POWERING DHAKA'S CIRCULAR ECONOMY THROUGH HYDROTHERMAL LIQUEFACTION: SUSTAINABLE SLUDGE MANAGEMENT AT THE DASHERKANDI SEWAGE TREATMENT PLANT

Nafis Ahmed Pantho*[1], Md Rahatul Islam[2], Dipa Chowdhury[3], Khaled Mohammad Nasim[4], and Md Khalekuzzaman[5]

[1] *Postgraduate Student, Khulna University of Engineering & Technology, Bangladesh, e-mail: nafis0056@gmail.com*
[2] *Postgraduate Student, Khulna University of Engineering & Technology, Bangladesh, e-mail: rahatulislam2828@gmail.com*
[3] *Postgraduate Student, Khulna University of Engineering & Technology, Bangladesh, e-mail: diparoy911@gmail.com*
[4] *Process Engineer, Sludge 2 Oil (SOIL), Khulna University of Engineering & Technology, Bangladesh, e-mail: kmnasim.zafri@gmail.com*
[5] *Professor, Khulna University of Engineering & Technology, Bangladesh, e-mail: kzaman@ce.kuet.ac.bd*

***Corresponding Author**

ABSTRACT

Effective wastewater treatment and sustainable sludge disposal are major issues in modern urban infrastructure. The increasing quantities of sewage sludge (SS) produced at treatment plants, which is high in moisture content, is one of the most significant challenges in wastewater technologies. In this study, the authors examined a promising hydrothermal liquefaction (HTL) technology as an alternative wastewater sludge management approach for South Asia's largest wastewater treatment plant, Dasherkandi Sewage Treatment Plant (DSTP). Characterization of the SS using proximate analysis, elemental analysis, and FTIR confirmed its suitability as an HTL feedstock, exhibiting an HHV of 10.2 MJ/kg and a volatile matter content of 59.57% (dry basis). XRF analysis further revealed the presence of catalytically active inorganic oxides, which are known to influence thermochemical conversion pathways. Hydrothermal liquefaction (HTL) of SS at 320°C and 20-25 MPa resulted in a biocrude yield of 28.5% (dry basis) using two-stage solvent-based extraction method. FTIR and GC-MS characterization further showed that the primary biocrude consisted mainly of esters, phenols, alcohols, ketones, unsaturated hydrocarbons, and a controlled fraction of nitrogen-containing and NSO heterocyclic compounds, while carbon number distribution analysis confirmed a strong dominance of middle-distillate-range compounds (>60%). This middle-distillate-rich composition highlights the suitability of the biocrude as an energy-dense fuel intermediate requiring comparatively mild upgrading. The HTL biocrude exhibited 95% energy recovery with a HHV 33.5-34.5 MJ/kg, while XRF analysis of the resulting biochar confirmed the recovery of inorganic compounds (Si, Fe, Ca, P, Al, and S). Being rich in SiO_2, the biochar shows potential for applications in the silica industry, while the by-product after the silica-extraction has potential to be directly utilized in agricultural fields as a soil amendment. The HTL aqueous phase showed a TOC value of 3160 mg/L and COD value of 7622 mg/L. The COD value of the aqueous phase is well above the threshold limit of DSTP treatment capacity and will require additional treatment recirculated to PSTP for final treatment. This study demonstrates that integrating HTL into DSTP offers a highly effective and circular alternative to conventional sludge management. The process yields substantial biocrude, mineral-rich biochar, and recoverable organics, enabling significant energy recovery and material reuse. Overall, HTL provides a scalable pathway for DSTP to reduce sludge burdens while advancing Dhaka toward a zero-waste, resource-efficient wastewater system.

Keywords: *Sewage sludge, Hydrothermal liquefaction, Wastewater treatment, Sludge Management, Circular economy*

1. INTRODUCTION

The global priorities are shifting toward sustainable energy systems and circular economy, the need for alternative fuels to conventional fossil fuel has become a must (Chand et al., 2019). In the modern world, wastewater is considered a valuable resource rather than mere waste, offering opportunities for energy recovery (McCarty et al., 2011). The ever-increasing amount of sludge generated in the wastewater treatment process is harmful to the environment, as well as is difficult to treat. Traditional disposal methods (e.g., landfill, anaerobic digestion, dewatering, and incineration) cause problems such as secondary pollution and high-cost (Fonts et al., 2012; Huang et al., 2014). The global production of (SS) from municipal wastewater treatment plants (WWTPs) is 45 million dry tons per year (Gao et al., 2020). Hence, managing sludge is still one of the most challenging issues in wastewater treatment plants all over the world due to the rapid increase in sludge generation, rising disposal costs, regulatory restrictions, and associated environmental and social concerns (Kor-Bicakci & Eskicioglu, 2019). Significant research and investments are ongoing all over the world to optimize the disposal and energy recovery method of the SS to produce value-added products while ensuring safe disposal.

Bangladesh is a rapidly urbanizing nation, facing significant challenges in managing wastewater sludge generated from large-scale treatment operations at the Dasherkandi Sewage Treatment Plant (DSTP), the largest WWTP in South Asia. DSTP treats approximately 500 MLD of wastewater, producing thousands of tonnes of sewage sludge annually, characterized by extremely high moisture content (80-95%). The current sludge management process includes a costly and energy-intensive sludge drying and incineration technology, capable of producing 270 m^3 of fly ash every day. Moreover, resource recovery opportunities diminish in this process.

Hydrothermal liquefaction (HTL) has emerged as a highly promising thermochemical conversion technology capable of converting wet biomass (70-90%) into energy-dense biocrude without requiring energy-intensive drying, making it particularly effective for wet-waste such as sewage sludge (Khalekuzzaman et al., 2024).

Raw sewage sludge (SS) inherently suitable for HTL due to its rich organic matrix, commonly contains over 95% of water, whereas, on a dry basis, it contains proteins (20-40 wt.%), lipids (10-25 wt.%), carbohydrates (14-32 wt.%), and lignin and ash (30-50 wt.%) (He et al., 2014), and hence it can also be regarded as a wet biomass. Through HTL of SS, the produced bio-oil after proper upgradation, can be used as liquid fuel or for chemical purposes (Huang et al., 2014), while the solid product, biochar (approximately half of the initial SS (dry weight)) saves a lot of hauling and disposal costs. The majority of heavy metals and nutrients are concentrated within biochar (Mulchandani & Westerhoff, 2016). As a result, this thermochemical conversion of SS can be the safest way to produce valuable products while mitigating any environmental risks. Recent studies have demonstrated that HTL of municipal sludge can yield biocrudes with fuel-range components suitable for upgrading into diesel- and kerosene-range hydrocarbons, while simultaneously producing nutrient-rich biochar and a chemical-laden aqueous phase that can be further valorized (Aktas, Liu, Basar, et al., 2024).

Given Dhaka's rapidly expanding population and its increasing energy demand, where a significant fraction of national electricity generation continues to rely on imported petroleum fuels, HTL offers a transformative opportunity.

However, no systematic study has yet evaluated HTL as an alternative sludge management process for DSTP, nor assessed its resource recovery potential within Dhaka's circular economy. This study addresses that gap by investigating the HTL conversion performance of DSTP sludge, analyzing the physicochemical characteristics of all product streams, and evaluating the technoeconomic viability of integrating HTL within the existing sludge management framework. By doing so, the study highlights a pathway for transforming Dhaka's wastewater burden into a renewable energy solution capable of advancing national sustainability goals.

2. METHODOLOGY

2.1 Feedstock Collection & Characterization

Sewage Sludge (SS) was collected from the Sludge Storage Tank of the Dasherkandi Sewage Treatment Plant (DSTP), Dhaka. The SS contained sludge from both primary and secondary sedimentation tanks. It was transported from the DSTP to the Sludge 2 Oil (SOIL) Pilot Plant in airtight containers to prevent compositional changes. The sludge was then disposed in a 1500L thickener in the plant to attain a desired total solid content. The thickened sewage sludge (SS) was characterized to evaluate its suitability as an HTL feedstock.

To evaluate the physical properties, proximate analysis of the SS were conducted using standard method (SM) 2450G (APHA, 2017), and ash content in the feedstock (FS) was evaluated using ASTM E 1755-01. The organic composition (CHNS) of the feedstock was measured using Elementar Vario MICRO Cube analyzer. Oxygen (O) content was estimated by difference using equation (1) (Beims et al., 2020).

$$O\ (wt\%) = 100 - (C + H + N + S + Ash) \tag{1}$$

The higher heating value (HHV) of the biomass (SS) was estimated using the correlation given in equation (2) developed by (Channiwala & Parikh, 2002).

$$HHV_{biomass/biochar} = 0.3491C + 1.1783(H - \frac{O}{8}) + 0.1005S - 0.0151N - 0.021Ash \tag{2}$$

The presence of inorganic components (e.g., Fe, Ca, Mg, etc.) can exhibit catalytic behaviour during hydrothermal reactions, influencing depolymerization, cracking, and char formation tendencies. To determine the inorganic composition of the biomass, X-ray fluorescence (XRF) analysis was conducted using a Bruker S6 Jaguar spectrometer (Bruker, Germany) equipped with wavelength-dispersive technology (WDXRF). Prior to analysis, the sample was oven-dried at 105 °C for 24 hours, ground to a fine powder, and pressed into uniform pellets using a hydraulic press to ensure consistent geometry and surface flatness.

Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted to identify functional groups present in the biomass samples inside a spectra range of 4000-400 cm^{-1}, using Shimadzu IRTracer-100 spectrometer (Shimadzu, Japan). OriginPro (version 2024) was used to correct the baseline, and the major spectra (cm^{-1}) peaks were compared with the standard bands associated with functional groups.

Additionally, high-quality commercial-grade extraction solvents (Ethyl Acetate, Acetone) were purchased from Richill Industries Pte. Ltd., Singapore, one of the leading chemical manufacturing companies.

2.2 Experimental Setup

2.2.1 *Hydrothermal liquefaction*

The SOIL HTL batch reactor was a vertical bomb-type reactor with a capacity of 12 liters and made of a combination SS 304 and SS 316 to ensure strength, durability, corrosion resistance under temperature and pressure and temperature. The thickened SS was transformed in an airtight vessel and poured into the reactor till 80% of its volume was filled to ensure safe pressure development and efficient heat transfer. The HTL reactor was heated at a rate of 5°C/min until reaching 320°C (20-30 MPa). The controlled heating rate was chosen to ensure uniform heat transfer and to promote the sequential decomposition of the feedstock constituents. The system was then retained at 320°C 60 minutes, allowing sufficient time for hydrolysis, depolymerization, and recombination reactions for proper liquefaction (Khalekuzzaman, Jemi, et al., 2025). After heating, the reactor was cooled-down to room-temperature with a built-in water-cooling system, and the HTL product was then discharged through an outlet drain valve located in the downward part of the reactor in an airtight container to reduce the loss. All HTL experiments were conducted in triplicate, and the results were averaged to ensure a profound yield and product quality assessment.

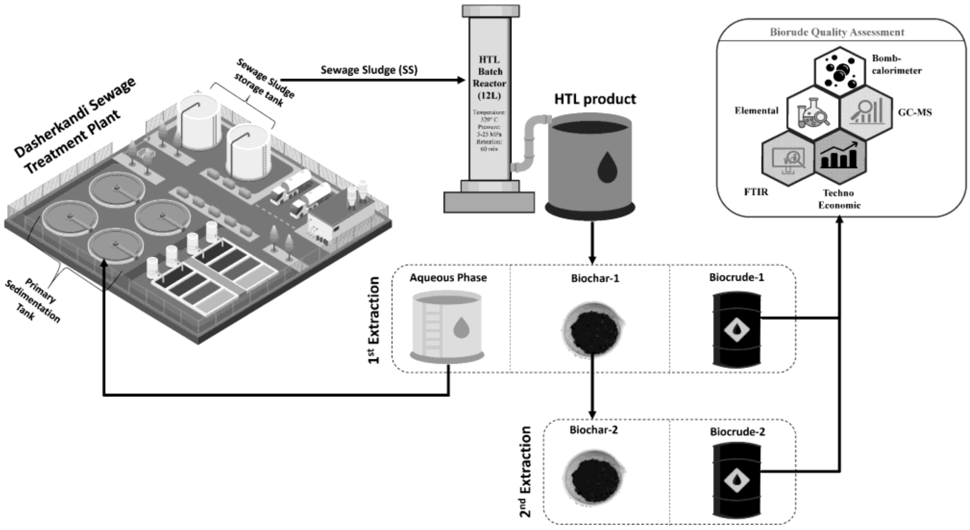

Figure 1: Experimental setup and process flow diagram.

2.2.2 Product Extraction & Yield Calculation

Following the HTL product collection, a novel two-stage biocrude extraction (TSBE) was applied, combining two green solvents, ethyl acetate (EA) and acetone (Ace) to maximize biocrude recovery. At first, EA was mixed in the airtight vessel with HTL product in a solvent to product ratio of 2:1. The mix was then uniformly mixed using an electric mixer conducted at 15000 rpm. A high-speed tubular three-phase separator centrifuge (GF75-J, 20,000 RPM) was then utilized to separate the biocrude-1, biochar-2, and aqueous phase. The extracted products were sampled and stored in a refrigerator (4°C) for further analyses and assessment. The biochar-1 was taken in an airtight vessel for the second extraction and then mixed with Ace in the same ratio and method as the first extraction with EA. Following this, centrifugation was performed with the same GF75-J to extract biocrude-2 and biochar-2. The extracted products were sampled and stored in a similar manner for quality assessment and analysis.

The yields of the extracted products were calculated on the basis of dry-weight percentage using equations (3)-(6) (Islam et al., 2022). In equation 4, the gas and losses yield were estimated by difference.

$$Biocrude\ Yield\ (\%) = \frac{Weight\ of\ Biocrude}{Weight\ of\ dry\ biomass} \times 100 \tag{3}$$

$$Biochar\ Yield\ (\%) = \frac{Weight\ of\ Biochar}{Weight\ of\ dry\ biomass} \times 100 \tag{4}$$

$$Aqueous\ Phase\ Yield\ (\%) = \frac{Weight\ of\ Aqueous\ Phase}{Weight\ of\ dry\ biomass} \times 100 \tag{5}$$

$$Gas\ and\ Losses\ (\%) = 100 - (Biocrude\ Yield + Biochar\ Yield + Aqueous\ Phase\ Yield) \tag{6}$$

2.3 Analysis of Products

2.3.1 Biocrude

The two biocrude samples were characterized in a structured sequence to ensure comprehensive quality evaluation. Elemental composition (CHNS) of the crude samples were determined using the same equipment as the biomass. Similarly, oxygen (O) content was calculated by difference. The higher heating value (HHV) of the crude samples were determined using equation (7).

$$HHV(MJ/kg) = 0.3383\,C + 1.422\,(H - \frac{O}{8}) \tag{7}$$

The molar ratios of biocrude, H/C, $H/C_{effective}$, O/C, and N/C were calculated using equations (8) to (11) with the C, H, N, and O (wt%) results acquired from the elemental analysis (Khalekuzzaman, Jahan, et al., 2025).

$$H/C = \frac{\frac{H}{1.008}}{\frac{C}{12.011}} \tag{8}$$

$$H/C_{effective} = \frac{\frac{H}{1.008} - \frac{2 \times O}{15.999}}{\frac{C}{12.011}} \tag{9}$$

$$O/C = \frac{\frac{O}{15.999}}{\frac{C}{12.011}} \tag{10}$$

$$N/C = \frac{\frac{N}{14.007}}{\frac{C}{12.011}} \tag{11}$$

Energy recovery (ER%) was calculated using equation (12).

$$ER\ (\%) = \frac{Biocrude\ Yield \times HHV(biocrude)}{HHV(feedstock)} \times 100 \tag{12}$$

FTIR analysis was conducted on the crude samples inside a spectra range of 4000-400 cm-1, using the same equipment, software, and standard bands to identify the presence of the functional groups.
To further assess the chemical composition and distribution of the biocrude samples, Gas Chromatography-Mass Spectrometry (GC-MS) was utilized using Clarus® 690 gas chromatograph (PerkinElmer, CA, USA), coupled with a Clarus® SQ 8 C mass spectrophotometer. For analysis, 1 µL sample was injected in spitless mode, with pure helium (99.999%) as the carrier gas at a constant flow rate of 1 mL/min for a total duration of 40 minutes. The column temperature was initially set at 60 °C, then gradually increased to 240 °C at a rate of 5 °C per minute, with a holding time of 4 minutes. A constant 280 °C was maintained as the inlet temperature (Zilani et al., 2021). The National Institute of Standards and Technology (NIST) database was used to identify chemical substances (Mikaia et al., 1984).

2.3.2 Biochar

Both biochar samples were characterized to evaluate the biocrude extraction, identify any residual extractable organics, as well as, assess their suitability for downstream applications. Elemental composition (CHNSO) was determined using the same equipment used for biomass/biocrude. The obtained elemental distributions were utilized to compute the molar ratios H/C, O/C, and N/C using equations (6), (8), and (9), providing insights into aromaticity, degree of carbonization, and nitrogen retention in the solid phase. The HHV of the biochar and biomass was calculated using the same equation (2). To determine the inorganic composition of the biochars, XRF analysis was conducted using the same equipment and procedure as biomass.

2.3.3 Aqueous Phase

The aqueous phase is a major part of the HTL extracted product, as the feedstock is usually rich in moisture content. Physiochemical properties such as pH, total organic carbon (TOC), chemical oxygen demand (COD) (WC et al., 2023). These parameters were compared with the limiting values of the DSTP influent to help determine necessary treatment requirements and recirculation feasibility.

3. RESULT AND DISCUSSION

3.1 Feedstock Characterization

The characterization presented in Table 1 demonstrated the suitability of the SS as a potential feedstock for HTL technology. Proximate analysis revealed the presence of 57% volatile solids (VS) in the total solids (TS) content of the biomass, reflecting a utilizable fraction of thermally convertible organics of valorisation to extract energy value. Although the composition of SS varies with location, operating conditions, and seasonal factors, the elemental analysis shows alignment with trends reported in the literature (Zhao et al., 2023). The HHV was observed to be 10.2 MJ/kg, which indicates the potential of the biomass as a HTL feedstock (Khalekuzzaman, Jahan, et al., 2025). The XRF analysis shows the inorganic composition of the SS, with high SiO_2 (30.48%), Fe_2O_3 (17.92%), CaO (13.97%), and P_2O_5 (12.00%), making it a suitable feedstock for hydrothermal liquefaction (HTL), as oxides of Fe and Ca could act catalytically during HTL, enhancing biocrude production efficiency and quality (Di Lauro et al., 2024). The FTIR analysis of the SS (Figure-3(a)) showed peaks around 1626 and 3383 cm^{-1} corresponding to proteins (N-H, C-N); while peaks around 1016, 1450 and 1530 cm^{-1} represented carbohydrates (C-O, O-H); peaks on the 2853 and 2913 cm^{-1} regions showed lipids (C-H) and lignocellulosic materials (C=C, C-C), typically found in sewage-derived biomass. The presence of diverse composition makes SS an excellent HTL feedstock, as proteins and lipids tend to increase biocrude yield through hydrolysis and depolymerization, while lignocellulosic components add to the carbon content for biocrude formation (Khalekuzzaman, Hasan, et al., 2025). Overall, the organic and inorganic diversity of SS has potential to enhance HTL conversion efficiency and product quality.

Table 1: Feedstock Characterisation using proximate, ultimate, and inorganic composition analysis.

Proximate composition (wt % of wet biomass)		**Elemental composition (wt % of dry biomass)**	
Moisture content (MC)	90.2 ± 0.02	C	26.47
Total Solids (TS)	9.98 ± 0.02	H	3.69
Volatile Solids (VS)	5.76 ± 0.04	N	1.82
Ash	3.77 ± 0.03	O	27.03
Fixed Carbon (FC)[a]	0.27 ± 0.03	S	0.99
HHV = 10.2 MJ/kg			
Inorganic composition (wt% of ash)			
Na_2O (%)	0.48	CaO (%)	13.97
MgO (%)	2.77	TiO_2 (%)	1.04
Al_2O_3 (%)	9.27	Mn_2O_3 (%)	0.39
SiO_2 (%)	30.48	Fe_2O_3 (%)	17.92
P_2O_5 (%)	12.00	CuO (%)	0.44
SO_3 (%)	7.60	ZnO (%)	0.67
K_2O (%)	2.67	BaO (%)	0.31

[a]FC=100-(MC+VS+Ash)

3.2 HTL Product Yield

The evaluated HTL products yields from HTL of SS is illustrated in Figure-2. Upon using the novel two-stage solvent-based extraction (EA, Ace), a biocrude yield of 28.5 wt% was achieved, which is higher than typical single-solvent extractions reported for municipal sludge (18-22 wt%) (Leng et al., 2018). Higher (up to 44 wt%) biocrude yield from HTL of SS has also been reported, which is primarily attributed to the difference in composition and source. The energy recovery (ER) from the HTL process was 95%, showing the high effectiveness of the sequential two-stage extraction strategy, which efficiently recovered both mid-polarity and low-polarity organics, thereby minimizing residual hydrocarbons in the biochar. The biochar yield in the first stage (45.7 wt%) supports single-stage extraction (38-54 wt%) (Chen et al., 2020; Huang et al., 2019; Leng et al., 2018). The final stage biochar (35 wt%) is lower than other relevant studies due to the sequential second stage extraction. Almost all the aqueous phase (33.1 wt%) was extracted in the first extraction stage, leading to no aqueous phase present in the second extraction. The minimal gas and loss proved the accuracy of the extraction process.

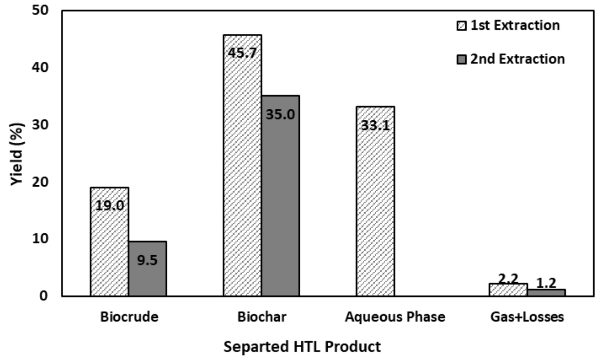

Figure 2: HTL Products yield.

3.3 Fourier Transform Infrared Spectroscopy Analysis

Figure 3 represents the FTIR analysis of the feedstock and biocrude sample extracted from both extractions, illustrating the functional groups present in the components. FTIR of the feedstock showed the presence of key functional groups that can be utilized through thermochemical conversion, discussed in previous section. FTIR analysis of biocrude from both extractions showed similar functional groups, indicating similar trend in quality. The FTIR spectra of biocrude-1 and biocrude-2 (Figure-3 (b) and (c)) confirm effective conversion of the feedstock into hydrocarbon-rich liquid fuels. Strong and well-defined absorbance bands in the 2850-3000 cm^{-1} region indicate the dominance of aliphatic C-H stretching from long-chain hydrocarbons, a key indicator of high fuel potential. The presence of carbonyl bands at 1700-1750 cm^{-1} reflects residual oxygenated compounds such as ketones, aldehydes, acids, and esters, typical of HTL biocrudes, while their comparatively moderate intensity suggests partial deoxygenation during liquefaction. Absorptions in the 1500-1650 cm^{-1} range reveal contributions from unsaturated and aromatic structures formed through cyclization and condensation reactions, which enhance energy density without excessive aromaticity. C-O stretching signals between 1000 and 1250 cm^{-1} and weak N-H bands near 3300-3500 cm^{-1} further indicate reduced but persistent oxygen- and nitrogen-containing functionalities relative to the feedstock (Eladnani et al., 2023). The spectra demonstrate that both biocrudes are predominantly aliphatic in nature with limited heteroatom content, highlighting their suitability as energy-dense intermediates; detailed quality assessment will be further substantiated through elemental analysis and GC-MS characterization.

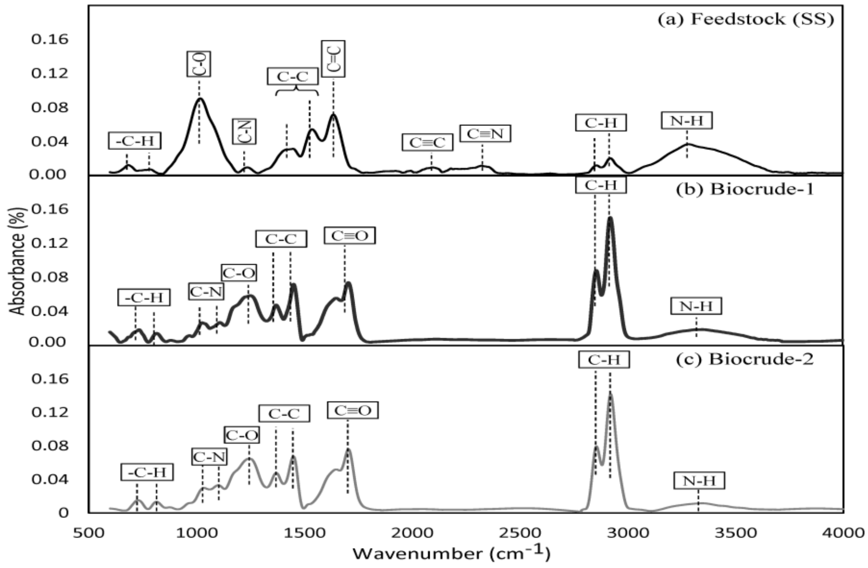

Figure 3: FTIR analysis of feedstock and biocrude samples.

3.4 Elemental Distribution

The elemental distribution of both biocrude and biochar sample are presented in Table 2. Both the biocrude samples showed similar HHV 33.5-34.5 MJ/kg, demonstrating similar energy quality, also verified through the FTIR spectra, aligned with similar studies (Zhao et al., 2023). The HHV of biochar-2 dropped to 4.6 from 5.4 MJ/kg in biochar-1, indicating successful biocrude extraction in the second stage.

Table 2: Elemental composition of Biocrude and Biochar.

Samples	Elemental composition (%)					HHV	Atomic molar ratio			
	C	H	N	O	S	(MJ/kg)	H/C	H/C$_{effective}$	O/C	N/C
Biocrude										
Biocrude-1	72.61	8.89	2.68	15.51	0.31	34.45	1.47	1.15	0.16	0.03
Biocrude-2	71.90	8.49	2.77	16.52	0.32	33.46	1.42	1.07	0.17	0.03
Petrocrude[a]	85.00	12.00	0.15	1.50		42-49	1.69	1.69	0.01	0.00
Biochar										
Biochar-1	19.70	2.55	1.72	34.97	1.06	5.40	1.55	-	1.33	0.07
Biochar-2	18.23	2.20	1.70	32.93	0.94	4.60	1.45	-	1.35	0.08

[a]Petro-crude elemental analysis was collected from (Koley et al., 2018)

Van Krevelen Diagram (Figure-4) compared the H/C with N/C and O/C ratios of biomass, biocrues, and commercial petrocrude. Both the biocrude shows similar trends, positioning them in a similar region. However, it is clear that, to reach the quality of petrocrude, biocrudes need further upgrading, to reduce O/C and N/C ratio, and increase H/C ratio (Huang et al., 2019).

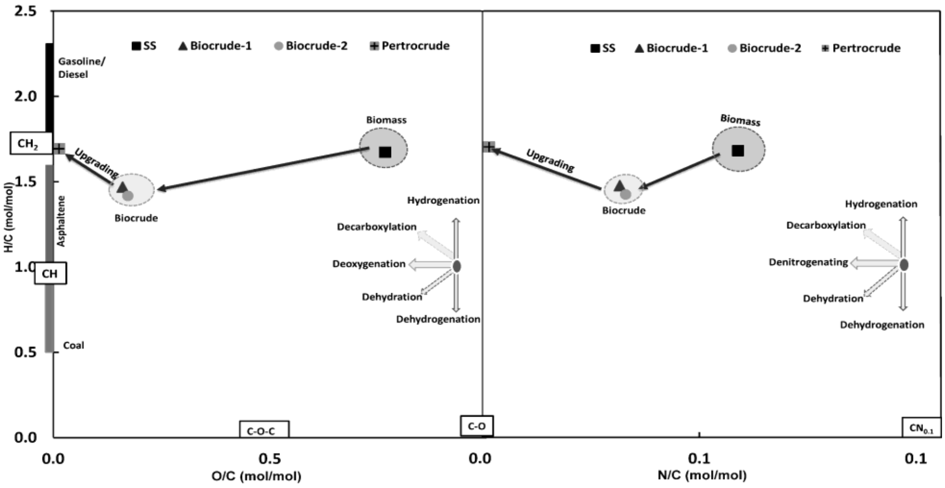

Figure 4: Van-Krevelen Diagram.

3.5 Chemical Properties of Biocrude

Figure-5 shows the GC-MS analysis of both the biocrude samples showing the detailed chemical composition of the biocrude products. Biocrude-1, recovered during the initial extraction step using ethyl acetate (EA), was dominated by esters (23%), followed by phenolic compounds (11%), alcohols (10%), ketones (9%), and unsaturated hydrocarbons (9%), combining with a notable proportion of nitrogen-bearing and NSO heterocyclic species (30%). This distribution indicates multiple concurrent conversion pathways during HTL of sewage sludge, where lipid-derived fractions undergo hydrolytic cleavage and subsequent ester-forming reactions, while protein-rich components decompose through thermal decomposition and condensation mechanisms, leading to the formation of nitrogen-containing and heterocyclic compounds. (Browning et al., 2024; Zimmermann et al., 2022). In contrast, biocrude-2, extracted from the residual biochar using Ace, exhibited an altered chemical distribution, characterized by a high proportion of organic acids (26%), reduced phenolic content (5%), and the absence of alcohols, ketones, and nitrogen-containing compounds. The richness of biocrudes in aromatic and ketones might be the effect of the metal oxide (Fe and Ca) present in the biomass (Huang et al., 2019). The presence of siloxane is due to the presence of high content of Si oxides in the biomass. This shift indicates that acetone extraction selectively recovered remaining oxygenated organic fractions while excluding heavier nitrogenous species, thereby confirming the effective secondary recovery of residual organics entrapped within the biochar matrix.

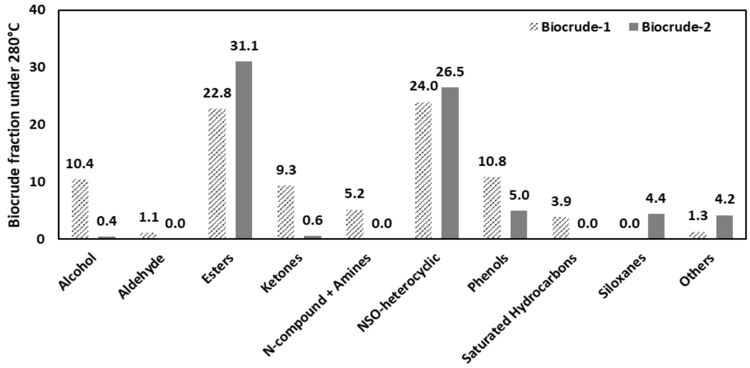

Figure 5: GCMS analysis of biocrude.

The carbon number distribution derived from GC-MS-identified compounds, highlighting variations in biocrude fractionation across light, middle, and heavy ranges. The results indicate a pronounced dominance of the middle-distillate fraction (>60%) in both the biocrudes, reflecting a favourable shift toward fuel-relevant carbon chains. This distribution suggests that inherent inorganic constituents in the feedstock, particularly alkaline earth metal oxides (CaO and MgO), play a catalytic role during liquefaction by facilitating decarboxylation, deoxygenation, and controlled cracking reactions (Sánchez-Bayo et al., 2019), which suppress the persistence of long-chain oxygenated species and promote the formation of shorter, more stable hydrocarbon structures, thereby enhancing the overall quality of the biocrude in terms of distillate-range composition.

3.6 Nutrients in Biochar

The XRF analysis of Biochar-2 shows a mineral-rich composition, consistent with sludge-derived feedstocks: MgO (14,219 mg/kg), P_2O_5 (39,143 mg/kg), K_2O (6,737 mg/kg), and CaO (40,424 mg/kg). The very high SiO_2 (211,007 mg/kg) and Al_2O_3 (45,136 mg/kg) reflect the inorganic residue typical of biosolids. Trace elements such as CuO (1,901 mg/kg) and ZnO (1,405 mg/kg) remain well within IBI maximum limits. Because of its elevated P, K, Mg, and Ca content, Biochar-2 has strong potential as a slow-release soil amendment, especially to improve nutrient-poor or acidic soils (Kujawska et al., 2024). Furthermore, the high Si and Al content and significant iron-oxide fraction (Fe_2O_3) make it attractive for non-agricultural uses, such as a sorbent in wastewater treatment (e.g., for phosphate or heavy-metal removal) (Hao et al., 2024).

3.7 Aqueous Phase Management Strategy

The HTL aqueous phase characteristics, shown in Table 3 demonstrates that it requires substantial pretreatment before recirculation to the PST to avoid organic overloading. Granular activated carbon (GAC) adsorption is an effective first step, capable of removing up to 60% of COD and reducing inhibitory phenolic compounds (Aktas, Liu, & Eskicioglu, 2024). Subsequent aerobic biological treatment, preferably after dilution, can further reduce COD by 67-95%, improving biodegradability and mitigating toxicity associated with nitrogenous organics in HTL effluents (Aktas, Liu, Basar, et al., 2024). Overall, a treatment train combining GAC adsorption, aerobic oxidation, optional anaerobic co-digestion, and membrane polishing provides a feasible pathway for reducing the organic load to DSTP-compatible levels.

Table 3: Aqueous phase quality.

Parameter	**HTL Aqeous phase**	**Maximum Allowed Threshold Value for DSTP**
pH	7.5	6.5-9.5
COD (mg/L)	7622	660
TOC (mg/L)	3160	-

4. CONCLUSIONS

This study demonstrates the promise of integrating HTL as a sludge management alternative framework for the DSTP, which can play a transformative role in powering Dhaka's transition toward a circular and resource-efficient urban metabolism. Comprehensive characterization confirmed that the DSTP sludge contains a favorable distribution of volatile solids, catalytic inorganic components, and nutrient-rich minerals, making it a technically viable feedstock for thermochemical conversion.

The optimized HTL process yielded a significant 28.5 wt% biocrude, alongside mineral-rich biochar and an aqueous phase containing recoverable organics, collectively illustrating a zero-waste pathway for energy recovery, material recycling, and nutrient circularity. FTIR and molecular-level analyses further revealed that the produced biocrude is predominantly aliphatic and hydrocarbon-rich, with moderate oxygenated and limited nitrogenous functionalities, while GC-MS and carbon number distribution analyses confirmed a dominance of middle-distillate-range compounds (>60%). This favourable carbon range, underscores the suitability of the biocrude as a fuel precursor requiring reduced upgrading severity. The two-stage extraction approach proved highly effective in maximizing crude recovery while minimizing residuals in the solid fraction, further enhancing overall process efficiency and resource utilization.

By converting problematic sewage sludge into a middle-distillate-rich biocrude alongside valuable co-products, HTL offers a practical solution to DSTP's growing sludge management challenge while simultaneously generating a domestic renewable energy stream. The integration of HTL within Dhaka's wastewater infrastructure could substantially reduce sludge volume, lower long-term operational burdens, and create opportunities for local fuel substitution, nutrient recovery, and industrial incorporation. In a whole, the findings provide a strong promise for scaling up HTL integration at DSTP and similar urban wastewater facilities, aligning sludge management with Bangladesh's broader circular economy ambitions and contributing directly to the achievement of SDGs 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), and 11 (Sustainable Cities).

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DECLARATION OF USE OF AI

AI-based tools were used exclusively for language editing and clarity improvement during manuscript preparation. The research methodology, data analysis, results, and conclusions were entirely developed and validated by the authors.

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