PROGRESS IN APPLIED SCIENCE AND TECHNOLOGY
Faculty of Science and Technology
Rajamangala University of Technology Thanyaburi
Prog Appl Sci Tech. 2024; 14(1):54-64
ISSN (Print): 2730-3012
ISSN (Online): 2730-3020
https://ph02.tci-thaijo.org/index.php/past

Research Article

Received: December 17, 2023
Revised: March 14, 2024
Accepted: March 20, 2024

DOI: 10.60101/past.2024.252105

Comparative Evaluation on Enhancing Fuel Properties of Biocoal from Bagasse Using Hydrothermal Carbonization and Torrefaction Processes

Jarunee Khempila[1*] and Pumin Kongto[2]
[1] *Department of Physics, Faculty of Science and Technology, Rajabhat Maha Sarakham University, Maha Sarakham 44000, Thailand*
[2] *Biomass Energy and Sustainable Technologies (BEST) Research Center, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*
*E-mail: jarunee.kh@rmu.ac.th

Abstract

This research investigates the thermochemical conversion of sugarcane bagasse into biocoal using a subcritical aqueous medium (water, 200–250°C) and a limited oxygen atmosphere (nitrogen, 250–300°C). The aim is to discover alternative renewable energy sources to replace fossil fuels. The effects of those different methods on the physiochemical properties of the solid product were determined. The best results of fixed carbon (37.13%), carbon content (62.17%), fuel ratio (0.61), and higher heating value (HHV) (25.75 MJ/kg) were obtained under hydrothermal carbonization (HTC) at 250°C. Additionally, the HTC process effectively reduced the ash and sulphur content of the solid products. Moreover, HTC was found to be a promising method for depolymerizing hemicellulose. Hydrochar produced at 250°C is located within the range of lignite, which is typically obtained at lower reaction temperatures compared to biochar samples. Consequently, the conversion of sugarcane bagasse into solid biofuel through HTC shows great potential from a thermochemical perspective.

Keywords: Biocoal, Bagasse, Hydrothermal Carbonization, Torrefaction

1. Introduction

The world is in an energy crisis due to our reliance on fossil fuels, which have caused environmental and economic challenges. Fossil fuel combustion releases greenhouse gases, leading to climate change and its adverse effects. Additionally, fossil fuel reserves are depleting rapidly, causing energy insecurity and price volatility. Furthermore, the extraction, transportation, and combustion of fossil fuels have severe environmental consequences, including pollution, ecosystem destruction, and health issues. To address these crises, there is an increasing global trend towards renewable energy sources as a response to these challenges. Renewable energy provides a sustainable and environmentally friendly substitute for fossil fuels. It helps reduce greenhouse gas emissions, promotes energy independence, and stimulates economic growth through the advancement of clean energy technologies. Transitioning to the use of renewable energy requires investments in research and development, government support, and infrastructure expansion. Key measures for addressing the energy crisis and decreasing our dependence on fossil fuels include promoting energy efficiency, advocating for the adoption of renewable technologies, and transitioning towards a low-carbon economy.

Renewable energy refers to a clean and sustainable source of energy, as it neither directly causes environmental damage nor depletes the source of power as it is continuously regenerated. Some of the key types of renewable energy include biomass, hydropower, wave and tidal, wind, solar, and geothermal. Each of these renewable energy sources has different characteristics, advantages, and considerations, and their use is essential for reducing dependence on fossil fuels and minimizing climate change.

In the heat and power generation sector, biomass plays an important role as an energy resource. It refers to organic materials derived from plants and forestry crops and residues, agricultural crop waste and residues, sewage and municipal waste, animal waste (dung and manure), and food industrial waste (1). These biomass feedstocks can be efficiently converted into thermal energy through various processes, such as combustion, gasification, and anaerobic digestion. There are various benefits to using biomass for heat generation. Because of its renewable nature, widespread availability, carbon neutrality, and possible economic advantages, biomass is a useful alternative to fossil fuels for satisfying heat demand while lowering greenhouse gas emissions and fostering sustainable development. Various biomass types, including sugarcane bagasse (SCB), can be utilized as renewable feedstocks for biofuel production. SCB is particularly noteworthy due to its abundance as an agricultural crop rich in lignocellulose and as a significant by-product of sugar production. However, there are several limitations to the direct utilization of biomass for energy production, such as its high moisture content, fibrous nature, hydrophilicity, high ash and volatile content, and low bulk density. To address these drawbacks, pre-treatment is required, with the appropriate procedure determined by the intended application and desired biomass end products.

Various technologies exist for converting biomass into fuels or energy, including torrefaction, hydrothermal carbonization, pyrolysis, carbonization, gasification, and combustion. These methods yield solids, liquids, gases, and energy (power or heat). The choice of conversion method depends on factors like the biomass type and desired product form. For example, biomass with high volatile matter is suitable for liquid and gas production, making pyrolysis and gasification appropriate. Conversely, biomass rich in fixed carbon is better for solid fuel production, favoring torrefaction and hydrothermal carbonization (HTC) (2). For applications that require a solid, carbon-rich product, like biocoal, torrefaction and HTC are promising options. Solid output from torrefaction and HTC ranges from 30–95% (3) and 37–66% (4) of the initial biomass weight, respectively. Torrefaction occurs at temperatures between 200°C and 300°C in a controlled oxygen environment (5), resulting in biochar, which, on the other hand, enhances biomass through pretreatment with hot-compressed water or subcritical water at moderate pressures and temperatures (180–260°C and 4.6 MPa, respectively) (6), producing solid products known as hydrochar. After treatment, the solid product has lower moisture, oxygen content, and biodegradation, as well as improved grindability, greater heating value, energy density, and carbon content. The characteristics of biomass allow it to be used as a co-firing fuel with coal.

Recent studies have conducted into the conversion performance of torrefaction and hydrothermal carbonization. According to Zhang et al., solid yields from microalgae were about the same, but hydrochar had higher heat values (HHV) of 21.10 to 25.39 MJ/kg and higher energy yields (72.48% to 92.29%) than biochar (7). Kambo and Dutta looked into how to make carbon-rich solid fuel from miscanthus. They found that torrefaction produced solid samples with lower energy density, grindability, and hydrophobicity compared to hydrochar, even though the reaction took longer (8). According to Ercan et al., hydrochars derived from hornbeam via hydrothermal carbonization exhibited higher degrees of carbonization than biochars produced from torrefaction under identical conditions (9). Babinszki et al. came to the conclusion that hydrochars enhanced the formation of aromatic compounds more than torrefied azolla during pyrolysis (10). According to Chen et al., the temperature needed for hydrothermal carbonization was lower than for torrefaction (around 100°C), with similar improvements in calorific value (11).

However, despite the abundance of published literature on the topic, there is a lack of comparative studies specifically focused on the torrefaction and hydrothermal carbonization of SCB. To address this gap and aid decision-making, this study aims to assess the viability of converting bagasse into biocoal and compare the effects of torrefaction and HTC on SCB. The solid products that were made and the parts of the biomass were studied, with a focus on the main parts of lignocellulosic biomass. The chemical composition of the solid products was determined through proximate and CHN(O)S elemental analyses. Comparing the solid products favorably with coal on a Van Krevelen diagram demonstrates the potential of biocoal for co-firing applications. Overall, the goal of this research is to determine the practicality of converting bagasse into biocoal, offering significant data for decision-making on the best thermal conversion process to utilize.

2. Materials and Methods

2.1 Feedstock preparation

In this study, the biomass feedstock used was SCB with a moisture content of 8.38 wt.%. The SCB was obtained domestically from Maha Sarakham, Thailand. The biomass was crushed with the use of a grinding machine (Model HC-800Y, Wuyi Haina Electric Appliance Co., Ltd., China) and filtered to reduce the particle size to below 1 mm. with an 18-mesh sieve (Gilson Business, Inc., USA). The samples were stored in sealed containers for future processing. Table 1 presents several characteristics of bagasse.

Table 1 Properties of raw sugarcane bagasse.

Fiber analysis (wt.%, dry basis)	
Hemicellulose	27.01
Cellulose	55.84
Lignin	14.44
Other*	2.71
Ultimate analysis (wt.%, dry basis)	
C	46.25
H	6.90
N	0.34
O**	44.12
S	0.14
Proximate analysis (wt.%, dry basis)	
Fixed carbon	14.71
Volatile matter	83.04
Ash	2.25
Moisture content***	8.38

*Calculated by difference (CL + HCL + LN + Others = 100%).
**Calculated by difference (C + H + N + O + S + Ash = 100%).
*** wt.%, as received basis

2.2 Torrefaction process

For the torrefaction procedure, a Nabertherm™ muffle furnace (Model L/LT, P310 Controller, Germany) was utilized. The process involved three temperature levels: 250°C, 275°C, and 300°C, with a fixed reaction period of 30 minutes. Each temperature level was tested three times, resulting in a total of nine experiments. In each experiment, 20 g of powdered bagasse was added to a tubular reactor, which was then placed into the furnace. During torrefaction, a carrier gas of N_2 with a purity of 99.99% was used, with a flow rate of 1 L/min. Heated the batch reactor at 10°C/min from ambient to the desired temperature and maintained it for 30 minutes (12). After the reaction, the reactor cooled to room temperature. The solid biochar samples (Figure 1) were stored in sealed plastic bags for analysis.

2.3 Hydrothermal carbonization process

Hydrothermal carbonization was done in a 500-mL high-pressure autoclave reactor (Xiamen Ollital Technology Co., Ltd.). At each of the three temperature levels (200°C, 225°C, and 250°C), three cycles were executed. Each experiment mixed 10 g of bagasse powder and 350 mL of deionized water in the reactor vessel. The vessel was sealed, and 99.99% pure nitrogen gas (Kasidith Trade Co., Ltd.) purged the reactor for 5 minutes. The reactor was then heated to the target temperature and maintained isothermally for 30 minutes. After the reaction, the reactor was immediately immersed in a cooling water bath to rapidly cool the temperature to room temperature. Filtered and dried the solid products, known as the hydrochar samples, in a 105°C oven for 24 hours. The samples of hydrochar (Figure 1) were weighed and then placed in airtight plastic bags.

2.4 Characterization

2.4.1 Solid Yield

Raw biomass transforms into solid, torrefied products to define "solid yield". These parameters were calculated using equation (2.1).

$$Solid\ yield(\%) = \frac{Mass\ of\ solid\ product}{Mass\ of\ raw\ biomass} \times 100 \qquad (2.1)$$

2.4.2 Proximate Analysis

The LECO TGA 801 thermogravimetric analyzer measured the volatile matter (VM), moisture content (MC), and ash content of the samples in accordance with ASTM D7582-15 (11). Subtracting the total amount of volatile matter and ash content from 100% determined the fixed carbon content (FC). The average value of the three repetitions of each test was utilized to present the results in weight percent on dry basis. The fuel ratio of biofuel is typically calculated by determining the ratio of fixed carbon to volatile matter in the product (13), as specified by equation (2.2).

$$Fuel\ ratio = \frac{Content\ of\ fixed\ carbon}{Content\ of\ volatile\ matter} \qquad (2.2)$$

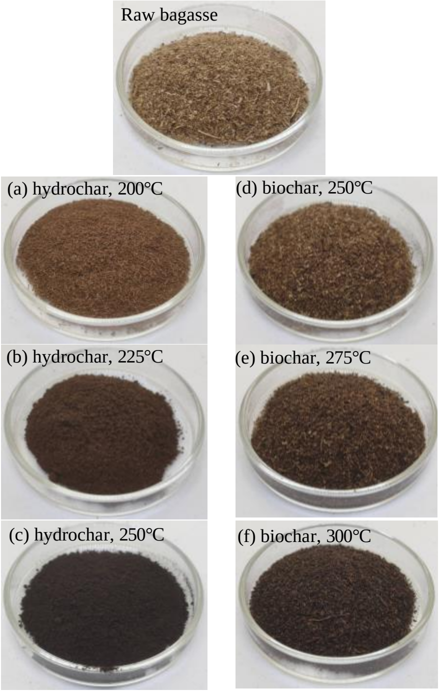

Figure 1 Biochar and hydrochars derived from sugarcane bagasse

2.4.3 Ultimate Analysis

The LECO TruSpec CHN elemental analyzer, in conjunction with the add-on sulphur module, was utilized to directly measure the contents of hydrogen (H), carbon (C), sulphur (S), and nitrogen (N). To calculate the oxygen (O) content, the total of C, H, N, S, and ash were subtracted from 100%. For accuracy, each experiment was repeated twice. Based on the dry basis analysis of C, H, and N, correlation curves from Fried et al. (14) were used to estimate the HHV by using equation (2.3).

$$HHV = 5.22C^2 - 319C - 164H + 38.6CH + 133N + 21028 \qquad (2.3)$$

2.4.4 Chemical compositions

The detergent fiber analysis is divided into neutral detergent fiber (NDF) and acid detergent fiber (ADF). The principal cell wall components found in NDF are cellulose, hemicellulose, and lignin. ADF is an estimate of the cellulose and lignin content of the sample. As a result, hemicellulose is approximated as NDF-ADF. Acid detergent lignin (ADL) was used for determining lignin and other substances (extractives and ash) (15). Two measurements were taken and reported as average percentages by weight (wt.%, dry basis).

3. Results and Discussion

3.1 Chemical composition of raw and treated sugarcane bagasse

The primary constituents of lignocellulosic biomass consist of cellulose, hemicellulose, and lignin, as well as additional components like extractives and ash. Figure 2 shows the chemical composition of raw and treated bagasse. The findings indicate that cellulose was the most abundant component in raw bagasse, representing about 54.8%, followed by hemicellulose at 26.8%. High-lignin biomass is typically desirable for high-energy fuel production. The study determined the lignin content of the bagasse to be only 14.4%, consistent with the study of Behnood et al., which found that bagasse is primarily composed of 44% cellulose, 27% hemicellulose, and 13% lignin content (16). Low lignin content in bagasse due to the fact that lignin is often found in higher concentrations in the woody parts of plants, such as stems and branches, rather than in the fibrous material like bagasse.

After treating bagasse, the results indicate that as the reaction temperature increased, the cellulose and hemicellulose content in solid products decreased significantly. Specifically, at a temperature of 300°C, the biochar sample exhibited complete gas and liquid transformation, with only 0.8% of any remaining hemicellulose. At 150°C, hemicellulose starts to break down thermally. The significant decomposition of hemicellulose occurs within the temperature range of 220°C to 280°C, according to some researchers (17). As a result, treating biomass with a high hemicellulose content results in a low mass yield. The temperature ranges for cellulose and lignin degradation are roughly 315°C – 400°C and 160°C – 900°C, respectively. As a result, lignin is more difficult to degrade than cellulose or hemicelluloses, making its conversion into biochar or hydrochar more effective (17,18). However, at the same reaction temperature, the hydrochar sample decomposed more hemicellulose than the biochar sample. For example, at 250°C, the hemicellulose content of the hydrochar and biochar samples was 1.6% and 14%, respectively. Subcritical water in the 220°C – 300°C temperature range produced the difference attributed to hydrochar. In its subcritical state, water acts as a self-neutralizing catalyst and benign solvent, making it highly efficient and extremely reactive in breaking hemicellulose glycosidic bonds (19). Because of this, it is clear that selective HTC is a better way to remove hemicellulose from bagasse than the torrefaction process. Cellulose degradation generally requires and occurs at a higher reaction temperature compared to hemicellulose degradation. Figure 2 shows that cellulose degradation was more pronounced in HTC than in torrefaction at 250°C. Due to the larger surface areas of the biomass samples and solvent, this assisted in more efficient heat transfer. The lignin content of the hydrochar sample increased throughout the HTC process, reaching 28.3% at 250°C, while the biochar sample was only 19.3%. HTC enhanced the decomposition of hemicellulose and extractives more efficiently than the torrefaction process, resulting in an increase in the lignin proportion. It is critical to remember that the thermal treatment process does not produce lignin. Significant changes in the proportions of the chemical composition occur due to the decrease in hemicellulose and cellulose after thermal treatment.

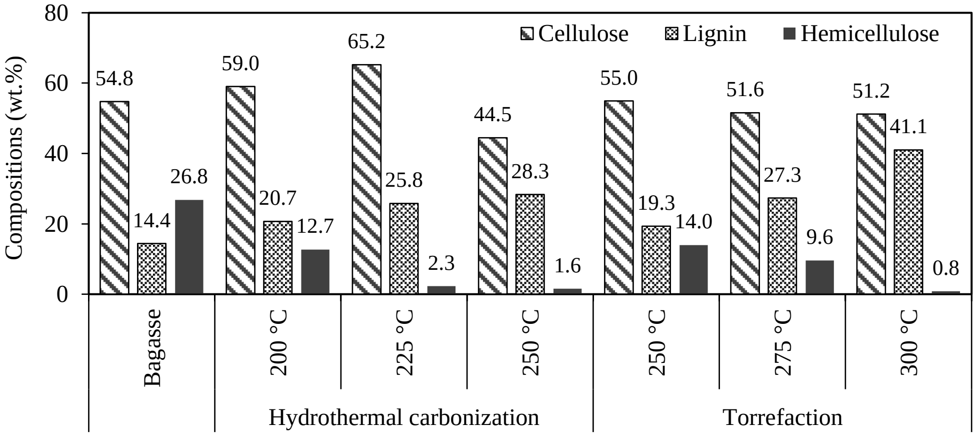

Figure 2 Lignocellulose compositions of bagasse treated by torrefaction and HTC processes.

3.2 Solid yield

The solid yield of treated bagasse at various reaction temperatures is illustrated in Figure 3. The solid yield of biochar samples ranged from 62.5% to 84.2%, while hydrochar samples had yields between 37.1% and 53.9%. Noteworthy is the considerable reduction in the solid yields of the treated samples as the reaction temperature increased in both treatment methods. For example, the solid yield of biochar samples decreased to 84.2% at 250°C, while the solid yield of hydrochar samples at the same temperature was only 37.1%. The solid yield from the HTC process is much lower than that from the torrefaction process. This is mostly because the degradation of hemicellulose in the HTC process was higher than in torrefaction process. The evidence supported is the results obtained from the fiber analysis shown in chemical composition (Figure 2). The analysis reveals hydrochar had a decrease in hemicellulose content from 26.8% to 1.6% at 250°C, representing a substantial loss of 94.1%. Hemicellulose generally decomposes at a temperature range of 220°C – 315°C, which is related to the reaction temperature in this study. In addition, during the HTC process, decomposition was accelerated under supercritical water.

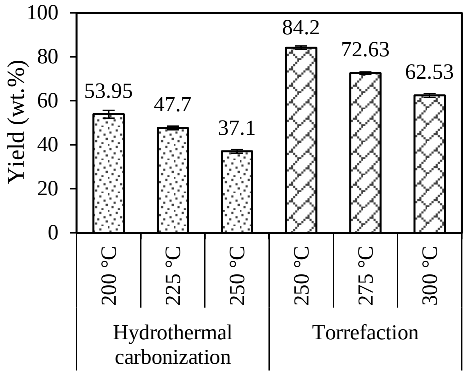

Figure 3 solid yield of sugarcane bagasse as a function of torrefaction temperature processed by HTC and torrefaction.

3.3 Proximate analysis and fuel ratio

Table 2 displays the results of the proximate analysis and fuel ratios of raw and treated bagasse. The MC, FC, VM, and ash content of raw bagasse were 8.38, 14.71, 83.04, and 2.25%, respectively. It is worth noting that raw bagasse has a relatively high volatile matter content. Its high volatile matter concentration (20) allows it to be burned directly or with coal. However, a large volatile ratio difference between biomass and coal may separate combustion zones, reducing combustion efficiency and increasing pollutant emissions (21). As shown in Table 2, it is evident that increasing the reaction temperature led to a significant decrease in the volatile matter content. For example, the hydrochar and biochar samples showed a minimum a volatile matter content of 60.55% and 70.88%, respectively. Volatile matter includes substances like gases and light hydrocarbons that vaporize at low temperatures. When chars have lower volatile matter content, fewer substances can vaporize readily at low temperatures. This means they might need a higher temperature to ignite and more heat to start burning (22). Also, since flammability relates to how easily something ignites, fewer volatile components can make the material less likely to catch fire spontaneously. In addition, increasing the reaction temperature not only led to a significant decrease in the volatile matter content but also improved the fixed carbon content. Char retains fixed carbon after removing volatile matter through heating without air. This stable carbon content makes materials less likely to decompose or burn at high temperatures, resulting in greater thermal stability (23).

Table 2 Results of proximate analysis and fuel ratio of raw and bagasse treated by torrefaction and HTC processes.

Torrefaction conditions	**Proximate analysis (wt.%, dry basis)**				**Fuel ratio (FC/VM)**
	MC*	**FC**	**VM**	**Ash**	
Raw bagasse	8.38	14.71	83.04	2.25	0.18
Hydrothermal carbonization					
200°C	0.83	14.42	84.54	1.04	0.17
225°C	1.12	18.72	80.11	1.17	0.23
250°C	1.32	37.13	60.55	2.32	0.61
Torrefaction					
250°C	1.46	15.65	82.59	1.76	0.19
275°C	1.71	20.32	77.19	2.49	0.26
300°C	2.34	25.81	70.88	3.31	0.36

* wt.%, as received basis

During the thermal process, a portion of hemicellulose and a small amount of cellulose decompose and release gas, leading to a reduction in the volatile components of the treated solid product. As a result, fixed carbon and ash proportions increase. The loss of volatile matter contributes to a decrease in solid yield, reinforcing this observation. Around 30% of the total mass disappears as volatile and permanent gases, predominantly CO_2, in addition to condensable species (24). At the same reaction temperature, it was observed that the hydrochar sample had more fixed carbon and less volatile carbon compared to the biochar sample. To illustrate, at a temperature of 250°C, the hydrochar sample contained 37.13% fixed carbon and 60.55% volatile matter, whereas the biochar sample contained 15.65% fixed carbon and 82.59% volatile matter.

Hydrochar and biochar samples showed an increase in ash content after thermal treatment at a reaction temperature of 250°C, as indicated in Table 2. The reduction in solid yield during thermal treatment processes leads to a higher concentration of metallic elements. Nevertheless, it is important to mention that at the same reaction temperature, the ash content of solid products from HTC treatment processes was lower than that from the torrefaction process. Moreover, decreasing volatile matter and increasing the fixed carbon content of treated bagasse have an effect on the fuel ratio of biochar and hydrochar. The fuel ratio is a significant parameter to consider, as it provides details about the type of combustion that can occur during the process. Lower VM and higher FC improved fuel ratios after treating bagasse, as seen in Table 2. At the same reaction temperature, the hydrochar exhibited a greater fuel ratio compared to the biochar. For instance, at 250°C, the hydrochar sample had the greatest fuel ratio of 0.61, while the biochar sample had the lowest fuel ratio of 0.19. Biomass often exhibits a low fuel ratio, resulting in rapid burnout, less unburned char from combustion, and more flaming in combustion. In contrast, treated biomass has a higher fixed carbon content and lower volatile matter after thermal treatment, which improves combustion stability. However, an elevated ignition temperature is necessary for treated biomass, despite its reduced combustion rate (25). The recommended fuel ratio range for coal is 0.5–3.0. Its fuel ratio of 0.61 demonstrates that the hydrochar sample produced at 250°C is particularly suitable for biomass co-firing.

3.4 Ultimate analysis and heating value

Table 3 shows the carbon, nitrogen, oxygen, and sulphur content of raw bagasse and the treated samples produced through HTC and torrefaction at different temperatures. The results indicate a consistent trend across both processes, with the treated samples exhibiting higher carbon content and lower oxygen content compared to the raw bagasse. Significantly, the carbon content shows a notable change. The raw bagasse had a carbon content of 46.25%. As the reaction temperature increased, there was a corresponding rise in the carbon content in both treatment methods. During torrefaction, the carbon content reached 47.46% at 250°C, while during HTC, it increased to 62.17%. This finding suggests that the HTC process has the potential to significantly enhance the carbon content of biomass to a greater extent than the torrefaction process at the same temperature.

During both the HTC and the torrefaction processes, the concentration of oxygen decreases as the thermal treatment becomes more intense. For example, the raw bagasse initially contained 44.12% oxygen. After torrefaction at a reaction temperature of 250°C, the oxygen concentration decreased to 43.91%, and during the HTC process, it fell even further to 29.37%. This indicates that the HTC process is capable of removing oxygen at relatively lower temperatures compared to the torrefaction method. Not only does the oxygen content decrease in the treated products, but the nitrogen content also experiences a reduction. The raw bagasse contained 0.34% nitrogen. Following the torrefaction process at 250°C, the nitrogen concentration in the biochar sample decreased to 0.28%, and it slightly increased to 0.41% at 275°C. The nitrogen concentration in the hydrochar samples increased from 0.22% at 225°C to 0.30% at 250°C. As a result of the thermal treatment at a low reaction temperature, the changes in nitrogen concentration were negligible (26). The HTC process showed a more significant positive effect on nitrogen removal from the pretreated samples compared to the torrefaction method in reducing nitrogen oxides (NO_x) emissions during combustion. As shown in Table 3, the raw bagasse was found to contain a sulphur concentration of 0.14%. Surprisingly, the sulphur level in all treated samples was significantly lower compared to the raw bagasse. This reduction in sulphur content was observed in the dissolved form within the liquid and gaseous components (27). Additionally, the nitrogen and sulphur concentrations in the treated samples were lower than those typically found in coal. This is advantageous because it results in lower or negligible emissions of nitrogen oxides (NO_x) and sulphur oxides (SO_x) in the flue gases. Therefore, solid fuels with lower nitrogen and sulphur content are more suitable for combustion or co-firing processes.

Table 3 Results of ultimate analyses and higher heating values of bagasse treated.

Torrefaction conditions	**Composition (wt.%, dry basis)**					**O/C**	**H/C**
	C	**H**	**N**	**O***	**S**		
Raw bagasse	46.25	6.9	0.34	44.12	0.14	0.72	1.79
Hydrothermal carbonization							
200°C	49.36	6.46	0.27	42.82	0.05	0.65	1.57
225°C	51.27	6.38	0.22	40.92	0.04	0.60	1.49
250°C	62.17	5.79	0.30	29.37	0.05	0.35	1.12
Torrefaction							
250°C	47.46	6.52	0.28	43.91	0.07	0.69	1.65
275°C	50.33	6.3	0.41	40.44	0.03	0.60	1.50
300°C	53.45	6.11	0.43	36.69	0.01	0.51	1.37

*Calculated by difference (C + H + N + O + S + Ash + MC = 100 %).

3.5 Energy properties

The enhancements in the oxygen, hydrogen, and carbon content of the treated bagasse significantly influenced the energy content of the solid product. During combustion, the carbon and hydrogen atoms in the sample undergo an exothermic interaction with oxygen. Figure 4 illustrates the relationship between these factors. It presents the HHV of raw and treated bagasse samples. The initial HHV measured for the raw sample was 18.48 MJ/kg, whereas the hydrochar and biochar derived from bagasse exhibited HHV within the ranges of 19.71–25.75 and 18.89–21.48 MJ/kg, respectively. These results indicate that the reaction temperature had a significant impact on the heating value of the treated bagasse. The findings of this study align with previous research on various biomasses, including both woody and non-woody biomass, such as Gliricidia, sugarcane trash, and oil palm mesocarp fiber (28–30). As the severity of torrefaction increased, the heating value of the treated samples also increased, primarily due to the reduction in hydrogen and oxygen content. As a result, the treated samples exhibited a greater abundance of C–C and C–H bonds, which contain a more pronounced potential for energy release compared to the O–H and C–O bonds found in the untreated materials.

The hydrochar sample obtained at 250°C exhibited an HHV of 25.75 MJ/kg, while the biochar sample produced at 300°C reached a maximum HHV of 21.48 MJ/kg. Importantly, the biochar sample generated at 250°C had the lowest HHV, suggesting that at temperatures higher than 250°C, torrefaction improved the thermal conversion of untreated bagasse. The biochar and hydrochar samples at 275°C and 225°C had statistically similar HHV values of 20.10 and 19.71 MJ/kg, respectively. These suggest that hydrochar samples can be produced at lower reaction temperatures with an equivalent or greater HHV than biochar samples. In addition, it is significant to mention that the fixed carbon content found in the samples has a direct influence on HHV. As demonstrated in Table 2, consequently, in order to enhance the HHV of the treated samples, it is necessary to increase the fixed carbon content. Furthermore, the decreased energy loss due to moisture evaporation results in elevated heating values for the treated samples, owing to the reduced moisture content.

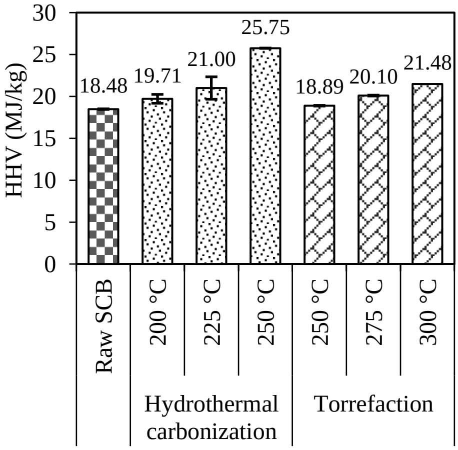

Figure 4 HHV of sugarcane bagasse as a function of temperature processed by HTC and torrefaction.

3.6 Atomic ratios H/C and O/C

The van Krevelen diagram in Figure 5 displayed the atomic oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios of biochar and hydrochar samples, along with the ratios of different types of coals. Raw bagasse had initial O/C and H/C ratios of 0.72 and 1.79, respectively. As the reaction increased, the atomic ratios of both biochar and hydrochar samples dropped, resulting in lower values compared to raw bagasse. This observation aligns with the results shown in Table 3 which indicate a decline in the concentrations of oxygen and hydrogen, accompanied by an increase in the carbon content. As a result, this reduction in atomic ratios was observed.

Interestingly, the hydrochar samples subjected to HTC at a lower temperature (250°C) exhibited lower O/C and H/C ratios compared to the biochar samples treated with torrefaction at 275°C and 300°C. The HTC-treated sample at 250°C was located within the range between peat and lignite, while the biochar sample was closer to the peat zone. The differentiation between torrefaction and HTC is due to the presence of water in the HTC process, which enhances the degradation of structural elements at a lower temperature. Considering the H/C and O/C atomic ratios typically observed in lignite, which range from 0.8 to 1.3 and 0.2 to 0.38, respectively (31), it is reasonable that the hydrochar sample at 250°C more closely approaches lignite.

The dehydration process resulted in a significant reduction of oxygenated surface functional groups in the samples, as well as the degradation of hemicellulose, which also led to an increase in the hydrophobicity of the treated biomass. As mentioned earlier, the treated products exhibited lower atomic H/C and O/C ratios compared to raw biomass, which gives them a coal-like nature. Furthermore, the reduced presence of oxygenated functional groups contributes to a decrease in smoke generation upon burning. Moreover, when coal and torrefied materials were mixed for combustion, this transformation assisted reduce their impact on flame characteristics (32).

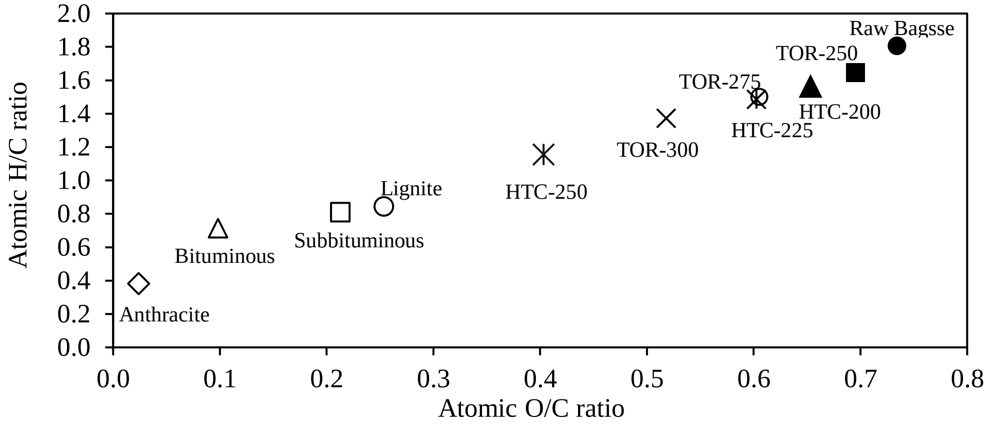

Figure 5 Van Krevelen diagram of treated bagasse obtained from torrefaction and HTC processes.

4. Conclusion

HTC offers a significant advantage over torrefaction in removing hemicellulose and extractives to enhance the fuel properties of biocoal derived from sugarcane bagasse. The high hemicellulose removal during HTC decreased the hydrochar yield compared to the biochar samples, but it enhanced the hydrochar quality by increasing the fuel ratio, carbon content, heating values, and reducing ash content. At the same reaction temperature, the hydrochar sample had more fixed carbon and less volatile carbon compared to the biochar sample. The hydrochar sample produced at 250°C (0.61) exhibits a fuel ratio that is especially suitable for biomass co-firing. The HTC process showed a more significant positive effect on nitrogen removal, reducing nitrogen oxides. The HTC-treated sample at 250°C was located within the range between peat and lignite, while the biochar sample was closer to the peat zone. The ash content of solid products from HTC at 200°C – 225°C was lower than that of raw materials, about 50% from the torrefaction process. This was beneficial for pretreating biomass to remove ash and decompose hemicellulose before turning it into thermal treatment due to the fact that HTC can occur at lower temperatures with elevated reactions.

Future research should focus on exploring innovative techniques for utilizing by-products generated during thermal treatment, such as ash and wastewater. Exploring the integration of thermal treatment processes with existing sugar or ethanol production facilities to develop integrated biorefinery concepts is recommended. Co-processing sugarcane bagasse with other lignocellulosic biomass feedstocks should also be investigated to enhance feedstock flexibility, product diversity, and overall process efficiency. Addressing these research directions can lead to the development of sustainable bioenergy, biofuels, and bioproducts, while addressing environmental concerns and promoting circular economy principles.

Acknowledgements

The authors would like to acknowledge and express their sincere appreciation to the Department of Physics, Faculty of Science and Technology, Rajabhat Maha Sarakham University, for their valuable research support. Their assistance has played a significant role in facilitating the successful completion of this study.

Declaration of conflicting interests

The authors declared that they have no conflicts of interest in the research, authorship, and this article's publication.

References

1. Iwuozor KO, Chizitere Emenike E, Ighalo JO, Omoarukhe FO, Omuku PE, George Adeniyi A. A review on the thermochemical conversion of sugarcane bagasse into biochar. Clean Mater. 2022;6:100162.
2. Olugbade TO, Ojo OT. Biomass torrefaction for the production of high-grade solid biofuels: a review. BioEnergy Res. 2020;13(4):999–1015.
3. Sarker TR, Nanda S, Dalai AK, Meda V. A review of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels. BioEnergy Res. 2021;14(2):645–69.
4. Sharma R, Jasrotia K, Singh N, Ghosh P, srivastava S, Sharma NR, et al. A comprehensive review on hydrothermal carbonization of biomass and its applications. Chem. Afr. 2020;3(1):1–19.
5. Cahyanti MN, Doddapaneni TRKC, Kikas T. Biomass torrefaction: an overview on process parameters, economic and environmental aspects and recent advancements. Bioresour. Technol. 2020;301:122737.
6. Lynam JG, Coronella CJ, Yan W, Reza MT, Vasquez VR. Acetic acid and lithium chloride effects on hydrothermal carbonization of lignocellulosic biomass. Bioresour. Technol. 2011;102(10):6192–9.
7. Zhang C, Chen WH, Saravanakumar A, Lin KYA, Zhang Y. Comparison of torrefaction and hydrothermal carbonization of high-moisture microalgal feedstock. Renew. Energy. 2024;225:120265.
8. Kambo HS, Dutta A. Comparative evaluation of torrefaction and hydrothermal carbonization of lignocellulosic biomass for the production of solid biofuel. Energy Convers. Manag. 2015;105:746–55.
9. Dang CH, Cappai G, Chung JW, Jeong C, Kulli B, Marchelli F, et al. Research needs and pathways to advance hydrothermal carbonization technology. Agronomy. 2024;14(2):247.
10. Babinszki B, Jakab E, Sebestyén Z, Blazsó M, Berényi B, Kumar J, et al. Comparison of hydrothermal carbonization and torrefaction of azolla biomass: analysis of the solid products. J. Anal. Appl. Pyrolysis. 2020;149:104844.
11. Chen WH, Ye SC, Sheen HK. Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating. Bioresour. Technol. 2012;118:195–203.
12. Mamvura TA, Pahla G, Muzenda E. Torrefaction of waste biomass for application in energy production in South Africa. South Afr. J. Chem. Eng. 2018;25:1–12.

13. Chen WH, Lu KM, Tsai CM. An experimental analysis on property and structure variations of agricultural wastes undergoing torrefaction. Appl. Energy. 2012;100:318–25.
14. Friedl A, Padouvas E, Rotter H, Varmuza K. Prediction of heating values of biomass fuel from elemental composition. Anal. Chim. Acta. 2005;544(1):191–8.
15. Kongto P, Palamanit A, Chaiprapat S, Tippayawong N, Khempila J, Lam SS, et al. Physicochemical changes and energy properties of torrefied rubberwood biomass produced by different scale moving bed reactors. Renew. Energy. 2023;219:119542.
16. Behnood R, Anvaripour B, Jaafarzadeh N, Farasati M. Oil spill sorption using raw and acetylated sugarcane bagasse. J. Cent. South Univ. 2016;23(7):1618–25.
17. Shankar Tumuluru J, Sokhansanj S, Hess JR, Wright CT, Boardman RD. A review on biomass torrefaction process and product properties for energy applications. Ind. Biotechnol. 2011;7(5):384–401.
18. Yang H, Yan R, Chen H, Lee DH, Zheng C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel. 2007;86(12): 1781–8.
19. Wolf M, Berger F, Hanstein S, Weidenkaff A, Endreß HU, Oestreich AM, et al. Hot-water hemicellulose extraction from fruit processing residues. ACS Omega. 2022;7(16):13436–47.
20. Wang Y, Yan B, Wang Y, Zhang J, Chen X, Bastiaans RJM. A comparison of combustion properties in biomass–coal blends using characteristic and kinetic analyses. Int. J. Environ. Res. Public. Health. 2021;18(24):12980.
21. Baxter L. Biomass-coal co-combustion: opportunity for affordable renewable energy. Fuel. 2005;84(10):1295–302.
22. Arauzo PJ, Atienza-Martínez M, Ábrego J, Olszewski MP, Cao Z, Kruse A. combustion characteristics of hydrochar and pyrochar derived from digested sewage sludge. Energies. 2020;13(16):4164.
23. de Paula Protásio T, Fernando Trugilho P, da Silva César AA, Napoli A, Alves de Melo ICN, Gomes da Silva M. Babassu nut residues: potential for bioenergy use in the North and Northeast of Brazil. SpringerPlus. 2014;3(1):124.
24. Mamvura TA, Danha G. Biomass torrefaction as an emerging technology to aid in energy production. Heliyon. 2020;6(3):e03531.
25. Chen WH, Du SW, Tsai CH, Wang ZY. Torrefied biomasses in a drop tube furnace to evaluate their utility in blast furnaces. Bioresour. Technol. 2012;111:433–8.
26. Li Y, Li L, Liu Y, Ren X, Chen J, Levendis YA. Sulfur and nitrogen release from co-pyrolysis of coal and biomass under oxidative and non-oxidative conditions. J. Energy Resour. Technol. 2020;5(46): 30001-30010.
27. Lin Y, Ma X, Peng X, Hu S, Yu Z, Fang S. Effect of hydrothermal carbonization temperature on combustion behavior of hydrochar fuel from paper sludge. Appl. Therm. Eng. 2015;91:574–82.
28. Wu N, Niu Q, Pieters J, Ronsse F. Influence of torrefaction as pretreatment on the fast pyrolysis of sugarcane trash. Energy Convers. Manag. 2023;291:117291.
29. Devaraja UMA, Senadheera SS, Gunarathne DS. Torrefaction severity and performance of rubberwood and Gliricidia. Renew. Energy. 2022;195:1341–53.
30. Mueanmas C, Rakmak N. Enhancing the fuel properties of oil palm mesocarp fiber using screw conveyor reactor torrefaction. Energy Convers. Manag. 2023;298:117772.
31. Tumuluru JS. Comparison of chemical composition and energy property of torrefied switchgrass and corn stover. Front. Energy Res. 2015;3(46).
32. Yang W, Wu S, Wang H, Ma P, Shimanouchi T, Kimura Y, Zhou J. Effect of wet and dry torrefaction process on fuel properties of solid fuels derived from bamboo and Japanese cedar. BioResources. 2017;12(4):8629–40.