EXPLORING THE SOLID FUEL POTENTIAL OF BIOCHAR DERIVED FROM HYDROTHERMAL LIQUEFACTION OF LIGNOCELLULOSIC BIOMASS

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ABSTRACT

Hydrothermal liquefaction (HTL) is an emerging thermochemical conversion process that converts biomass into biofuels under subcritical water conditions. While recent HTL research largely focused on biocrude production and upgradation, the solid by-product (biochar) gets relatively less attention, even though it offers promising potential as a solid fuel. Therefore, this study investigates the physicochemical characteristics of biochar produced from sawdust (SD) and rice husk (RH) for their potential as a solid fuel. A large-scale batch reactor (12-L) was used for the HTL at 320 °C, 60 minutes retention time, and 20–40 MPa of pressure. Both feedstocks yielded significant amounts of biochar (>50%) and moderate biocrude yields (22% for SD and 20% for RH). SD biochar showed better solid fuel characteristics, with 60.1 wt% carbon, 38.9 wt% fixed carbon (FC), and a higher heating value (HHV) of 24.3 MJ/kg. This was equivalent to sub-bituminous coal (20-23 MJ/kg) and much higher than lignite (15-19 MJ/kg). In comparison, RH biochar has 40.4 wt% carbon, 26.6 wt% FC, and an HHV of 14.5 MJ/kg, which is comparable to lignite coals. However, XRF analysis revealed that RH biochar contained 87.8 wt% SiO_2 in its ash, highlighting its potential for secondary applications in ceramics, cement additives, and silica-based composites. These findings were verified by the FTIR spectra, which revealed that SD biochar had significant aromatic C=C stretching and fewer oxygenated functional groups, whereas RH biochar had substantial Si-O and C-O stretching from its silica-rich matrix. The energy densification ratio (EDR) for SD and RH was 1.2 and 1.0, respectively, with energy yields (EY) of 46.7% and 52%. According to a techno-economic study based on national biomass availability, these feedstocks could produce 1.94 million tons of bio-crude and 4.63 million tons of biochar per year, which would replace approximately 100% of Bangladesh's annual crude oil imports and 32% of its coal imports. Overall, SD biochar has promising prospects as a high-quality biocoal for power production and heating, but RH biochar is better suited for co-firing and value-added mineral recovery. The dual valorisation of HTL-derived biochar as both a renewable solid fuel and a material precursor provides an integrated pathway for circular bioeconomy growth, furthering Bangladesh's shift to greener energy.

Keywords: *Hydrothermal liquefaction, Lignocellulosic biomass, Biochar, Clean Energy, Circular bioeconomy.*

1. INTRODUCTION

The increasing demand for low-carbon energy systems has accelerated interest in thermochemical conversion techniques for converting lignocellulosic biomasses (LCB) like rice husk (RH), rice straw, corn stover, sawdust (SD), wood chips, etc., into renewable biofuels (Begum et al., 2024). Among these, hydrothermal liquefaction (HTL) is a promising technology which uses water as a solvent and operates under subcritical water conditions (250-374 °C, 10-25 MPa) to produce a biocrude similar to petroleum crude oil (Khalekuzzaman et al., 2025). The process simultaneously produces significant amounts of solid residue, commonly referred to as biochar. Although the majority of HTL research on LCBs has focused on process optimisation, catalytic upgrading, and refining of bio-crude, depending on the type of biomass and HTL working circumstances, this biochar usually yields between 30-60 wt% (Gai et al., 2015; Hardi et al., 2017; Karagoz et al., 2005; Nazari et al., 2015; Saral & Ranganathan, 2022).

Despite the significant amount of biochar yield, it received comparatively limited attention from the scientific and industrial community. Previous studies have primarily explored its application as a soil amendment or carbon sequestration medium (Arun et al., 2018; Verma et al., 2023), whereas its potential as a solid fuel remains underexplored. HTL biochar is produced under hydrothermal conditions that promote deoxygenation, aromatization, and carbon densification, often resulting in a material with elevated carbon content (60 - 68%), lower O/C ratios, and heating values ranging from 17 to 25 MJ/kg, approaching those of low-rank coals like lignite and sub-bituminous coal (Nava-Bravo et al., 2025; Yuan et al., 2019). These attributes indicate the potential of HTL biochar derived from LCBs as a renewable, drop-in solid fuel for combustion or co-firing applications.

The characteristics of the feedstock have a significant impact on the potential of HTL biochar as a solid fuel. While fecal sludge, sewage sludge, and microalgae are feedstocks rich in protein and lipids, LCBs consisted mostly of cellulose, hemicellulose, and lignin. LCB often have a higher biochar yield due to its higher thermal resistance compared to protein and lipid-rich biomass. Furthermore, LCB has a substantial amount (10% to 30% with respect to total solids) of fixed carbon (FC), which is a key component of conventional coal (The Science of Victorian Brown Coal, 1991). During HTL, most of the FC remains in the solid phase, leading to a higher biochar yield rather than being transformed into bio-crude (Kabir et al., 2022). Among various LCBs, SD and RH are commonly used feedstocks in HTL studies. Hardi et al. (2017) reported a 14% bio-crude yield from pinewood SD via HTL, where the resulting biochars have a HHV ranging from 21.3 to 28.3 MJ/kg. Similarly, Nava-Bravo et al. (2025) investigated HTL on corn stover and observed that bio-crude and biochar yields of 19.4% and 39.5%, respectively. The produced biochar possesses a higher heating value (HHV) of 25.4 MJ/kg and a carbon content of 61.7%. In another study, although Gai et al. (2015) reported a bio-crude yield of 13.5% from RH; they provided limited information regarding biochar characteristics. Although several studies have characterized HTL biochar, a detailed evaluation focusing on the solid fuel potential of LCB-derived biochar has not been conducted yet.

The present study addresses this gap by evaluating the solid fuel performance of biochar derived from sawdust (SD) and RH produced via a pilot-scale HTL process. Elemental composition, proximate analysis, Fourier transform infrared spectroscopy (FTIR) analysis, HHV, atomic ratios, and energy yield are used to assess their applicability as coal alternatives, while X-ray fluorescence (XRF) was used to identify the metal oxide compositions for mineral recovery and non-fuel applications. The results highlight the potential of HTL biochar from low-value residues into a renewable solid fuel co-product within an integrated biorefinery framework.

2. METHODOLOGY

2.1 Study Design

This study builds upon the author's existing work, which focused on the optimization and characterisation of bio-crude produced from SD and RH. In this study, the by-product solid residue (biochar) and water-soluble organics (WSO) produced under the same HTL conditions are checked for their potential as a solid fuel and material recovery. The goal is to understand their potential applications as a renewable solid fuel and material recovery opportunities for non-fuel applications.

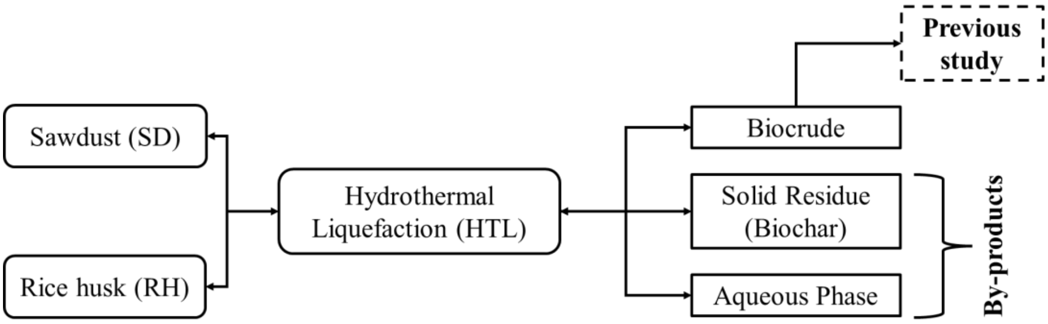

Figure 1: Design of this study

2.2 Biochar Production and Preparation

Biochar was generated as a solid by-product from SD and RH after extracting the bio-crude via HTL in a large-scale (12-L) batch reactor at the *Sludge to Oil (SOIL)* pilot plant, Khulna University of Engineering and Technology, Bangladesh. The HTL experiments were conducted at 320 °C with a retention time of 60 minutes, under operating pressures ranging from 20 to 40 MPa and a controlled heating rate of 5 °C min^{-1}. The resulting bio-crude and biochar yields were 22 wt% and 50 wt% for SD, and 20 wt% and 52 wt% for RH, respectively. The collected biochar samples were oven-dried at 105 °C for 24 hours to ensure complete moisture removal and subsequently stored at 4 °C until further analysis.

2.3 Biochar Characterisation

The physicochemical properties of the biochar were evaluated through proximate and elemental analyses, bomb calorimetry, FTIR spectroscopy, and X-ray fluorescence (XRF) analysis.

2.3.1 Proximate and Elemental Analysis of Biochar

Proximate analysis of the biochar was carried out to determine its moisture content, total solids (TS), volatile matter (VM), ash content, and fixed carbon (FC). TS and VM were measured at 105 °C for 3 hours (ASTM E1756) and 950 °C for 7 minutes (ASTM E872), respectively. Ash content was determined at 950 °C for 4 hours following the ASTM D3174 standard. The FC content was calculated by difference using equation (1). The fuel ratio (FR), representing the ratio of FC to VM, was calculated using equation (2).

$$FC\ (wt.\%) = 100 - VM\ (wt.\%) - Ash\ (wt.\%) \tag{1}$$

$$FR = FC / VM \tag{2}$$

Elemental analysis (C, H, N, S) of the biochar was undertaken using a CHNS elemental analyzer (Elementar vario Micro Cube, Germany), with oxygen content determined by difference using equation (2)

$$O\ (wt.\%) = 100\% - \text{sum of } (C, H, N, S, \text{and Ash}) \quad (3)$$

2.3.2 Higher Heating Value (HHV) and Energy Analysis

The HHV defines the energy potential and quality of the solid fuel, making it one of the most important parameters in fuel characterization. The HHV was calculated using equation (3).

$$HHV\ of\ biochar = 0.3491C + 1.1783\ (H - O/8) + 0.1005S - 0.0151N - 0.021Ash \quad (4)$$

To evaluate the energy enhancement of the biochar relative to the feedstock, the energy densification ratio (EDR) was calculated using equation (4). The energy yield (EY) of the biochar, indicating the fraction of energy retained from the original feedstock, was calculated by equation (5).

$$EDR = HHV\ of\ biochar / HHV\ of\ feedstock \quad (5)$$

$$Energy\ Yield\ (\%) = Biochar\ Yield\ (\%) \times EDR \quad (6)$$

2.3.3 Functional Group Analysis

The FTIR analysis was used to identify the chemical bonding type and functional groups present in the biochar sample using a Shimadzu IRTracer-100 spectrometer (Shimadzu, Japan), with a high signal-to-noise ratio of 60,000:1 and a spectra range of 600 cm^{-1} to 4000 cm^{-1} at a resolution of 0.25 cm^{-1}. The baseline was corrected using OriginPro software (Version 2024), and the major wavenumbers (cm^{-1}) were compared with standard wavenumber bands associated with specific functional groups.

2.3.4 Metal Oxide Analysis

The inorganic metal oxides present in the biochar were determined using X-ray fluorescence (XRF). The XRF was conducted using a Bruker S6 Jaguar spectrometer (Bruker, Germany) with wavelength-dispersive XRF technology to identify inorganic metal oxides. Samples were oven-dried at 105 °C for 24 hours, finely ground, and pressed into pellets to ensure consistent geometry and flatness.

3. RESULTS AND DISCUSSION

3.1 Feedstock Characterization

The proximate, ultimate, and inorganic metal oxides of RH and SD are presented in Table 1. Both feedstocks showed a relatively higher VM (78-83 wt.% on a dry basis) and C content (38-48 wt.%), indicating a strong potential for energy-rich product formation. Although RH contained a significant ash fraction (10.3 wt.% on a dry basis), which is dominated by SiO_2, reflecting its mineral-rich composition and potential suitability for value-added material recovery.

The elemental ratios (H/C and O/C) were 1.75 and 0.83 for RH, and 1.66 and 0.68 for SD, respectively, suggesting that both feedstocks contain adequate hydrogen and moderate oxygen levels favourable for bio-crude formation. The HHV ranges between 15 to 20 MJ/kg, further confirming their viability as renewable energy feedstocks. Overall, the compositions of RH and SD indicate promising potential for integrated waste-to-energy and resource recovery pathways through HTL.

The X-ray fluorescence (XRF) analysis showed that SD contains a minimal amount of metal oxides due to its lower ash content, whereas RH ash is dominated by SiO_2, with trace amounts of CaO, Fe_2O_3, P_2O_5, Al_2O_3, MgO and K_2O, highlighting its potential for non-fuel mineral recovery applications.

Table 1: Characterization of rice husk (RH) and sawdust (SD)

Components	**RH**	**SD**
Proximate composition (wt.%)[a]		
Moisture content	9.8 ± 0.18	11.8 ± 0.18
Total solids (TS)	90.1 ± 0.00	88.2 ± 0.14
Volatile matter (VM)	70.1 ± 0.21	73.5 ± 0.44
Ash	9.3 ± 0.07	1.1 ± 0.12
Fixed Carbon (FC)[c]	10.9 ± 0.02	13.7 ± 0.70
Elemental composition (wt. %)[b]		
C	37.7	47.9
H	5.5	6.6
N	1.8	0.4
O[c]	41.9	43.5
S	0	0
Elemental molar ratio (mole/mole)		
H/C	1.75	1.66
O/C	0.83	0.68
N/C	0.04	0.01
Chemical formula	$CH_{1.75}O_{0.83}N_{0.04}$	$CH_{1.66}O_{0.68}N_{0.01}$
HHV (MJ/kg)	15	20
Metal Oxide (wt.%)		
SiO_2	21.24	0.36
CaO	0.47	2.1
Fe_2O_3	0.28	0.18
P_2O_5	0.87	0.2
Al_2O_3	0.14	-
MgO	0.33	-
K_2O	0.87	0.7

[a] Wet basis; [b] Dry basis; [c] By difference

3.2 Biochar Characterization for Fuel Applications

3.2.1 Physico-chemical Properties

Table 2 and Table **3** showed the proximate and elemental compositions of RH and SD biochar, and compared them with conventional low rank coal, like lignite and sub-bituminous coal. The values of lignite and sub-bituminous coal were summarized from several studies. The comparison highlighted that both biochar samples possess similar characteristics of low-rank coals, which demonstrates their potential as renewable solid fuels.

Table 2: Proximate composition (on dry basis) of biochar samples

Components	**RH**	**SD**	**Lignite coal**[a]	**Sub-bituminous coal**[b]
Volatile matter (VM)	59.2	57.4	41.1 – 54.0	34.9 – 42.6
Ash	14.2	3.7	8.6 – 22.0	4.1 – 8.8
Fixed carbon (FC)	26.6	38.9	23.9 – 41.2	37.9 – 55.6
Fuel ratio (FR)	0.5	0.7	0.6 – 0.8	1.1 – 1.3

[a](Badour et al., 2012; Jewulski et al., 2014; Rizkiana et al., 2019)
[b](Bu et al., 2017; Faizal et al., 2021; Rizkiana et al., 2019)

As shown from the proximate analysis from Table 2, the FC content of SD biochar falls within the range of sub-bituminous coal and lignite coal, whereas RH biochar aligns more closely with the lower range of lignite. FC is an important parameter for coal as it indicates the amount of combustible residue left after VM burns off (Sarkar, 2015). FC correlates with the heating value, which aligns with this study, as SD showed a high HHV of 24.3 MJ/kg due to its high FC content. The VM of both biochar (57.4–59.2 wt%) was slightly higher than typical lignite and sub-bituminous coals, indicating unconverted volatile components still remained after the HTL process. The ash content of RH biochar (14.2 wt%) exceeds that of coals, primarily because of the high silica content in RH, while SD biochar showed a lower ash level within the range of sub-bituminous coal.

Table 3: Elemental analysis (on dry basis) of biochar samples

Samples	**Elemental composition (%) on dry basis**					**HHV (MJ/kg)**	**Ref.**
	C	**H**	**N**	**O**	**S**		
SD	60.1	5.5	0.6	30.9	0.04	24.3	This study
RH	40.4	3.9	1.8	40.7	0.17	14.5	
Lignite coal	37 – 50	3.5 – 5.6	0.6 – 0.8	42.5 – 55.8	0.96 – 2.33	15.5 – 19.7	(Nyakuma, 2019)
Sub-bituminous coal	68.2 – 74.8	4.8 – 5.5	1.0 – 1.7	17.4 – 21.5	0.1 – 0.7	20.3 – 22.7	(Samsudin et al., 2021)

Elemental composition is an important parameter for fuels. As shown in , SD biochar contains 60.1% C and 5.5% H, which is comparable to sub-bituminous coal, whereas RH biochar contains 40.4% C and 3.9% H, which are close to the ranges for lignite coal. The higher oxygen content in RH biochar relative to SD biochar is attributed to its ash-bound oxygenated minerals. Consequently, the HHV of SD biochar approaches that of sub-bituminous coal, while RH biochar is comparable to lignite.

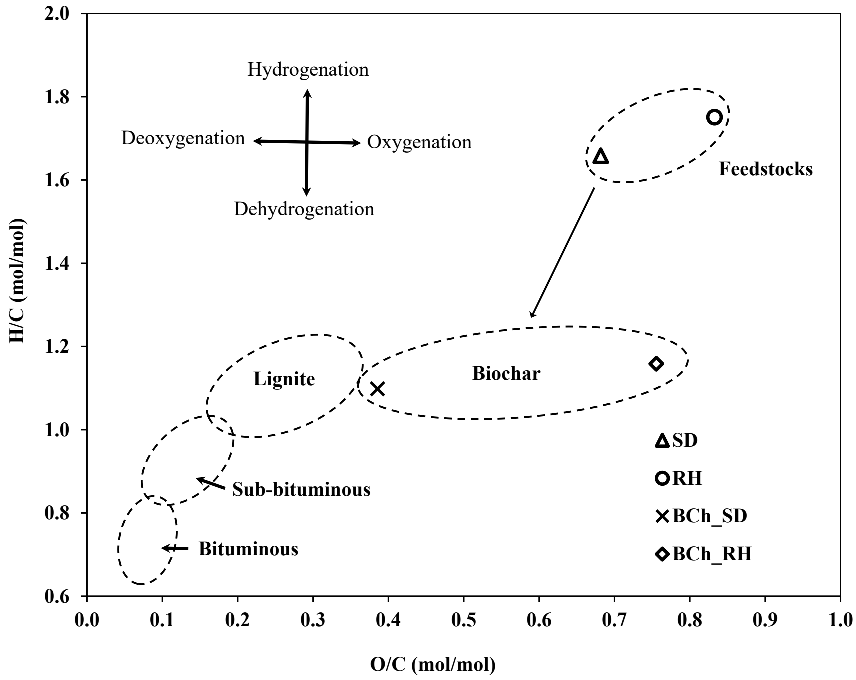

Figure 2: Van Krevelen diagram of biochar and feedstocks based on elemental analysis.

The Van Krevelen diagram in Figure 2 further provides insight into the chemical transformation of the feedstocks and their resulting biochar. Both RH and SD biochar exhibit a reduction in H/C and O/C molar ratios than the feedstocks, confirming that deoxygenation and dehydration reactions occurred during the HTL process. The RH and SD biochar lie in the region of lignite, which suggests that HTL effectively converted the SD and RH into coal-like solids along with bio-crudes. Also, the improved energy density and elemental composition showed their potential as a solid fuel. The SD biochar, with a lower O/C ratio and slightly reduced H/C ratio, indicates superior fuel quality compared to RH biochar, which is consistent with its higher FC and HHV values.

3.2.2 FTIR Analysis

The FTIR spectra of the RH and SD biochar in Figure 3 showed the key functional groups present in the biochar, which indicates their chemical characteristics. A broad peak in the range of 1000-1100 cm^{-1} corresponds to Si-O and C-O stretching. This peak was more intense in RH biochar due to the high silica content, which aligns with the XRF analysis in Table 4. The Si-O signal highlights the potential of RH biochar as a silica-rich feedstock for applications in ceramic or adsorbent production. In contrast, SD biochar showed much weaker Si-O bands, consistent with its lower ash and SiO_2 contents, which confirms that it is a more carbon-dominated biochar.

The peaks in the 1400-1600 cm^{-1} range are associated with C=C aromatic ring, indicating the formation of thermally stable aromatic structures during HTL. This is due to deoxygenation and dehydrogenation reactions, consistent with the Ven Krevelen diagram. The presence of these aromatic structures in the SD biochar indicates its suitability as a solid fuel, comparable to low-rank coals. Meanwhile, the peaks at 2850-2950 cm^{-1} corresponding to aliphatic C-H stretching are weaker in both samples, confirming the breakdown of cellulose and hemicellulose during HTL. The diminished C-H intensity further supports the formation of more condensed aromatic carbon structures favourable for energy-dense fuel.

Overall, the FTIR results support the CHNS and proximate analyses, demonstrating that the HTL process effectively transformed biomass into carbon-rich solids with reduced oxygen fractions. SD biochar, characterized by higher carbon and energy content, is more suitable as a coal-like solid fuel, while RH biochar, enriched in Si-O functionalities, offers dual valorisation potential as both a moderate-grade fuel and a silica-rich precursor for high-value material applications.

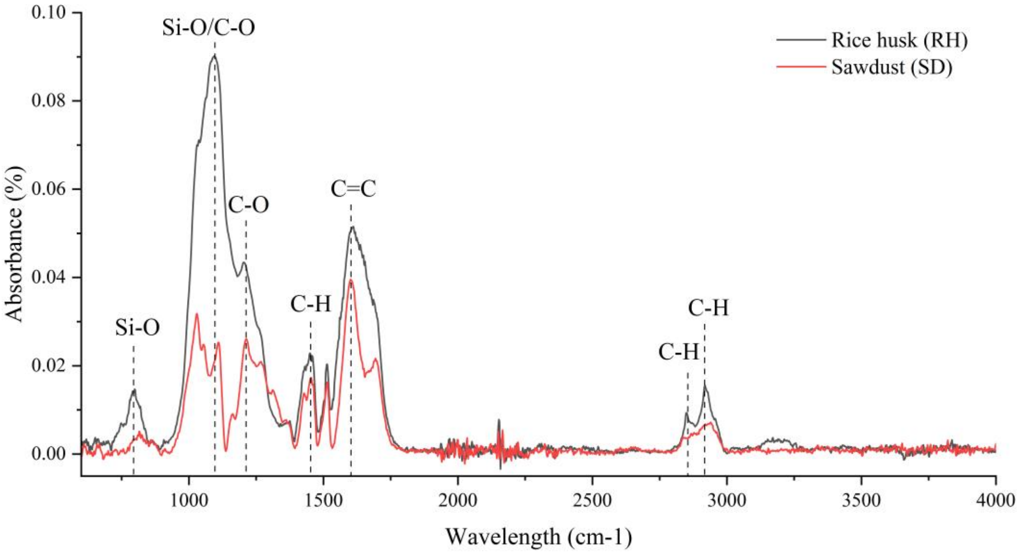

Figure 3: Functional group analysis of biochar samples.

3.2.3 Energy Characteristics and Fuel Performance

The HHV is one of the most important indicators of the energy potential of biochar produced from HTL (Qian et al., 2020). As shown in Figure 4, the HHVs of SD and RH biochar were 24.3 MJ kg^{-1} and 14.5 MJ kg^{-1}, respectively. These results indicate that the HTL process effectively enhances the energy density of the SD biochar, which indicates it is a more carbon-rich and thermally stable structure.

The energy densification ratio (EDR) further supports this trend, with SD and RH having an EDR of 1.2 and 1.0, respectively. This indicates that the SD biochar undergoes a greater degree of upgradation as it retains a larger fraction of its initial energy in the biochar. The corresponding energy yield (EY) of 46.7% for SD and 52% for RH confirms that both feedstocks preserve a considerable portion of their energy within the solid phase.

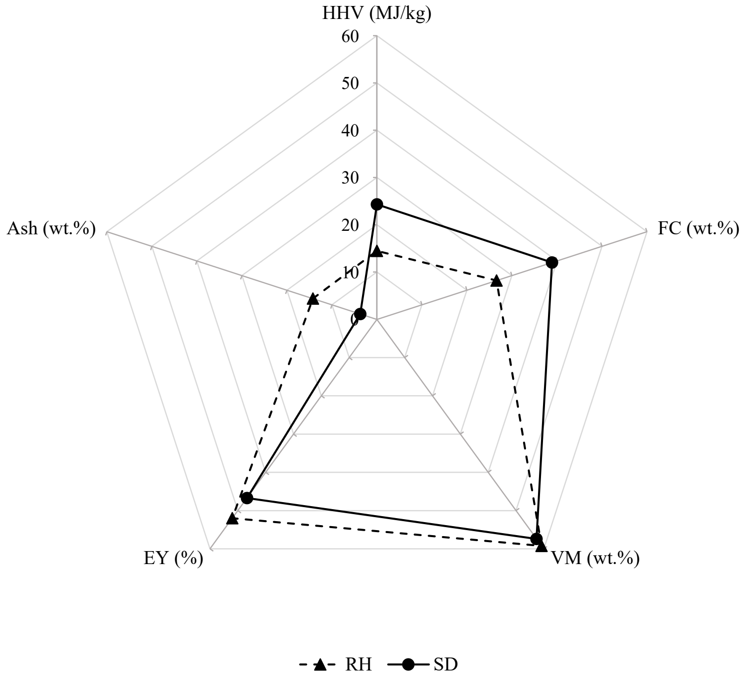

Figure 4: Radar plot comparing key fuel properties of rice husk (RH) and sawdust (SD) biochars

The superior HHV and EDR of SD biochar aligned with its higher FC (38.9 wt%) and lower oxygen content (30.9 wt%). However, RH biochar, having a moderate HHV and elevated ash content (14.2 wt%), lowers its HHV. Despite this limitation, the RH biochar can be co-combusted with other conventional coals and offers additional potential as a silica-rich resource for material recovery.

The VM and fuel ratio (0.5–0.7) of both biochars indicate favourable ignition properties and stable combustion behaviour, comparable to sub-bituminous coals. The relatively high volatile fraction ensures easy ignition, while the substantial FC content supports sustained heat release (Sullivan, 2017). This combination of properties renders HTL-derived biochar particularly suitable for co-firing with conventional coal.

3.3 XRF Analysis for Mineral Recovery

XRF analysis provides an effective way to detect the mineral compositions present in the biochar ash. As shown in Table 4, the ash derived from RH biochar contains 87.8% of SiO_2, reflecting the highly siliceous nature of RH ash. The other metal oxides, like CaO, Fe_2O_3, P_2O_5, Al_2O_3, MgO and K_2O present at a very low concentration. In contrast, the ash from SD biochar is enriched in CaO and K_2O. The high SiO_2 fraction in RH ash suggests its potential applications in silica-based materials, such as zeolites, amorphous silica, pozzolanic additives for cement, and ceramics (Zharmenov et al., 2022). Since RH ash is already widely used in industry as a valuable silica source, HTL-derived RH biochar ash may serve similar purposes.

Although SD biochar contains less amount of ash in its biochar, the elevated levels of CaO and K_2O in SD ash can be used in soil amendment or fertilizer precursor. The presence of P_2O_5 (5.6 wt%) in SD ash further enhances its agronomic value (Jastrzebska et al., 2016). Such mineral-rich biochar ash can support a circular bioeconomy, where HTL produces both bio-crudes and nutrient-recovery biochar from lignocellulosic biomass.

Table 4: Inorganic metal oxide composition (on dry basis) of biochar ash

Metal oxide (wt%)	**RH**	**SD**
SiO_2	87.8	10.2
CaO	1.9	59.3
Fe_2O_3	1.2	5.1
P_2O_5	3.6	5.6
Al_2O_3	0.6	-
MgO	1.4	-
K_2O	3.6	19.8

3.4 Techno-Economic Evaluation

In this study, the techno-economic evaluation was conducted only from the Bangladesh perspective. In Bangladesh, approximately 1 million metric tons (Mt) of SD (Islam et al., 2004) and 9.7 Mt of RH (Parvez, 2023) produces every year. Additionally, these biomasses have high total solids (TS) and volatile content, which is suitable for producing bio-crude and biochar simultaneously through the HTL process.

Based on the bio-crude and biochar yields from this study, the potential annual production of bio-crude and biochar from SD and RH is shown in Table 5. The conversion of SD and RH through HTL has the potential to produce nearly 1.94 Mt of bio-crude and 4.63 Mt of biochar per year. This huge production has the potential to replace approximately 100% of Bangladesh's annual crude oil import demand of 1.4 Mt (UNB, 2023) and around 32% of its annual coal imports of 13.3 Mt (The Global Economy, 2023).

Table 5: Estimated annual bio-crude and biochar production potential from SD and RH in Bangladesh and their substitution capacity for imported fossil fuels

Mass, Energy, and Economic Indicators	**SD**	**RH**	**Total**
Annual generation (Mt, wet basis)	1	9.7	10.7
Total solids (wt%)	88	90.1	-
Dry feedstock (Mt)	0.9	8.74	9.62
Bio-crude yield (wt%)	22	20	-
Biochar yield (wt%)	50	52	-
Annual bio-crude production (Mt)	0.2	1.75	1.94
Annual biochar production (Mt)	0.4	4.19	4.63
Equivalent crude oil replacement (%)	14	125	≈100
Equivalent coal replacement (%)	3	28.7	≈32
Estimated market value (million USD)*	114	1,509	1,623

*Assuming crude oil price ≈ USD 600 t^{-1} and coal price ≈ USD 100 t^{-1}.
Mt = million metric tons.

From the economic point of view, the projected market value of the bio-crude and biochar is approximately USD 1.6 billion per year (USD 1.16 billion for bio-crude and USD 463 million for biochar). These economic benefits demonstrate the strong financial and strategic viability of HTL technology for large-scale implementation in Bangladesh's emerging bioenergy sector.

4. CONCLUSIONS

This study investigates how biochar produced as a by-product from hydrothermal liquefaction (HTL) of sawdust (SD) and rice husk (RH) can be used as a solid fuel and material recovery resource. The results show that SD biochar contains a high amount of fixed carbon content and higher heating value (HHV), which is comparable to sub-bituminous coal. In contrast, RH biochar has a lower HHV and higher ash content. Remarkably, the ash was found to be highly enriched in SiO_2 (87.8 wt%). This makes it especially promising for non-fuel applications such as silica recovery, ceramic production, or as a pozzolanic additive in cement. FTIR and elemental analyses confirmed enhanced aromaticity and carbon content in the SD biochar. The complementary characteristics of SD and RH biochar suggest an integrated valorisation approach, where SD biochar has the potential of used as a solid fuel and RH biochar can be co-fired with conventional coal or utilized for material recovery. Techno-economic evaluation indicated that large-scale HTL of Bangladesh's available SD and RH biomass could produce approximately 1.94 Mt of bio-crude and 4.63 Mt of biochar annually, collectively substituting up to 100% of imported crude oil and 32% of coal demand. Therefore, HTL of SD and RH represents a viable route for enhancing national energy security, promoting circular bioeconomy, and advancing the transition toward low-carbon, sustainable energy systems.

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