CARBON FOOTPRINT ASSESSMENT OF HYDROTHERMAL LIQUEFACTION OF WET-WASTE FOR BIOCRUDE PRODUCTION

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ABSTRACT

Globally every year approximately 600–700 Mt of solid waste and 250–300 Mt of wet-waste (fecal sludge (FS)) are not managed properly. The waste management sector being responsible for about 5% of the emissions is a big source of greenhouse gas (GHG) emissions. The vast expanse of peatlands spanning globally around 463 million hectares stores approximately 600 billion tons of peat carbon, with 80.8 billion tons in a degrading state is a potential source of GHG emission. "Waste to Energy (WtE)" has the potential to address current global crises, such as energy crisis, GHG emissions, climate change, and global warming. Hydrothermal liquefaction (HTL), while holding great promise in terms of bioenergy production, requires a nuanced understanding of its carbon footprint to ensure that the benefits it offers are not compromised by adverse environmental effects. Carbon footprint analysis can be an essential tool to understand the process's contribution to reducing GHG emissions, carbon sequestration, and sustainable energy production. This study evaluated carbon footprints associated with biocrude production in three different feedstocks (FS, P, and OSW). The evaluation was conducted on a 10L sample of each feedstock having a potential to emit 1.4-1.85 Kg CO_2e (equivalent CO_2), the reactor used a 9.7 KW-h electricity producing 4.9 Kg CO_2e emission. Among the products of the HTL runs, biocrude showed the potentiality of emitting 0.75-1.0 Kg CO_2e, whereas, the other two products, biochar, and aqueous phase showed carbon sequestration potential of 0.3-1.0, 0.09-0.2 Kg CO_2e respectively. With optimization of the HTL process and the surrounding environment, such as introducing renewable energy as the power source and planting more trees, the process can be converted into a carbon-negative process. As the global community strives to transition towards a low-carbon future, this research endeavors to inform policymakers, researchers, and industry stakeholders on the potential benefits and challenges posed by HTL as a waste conversion technology.

Keywords: *Hydrothermal liquefaction, Carbon Footprint, Carbon Emission, Carbon Sequestration, Carbon Balance.*

1. INTRODUCTION

The rapid pace of global development is accompanied by elevated energy consumption and environmental pollution, giving rise to substantial emissions of greenhouse gases (GHGs). These emissions contribute to climate change and the phenomenon of global warming. Fossil fuel, the prime source to meet (80%) the current immense energy demand is a limited resource. The current reserve of fossil fuels is given in the table-1.

Table-1: Fossil Fuel Reserves by 2020 (Energy Institute Statistical Review of World Energy, 2023)

Coal	Gas	Oil
139 years	49 years	57 years

Additionally, with this highly useful resource, comes the hazard of high levels of environmental pollution. About 75% of all greenhouse gas emissions (GHG) and 90% of all CO_2 emissions come directly from the burning of fossil fuels (coal, oil, gas) (Carbon dioxide (CO2) and the carbon cycle, 2023). Fossil fuel burning is a highly carbon-positive approach to acquiring energy. This carbon-positivity of fossil fuels affects the environment adversely. As a result, sustainable and eco-friendly approaches toward energy production have become one of the top most priorities in the modern world. On the other hand, renewable energy sources, such as, solar, wind, and hydro-energy, although carbon-neutral, are difficult to acquire the necessary amount throughout the year. Environmental conditions, seasons have a large impact on these sources. In the face of escalating environmental concerns and the urgent need for sustainable energy solutions, the exploration of alternative methods for waste management and bioenergy production has gained significant momentum (USA Patent No. US 7.964,761 B2, Jun. 21, 2011). Hydrothermal Liquefaction (HTL) emerges as a promising technology, offering a multifaceted solution by simultaneously addressing the challenges of wet-waste disposal and contributing to the production of valuable biofuels (Kabir & Khalekuzzaman, 2022).

Globally every year approximately 600–700 Mt of solid waste and 250–300 Mt of wet-waste (fecal sludge (FS)) are not managed properly (Strande and Brdjanovic, 2014). Unmanaged waste is responsible for at least 5% of the total GHG emissions of the earth (Bogner et al., 2008). Effective management of fecal sludge (FS) poses a significant challenge for developing countries, hindering their progress toward achieving sustainable development goals (SDGs) (Spinosa & Doshi, 2021). Highlighting the potential of FS for the HTL process, (Sharma et al., 2020) recommended it as a highly promising biomass, estimating a higher heating value (HHV) of 14 MJ/kg and solid content of 7–9%. (Lu et al., 2017) demonstrated the conversion of human feces into biocrude (yield 34.4% and HHV 40.3 MJ/kg) using HTL, without the need for pretreatment. Furthermore, a study in the United States projected that HTL of wastewater sludge could enhance energy recovery (ER) by 188% and eliminate approximately USD 3.3×10^9 per year in sludge disposal costs (Seiple et al., 2020).

Solid wastes predominantly consist of an organic fraction, constituting approximately 45–50%, with a significant portion, ranging from 70% to 85%, attributed to moisture content(Campuzano & González-Martínez, 2016). Studies conducted by (Hossain et al., 2022a; Kabir & Khalekuzzaman, 2022) showed that the crude from HTL of OSW had a Higher Heating Value (HHV) of 28-40 MJ/Kg indicating a high potential of OSW to be used as a feedstock in HTL.

Peat is a partially decomposed form of plant or organic matter (lignocellulosic) typically found in wet areas such as peatlands, bogs, and mires. These peatlands, covering approximately 3% of the Earth's surface, hold significant global importance. According to (Leifeld & Menichetti, 2018), the vast expanse of peatlands, spanning around 463 million hectares globally, stores an estimated 600 billion tons of peat carbon, with 80.8 billion tons in a degrading state. This reservoir poses a potential emission source, contributing to an annual release of 1.9 (0.31–3.38) $\times$ 109 tons CO_2e. GHGs. (Hossain et al., 2022b; Kabir et al., 2022) showed peat has the potential to be used in HTL technology as a feedstock with its crude product having HHV of 25-35 MJ/Kg.

These findings underscore the potential of HTL as a transformative technology for the sustainable management of Faecal Sludge (FS), Peat (P), and Organic Solid Waste (OSW) offering both energy recovery and cost-effective waste treatment solutions.

A carbon footprint assessment involves measuring the complete greenhouse gas emissions, represented in carbon dioxide equivalents (CO_2e), associated with a specific individual, organization, product, or activity. This assessment encompasses both direct and indirect sources of emissions across the entire life cycle, providing a comprehensive understanding of the environmental impact. Product carbon footprints refer to life cycle assessments specifically focused on global warming. These assessments detail the environmental emissions of greenhouse gases throughout the entire life cycle of a product (Henriksson et al., 2015). The HTL of biomass technology has the potential to be a carbon-neutral or carbon-negative technology due to its by-products (biochar & aqueous phase) contributing to carbon sequestration. The potentiality of biomass energy being carbon negative is illustrated in figure-1. However, only a handful studies have been conducted to pursue the potentiality of HTL of wet-waste to be a carbon-neutral or carbon negative technology. Therefore, this research embarks on a comprehensive investigation into the carbon footprint associated with HTL of wet-waste (FS, P, OSW), with a deep investigation of the carbon pathway throughout the entire process.

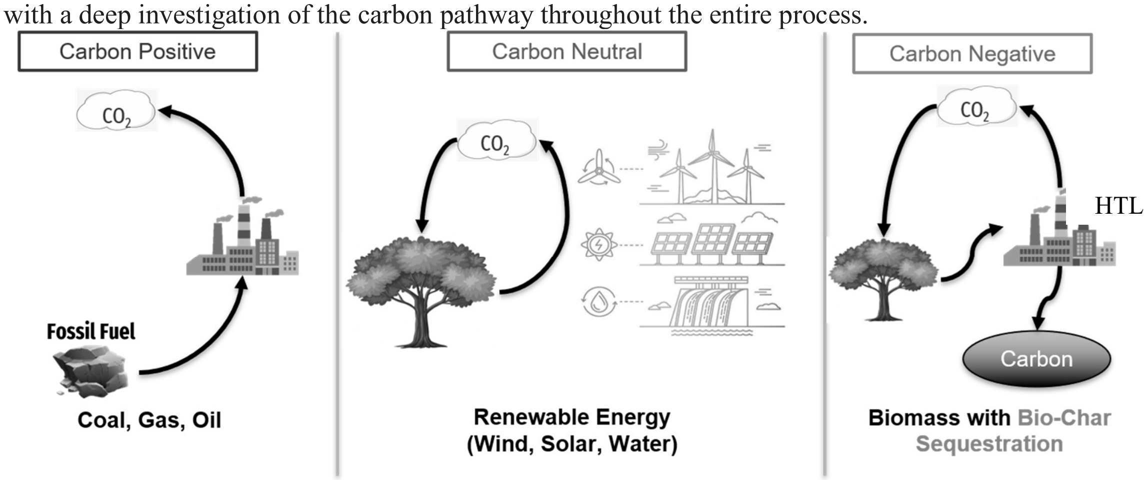

Figure-1: Possibility of Biomass energy being Carbon Negative

2. MATERIALS AND METHODOLOGY

2.1 Description of the Assessment Process

A closer look was taken at the environmental impact of turning wet-waste into energy using hydrothermal liquefaction (HTL) in our experiments to figure out the carbon footprint of the entire process from start to finish. A cradle-to-grave assessment method is used in this study. The lab-scale biofuel production process from fecal sludge (FS), peat, and organic solid waste (OSW) using HTL respectively is assumed to be the base of this assessment.

2.2 Feedstock collection and transportation

This study used three types of feedstocks: FS, peat, and OSW. FS sample was collected from the second chamber of the septic tank in the residential area of KUET. The peat sample was obtained from the Abnali wetland region, Khulna District specifically from a depth of 6 to 8 feet. The Municipal Solid Waste (MSW) sample was collected from the Khulna University of Engineering & Technology (KUET) waste management plant. As a means of transportation, to convey the sample to the laboratory, hand-pulled vans were used.

2.3 Pre-processing and storage of feedstock

After collection, the organic component of MSW (OSW), including food, paper, and wood residue was separated. The FS, peat, and OSW samples blended separately to form a homogeneous slurry. The peat and OSW samples were sieved (2 mm sieve). The well-blended samples were stored in a laboratory refrigerator (4◦C) until the HTL experiment was conducted.

2.4 Hydrothermal liquefaction (HTL)

The HTL experiments were carried out in a 25 mL stainless steel (SS 304) batch reactor with a working volume of 10 mL. In each HTL run, biomass was added directly to the reactor, and the system was sealed mechanically using a copper gasket and steelhead. Subsequently, the sealed reactor was placed in a Carbolite ESF 12/2, Bamford, Sheffield model Furnace. The HTL experiment was conducted at 300 ◦C with a heating rate of 65 ◦C/min and a 60-minute reaction time (Dandamudi et al., 2020).

2.5 Product separation from HTL product

After 60 minutes in the furnace, the reactor was taken out and cooled down for 10 minutes using tap water, and the compressed gases were vented out upon opening the head. The HTL effluent was dissolved in a 30 mL dichloromethane (DCM) solution (Dandamudi et al., 2020). The resulting mixture was then transferred into 15 mL polypropylene centrifuge tubes and vortexed for 5 minutes to dissolve the organic phase into DCM. The product mixture, consisting of biocrude, biochar, and the aqueous phase, was centrifuged using a NUVE NF 800/800R multi-purpose benchtop centrifuge at 4000 rpm for 10 minutes to separate each layer product ((Khalekuzzaman et al., 2021), 2020; Xu et al., 2019). The HTL products were separated into three layers: aqueous phase (top layer), biochar (middle layer), and DCM-dissolved biocrude/oil (bottom layer). The aqueous phase and DCM-dissolved biocrude layer were then separated using a 3 mL syringe. Finally, the DCM of the organic phase was evaporated in a rotary evaporator, and the biocrude samples were stored in a lab freezer until further analysis. Additionally, the aqueous phase and biochar samples were dried in an oven (65 ◦C) overnight and stored in the refrigerator for subsequent analysis. The experimental flow diagram is illustrated in Figure-2.

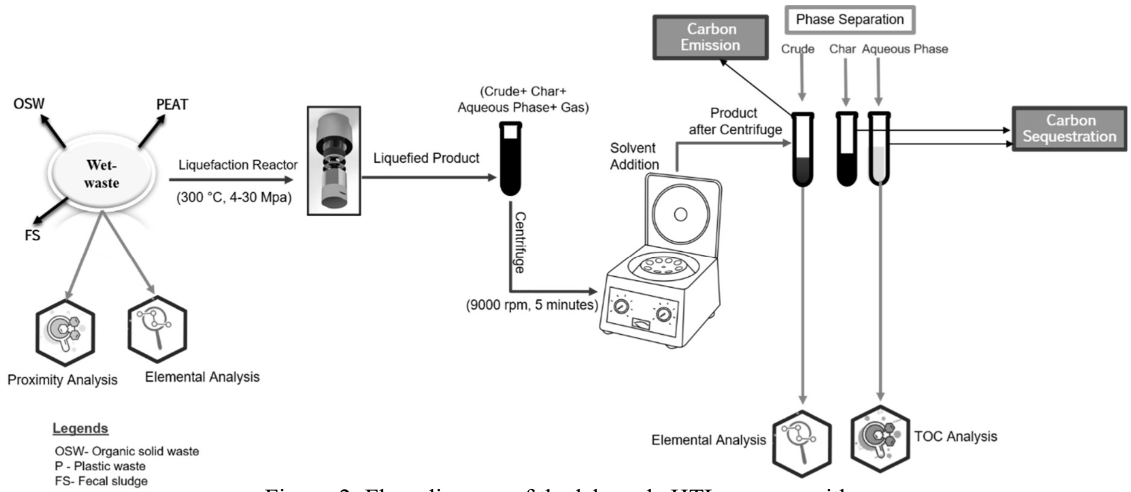

Figure-2: Flow diagram of the lab-scale HTL process with conducted analysis

2.6 Yield Calculation

The determination of all experimental HTL products (biocrude, biochar, aqueous phase, and gas phase) was conducted on a dry basis. The percentage weight yields for biocrude, biochar, aqueous phase, gas, conversion rate, and energy recovery (ER) were computed using the equations (1) – (4), as outlined in prior works (Chopra et al., 2019; Feng et al., 2018).

$$\text{Biocrude yield (\%)} = (\text{mass of biocrude}) / (\text{mass of biomass}) \times 100\% \tag{1}$$

$$\text{Biochar yield (\%)} = (\text{mass of biochar}) / (\text{mass of biomass}) \times 100\% \tag{2}$$

$$\text{Aqueous phase (\%)} = (\text{mass of aqueous phase}) / (\text{mass of biomass}) \times 100\% \tag{3}$$

$$\text{Energy recovery (ER\%)} = (HHV_{(biocrude)} \times Y_{(biocrude)}) / (HHV_{(dry\ biomass)} \times 100 \tag{4}$$

Equations (5) and (6) were used to calculate the Higher Heating Value (HHV) (Channiwala & Parikh, 2002). Here, C, H, O, N, and AC represent the percentage weight of carbon, hydrogen, oxygen, nitrogen, and ash content, respectively.

$$HHV_{(biocrude)} = 0.3383C + 1.422(H - O/8) \tag{5}$$

$$HHV_{(biomass)} = 0.3491C + 1.1783H - 0.1034O - 0.0151N - 0.021AC \tag{6}$$

2.7 Analytical methods

Following the methodology outlined by (Fan et al., 2021), the hydrogen-to-carbon effective (H/C_{eff}) ratio of the feedstocks was computed using Eq. (7) as a means to justify their potential for biocrude conversion as shown in previous studies (Hossain et al., 2022b; Kabir & Khalekuzzaman, 2022).

$$H/C_{eff} = (H - 2O) / C \tag{7}$$

2.7.1 Elemental Analysis

Elemental composition analysis of biomass, biocrude samples was carried out using a CE-440 elemental analyzer (Exeter Analytical Inc., USA), determining the levels of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). To supplement this, empirical equations (8) – (11) from (Parikh et al., 2007) were employed for a comparative analysis of the carbon, hydrogen, oxygen, and HHV values of biomass samples based on elemental analysis. Proximate analysis of biomass samples (FS, Peat, OSW), encompassing parameters such as total solids (TS), moisture content (MC), and volatile matter (VM) adhered to the (Standard Methods for the Examination of Water and Wastewater, 1999) (SM 2540 G). The ash content was determined using ASTM E1755-01 and Ash Content is found using ASTM D 3175-02. Furthermore, the higher heating value (HHV) of biomass samples was gauged using a bomb calorimeter (Adnace B.C.M, Sl. No. B216055), with the obtained HHV values compared against those derived from elemental analysis.

$$C=0.635FC + 0.460VM–0.095AC\ (\%) \tag{8}$$

$$H=0.059FC + 0.060VM + 0.010AC\ (\%) \tag{9}$$

$$O =0.340FC + 0.469VM –0.023AC\ (\%) \tag{10}$$

$$HHV_{(biomass)} =0.3536FC + 01559VM–0.0078AC\ (MJ/ kg) \tag{11}$$

2.7.2 Deamination of Carbon content in the Aqueous phase and biochar

Total Carbon (Organic and Inorganic) in the aqueous phase was determined by using Sievers InnovOx ES Laboratory Total Organic Carbon (TOC) Analyzers. As for the biochar, the carbon content was determined by mass balancing with the following Eq. (12).

$$C_{(biochar)} = C_{(biomass)}-C_{(biocrude)}-C_{(aqueous\ phase)} \tag{12}$$

2.8 Equivalent CO_2 (CO_2e) calculation

The weight of carbon content in feedstocks and products (biocrude, biochar, aqueous phase) was converted to the equivalent weight of CO_2e using equation (13). The GHG emission (CO_2e) due to the electric energy consumed in the HTL process was calculated using equation (14) formed using the data from(CLIMATE TRANSPARENCY REPORT, 2020 BANGLADESH). Net carbon balance was calculated using equation (15)

$$CO_2e = C \times 3.67 \tag{13}$$

$$CO_2e\ (kg) = \text{Electric Energy Consumed (KW-h)} \times 504/1000 \tag{14}$$

$$\text{Net Carbon Balance= Sum of all Carbon Emissions – Sum of all Carbon Sequestration} \tag{15}$$

3. RESULT AND DISCUSSION

3.1 Characterization of Feedstock

The proximate, elemental analysis, and elemental molar ratios with HHV of the three feedstocks FS, Peat (P), and OSW. Proximate analysis revealed elevated organic content, specifically volatile matter, in all three biomass, FS (6.76%), P (8.19%), and OSW (12.13%) compared to ash content (<5%), complemented by an adequate amount of fixed carbon (0.5–1.9%). Elemental analysis unveiled the carbon, hydrogen, nitrogen, sulfur, and oxygen content in the feedstocks, FS, P, and OSW respectively. The higher heating value (HHV) of OSW (16.94 MJ/kg) was the highest among the three feedstocks. FS and P's HHV was found 10.29 and 15.05 MJ/kg respectively. HHV values for both P and FS aligned with those of other feedstocks used in previous Hydrothermal Liquefaction (HTL) studies (Ali Shah et al., 2021; Mugerwa et al., 2019). H/C_{eff} ratios were found 0.28 for FS and 0.36 for P, and 0.38 for OSW, identified through elemental analysis, indicating a high prospect of energy-dense biocrude production. (B. Li et al., 2021) explored how an elevated H/C_{eff} ratio in the feedstock could boost the biocrude production rate during liquefaction, while a low H/Ceff ratio (below 0.2) prominently results in char formation. Hence, the FS, P, and OSW all revealed their substantial potential for liquefaction.

The characteristics of the three feedstocks are given below in table-2. The characteristics showed similar characteristics to previous studies and their high potential to be used as a feedstock for HTL to produce biocrude.

Table-2: Characterization of Feedstock

Components	**FS**	**Peat**	**OSW**
Proximate Analysis (wt %)			
Moisture	88.13±0.24	91.81±0.22	90.63±0.27
Total Solids	11.87±0.31	8.19±0.21	9.37±0.37
Volatile Matter (VM)	6.76±0.32	5.37±0.25	7.92±0.47
Ash Content	4.46±0.23	1.79±0.21	0.62±0.24
Fixed Carbon[a]	0.65±0.19	1.03±.20	0.85±0.07
Elemental Composition (dry basis, wt%)			
C	27.67	39.52	44.2
H	4.12	5.11	6.35
N	2.32	2.05	3.27
S	0.58	0.06	0.15
O[a]	27.74	31.40	39.63
Elemental Molar Ratio			
H/C	1.79	1.55	1.72
O/C	0.75	0.60	0.67
N/C	0.07	0.04	0.06
H/C_{eff}	0.28	0.36	0.38
HHV ($MJ\ Kg^{-1}$)	10.82	16.08	18.63

[a] by difference: O (wt%) = {100 – the sum of (C, H, N, S, Ash)}, Fixed carbon, (%) = {100 – (moisture+ volatile matter+ ash content).

3.2 Elemental analysis based on proximate analysis

In adherence to the experimental elemental compositions of biomass, empirical equations were applied, considering a moisture content (MC) of 6.16% for P and 6% for FS, as specified by (Saffe et al., 2019; Shen et al., 2010). Employing these MC values, we subsequently computed the proximate analysis data (VM, FC, and AC). For FS, the corresponding proximate analysis data were VM (56.95%), FC (5.47%), and AC (37.48%), while for P, they were VM (65.51%), FC (12.57%), and AC (21.86%), and for OSW, the values were VM (84.53%), FC (9.07%), and AC (6.4%).

Consistent with earlier studies by (Saffe et al., 2019; Shen et al., 2010), we utilized the proximate analysis data to determine the elemental compositions (C, H, and O) and higher heating value (HHV) of the biomass. The elemental compositions derived from these equations closely mirrored the experimental results, as outlined in Table 3.

This observation verifies the result from elemental analysis as well as suggests that the elemental composition (C, H, and O) and HHV of any biomass can be economically estimated from its proximate analysis data.

Table-3: Comparing the elemental analysis results obtained from the elemental analyzer with those derived from the developed empirical equation for FS, P, and OSW.

	Elemental Analysis Result			**Elemental Analysis by empirical eq. (10)-(13)**		
Components	FS	P	OSW	FS	P	OSW
C (wt%)	27.67	39.52	44.2	26.10	36.07	44.03
H (wt%)	4.12	5.11	6.35	4.12	4.89	5.67
O (wt%)	27.74	31.40	39.63	27.71	34.52	42.58
HHV (MJ/kg)	10.82	16.08	18.63	10.52	14.50	16.34

3.3 Yields from HTL of biomass

Hydrothermal liquefaction (HTL) yields of biomass are contingent on various parameters, including temperature, retention time, solid loading, and biomass composition, serving as critical variables for product yield (H. Li et al., 2014). Consistent with recommended HTL parameters ((Dandamudi et al., 2020; Wang et al., 2013), our study conducted all HTL at an operating temperature of 300 °C, TS loading of 8–10%, and a reaction time of 60 minutes. The product distribution of biocrude, biochar, and the aqueous phase from HTL of FS, P, and OSW feedstocks are illustrated in Figure-3.

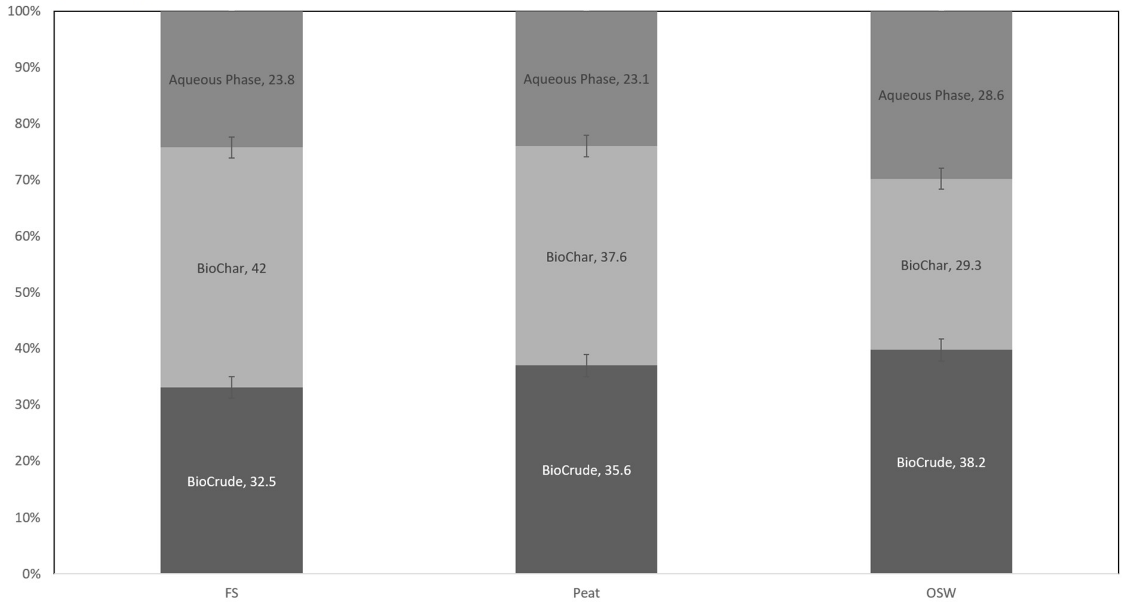

Figure-3: Yields from HTL of FS, Peat, and OSW.

3.4 Elemental Analysis and energy recovery of biocrude

The elemental analysis of both biomass and biocrude indicated elevated carbon and hydrogen contents in the biocrude samples compared to the biomass, signifying energy accumulation during the Hydrothermal Liquefaction (HTL) (refer to Tables 1 and 2). Biocrude samples from FS, P, and OSW exhibited higher levels of carbon and hydrogen than their corresponding biomass, suggesting an increase in hydrocarbons at the expense of nitrogen and oxygen compounds. Nitrogen and oxygen content was comparatively lower in all biocrude samples than in biomass, indicating denitrogenating and deoxygenation. Consequently, the O/C and N/C ratios were lower in biocrude samples than in biomass. The N/C (<0.02) of all biocrude samples met petro-crude specifications, but their O/C ratios (>0.02) did not meet the criteria (Koley et al., 2018), suggesting the need for upgradation to reduce oxygen rather than nitrogen. The Higher Heating Value (HHV) of the crude samples showed a significant increase. These results underscore the positive energy outcome of the HTL process. Notably, the highest HHV was achieved from the crude sample from HTL of OSW. The Energy Recovery (ER %) values of the FS, P, and OSW samples were found 45.19%, 43.73%, and 70.81% respectively, showing the OSW had the highest energy recovery among the three feedstocks.

Table-4: Elemental Analysis of biocrude sample from HTL of FS, P, and OSW

Components	**FS**	**P**	**OSW**
Elemental Composition (dry basis, wt%)			
C	60.28	58.55	64.19
H	8.45	10.89	8.74
N	0.39	0.67	5.03
O	31.17	28.68	21.12
Elemental Molar Ratio			
H/C	1.68	2.23	1.63
O/C	0.39	0.37	0.25
N/C	0.01	0.01	0.07
H/C_{eff}	0.91	1.50	1.14

ER%	45.19	43.73	70.81

3.5 Total Carbon in the Aqueous Phase and biochar

After the separation of the aqueous phase, it was stored in the laboratory refrigerator. Using a calibrated Sievers InnovOx ES Laboratory Total Organic Carbon (TOC) Analyzer, total carbon in the aqueous phase was determined. The aqueous phase from OSW showed the most carbon (C) content, 182000 mg/L, whereas the aqueous phase of FS and P showed 100000 and 142000 mg/L of total C content. This indicates a significant amount of carbon is captured in aqueous phase during the HTL process. Carbon content in biochar from HTL of FS, P, and OSW was calculated using equation (12). The resulting carbon contents are presented in table-5.

Table-5: Total Carbon in the Aqueous phase and biochar

Components	**FS**	**P**	**OSW**
TOC Analysis			
Total Carbon (mg/L)	72000	132000	152000
C content in Biochar using eq (12)			
C (wt%)	14.01	41.56	52.33

3.6 Energy Consumption in the HTL

An HTL process run on a pilot scale was conducted to learn the energy consumption of single batch production of biocrude from biomass. The result showed that approximately 9.7 KW-h electric energy is consumed in a single batch of HTL of a 10L batch reactor. This gives a realistic energy consumption scenario in a large-scale production. The energy vs time graph is given in figure-4.

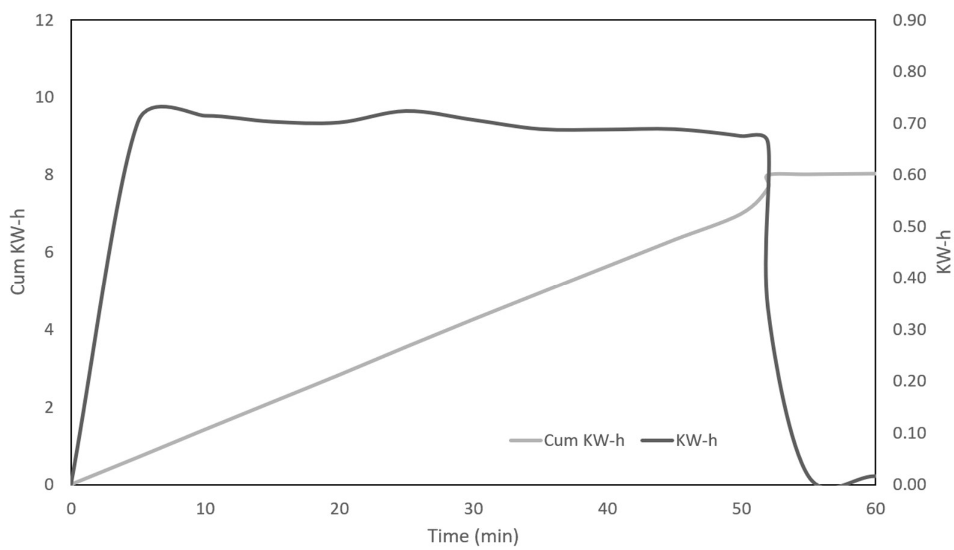

Figure-4: Energy vs Time graph of a single run of a 10L batch reactor.

3.7 Carbon Footprint Assessment

From the elemental analysis of feedstock samples & biocrude samples, TOC analysis of the aqueous phase, and several equations mentioned above, we can find the approximate carbon percentage in feedstock and the HTL products. Among the HTL products, the highest carbon content (50-70%) was obtained in the biocrude, whereas the biochar contained 20-40% and the aqueous phase contained 6-10% of the carbon from the feedstock. This reflects the high potential of producing bio-energy from the feedstocks. The resulting Carbon content (%) in HTL products is shown in the figure-5. Although the lab-scale experiments were conducted on a very small amount of sample, for a clear projection of the scenario, the assessment was carried out for a 10L feedstock sample. The summary of the GHG emission in various stages of the HTL process is given in table-6

Table-6: GHG emission (Kg CO_2e) ins various stage of HTL

	FS	P	OSW
Feedstock	1.45	1.43	1.82
Electricity	4.9	4.9	4.9
Biocrude	1.02	0.75	1.01
Biochar	0.33	0.56	1.01
Aqueous phase	0.09	0.08	0.18

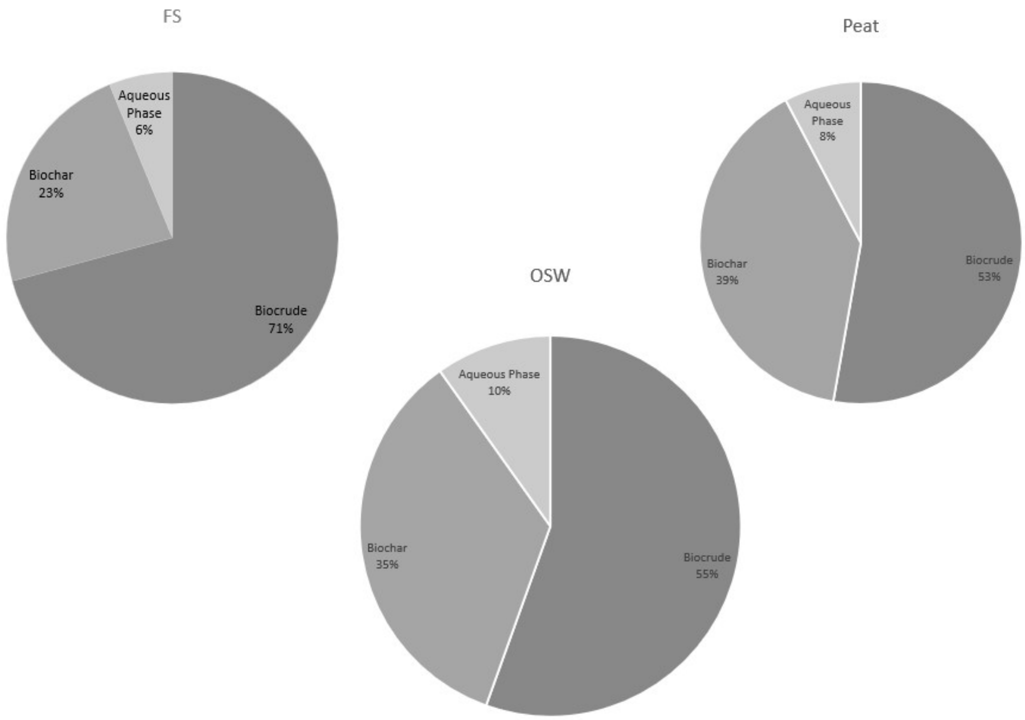

Figure-5: Carbon percentage in HTL products

3.7.1 Addressing Carbon Emission Profile

3.7.1.1 Raw Materials

As we already mentioned earlier, the raw feedstock materials (FS, P, OSW) are contributors to greenhouse gas (GHG) emissions. If they are left unmanaged, various reactions will occur over time and GHG emission will definitely occur. 10L feedstock samples of FS, P, and OSW were found responsible for nearly 1.45, 1.43, and 1.82 Kg equivalent CO_2 (CO_2e) emissions. Using these samples for HTL can open a potential path to the safe management of these wastes, sustainable energy generation process, and add economic value to the wastes.

3.7.1.2 Energy Consumption in HTL

The main source of power for HTL was electricity. The furnace was conducted on electricity. The main source of our electricity is coal. Bangladesh has a high CO_2 emission rate per KW-h electricity usage. According to the (CLIMATE TRANSPARENCY REPORT, 2020 BANGLADESH), 504g of CO_2 is emitted with every 1 KW-h use of electricity in Bangladesh. The energy consumption for the lab-scale furnace was 2KW-h. However, for the assessment of 10L samples, a pilot-scale 10L batch reactor's energy consumption was studied. Through direct use of electricity, a 10L batch reactor would cause an emission of 4.9 kg of CO_2e. The main emission of the HTL process is through the heating of the reactor. However, though industrialization of the process or using a bigger reactor or continuous reactor can cause less emission and as an alternative to this, usage of renewable energy such as windmills, solar energy, and hydro energy, GHG emission can be reduced to almost zero.

3.7.1.3 HTL Product: Biocrude

Biocrude from HTL products of each sample contained high carbon content, potentially making it an option to be refined and used as various bio-energy products. The biocrude will ultimately be used as an alternative to fuels and produce GHG. The potential emission from the biocrude of an HTL of 10L sample of FS, P, and OSW was anticipated to be 1.02, 0.75, and 1.01 Kg CO_2e respectively. The potential path of achieving a renewable energy source with an environment-friendly process has been enriched via HTL of wet-waste, as clearly, there will be GHG emissions from biocrude, but a large portion of the carbon content is sequestrated and managed safely.

3.7.2 Addressing Potential Carbon Sequestration

3.7.2.1 HTL product: Biochar

The biochar products from each HTL have a high potential to be used in the agriculture and water treatment industry. The biochar fraction obtained from 10L feedstock of FS, P, and OSW was anticipated to have 0.33, 0.56, and 1.01 Kg CO_2e respectively. The carbon content in biochar samples is anticipated to be sequestrated safely in soil.

3.7.2.2 HTL product: Aqueous phase

The aqueous phase products from HTL of FS, P, and OSW ought to have 0.09, 0.11, and 0.18 Kg CO_2e respectively. The aqueous phase also functions as a storage medium for carbon content. The carbon content will eventually reach soil or water and be sequestrated. However, the safe disposal of the aqueous phase is to be decided on its properties.

3.7.2.3 Natural Sequestration of Carbon

Naturally trees, soil and water sequestrate carbon. The major contributor of carbon sequestration is trees, as they intake CO_2 for their photosynthesis process. Bangladesh has a forest area of 2.6 million hectares, approximately 17.4% of the total land area of Bangladesh. (Muqsudur Rahman Forest Resources, 2016.) On average, every year the tree tissue in the forests of Bangladesh stores 92 tons of carbon per hectare. So, the average carbon sequestration rate is 6.42×10^{-5} Kg $CO_2e/m^2/min$. At this rate, the CO_2e in biocrude samples will be sequestrated for 8-11 days (considering 1 m^2 area as a working area).

3.7.3 Carbon Balance

The net carbon under different scenarios is provided in table-7. With the gradual optimization of the best scenario for the HTL process, the net carbon balance can be made negative. Ensuring renewable energy sources can make a huge difference in making the process near carbon neutral. However, the increase in the volume of samples can also have a huge impact on making the process carbon neutral. So, industrialization of the process has a high potential in achieving a near-neutral carbon balance process with economically beneficial products from HTL of waste. HTL of wet waste can be a key process in achieving sustainable energy with a carbon-neutral or carbon-negative process. Another important observation from this study is that, to become carbon neutral trees are and always will be the most essential tool, as we can see, the process of being fully carbon neutral involves natural carbon sequestration whose main contributor is trees. So, in addition to optimizing industrial development and modern advancement, planting trees is a necessity for mankind and Mother Earth.

Table-7: Net Carbon Balance (kg CO_2e) under various scenarios

Scenarios	**Carbon Balance (Kg CO_2e)**		
	FS	**P**	**OSW**
Without HTL	+1.45	+1.43	+1.82

Considering national electric grid electricity as a power source for the HTL reactor (without natural sequestration)	+5.5	+4.98	+4.72
Considering Renewable Energy as the power source for the HTL reactor (without natural sequestration)	+0.6	+0.08	-0.18
Considering natural sequestration and Renewable Energy as the power source to the HTL reactor (11 days after the full use of the biocrude)	-0.42	-0.67	-1.19

4. CONCLUSION

The carbon footprint assessment of hydrothermal liquefaction (HTL) of wet waste provides valuable insights into the environmental sustainability of this waste-to-energy conversion process. In this study, the GHG emissions associated with the entire HTL process have been systematically analyzed, from feedstock collection to the production of biocrude after the use of biocrude, considering various parameters such as energy consumption, greenhouse gas emissions, and resource utilization. Various aspects of carbon emissions and energy utilization throughout the entire life cycle of HTL were inspected, shedding light on both the challenges and potential benefits associated with this technology. The findings reveal the potential of HTL as a promising technology for managing wet waste while minimizing the overall carbon footprint. The conversion of wet waste into valuable biocrude demonstrates a viable pathway toward renewable energy production. The biochar and aqueous phase work as carbon capture technology. The results indicate that HTL can contribute to a more sustainable waste management strategy by reducing the reliance on conventional fossil fuels and mitigating greenhouse gas emissions. However, it is crucial to recognize that the environmental impact of HTL can be influenced by various factors, including feedstock composition, process conditions, and energy sources. Optimization of these parameters is essential to enhance the overall efficiency and minimize environmental burdens associated with the HTL process. A deep study on the Life Cycle Assessment (LCA) of HTL processes and products can lead to insightful findings. As a whole, HTL has the potential to become a key component in creating a sustainable and eco-friendly energy solution that contributes positively to the broader goal of mitigating climate change and promoting environmental stewardship.

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