A bomb calorimeter (IKA C200, Germany) was used for HHV analysis. Proximate and elemental analyses were conducted using ASTM-standard protocols. PW analysis was performed using a TOC analyzer (Aurora 1030 W, USA) and an HPLC (SCION LC6000, Netherlands). The surface morphology was examined by scanning electron microscopy (SEM; Hitachi S-4800, Japan).

3) Experimental procedure

3.1) HTC process

Dried and ground UTW (0.15–0.45 mm) was mixed with distilled water at a biomass-to-water (B/W) ratio of 1:5 (16 g of biomass to 80 g of water). HTC was conducted at 180, 220, and 240 °C for residence times of 1, 2, and 3 h, respectively, to determine the optimal HTC conditions. The temperature range (180–240 °C) and residence time (1–3 h) were chosen because the literature shows that this window effectively enhances hydrochar formation and fuel quality without excessive degradation (Martinez et al., 2021). A biomass-to-water ratio of 1:5 was selected from preliminary tests to ensure good mixing and stable HTC performance, which is consistent with the ratios commonly used in prior studies. After cooling, the solid hydrochar was separated by vacuum filtration, washed, and dried at 105 °C for 24 h to a constant weight. In this study, postfiltration washing was not intentionally performed. This occurred

to preserve surface-bound and deposited organic compounds formed during HTC and PW recirculation. This is because the deposits contribute directly to the enhanced properties and energy content of the hydrochar. Washing may remove some parts of the secondary carbonaceous products, thus leading to an underestimation of the practical fuel properties of the fabricated hydrochar. The filtrate was stored at 5 °C for PW analysis or reuse. All experiments were performed in triplicate using homogenized UTW feedstock. Reproducibility was confirmed by relative standard deviations < 5% across replicates for the MY, HHV, and EY values.

3.2) Processing water recirculation

The experimental procedure for the HTC of UTW is illustrated in Figure 1. Following the identification of optimal HTC conditions (240 °C, 3 h), the PW from each run was reused for the next cycle at a 1:1 volume ratio with fresh distilled water (DW). A 1:1 PW:DW ratio was chosen to maximize PW reuse while retaining a sufficient PW volume for the other analytical tests in this study. In practical applications, almost 100% of the available PW can be recirculated (topping up only evaporated loss). This process was repeated for 10 recirculation cycles. Each run used 16 g of fresh biomass and 80 g of total liquid (PW + DW). The effects of PW recirculation on the yield and fuel quality of the resulting hydrochar were assessed across cycles HC-0 to HC-10.

4) Analytical methods

4.1) Hydrochar characterization

The HHV of the hydrochar samples was measured with a bomb calorimeter in accordance with the ASTM D5865-13 standard. Proximate analysis was performed to determine the moisture content, volatile matter content, and ash content in accordance with ASTM D3173, D3175, and D3174, respectively. Fixed carbon was calculated by the difference of 100% and the combined contents of moisture, volatile matter, and ash. The elemental composition, including carbon (C), hydrogen (H), nitrogen (N), and sulfur (S), was determined using a CHNS elemental analyzer (Flashmart, USA) following ASTM D3176, while the oxygen content was calculated by subtracting the sum of the measured elements and ash from 100%. An SEM analyzer (S-4800 Hitachi, Japan) was used to analyze the surface morphology of the hydrochar samples, which were gold-coated before imaging to enhance the conductivity.

4.2) Processing water analysis

The TOC content in the PW was determined using a TOC analyzer (Aurora 1030 W, USA) in accordance with the ASTM D7573 standard. The concentrations of acetic acid and formic acid were determined by high-performance liquid chromatography (SCION LC6000, Netherlands) following the ASTM E841 standard. The pH of the PW was monitored using a digital pH meter (S220, Mettler Toledo, China).

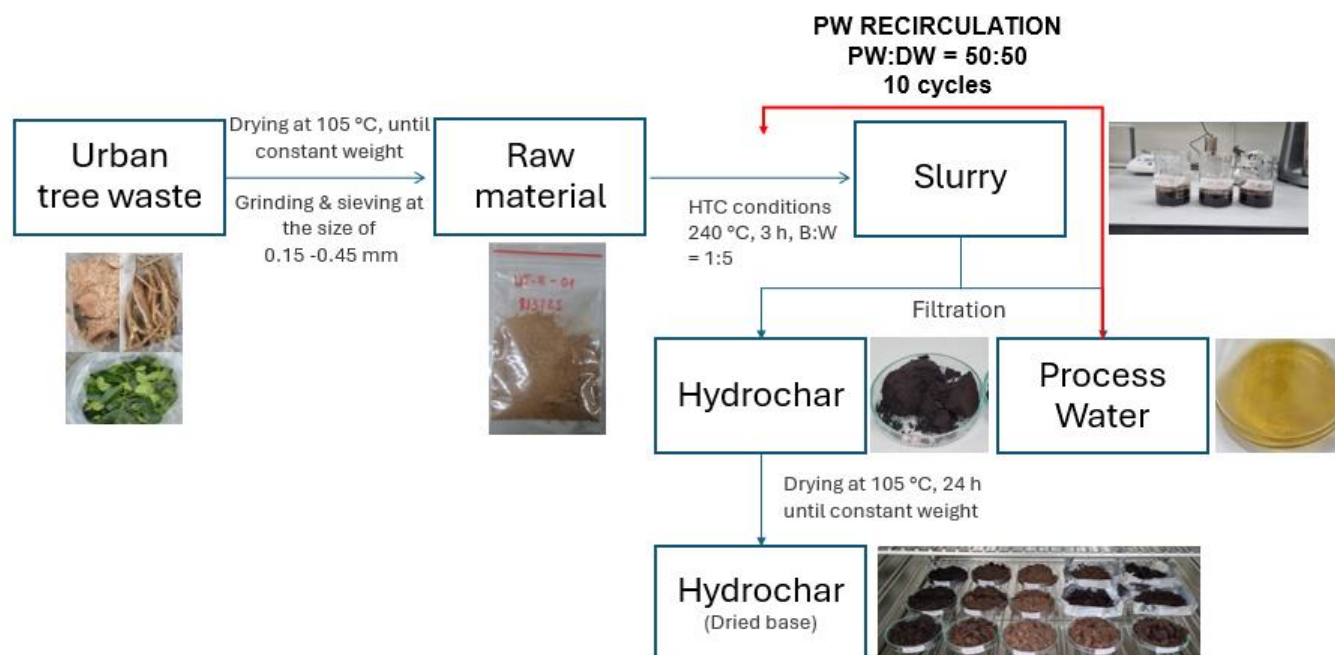


Figure 1 HTC experimental procedure.

5) Data analysis

5.1) Yield and energy metrics

The mass yield (MY) was calculated as the percentage of dry hydrochar recovered from the original dry biomass using Eq. 1.

$$\text{MY (\%)} = \frac{\text{Mass of dry hydrochar}}{\text{Mass of dry biomass}} \times 100 \quad (\text{Eq.1})$$

Energy densification (ED), which is the ratio of the higher heating value (HHV) of the hydrochar to that of the raw biomass, was determined utilizing Eq. 2.

$$\text{ED} = \frac{\text{HHV Hydrochar}}{\text{HHV Biomass}} \quad (\text{Eq.2})$$

The energy yield (EY), which represents the overall energy retained in the hydrochar, was calculated by employing Eq. 3 (Sharma et al., 2020).

$$\text{EY (\%)} = \text{MY} \times \text{ED} \quad (\text{Eq.3})$$

All EY values were calculated on a dry weight basis.

5.2) HHV predictive model

A multiple linear regression model was developed to estimate the HHV of hydrochar using proximate analysis data. The model incorporated the ash content (AC), volatile matter (VM), and fixed carbon (FC) and is expressed in Eq. 4.

$$\text{HHV (mg kg}^{-1}\text{)} = a \times \text{FC} + b \times \text{VM} + c \times \text{AC} + d \quad (\text{Eq.4})$$

where a, b, c, and d are regression coefficients derived from the experimental data.

Among several investigated formulations, the model with the best statistical performance was selected on the basis of three error metrics, namely, the mean error (ME), mean absolute error (MAE), and root mean square error (RMSE), defined by Eqs. 5 and 6 (Nhuchhen and Salam, 2012) and Eq.7 (Brandić et al., 2024), respectively.

$$\text{ME} = (1/n) \times \sum (y_i - \hat{y}_i) \quad (\text{Eq.5})$$

$$\text{MAE} = (1/n) \times \sum |y_i - \hat{y}_i| \quad (\text{Eq.6})$$

$$\text{RMSE} = \sqrt{(1/n) \times \sum (y_i - \hat{y}_i)^2} \quad (\text{Eq.7})$$

Here, y_i represents the experimentally measured HHV, $\hat{y}_i$ is the predicted HHV, and n is the number of samples. The final model was validated using independent datasets to ensure its predictive reliability.

Results and discussion

1) Optimization of HTC conditions

The HTC of UTW was performed at 180, 220, and 240 °C for 1–3 h to identify the optimal conditions for hydrochar fabrication (Figure 2). A biomass-to-water (B: W) ratio of 1:5 (16 g dry biomass to 80 g distilled water) was applied in all the runs. This ratio, supported by previous studies and a screening experiment, improved heat transfer and biomass–solvent interactions while minimizing processed water generation. Since higher dilution ratios suppressed secondary carbonization and increased water treatment burdens, a ratio of 1:5 was selected as the practical and energy-efficient condition for moist lignocellulosic biomass as UTW.

As shown in Figure 2, the MY decreased at higher temperatures and longer residence times because of intensified depolymerization, dehydration, and decarboxylation. Conversely, the HHV of hydrochar intensified under harsher conditions, reflecting increased carbon content and fuel densification. The highest HHV (22.95 MJ kg⁻¹) was obtained at 240 °C after 3 hours, although the MY decreased by 62%. EY, integrating both MY and HHV, peaked under these same conditions, reaching approximately 90%. Therefore, 240 °C for 3 h was considered the optimal HTC condition and was applied for subsequent experiments on process water recirculation.

2) Effect of PW recirculation on hydrochar properties

To reduce freshwater demand and improve the sustainability of the HTC process, the PW generated under optimal conditions (240 °C, 3 h, B:W = 1:5) was recirculated across ten consecutive runs. In each cycle, the PW from the previous run was blended with distilled water at a ratio of 1:1 to form the reaction medium. This study aimed to examine the influence of soluble organics accumulated in PW on the yield and fuel properties of the resulting hydrochar. The results are displayed in Figure 3.

The hydrochar performance indicators, including MY, HHV, and EY, varied across cycles, reaching a clear optimum around the fifth run (Figures 3 and 4). MY decreased slightly during the first three recirculation cycles but then increased sharply to a peak near 60% at HC-5. The HHV showed a parallel trend, increasing steadily to 22.18 MJ kg⁻¹ during the same cycle. The HHV improvement can be attributed to the enrichment of dissolved organic compounds (e.g., acetic acid, formic acid, and furan derivatives) in the PW, which favored secondary carbonization and carbon deposition onto hydrochar (Ipiales et al., 2024). The decrease in HHV during the first three cycles was ascribed to inhibitor buildup (e.g., formic acid), whereas the sharp increase during the fifth run resulted from the optimal TOC concentration (45 g L⁻¹), which enabled secondary carbonization and redeposition. This assump-

tion was confirmed by the decrease in the TOC content after the fifth run, which is further explained later.

The TOC in the PW represents the concentration of dissolved carbonaceous intermediates generated during HTC. It continuously increased from HC-0 to HC-4, reaching a maximum of approximately 45 g L^{-1} , indicating the accumulation of reactive organic compounds in the liquid phase. The sharp decrease in TOC at HC-5, together with peak MY and HHV, indicates that these dissolved carbons were consumed via secondary reactions and repolymerized onto the hydrochar, thereby increasing the carbon density and heating

value of the hydrochar. Beyond cycle 5, both the MY and the HHV decreased, indicating that the conversion decreased with increasing number of recirculation cycles.

In addition, controlling PW recirculation for up to five cycles improved hydrochar quality, halved freshwater consumption, and reduced wastewater generation. Beyond this point, diminishing returns were attained. Consistent with prior studies on agricultural residues, this work provides novel insights into lignocellulosic UTW biomass, a largely underexplored feedstock for HTC.

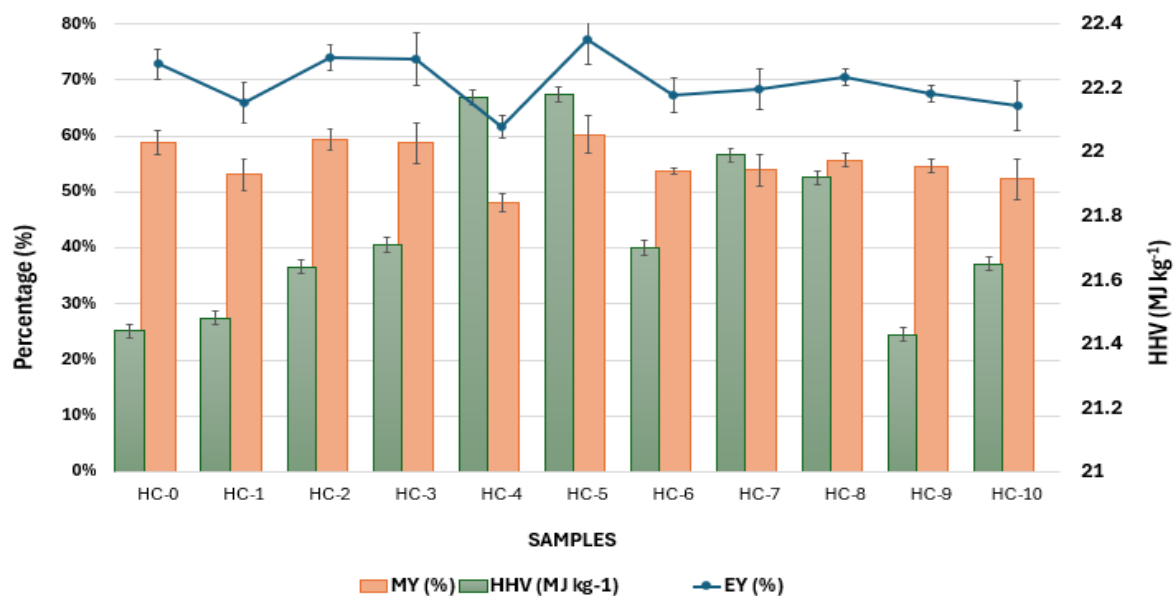


Figure 2 MY, EY, and HHV trends under HTC conditions.

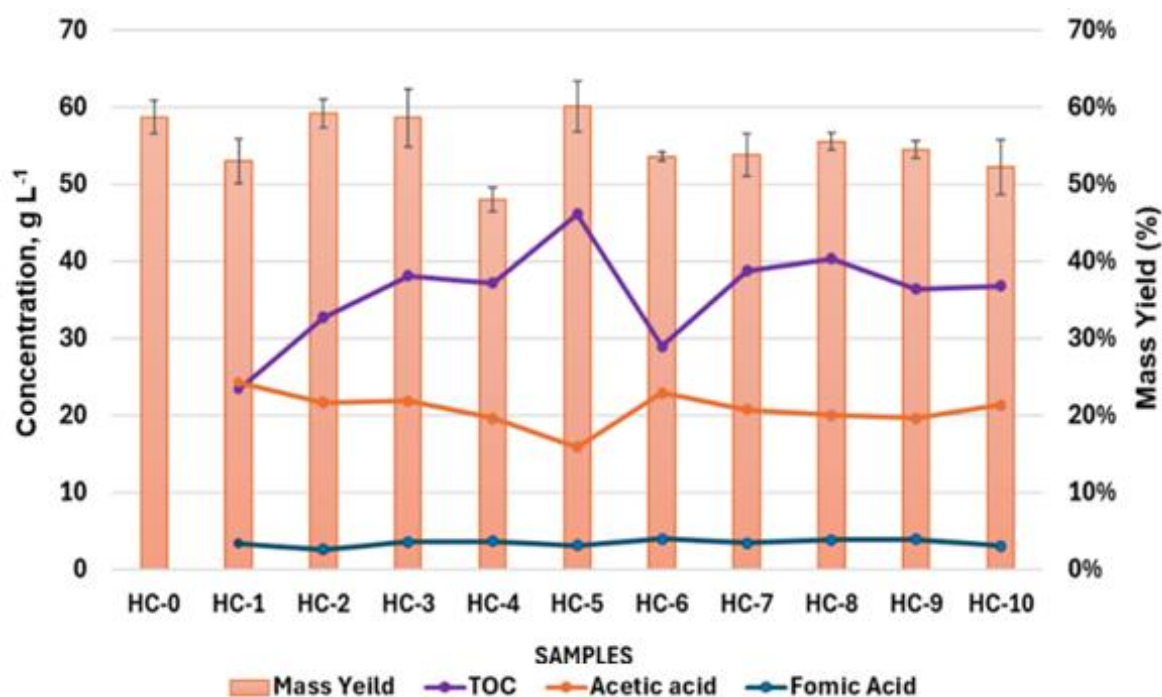


Figure 3 Relationships between the organic content of PW and the MY of hydrochar.

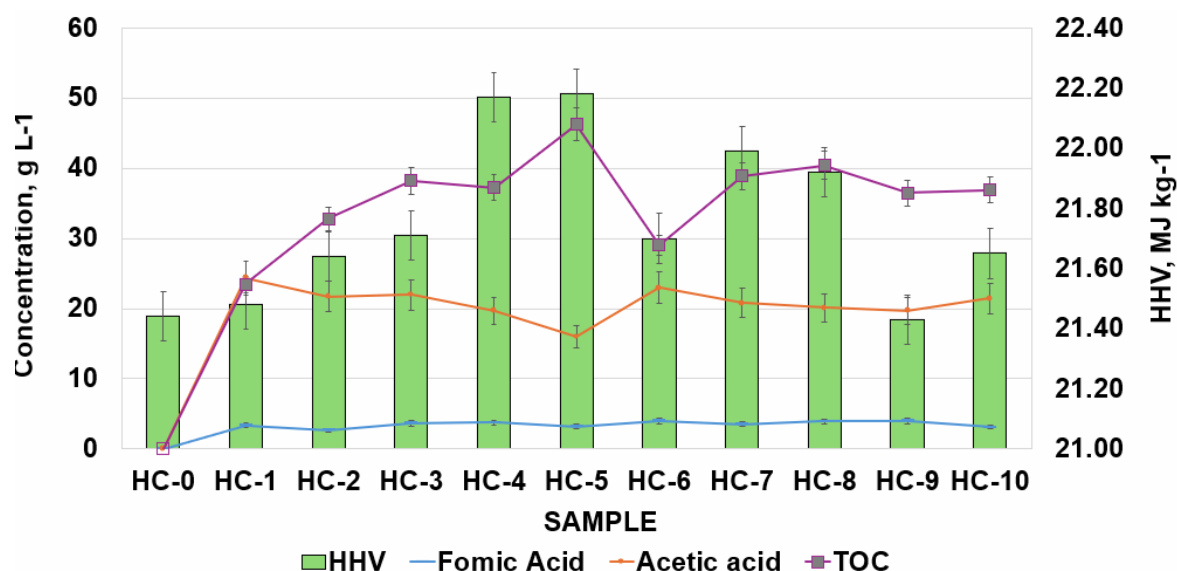


Figure 4 Relation between the organic content of PW and the HHV of hydrochar.

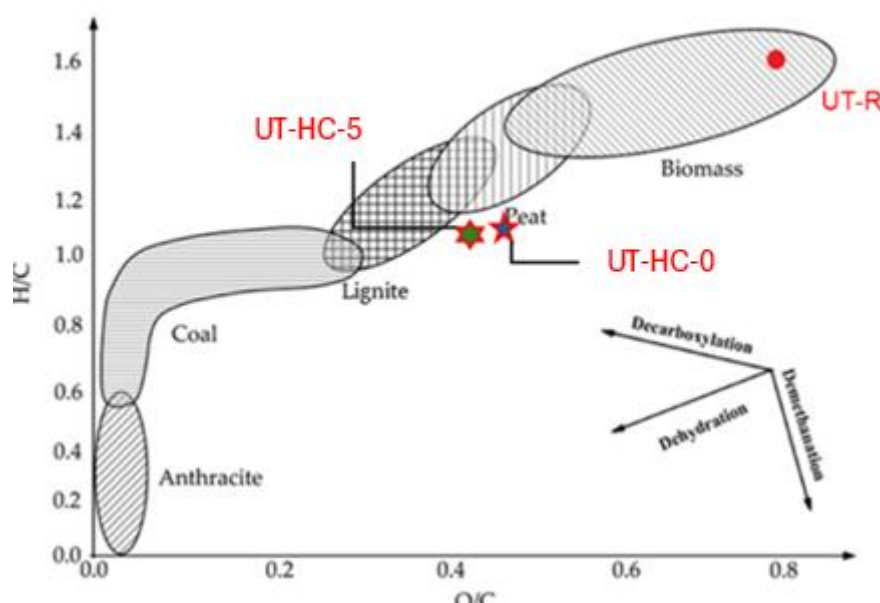


Figure 5 Van Krevelen diagram for raw UTW biomass (UT-R) and UTW-derived hydrochar without PW recirculation (UT-HC-0) and with 5-cycle PW recirculation (UT-HC-5).

3) Relation between process water composition and hydrochar quality

PW recirculation resulted in notable alterations in the elemental composition of hydrochar. Specifically, the C content increased, whereas the O content decreased. Compared with the raw UTW biomass (UT-R), the UTW-derived hydrochar without PW recirculation (UT-HC-0) had higher C and lower O contents, and the UTW-derived hydrochar with 5-cycle PW recirculation (UT-HC-5) exhibited the greatest C enrichment. The nitrogen (N) content increased in the UT-HC-0 but decreased in the UT-HC-5, possibly because of N solubilization in or volatilization from the saturated PW (Cavali et al., 2023). This reduction is environmentally benign, as it may decrease NO_x emissions during hydrochar combustion.

The van Krevelen diagram for the UTW biomass and UTW-derived hydrochars with and without PW recirculation is shown in Figure 5. UT-R was positioned in the biomass region, whereas UT-HC-5 shifted closest to the coal-like zone. The decreasing trends in the O/C and H/C ratios confirmed the increased carbonization, dehydration, and condensation, indicating that PW reuse intensified HTC reactions and improved hydrochar aromaticity and thermal stability. This highlights the potential of UT-HC-5 as an alternative to conventional fossil fuels (peat, lignite, and coal).

As demonstrated by the SEM images in Figure 6, structural evolution clearly occurred from the raw biomass to the hydrochar. Accordingly, compared with UT-R and UT-HC-0, UT-HC-5 has more compact and

aggregated surfaces, suggesting enhanced secondary carbon deposition during PW recirculation.

The CHNS analysis results revealed that the C content increased from 43% in UT-R to 54% in UT-HC-5, whereas the O content decreased correspondingly, resulting in lower O/C ratios and improved fuel quality. This compositional shift was consistent with the measured HHV increase from approximately 17.31 MJ kg⁻¹ (UT-R) to more than 221.8 MJ kg⁻¹ (UT-HC-5). The pH of the HTC process water remained acidic (~4.0–5.5) and stabilized during later cycles, confirming the presence and subsequent equilibrium of organic acids that influence hydrochar formation and energy properties.

4) Selection of a suitable HHV predictive model

A total of 21 datasets from proximate analysis were used to evaluate the performance of 15 empirical models for predicting the HHV of hydrochar. Model accuracy was assessed using three statistical error metrics, namely, ME, MAE, and RMSE, with RMSE prioritized because of its sensitivity to large errors in energy applications (Channiwala et al., 2002). The results are given in Table 1. Among the tested models, model No. 5, proposed by Sahito et al. (2013) and defined as $HHV = 0.196 \times FC + 14.119$, achieved the best performance. It yielded the lowest ME (−0.32), MAE (0.75), and RMSE (1.11), indicating strong accuracy, minimal bias, and high predictive reliability (Sahito et al., 2013). Models primarily based on VM or AH showed higher

prediction errors. These findings confirm that fixed carbon is the most reliable predictor of HHV for HTC-derived hydrochar, which is consistent with previous findings (Demirbas, 1997). As a result, model No. 5 was selected as the preferred equation for estimating HHV for further data interpretation.

5) Applicability of the fabricated hydrochar as a solid biofuel

The raw urban tree waste (UT-R) and urban tree waste-based hydrochar produced by 5-cycle PW recirculation are compared with other hydrochars produced from the HTC of agricultural wastes with PW recirculation in previous studies and traditional solid fuels in terms of HHV and proximate composition in Figure 7. The HHV of UT-HC-5 (22.18 MJ kg⁻¹) was greater than that of UT-R (17.31 MJ kg⁻¹). This can be explained by their proximate composition. Accordingly, compared with the UT-R sample, the UT-HC-5 sample contained higher percentages of fixed carbon (43.99%) but lower proportions of ash (5.51%) and volatile matter (50.50%), at 41.83%, 6.51%, and 61.66%, respectively. The superior HHV value of UT-HC-5 to that of UT-R can be further supported by their ultimate analysis, confirming that compared with UT-R, UT-HC-5 contained a higher percentage of C (54.70%) but a lower percentage of O (33.06%) and H (5.02%), which were 43.27%, 44.47%, and 5.63%, respectively.

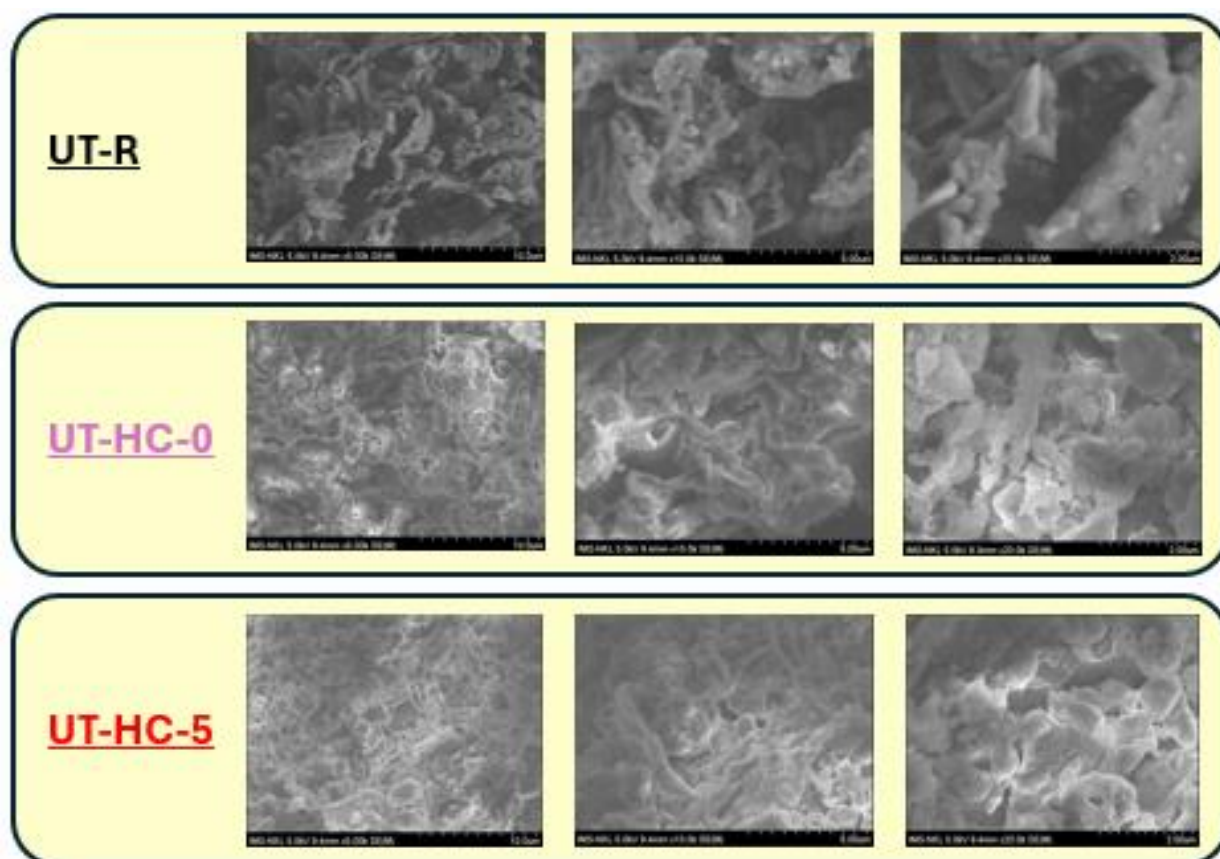
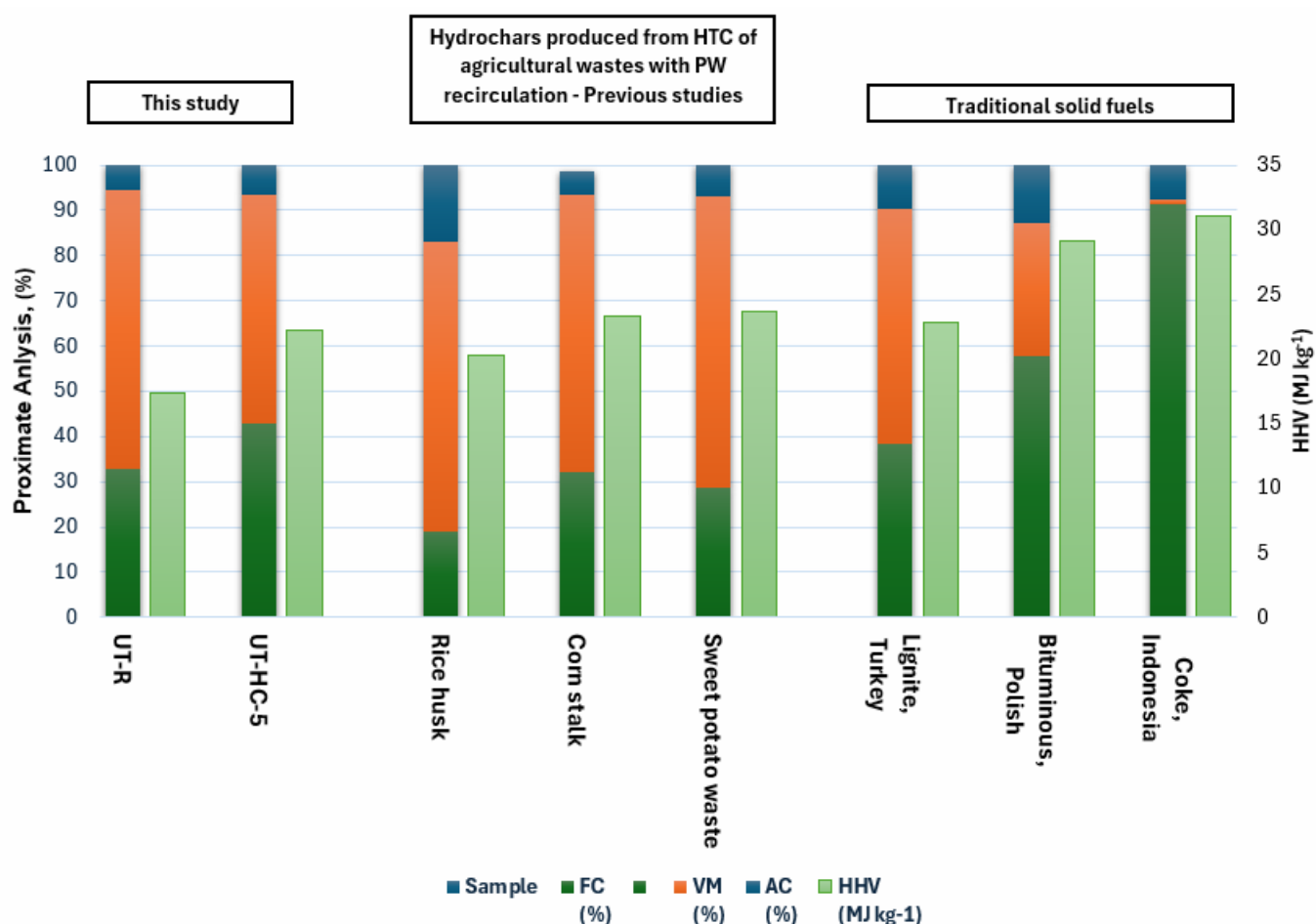


Figure 6 SEM images of (a) UT-R, (b) UT-HC-0, and (c) UT-HC-5.

Table 1 Selection of the HHV prediction model for hydrochars

No.	Equation	ME	MAE	RSME	Reference
1	$HHV = 19.914 - 0.2324AC$	2.19	2.29	2.64	Nhuchhen and Salam (2012)
2	$HHV = 10.982 + 0.1136VM - 0.2848AC$	4.78	4.78	5.12	Özyüğüran and Yaman (2017)
3	$HHV = 20.067 - 0.234AC$	2.04	2.19	2.53	Nhuchhen and Afzal (2018)
4	$HHV = 26.601 - 0.304AC - 0.082VM$	0.78	1.31	1.44	Nhuchhen and Afzal (2018)
5	$HHV = 0.196FC + 14.119$	-0.32	0.75	1.11	Sahito et al. (2013)
6	$HHV = 0.356248VM - 6.998497$	6.66	6.66	7.27	Nhuchhen and Afzal (2018)
7	$HHV = -0.1882VM + 32.94$	-1.28	1.37	1.74	Demirbas (2009)
8	$HHV = 0.1905VM + 0.2521FC$	0.65	1.34	1.46	Yin (2011)
9	$HHV = 20.86 - 0.261AC$	1.43	1.81	2.05	Nhuchhen and Afzal (2018)
10	$HHV = -13.173 + 0.416VM$	9.32	9.32	9.84	Nhuchhen and Afzal (2018)
11	$HHV = 35.4879 - 0.3023AC - 0.1905VM$	-1.74	1.76	2.02	Nhuchhen and Afzal (2018)
12	$HHV = 18.96016 - 0.22527AC$	3.10	3.11	3.44	Nhuchhen and Afzal (2018)
13	$HHV = 0.1846VM + 0.3525FC$	-2.49	2.49	2.69	Nhuchhen and Afzal (2018)
14	$HHV = 0.3543FC + 0.1708VM$	-1.74	1.75	2.01	Cordero et al. (2001)
15	$HHV = 32.18 - 0.09VM - 0.71AC$	-1.71	1.71	1.97	Özyüğüran et al. (2019)

**Figure 7** Comparison of the potential of UT-HC-5 as an alternative to conventional fossil fuels and hydrochars from other studies (Chen et al., 2018; Ding et al., 2023; Koukouzas et al., 2007; Wang et al., 2020; Yaman et al., 1999; Yang et al., 2005).

As shown in Figure 7, the HHV of UT-HC-5 (22.18 MJ kg⁻¹) was comparable to that of other hydrochars produced from the HTC of agricultural waste coupled with PW recirculation, such as sweet potato waste-derived 4-cycle hydrochar (23.65 MJ kg⁻¹) (Chen et al., 2018), corn stalk-derived 4-cycle hydrochar (23.31 MJ kg⁻¹) (Wang et al., 2020), and rice husk-derived 4-cycle hydrochar (20.3 MJ kg⁻¹) (Ding et al., 2023). Although the HHV of UT-HC-5 (22.18 MJ kg⁻¹) was equivalent to that of lignite (22.80 MJ kg⁻¹) (Yaman et al., 1999), it was still lower than that of bituminous coal in Poland (29.2 MJ kg⁻¹) (Koukoulzas, 2007) and coke in Indonesia (31.1 MJ kg⁻¹) (Yang et al., 2005). This is probably because the fixed carbon content of UT-HC-5 (42.99%) was comparable to that of lignite (38.30%) but much lower than that of bituminous coal in Poland (57.71%) and coke in Indonesia (91.47%). The results revealed that compared with traditional solid fuels, UT-HC-5 falls

within the mild-grade solid fuel category and demonstrates competitive energy performance. This also highlights the need to seek an effective strategy to further increase the HHV value of UT-HC-5.

A comparison of the UT-HC-5 and the Vietnam National Standard (TCVN 8910:2020) for solid fuels is presented in Table 2. With a heating value of 5,297 cal g⁻¹, it exceeded that of peat and unclassified fuels and approached that of lump coal, confirming strong energy densification. Ash (5.51%) and sulfur (< 0.01%) contents were within safe limits, suggesting its ability to undergo clean combustion. Although the volatile matter content was high (50.5%), which might affect the solid fuel stability, it enabled rapid ignition and co-firing uses. Overall, the UT-HC-5 meets or surpasses key national benchmarks, highlighting its potential as a solid biofuel for Vietnam's industry.

Table 2 Evaluation of the UT-HC-5 according to the Vietnam National Standard for solid fuels

Parameter	TCVN 8910:2020 requirements for commercial coals				This study
	Lump coal	Fine coal	Peat	Unclassified	UT-HC-5
Particle size (mm)	6 -100	≤ 25	≤ 0.5	≤ 200	Not applicable
Ratio of particle size (< 6 mm, %)	≤ 20	≤ 50 and 10% Oversized	15% Oversized	-	Not applicable
Ash (% , d.b)	3-16	5-45	27-35	31-45	5.51
Moisture (≤, %, ar)	6	23	25	16	Not applicable
Volatile matter (≤, %, d.b)	8	31	8	36	50.5
Sulfur (≤, %, d.b)	1.75	4	1.75	9	< 0.01
HHV (cal g ⁻¹ , d.b)	6,700	4,100	5,000	3,650	5,297

Conclusions

In this study, UTW was successfully converted into high-quality solid biofuel via HTC coupled with PW recirculation. The optimal HTC conditions for UTW-derived hydrochar fabrication were determined to be 240 °C for 3 h with a biomass-to-water ratio of 1:5. The obtained hydrochar was characterized by an HHV of 22.95 MJ kg⁻¹ and an approximately 90% energy yield. The recirculation of PW for up to five cycles was most effective at reducing the freshwater demand for the HTC process (by up to 50% per cycle), improving the fuel properties and enhancing the surface porosity of the hydrochar. A multiple linear regression model based on fixed C content was validated for rapid HHV prediction of hydrochars. Furthermore, the HHV, ash, and sulfur content of the fabricated hydrochar UT-HC-5 satisfied the Vietnam National Standard (TCVN 8910:2020) for solid fuels, confirming its applicability as a clean solid biofuel. Overall, HTC coupled with PW recirculation provides a technology-viable and resource-efficient pathway for

the valorization of UTW as a renewable energy source. These results are crucial for promoting the upcycling and sustainable management of UTW in Vietnam. A detailed technoeconomic analysis should be conducted in future pilot-scale studies to confirm the economic feasibility of converting UTW into high-quality solid biofuel via HTC coupled with PW recirculation.

Data availability statement

Information and data used in the study will be disclosed upon request.

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Author contributions

Nguyen Huong Giang: Methodology, Validation, Formal analysis, Investigation, Writing – Original draft

Nguyen Thi An Hang: Conceptualization, Methodology, Writing – Review & editing, Supervision, Project administration

Bui Thi Hang: Resources, Data curation, Visualization

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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