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PEAT-TO-BIOCRUDE VIA HYDROTHERMAL LIQUEFACTION: UNLOCKING A PROMISING PATHWAY FOR SUSTAINABLE ENERGY

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ABSTRACT

Wetlands, like peat, have been the subject of many studies to discover how they could contribute to restoring ecosystems and slow down climate change. At the same time, little investigation has been done on its potential as a source of clean energy. Hydrothermal liquefaction (HTL) is a direct way to turn wet biomass into energy-rich biocrude without the need for pre-drying. This study reveals the biocrude conversion potential of underutilized, carbon-rich peat via hydrothermal liquefaction. HTL took place in a batch reactor at 320 °C for 60 minutes using peat as the feedstock. For proper extraction of the biocrude, a green solvent (ethyl acetate) was used. Proximate and ultimate analysis, HHV determination, FTIR, GC-MS, and TGA were utilized to assess the HTL products' quality. The ethyl acetate extraction produced 23.5 wt% (dry-feed basis) biocrude, and the rest of the mass was made up of biochar (67.2 wt%), the aqueous phase, and small amounts of gas and losses (9.26 wt%). The elemental analysis showed that the biocrude had more carbon (73.7 %) and hydrogen (8.3 %), but less oxygen (15.2 %). The biocrude had a higher heating value (HHV) of 34 MJ kg^{-1}, which is close to the petroleum fuel. FTIR spectra showed notable peaks for aliphatic C–H stretches, carbonyls (C=O), and aromatic groups, which indicate that hydrocarbons and oxygenates form the main components of the biocrude. GC–MS analysis showed that esters, hydrocarbons, and phenols were the most dominant compounds. TGA also suggested that the biocrude mostly contain middle to heavy fractions (diesel and fuel oil). Overall, peat liquefaction demonstrates a promising pathway for producing energy-dense biocrude, which bridges the gap between renewable biomass resources and sustainable fuel production.

Keywords: *Hydrothermal liquefaction, peat, biocrude, sustainable energy*

1. INTRODUCTION

The energy demand of the world has grown rapidly due to growing population and rapid industrial advancements. It is predicted to have increased by at least 50% by 2030 (Mugerwa et al., 2019). Fossil fuels are still the most common source of energy today, but their widespread use is causing serious environmental issues like high greenhouse gas (GHG) emissions, climate change, and global warming. According to the International Energy Agency (IEA, 2020), fossil fuel combustion process produces about Gigatons of greenhouse gas, which is about 54% more than it was in 1973, emphasizing the seriousness of the current energy situation (Gani, 2021). Energy recovery from waste and biomass has drawn more attention as a sustainable alternative. According to Yong et al. (2016), turning biomass into solid, liquid, and gaseous biofuels could provide almost 30% of the world's energy needs. In this regard, the "Waste-to-Energy" strategy offers a dual benefit by lowering greenhouse gas emissions as well as reducing pollution levels, which in terms helps in the fight against climate change, in addition to providing a renewable energy source (Iqbal & Kang, 2021).

Peatland restoration and harvesting have been identified as one of the most successful methods for reducing the effects of climate change among potential biomass resources. According to a life cycle assessment, peat collected from drained peatlands has the potential to reduce greenhouse gas emissions by up to 35%. As a result, using drained peatlands as feedstock for biofuel production has the additional benefit of reducing emissions and producing renewable energy. Countries like Rwanda, Canada, and Russia have already started considering peat as a potential energy source, with application ranging from generating electricity to producing liquid fuel (like Fischer-Tropsch diesel) as an alternative to first-generation biomass (Mutka & Nyrönen, 2008).

Moreover, peat is a desirable feedstock for thermochemical conversion because of its physiochemical properties. It is a partially decomposed lignocellulosic structure. Worldwide availability of peat is 463 million hectares of peatlands (Jin et al., 2009). According to Li et al. (2011), peat has a high energy value and crude conversion rate of 19–40%. These characteristics supports its potential as a feedstock for bioenergy.

One efficient method for converting lignocellulosic and wet biomass, such as peat, into energy-dense biocrude is hydrothermal liquefaction (HTL). The suitability of peat for liquid fuel production was conducted by Xu & Donald (2012). That study confirmed HTL as a potential route for the sustainable use of peat.

To obtain high-quality biocrude choice of extraction solvent is necessary. Solvent is influenced by polarity, chemical structure, and hydrogen bonding. This is important for the separation of biocrude from the aqueous phase and biochar (Zhu et al., 2017). Numerous studies used both polar solvents (methanol, ethanol, and acetone) (X. Yang et al., 2014) and non-polar solvents (hexane, heptane, decane, cyclohexane, and hexadecane) (Valdez et al., 2011). However, the composition of the feedstock affects solvent effectiveness (Lu et al., 2019). In the HTL of *Nannochloropsis sp*., Valdez et al. (2011) found that using non-polar solvents increased the biocrude yields. However, for spent coffee grounds, acetone and dichloromethane (DCM) worked better than hexane (J. Yang et al., 2019). Similarly, DCM and chloroform performed best in sewage sludge liquefaction (Qian et al., 2017). Moderately polar solvents are particularly effective because they can extract a wide range of biocrude fractions (X. Yang et al., 2014). Ethyl acetate (EA), for example, showed excellent performance in agricultural biomass HTL (Chand et al., 2019).

Prior to this work, the use of peat as a specific biomass for the production of biocrude had not been thoroughly investigated. Even though previous study of authors examined peat liquefaction on a laboratory scale, this study only focuses on the pilot-scale hydrothermal liquefaction of peat using ethyl acetate (EA) as a moderately polar solvent to evaluate its efficiency in biocrude recovery. To assess its quality produced biocrude was further tested using FTIR, elemental, GC–MS, and TGA analyses.

2. METHODOLOGY

Feedstock collection, characterization, process and process analyses are described in the following sections.

2.1 Feedstock Collection

Peat (P) was collected from the Terokhada wetland area in Khulna, Bangladesh, which depth was six to eight feet. Peat sample was mixed with distilled water and then sieved through a 2 mm sieve to get rid of any extra particles to form uniform slurry. Some sample was kept in a lab refrigerator at 4 ºC for further analysis.

2.2 Solvent Collection

Ethyl acetate (EA) was used in this study as extraction solvent. It is a moderately polar solvent with a polarity index of 0.228 (Zhao et al., 2022) and boiling point of 77ºC (Kenig et al., 2001). Commercial-grade EA was purchased from chemical manufacturing company, Richill Industries Pte. Ltd., Singapore.

2.3 HTL Operation

The HTL process was performed in a 12 liter batch reactor which has working volume of 10 liter. The reactor was constructed with a combination of stainless-steel grades SS 304 and SS 316. This HTL process was conducted at 320 ºC for 60 minutes (15 to 20 MPa) and had a heating rate of 4.8ºC/min. The reactor was cooled using a built-in cooling system after liquefaction. Then HTL product was collected through a drain valve. In the next step, HTL products (biocrude, biochar, and aqueous phase) were separated at 30 Hz frequency using a high-speed industrial tubular centrifuge machine (GF75-J Solid Liquid Separator, China). The product was mixed with EA at 1:2 ratio and centrifuged to separate the HTL products. Figure 1 shows the experimental process of this study.

After the biocrude extraction, solvent was removed using a solvent recovery unit. The biocrude sample was collected and stored in a laboratory refrigerator to analyze its properties. Biochar was air-dried and stored for further analysis.

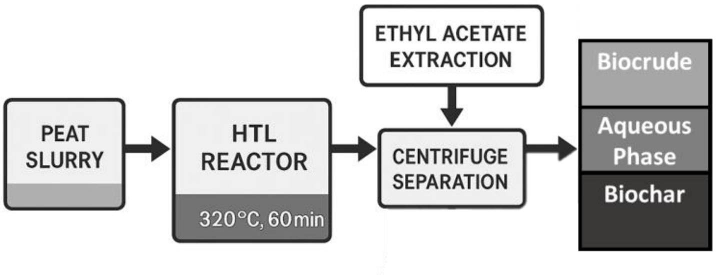


Figure 1: Experimental flow diagram of HTL of peat

2.4 Analytics

Feedstock proximate analysis was done using standard SM 2540 G method (Lipps et al., 2023) for determining moisture, volatile matter, ash, and fixed carbon. The ash content was measured using the ASTM E 1755-01 standard (E48 Committee, 2010). FTIR, GC-MS, elemental analysis, and thermogravimetric analysis (TGA) was used to measure the biocrude quality.

The carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content of the biomass, biocrude, and biochar were analyzed using the Elementar vario Micro Cube (Germany). Oxygen percentage was calculated using equation (1) (Makut et al., 2022).

$$O(wt\%) = 100\% - \text{sum of } (C, H, N, S, \text{and Ash}) \quad (1)$$

Moreover, the molar ratios were calculated using equations (2) to (4) (Yang et al., 2018).

$$H/C = (H/1.008)/(C/12.011) \quad (2)$$

$$O/C = (O/15.999)/(C/12.011) \quad (3)$$

$$N/C = (N/14.007)/(C/12.011) \quad (4)$$

$$(\text{Yield})_{\text{biocrude}}\ (\text{wt\%}) = (\text{mass of biocrude (g)}) / (\text{mass of biomass (g)}) \times 100\% \quad (5)$$

$$(\text{Yield})_{\text{biochar}}\ (\text{wt\%}) = (\text{mass of biochar (g)})/(\text{mass of biomass (g)}) \times 100\% \quad (6)$$

$$(\text{Yield})_{(\text{Aqueous+Gas+others})}\ (\text{wt\%}) = 100\% - (\text{Yield})_{\text{biocrude}}\ (\text{wt\%}) - (\text{Yield})_{\text{biochar}}\ (\text{wt\%}) \quad (7)$$

$$H/C_{\text{eff}} = ((H-2O))/C \quad (8)$$

The higher heating value (HHV) of the biomass, biochar, and biocrude samples was determined using equations (9) and (10), respectively (Parikh et al., 2005).

$$(\text{HHV})_{(\text{biomass/biochar})} = 0.3491C + 1.1783H - 0.1034O - 0.0151N - 0.021\text{Ash} \quad (9)$$

$$(\text{HHV})_{\text{biocrude}} = 0.3383C + 1.422\ (H - O/8) \quad (10)$$

3. RESULTS AND DISCUSSION

Major findings of this study are given in the following sections to analyse the potentiality of peat liquwgfaction.

3.1 Conversion Potential of Peat

Table 1 shows the feedstock proximate and elemental properties. Volatile matter of the feedstock is around 73% of the total solids (TS) as given in Table 1. Elemental analysis revealed a higher heating value (HHV) of 15.6 MJ/kg and a H/C_{eff} ratio of 0.26.

Table 1: Feedstock properties

Components	**Peat**
Proximate analysis (wt.%)	
Moisture content	90.0 ± 0.03
Total solids (TS)	10 ± 0.07
Volatile solid (VS)	7.3 ± 0.01
Ash	2.5 ± 0.01
Fixed carbon (FC) [a]	0.2 ± 0.01
Elemental analysis (dry basis, wt.%)	
C	38.2
H	5.6
N	2.3
O [a]	38.5

S	1.3
Elemental molar ratio (mol/mol)	
H/C	1.77
O/C	0.76
N/C	0.05
Chemical formula	$CH_{1.77}O_{0.76}N_{0.05}$
H/C_{eff}	0.26
HHV (MJ/kg)	15.6

[a] by difference. O (wt%) = 100 – the sum of (C, H, N, S, Ash). FC (%) = 100 – sum (MC + VS + ash)

3.2 Product distribution

Figure 2 shows the yield of HTL products. Under the above mentioned HTL conditions, extraction with ethyl acetate (EA) yielded a biocrude of 23.5 wt% on a dry-feed basis, which conforms with the study by Li et al. (2011). The remaining mass was mainly the solid biochar (67.2 wt%) and the aqueous phase, with gaseous products and process losses contributing small amounts (9.26 wt%).

Research on HTL of various biomass types is growing, but few studies specifically address peat liquefaction. This study aims to fulfill this gap by investigating the conversion characteristics of peat under the HTL process with a moderately polar solvent and focusing on the yield distribution and properties of the resulting products. The findings are discussed in detail in the following sections.

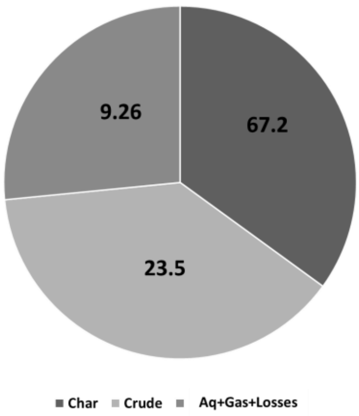


Figure 2: HTL product distribution with ethyl acetate extraction

3.3 Structural analysis of feedstock, biocrude, and biochar

Figure 3(a) denotes observable peaks for peat, such as C-H, C-O, and C=C stretches. Therefore, peat reveals its notable potential for liquefaction.

Figure 3(b) shows FTIR spectra for both biocrude and biochar. FTIR spectra reveal observable peaks corresponding to aliphatic C–H stretches (2800–3000 cm^{-1}), carbonyls (C=O), and aromatic features, confirming that energy-rich hydrocarbons and oxygenates dominate the biocrude fraction for EA extraction.

FTIR analysis of the biochar shows small peaks corresponding to C–O and C-H groups, which suggests that biochar has the potential to be used as an adsorption material to extract pollutants from wastewater (Enaime et al., 2020).

A comparison of the FTIR spectra of biocrude and peat shows a decrease in the intensity of characteristic peaks around 3364 cm^{-1} (–OH). Conversely, the bands at 2800–3000 cm^{-1} ($–CH_2$, $–CH_3$) and 1458 cm^{-1} (C–H) exhibited enhanced intensities. The breakdown and reduction of oxygenated functional groups like -COOH along with the creation of aliphatic hydrocarbons (alkanes and alkenes) are indicated by these spectral changes.

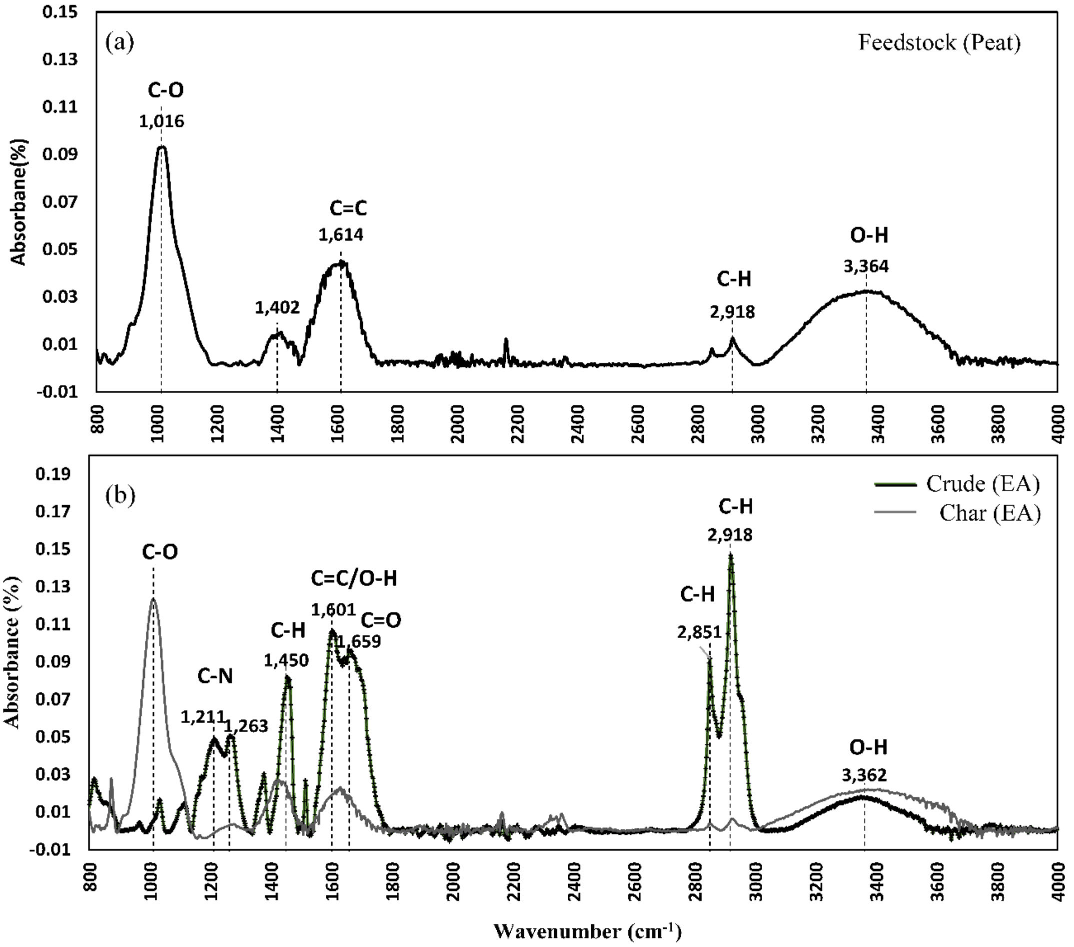


Figure 3: FTIR spectra of (a) feedstock (Peat), (b) EA-extraction, and (c) Ace-extraction

3.4 Analysis of Elemental Composition

The energy density of biocrude was evaluated using elemental analysis with hydrogen-to-carbon effective ratios, atomic molar ratios, and heating value. Table 2 presents a summary of the findings and a comparison with traditional petrocrude (Khalekuzzaman et al., 2024).

The carbon (73.7 wt%) and hydrogen (8.3 wt%) contents of the biocrude made with ethyl acetate (C-EA) were significantly higher than those of the feedstock (C: 38.2 wt%, H: 5.6 wt%). On the other hand, its oxygen (15.2 wt%) and nitrogen (2.2 wt%) contents decreased compared to the feedstock (N: 2.3 wt%, O: 38.5%), which is similar to findings of Zhao et al. (2022). Only 27.1 wt% carbon and 2.6 wt% hydrogen were present in the corresponding biochar (CH-EA).

Table 2: Elemental analysis of biocrude and biochar

Components	C-EA	CH-EA	Petrocrude
C (wt%)	73.7	27.1	83.00
H (wt%)	8.3	2.6	12.00
N (wt%)	2.2	2.3	0.20
O (wt%)	15.2	37.4	4.00
S (wt%)	0.7	0.6	0.00

HHV (MJ/Kg)	34.0	8.0	42-49
H/C (mol/mol)	1.3	--	1.73
O/C (mol/mol)	0.2	--	0.04
N/C (mol/mol)	0.03	--	0.01

Figure 4 (van krevelen diagram) shows the reaction pathway of the HTL process from feedstock to biocrude.

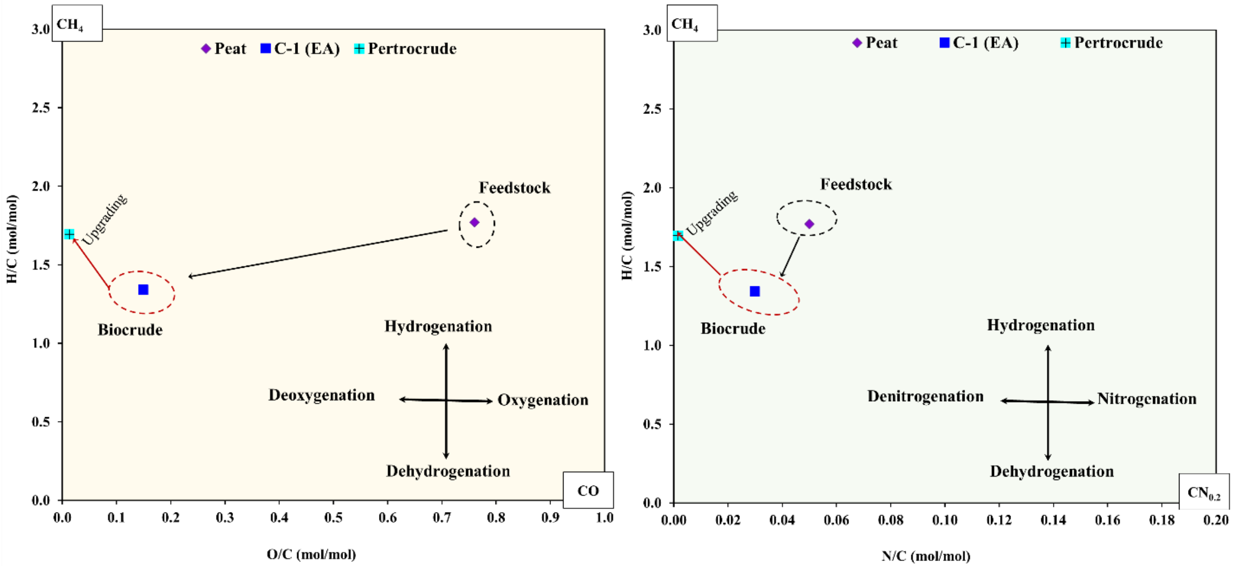


Figure 4: Van Krevelen diagram of EA-extracted biocrude sample

In the biocrude oxygen-to-carbon (O/C) ratio of 0.2 was found, which indicates deoxygenation. The nitrogen-to-carbon (N/C) ratio decreased to 0.03, indicating denitrogenation.

The findings shows that EA extraction improved biocrude quality by decreasing oxygen and nitrogen content while increasing carbon and hydrogen contents. Further upgrading, such as hydrotreating, is required to improve biocrude quality.

3.5 Chemical composition

The chemical composition of the biocrude samples extracted with EA (C-EA) was examined using GC-MS. Figure 5 presents the GC-MS analysis results showing the key biocrude compositions, and Table 3 lists the chemical compounds with their corresponding percentage areas based on the chromatographic peaks at the respective retention times.

Esters (19.7%), hydrocarbons (18%), and phenols (28.2%) were the most abundant chemical groups found in the biocrude. The contribution of other groups include alcohols (7.4%), amides (3.8%), aromatics (8.1%), ketones (4.4%), organic acids (5.9%), and minor amounts of N & O heterocyclic compounds (1.5%) and others (2.3%). Relatively high amount of phenolic compounds suggests that lignin-derived structures were partially depolymerized. Esters and hydrocarbons, which together account for nearly 38% of the total composition, exhibit favourable biofuel characteristics because these fractions contribute to energy density and combustion efficiency. However, further upgrading would be necessary to reduce phenolic content and enhance hydrocarbon yields.

Among these, phenolic compounds were dominant, including phosphonic acid, (p-hydroxyphenyl)-, phenol, 2-methoxy-, p-cresol, and 2-methylphenol, as presented in Table 3. Esters constituted chiefly by hexanedioic acid, bis(2-ethylhexyl) ester, hexacosyl acetate, and fumaric acid heptadecyl 2,2,3,3,4,4,5,5-octafluoropentyl ester. Hydrocarbons predominantly contain hentriacontane (1.1–

1.6%), triacontane (1.6–2.5%), and octadecane, 2,6,10,14-tetramethyl- (1.4%). Alcohols such as 1-hexacosanol and isoheptadecanol were also detected in appreciable amounts. Amides were mainly represented by 9-octadecenamide (z)-, while the aromatic fraction included ethylbenzene, quinoline-4-methyl, and 2-(p-fluorophenyl)-1-methylbenzimidazole. Additional fractions included ketones, such as 1-butanone, and 1-(4-hydroxyphenyl)-, as well as organic acids like phthalic acid derivatives, and N & O-heterocyclic compounds, including 2,5-piperazinedione derivatives. Collectively, the major compounds- phenol derivatives, esters, long-chain hydrocarbons, and oxygenated aromatics- reflect the partial depolymerization of lignin and cellulose components in peat. While the significant phenolic content highlights the need for upgrading, the presence of hydrocarbons and esters demonstrates the potential of peat-derived biocrude as a renewable energy precursor.

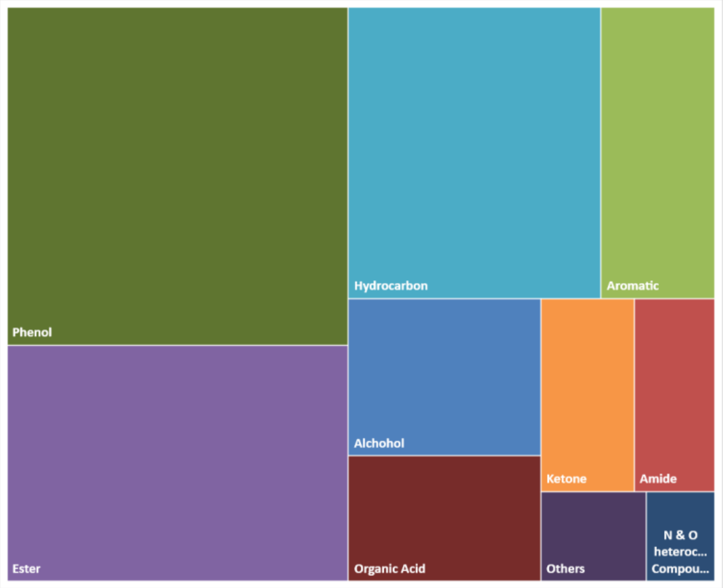


Figure 5: Chemical composition of biocrude samples with EA extraction

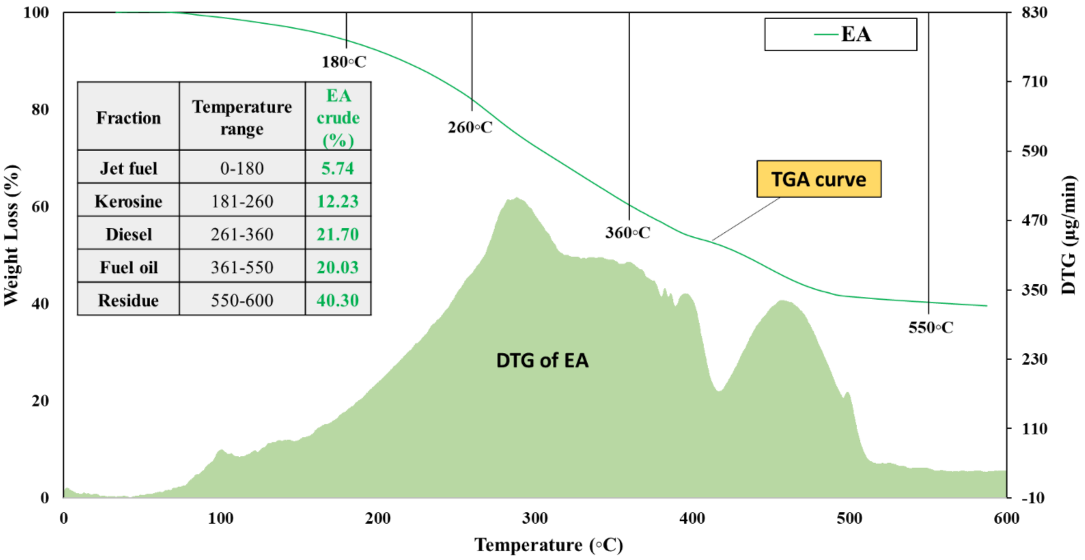
Table 3: Major chemical compounds of biocrude samples

Chemical Types	Chemical Compounds	R.T	Bio-crude (%)
Alcohol	1-HEXACOSANOL	45.7	2.7
	ISOHEPTADECANOL	35.1	1.1
Amide	9-OCTADECENAMIDE, (Z)-	42.9	3.2
Aromatic	ETHYLBENZENE	5.8	0.7
	2-(P-FLUOROPHENYL)-1-METHYLBENZIMIDAZOLE	15.8	3.1
	QUINOLINE, 4-METHYL-	18.6	0.8
Ester	CHLOROACETIC ACID, TETRADECYL ESTER	29.3	0.4
	CHLOROACETIC ACID, TETRADECYL ESTER	34.7	0.6
	FUMARIC ACID, HEPTADECYL 2,2,3,3,4,4,5,5-	41.4	1.0

	OCTAFLUOROPENTYL ESTER		
	HEXANEDIOIC ACID, BIS(2-ETHYLHEXYL) ESTER	43.7	4.7
	HEXANEDIOIC ACID, BIS(2-ETHYLHEXYL) ESTER	44.3	1.3
	HEXANEDIOIC ACID, BIS(2-ETHYLHEXYL) ESTER	45.2	3.2
	HEXACOSYL ACETATE	45.5	1.9
	HEXACOSYL ACETATE	50.8	1.5
Ether	METHYL TETRATRIACONTYL ETHER	53.7	0.3
Hydrocarbon	1R,2C,3T,4T-TETRAMETHYL-CYCLOHEXANE	28.7	1.0
	HENTRIACONTANE	37.4	1.1
	HENTRIACONTANE	39.6	0.9
	OCTADECANE, 2,6,10,14-TETRAMETHYL-	40.0	1.4
	DOTRIACONTANE	40.7	1.3
	HENTRIACONTANE	41.7	0.9
	TRIACONTANE	42.3	1.6
	HENTRIACONTANE	48.0	1.6
	TRIACONTANE	56.2	2.5
Ketone	1-BUTANONE, 1-(4-HYDROXYPHENYL)-	20.4	1.4
N & O heterocyclic compounds	2,5-PIPERAZINEDIONE, 3,6-BIS(2-METHYLPROPYL)-	33.4	0.8
	2,5-PIPERAZINEDIONE, 3,6-BIS(2-METHYLPROPYL)-	33.8	0.7
Organic Acid	OCTANOIC ACID, HEXADECYL ESTER	21.7	0.7
	GLUTARIC ACID, DODEC-2-EN-1-YL 1-NAPHTHYL ESTER	22.0	0.4
	PHTHALIC ACID, 3,5-DIMETHYLPHENYL 4-ISOPROPYLPHENYL ESTER	22.5	1.1
	5-(.BETA.-BROMOALLYL)-5-(1-METHYLBUTYL)BARBITURIC ACID	25.2	1.0
Phenol	PHOSPHONIC ACID, (P-HYDROXYPHENYL)-	6.4	3.9
	PHENOL, 2-METHYL-	8.2	1.0
	P-CRESOL	8.8	2.1
	PHENOL, 2-METHOXY-	9.2	5.5

3.6 TGA

Figure 6 shows TGA of peat-derived biocrude. Volatile range of the biocrude was up to 600 °C. About 59.7% volatile fractions were found of the biocrude, with 5.7% jet fuel (0-180 °C), 12.2% kerosene (181-260 °C), 21.7% diesel (261-360 °C), and 20.0% fuel oil (361-550 °C). After 550 °C, a large residue of 40.3% was found, which suggests heavy residue. The high amount of diesel and heavy fuel fraction in the biocrude indicates that the biocrude is mainly middle to heavy rich fractions.



Fraction	Temperature range	EA crude (%)
Jet fuel	0-180	5.74
Kerosine	181-260	12.23
Diesel	261-360	21.70
Fuel oil	361-550	20.03
Residue	550-600	40.30

Figure 6: TGA of EA-extracted biocrude

4.0 CONCLUSIONS

This study evaluated the feasibility of hydrothermal liquefaction of peat. The results showed that ethyl acetate was highly successful in achieving a biocrude yield of 23.5 wt% with an HHV of around 34 MJ/kg. FTIR, GC-MS, and elemental analysis revealed the presence of hydrocarbons, esters, and phenolics. TGA revealed that biocrude consists middle to heavy fractions (diesel and fuel oil). The findings show that peat can be converted into high-energy liquid fuel via HTL despite being a low-rank biomass. The production of biofuels from drained or degraded peatlands is good for the environment since it produces renewable energy and lowers methane emissions from uncontrolled peat. Future work should concentrate on catalytically improving biocrude to improve its stability and fuel efficiency.

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DECLARATION OF USE OF AI

AI tools were used solely for language improvement purposes, including sentence restructuring, and clarity enhancement. The AI tools did not contribute to the research design, data collection, data analysis, interpretation of results, or generation of scientific content. All technical content, analyses, results, and conclusions are the original work of the author.

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