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# Analysis and Characteristics of Hydrochar and Liquid Products Produced via Hydrothermal Liquefaction of Poultry Wastes

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**Abstract**

Hydrothermal liquefaction (HTL) of poultry waste is a potential method for converting high-moisture organic wastes into energy-dense solid and liquid products. In this study, the conversion of poultry waste into biocrude and hydrochar via HTL was explored. The fuel properties and chemical structure of biocrude and hydrochars were examined using standard fuel analytical and spectroscopic techniques. The products were produced from poultry waste via HTL at temperatures ranging from 200 to 350 °C, in 50 °C increments, with a reaction time of 30 minutes. The findings revealed a clear relationship between temperature and product distribution. Specifically, the yield of hydrochar decreased from 24.78 wt% at 200 °C to 23.05 wt% at 300 °C, and the liquid yield increased from 12.14 wt% to 21.15 wt%, indicating that higher temperatures promote better depolymerization and solubilization. Elemental analysis revealed a higher carbon content of 67.26% and a lower oxygen content of 18.96%. This led to an increase in the higher heating value of 31.10 MJ $kg^{-1}$. The liquid products had an acidic pH level of 5.5, which indicated the presence of organic acids. However, elemental analysis revealed a significant nitrogen content of 5.13% in biocrude. As a result, bio-oil produced from HTL of poultry waste should be upgraded through hydrotreatment (hydrodeoxygenation and hydrodenitrogenation) with $H_2$ or a catalyst to minimize oxygen and nitrogen before utilization as a transportation and heating fuel. Therefore, conducting HTL at higher temperatures significantly increases liquid yield and energy density while minimizing solid waste. These findings highlight the significant potential for using poultry waste in HTL to produce sustainable bioenergy and valuable liquid intermediates.

**Keywords:** Hydrothermal liquefaction; poultry waste; biomass valorization; hydrochar; liquid product; physicochemical characterization; waste-to-energy; thermal conversion

## 1. Introduction

The global poultry industry has experienced significant growth, resulting in a dramatic increase in the manufacture of poultry wastes such as manure, litter, feathers, and processing residues. These wastes are particularly high in organic matter, proteins, lipids, nitrogen, and minerals; however, improper management leads to severe environmental issues, considering nutrient leaching, eutrophication of water bodies, along with the emission of greenhouse gases and spread of pathogens (Bolton & Smith, 2019; Lynch et al., 2020). Researchers highlight the growing inevitability of traditional disposal options (land application, open dumping, etc.) becoming unsustainable in many developing countries like Nigeria, owing to both land shortage and increasing environmental regulations (Zhang et al., 2024; Alam et al., 2025). Thus, there is an increasing demand for novel and sustainable wastes-to-energy technologies that can valorize poultry wastes while counteracting environmental hazards.

Hydrothermal liquefaction (HTL) has been considered a potential thermochemical conversion technology for wet biomass due to the use of hot compressed water and the absence of energy-intensive drying (Deepika et al., 2024). HTL is a process that yields several product streams from the conversion of organic feed stocks, with solid primarily being hydrochar; bio-crude or aqueous liquid products, gases, and minor residue. HTL is also most appropriate for chicken waste, which has high moisture content and a complex biochemical composition compared to conventional pyrolysis and combustion (Liu et al., 2023).

Hydrochar produced by hydrothermal liquefaction is gaining popularity as a solid biofuel, a soil enhancer, and a material for capturing substances. This interest comes from its higher carbon content, improved heating value, and altered surface properties (Pasipanodya et al., 2024; Mohan et al., 2025). Furthermore, the liquid residual, also known as aqueous phase or bio-oil precursors, are high in valuable organic compounds such as carboxylic acids, phenolics, ketones, and nitrogen-based ingredients. These can be converted into fuels or specialty chemicals (Negahdar et al., 2016; Ameh et al., 2024). However, it is important to note that how these products are formed and their quality can vary based on factors such as temperature, the length of time they are kept in the process, and the type of materials used.

Despite the increasing research on HTL of different types of biomass, there’s still a lack of detailed studies that focus on the combined analysis and characterization of hydrochar and liquid products specifically from poultry waste. To truly optimize HTL conditions and pinpoint practical end-use applications, we need a solid understanding of their physicochemical, elemental, and energy properties. This study aims to fill that knowledge gap by systematically examining the characteristics of hydrochar and liquid products derived from the hydrothermal liquefaction of poultry waste, ultimately contributing to more sustainable waste management and bioenergy recovery strategies.

## 2.0 Materials and Methods

### 2.1 Material Sourcing and Preparation

Poultry waste was sourced from local poultry farms in Ozoro, Delta State, Nigeria, following ethical and regulatory guidelines (Das et al., 2026). The poultry waste was collected, sorted to remove non-biomass materials, and transported to the laboratory. The poultry waste was sun-dried for 72 h to reduce moisture content and improve grindability (Ayub et al. 2023). After drying, it was ground to a uniform particle size of 1-2 mm, making it suitable for the HTL process. The ground samples were then stored in airtight containers to prevent moisture absorption and degradation, ensuring their quality for use in experiments (Ayub et al. 2022).

### 2.2 Hydrothermal Liquefaction Experiment

The HTL of poultry waste was conducted using a locally fabricated batch reactor in the Chemical Engineering laboratory of the Delta State University, Oleh Campus, Nigeria. The reactor, made from stainless steel with a 500 ml capacity, is specifically designed to handle the high temperatures and pressures essential for the HTL process. It is equipped with an electric heating mantle that allows for precise temperature control up to 400 °C, ensuring the necessary conditions for efficient liquefaction. A high-pressure gauge is installed to measure pressures up to 30 MPa, critical for maintaining the reactor’s integrity during the process. Additionally, a thermocouple is used to continuously monitor the internal temperature, providing accurate data throughout the experiment. A magnetic stirrer is also incorporated to ensure uniform heat distribution within the reactor, which is crucial for consistent and reliable results. The HTL process was carried out under varying conditions of temperature (200 °C – 400 °C) at 50 °C intervals to capture subcritical water behavior and its transition toward near-critical according to Cunha e al. (2018), pressure of 10 MPa to ensure that water remains in liquid phase at elevated temperatures according to Jia et al. (2017), and residence time of 30 min to examine the impact of temperature (Li & Long, 2019) and to investigate their effects on biocrude yield. Therefore conducting HTL experiments under this condition is consistent with literature (He et al., 2018; Leon et al., 2019; Feng et al., 2021; Mozhiarasi & Natarajan, 2022).

### 2.3 Characterization of the Feedstock and HTL Products and its Biocrude Properties

The feedstock, biocrude, and hydrochar were characterized using various analytical techniques to evaluate their properties and suitability for further applications. Proximate analysis was conducted to determine the moisture content, volatile matter, fixed carbon, and ash content of the feedstock and hydrochar, following ASTM D3173-17 and ASTM D3172, as described by Guo et al. (2025). Ultimate analysis was performed to determine the elemental composition (C, H, N, S, O) using a CHNS analyzer (Flash EA 1112, Italy), following ASTM D5373 and ASTM D4239-11, as described by Isemin et al. (2021) and Guo et al. (2025). According to the ASTM D2015-00 standard, the high heating value (HHV) was measured with a bomb calorimeter, and, as suggested by Chukwuneke et al. (2019) and Orugba et al. (2021), Equations 1 and 2 were used to calculate the heating values (HHV & LHV).

$$\mathrm{HHV} = 0.3491\ \mathrm{C} + 1.1783\ \mathrm{H} + 0.1005\ \mathrm{S} - 0.1034\ \mathrm{O} - 0.0151\ \mathrm{N} \quad (1)$$

$$\text{LHV (MJ/kg)} = \text{HHV} - (0.28 \times \text{H}) \quad (2)$$

The carbon, hydrogen, and oxygen content of the CHNSO samples was used to calculate the hydrogen-carbon (H/C) and oxygen-carbon (O/C) ratios of the briquette samples produced under optimal conditions, using Equations 3 and 4, respectively, as described by Ezenwa *et al*. (2024).

$$\text{H/C} = \frac{\%\ weight\ of\ Hydrogen/molar\ weight\ of\ Hydrogen}{\%\ weight\ of\ Carbon/molar\ weight\ of\ Carbon} \quad (3)$$

$$\text{O/C} = \frac{\%\ weight\ of\ Oxygen/molar\ weight\ of\ Oxygen}{\%\ weight\ of\ Carbon/molar\ weight\ of\ Carbon} \quad (4)$$

Biocrude produced at optimum conditions was characterized by viscosity, Ph, and ash content. Viscosity was measured using a digital Brookfield DV-E spindle 5. The pH values of the various bio-oil samples collected were measured at room temperature with a portable pH meter (HQ 30 d Flexi). The fuel features of the biocrude under optimal production conditions were assessed using the ASTM standard procedure for petroleum products according to Chukwuneke et al. (2019). The flash and fire points were obtained using ASTM D93 testing techniques, whereas the pour and cloud points were established using ASTM D97 testing methods. The cetane index and aniline point were determined using the procedures described by Chukwuneke et al. (2021) and Sinebe et al. (2026). TGA was employed to evaluate the thermal stability and decomposition behavior of the feedstock and hydrochar. The samples were heated in a thermogravimetric analyzer (PerkinElmer TGA 4000) from room temperature to 900°C at a controlled heating rate in an inert atmosphere. The weight loss was recorded as a function of temperature to determine thermal stability, decomposition temperatures, and the proportion of volatile components following Chukwuneke et al. (2023) and Chukwuneke et al. (2025). The samples were analyzed using an FTIR spectrometer (Thermo Fisher Nicolet Is10) over a wavelength range of 4000 $\text{cm}^{-1}$ to 500 $\text{cm}^{-1}$ following Chukwuneke et al. (2023).

## 3.0 Results and Discussion

### 3.1 Proximate and Ultimate Analysis of the Feedstock

The poultry waste was characterized using proximate and ultimate analysis. The results of the proximate, ultimate, and heating rate analysis conducted on the feedstock are presented in Table 1.

**Table 1: Proximate and Ultimate Analysis of Poultry Waste**

| Properties | Symbol | Unit | Values |
|---|---|---|---|
| **Proximate Analysis** | | | |
| Moisture content | **MC** | wt.% | 11.42 ± 0.15 |
| Fixed carbon | **FC** | wt.% | 17.18 ± 0.23 |
| Volatile matte | **VM** | wt.% | 63.72 ± 0.46 |
| Ash content | **AC** | wt.% | 7.68 ± 0.22 |
| **Ultimate Analysis** | | | |
| Carbon | **C** | wt.% | 48.95 ± 1.05 |
| Hydrogen | **H** | wt.% | 5.44 ± 0.21 |
| Oxygen | **$O^a$** | wt.% | 42.57 ± 1.40 |
| Nitrogen | **N** | wt.% | 2.68 ± 0.28 |
| Sulfur | **S** | wt.% | 0.36 ± 0.02 |
| Hydrogen/Carbon | **H/C** | - | 0.667 |
| Oxygen/Carbon | **O/C** | - | 0.326 |
| **Heating Rate** | | | |
| Higher heating value | **HHV** | MJ/kg | 19.09 |
| Lower heating value | **LHV** | MJ/kg | 17.57 |

[a] By difference, taking into account the quantity of ashes

The characterization of poultry waste is outlined in Table 1, indicating that poultry waste is rich in carbon content (48.95 ± 1.05 wt.%) and volatile matter (63.72 ± 0.46 wt.%), particularly in relation to the hydrogen element, while the presence of sulfur is in trace amounts (0.36 ± 0.02 wt.%). Table 1 shows that poultry waste is high in VM, which implies that the higher the VM, the faster the combustion and the burning temperature. A relatively high FC indicates an improved char production during the hydrothermal liquefaction conversion process, suggesting that poultry waste can be more exposed to solid combustion. Therefore, FC of 17.18 ± 0.23 wt.% from poultry waste makes it a promising hydrothermal liquefaction feedstock. The MC accounted for 11.42 ± 0.15 wt.%, while the AC accounted for 7.68 ± 0.22 wt.%. This agrees with the findings of (Pandy *et al.*, 2021; Gu *et al.*, 2023).

The ultimate analysis gave the following results: low nitrogen content (2.68 ± 0.28 wt.%), low hydrogen content (5.44 ± 0.21 wt.%), high carbon content (48.95 ± 1.05 wt.%), and finally, a very high oxygen content (42.57 ± 1.40 wt.%), obtained by difference. These values allowed the calculation of the HHV and lower heating value (LHV) of the PW, indicating the HHV of 19.09 MJ/kg and LHV of 17.57 MJ/kg. This value is comparable to that obtained in other works (Hejna *et* al., 2022; Bernal *et al.*, 2023). The amount of Carbon and Hydrogen content in the samples signifies that the samples have high combustibility, indicating that the fuel may successfully replace conventional fossil fuels, as evidence in the higher H/C and O/C ratios obtained from the poultry waste. Both C and H contents are similar to the ones found in the literature; however, N content appears to be higher. The high amount of N may be caused by the high amount of protein and uric acid (Hejna *et al.*, 2022). A high content of N is inadvisable in fuel as these elements are responsible for the emission of Nox emissions, which consequently pollute the environment. However, the higher HHV and lower S content confirm that poultry waste is a promising fuel source.

### 3.2 Functional Group Characterization of Poultry Waste

The FTIR spectrum analysis revealed the functional group compositions present in the poultry waste at wavelengths spanning from 4000 to 400 cm$^{-1}$, as shown in Figure 1. The occurrence of broadband between 3200 and 3550 cm$^{-1}$, corresponding to 3257.7 cm$^{-1}$, was attributed to O-H stretching vibrations of hydroxyl groups from alcohols, phenol, methanol, ethanol, and carboxylic groups bonding to aromatic rings. The adsorption bands of 2926.0 cm$^{-1}$ and 2855.1 cm$^{-1}$ are attributed to stretching of the C-H saturated bond, indicating the presence of aliphatic alkanes and alkenes. This indicates the presence of cellulose and lignin in the poultry waste.

The stretching vibrations of C≡N bond in nitriles (also known as cyanides), C≡C bond in terminal alkynes, and C≡C bond in internal alkynes are also revealed at absorption bands of 2322.1 cm$^{-1}$, 2102.2 cm$^{-1}$, and 1994.1 cm$^{-1}$, respectively. The band's adsorption at 1889.8 cm$^{-1}$ and 1744.4 cm$^{-1}$ could be attributed to C≡O and C=O stretching bands, most likely from metal carbonyl and esters, respectively. The detected adsorption band peaks at 1636.3 cm$^{-1}$ and 1543.1 cm$^{-1}$ indicate the presence of C=C stretching and N-H bending vibration from alkenes and amide compounds, respectively, whilst the band adsorption at 1405.2 cm$^{-1}$ could be due to C-H bending vibration from aromatic compounds. Peaks at 1244.9 cm$^{-1}$ and 1148.0 cm$^{-1}$ suggest the existence of C-O stretching vibration forms of aromatic ethers and aliphatic ethers compounds, respectively, whilst the stretching vibration at 1077.2 cm$^{-1}$ shows the existence of primary alcohols (C-O). The adsorption band at 995.2 cm$^{-1}$ could be induced by C=C bending vibrations from an alkene, whereas the band absorbance at 861.0 cm$^{-1}$ could be generated by C-H bending vibrations from an aromatic compound. Researchers working with poultry waste and litter have discovered the majority of the functional groups (Daramy *et* al., 2020; Santos *et al.*, 2022; Alaneme *et al.*, 2025).

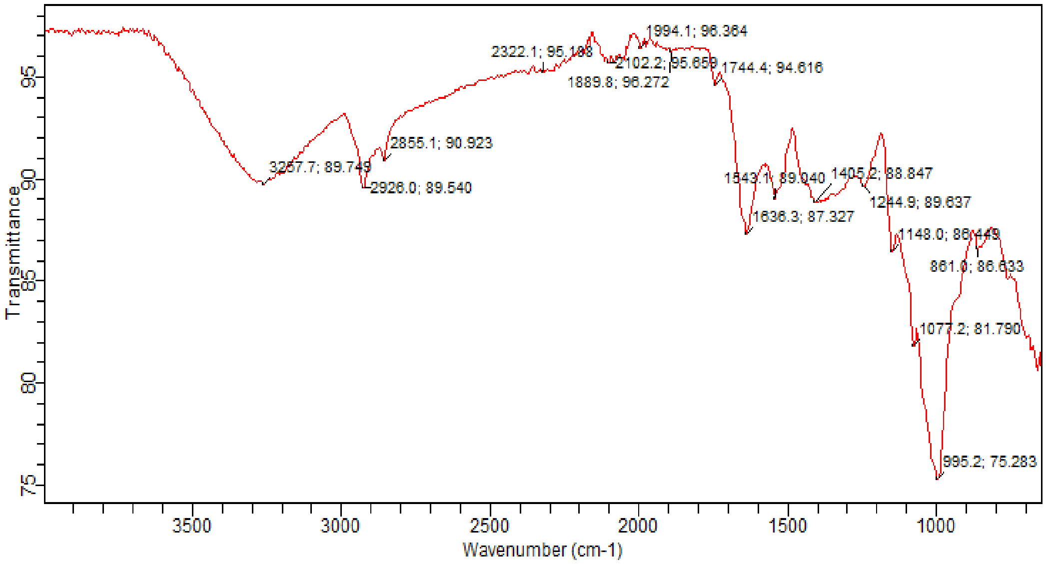

**Figure 1: FTIR Spectra Analysis of Poultry Waste**

### 3.3 Thermal Decomposition Analysis of Poultry Waste

The results of thermogravimetric analysis describing the thermal degradation of the PW are presented in Figure 2. Figure 2 displays the TGA/DTA curves obtained at a heating rate of 20 ºC/min. Three distinct degradation stages are observed: dehydration, devolatilization, and char formation. The dehydration stage occurs between 24.44 °C and 255 °C, involving the loss of moisture and light volatile compounds present in the biomass (Chukwuneke *et al.*, 2025). This stage is characterized by a slight weight loss (approximately 9.417 wt.%) due to the evaporation of water and other light volatiles. The PW retained hemicellulose, cellulose, and lignin despite reaching temperatures of around 255 ◦C. The highest biomass weight loss is recorded in the second stage, occurring over a wide temperature range of 255-525 °C. During the second phase, devolatization occurs at temperatures ranging from 255 ◦C to 525 ◦C, resulting in faster mass loss.

The second phase results in a mass loss of approximately 43.03 wt.%. This stage is characterized by two sub-regions: hemicellulose and cellulose decomposition. During this stage, significant weight loss is observed as the major organic components of the poultry waste decompose. The third stage, representing lignin decomposition and char formation, occurs above 525°C. This is the final decomposition stage, where the remaining poultry waste slowly decomposes into char. The final residue after char formation is relatively higher compared to higher heating rates. The maximum thermal degradation (DTA peak) occurs at 355 ◦C. The temperature at which approximately 47 wt.% of the loaded PW mass decomposed was 558.65 ◦C. Hemicellulose's longer decomposition temperature range (210-330 ◦C) is due to the presence of acetyl groups in its amorphous and random structure made of ordered microfibrils, making it more thermally stable than cellulose (310-400 ◦C). Degradation occurred in the third temperature zone between 550 ◦C and 990 ◦C, resulting in a dry mass loss of approximately 20.38 wt.%. During this phase, lignin slowly decomposes. The slow rate is due to the structure of lignin, which is composed of a complex structure and is thus thermally stable. After the third phase, approximately 22.62 wt.% of incombustible matter remained. Similar decomposition stages were recorded in the thermal analyses of different materials (Hadroug *et al.*, 2019; Yahya *et al.*, 2023; Nyoni & Kelebopile, 2023; Chukwuneke *et al.*, 2025).

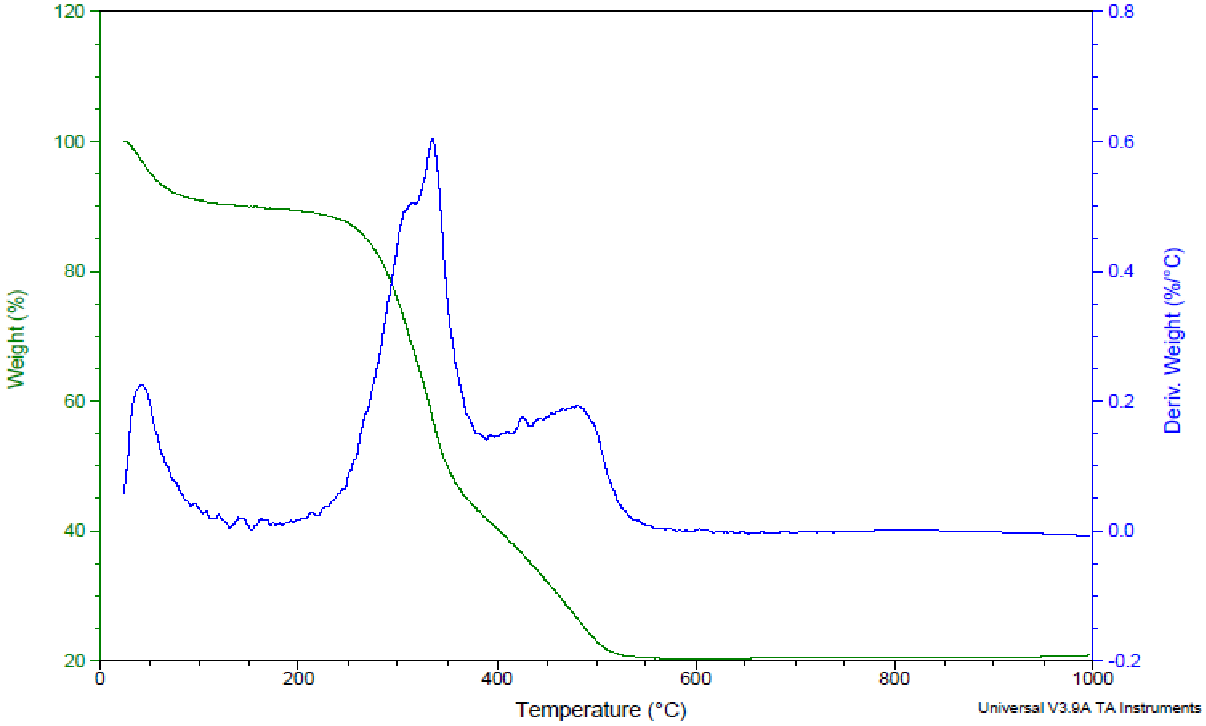

**Figure 2: TGA/DTA Analysis of Poultry Waste**

### 3.4 Production of Biocrude Yield

Product yields of all four phases are disclosed in Table 2 for HTL of poultry waste. The biocrude oils show a range from 12.14-21.15 wt.% with a maximum at a temperature of 300℃.

**Table 2: Products Yields from HTL of Poultry Waste**

| HTL of Poultry Waste | | Biocrude Yield (%) | Hydrochar (%) | Liquid (%) | Gas (%) |
|---|---|---|---|---|---|
| Temperature (ºC) | Reaction Time (min) | | | | |
| 200 | 30 | 12.14 ± 0.25 | 24.78 ± 0.51 | 21.15 ± 0.82 | 41.93 ± 0.42 |
| 250 | | 17.08 ± 0.32 | 23.91 ± 0.62 | 18.60 ± 0.65 | 40.41 ± 0.35 |
| 300 | | 21.15 ± 0.15 | 23.05 ± 0.71 | 15.67 ± 0.47 | 40.13 ± 0.25 |
| 350 | | 17.38 ± 0.41 | 20.18 ± 0.49 | 3.25 ± 0.15 | 59.19 ± 0.75 |

Temperature significantly increased biocrude yield, but only to an optimal level. Lower temperatures, approximately 200 °C, resulted in lower yields (12.14%), indicating that the thermal depolymerization process was incomplete and that the conversion of complex organic compounds into oil was limited. When the temperature was increased to 300 °C, it was observed the maximum yield of 21.15%. Biocrude oils yield in this study showed a higher yield when compared to the study by Vadlamudi et al. (2024). These results agree with previous studies on hydrothermal treatment of poultry/chicken manure (Kuncaka et al., 2021; Odales-Bernal et al., 2025). This temperature appears to give sufficient energy for hydrolysis, decarboxylation, and re-polymerization of lipids and proteins into oil-phase organics (Aierzhati et al., 2021). However, increasing the temperature to 350 °C reduced the yield to 17.38%. This decrease is most likely caused by secondary cracking, gasification, and the formation of char under these higher thermal conditions. The breakdown of biocrude intermediates reduces oil-phase recovery while increasing gas and solid byproducts (Xu et al., 2025). In general, lower biocrude oil yields can be attributed to high ash content and the nature of the feedstocks (Hejna et al., 2022). The standard deviation depicted is due to triplicates performed for each scenario mentioned. While the hydrochar yield decreases as the temperature increases. A similar pattern follows in liquid yield. This yield range is consistent with previous literature on animal-waste-based feedstocks, which typically ranges between 15% and 30% (Chen et al., 2020a).

### 3.5 Physico-Chemical and Fuel Properties of Biocrude Produced

Table 3 compares the elemental composition of poultry-waste-derived biocrude produced using HTL under optimal conditions to the corresponding conventional petroleum crude.

**Table 3: Elemental Composition of Poultry-Waste-Derived Biocrude Yield**

| Element | Symbol | Value (wt%) | Petroleum Crude (Zhang et al., 2020) |
|---|---|---|---|
| Carbon | C | 67.26 ± 1.25 | 83–87 |
| Hydrogen | H | 8.15 ± 0.34 | 11–14 |
| Nitrogen | N | 5.13 ± 0.52 | <0.2 |
| Oxygen | O | 18.96 ± 0.22 | <1 |
| Sulfur | S | 0.5 ± 0.02 | 0.1–3 |
| Hydrogen/ Carborn | H/C | 0.727 | 1.6 – 2.0 |
| Oxygen/ Carbon | O/C | 0.106 | 0.001 – 0.02 |
| Higher heating value | HHV | 31.10 | 42–45 |
| Lower heating value | LHV | 28.82 | - |
| Cetane Index | CI | 32.50 | 45 – 55 |

The poultry biocrude has a high carbon content of 67.26 ± 1.25% and a moderate hydrogen concentration of 8.15 ± 0.34%, indicating a hydrocarbon-rich composition, similar to other lipid-based feedstocks. However, the oxygen concentration is high (18.96 ± 0.22%), implying that some deoxygenation happened during the hydrothermal liquefaction (HTL) process. This emphasizes the need for thermal upgrading, notably hydrodeoxygenation, to increase energy density and stability. The nitrogen content is relatively high, at 5.3%, as one would expect given the protein composition in poultry waste. Throughout HTL, numerous nitrogenous chemicals such as amides, pyridines, and indoles are formed, which can hurt fuel quality; hence, they must be reduced throughout the upgrading process. Although the sulfur content is low at 0.5 ± 0.02%, it is still higher than that of other microalgae biocrudes, and if not adequately processed, it may result in Sox emissions (Leng et al., 2018; Zhang et al., 2020).

The elemental composition findings suggest that poultry waste can produce a biocrude with a promising carbon-to-hydrogen ratio, which falls between lignocellulosic bio-oil and fossil diesel. While the oxygen and nitrogen levels are slightly greater than those found in petroleum fuels, they remain within a range that allows thermal upgrading to renewable diesel or jet fuel. Furthermore, the decreased sulfur level makes it a more environmentally friendly option than oils obtained from fossil fuels. The higher heating value (HHV) of 31.10 MJ/kg for the biocrude obtained from poultry waste is comparable to conventional HTL biocrudes, falling between lignocellulosic bio-oils and fossil diesel, which is around 43 MJ/kg (Srivastava et al., 2025; Chukwuneke et al., 2025). This shows a fair energy density, owing mostly to its high carbon content (67.26 ± 1.25%) and hydrogen content (8.15 ± 0.34%), as well as a comparatively low oxygen percentage (18.96 ± 0.22%) when compared to other biomass sources (Bagchi et al., 2021; Srivastava et al., 2025). This value demonstrates that HTL effectively concentrates the chemical energy contained in poultry waste materials into an oil-based product with solid combustion potential and heating performance. However, the presence of oxygen and nitrogen reduces its HHV and impairs thermal stability, implying that additional hydrotreatment may be required to improve fuel quality and meet renewable diesel standards.

**Table 4: Physico-chemical Properties of Biocrude Derived from Poultry Waste via HTL**

| Property | Unit | Value | Standard / Method |
|---|---|---|---|
| Density | g/cm³ | 0.871 | ASTM D4052 |
| Kinematic Viscosity @ 40°C | mm²/s | 10.7 | ASTM D445 |
| Acid Value | mg KOH/g | 37 | ASTM D664 |
| Free Fatty Acid (FFA) | wt% | 22 | AOCS Ca 5a-40 |
| Saponification Value | mg KOH/g | 181 | AOCS Cd 3-25 |
| Iodine Value |  | 73 | AOCS Cd 1-25 |
| Peroxide Value | mleq/kg | 9.4 | AOCS Cd 8b-90 |
| Refractive Index (30 °C) | $n_D$ | 1.39 | ASTM D1218 |
| pH | — | 5.5 | ASTM D6423 |
| HHV | MJ/kg | 31.10 | ASTM D240 |
| Color / Appearance | — | Dark brown, viscous | Visual |
| Odor | — | Pungent, phenolic | Sensory |

Table 4 shows that the study of poultry-waste-derived biocrude reveals to be a complex blend of oxygenated hydrocarbons, fatty acids, and aromatic compounds, falling between raw bio-oil and processed fuel. It has a density of 0.871 g/cm³ and a kinematic viscosity of 10.7 mm²/s, making it denser and more viscous than standard diesel. This indicates that heavy, oxygen-rich molecules formed during HTL through secondary polymerization and condensation processes. The acid value, which is 37 mg KOH/g, along with FFA value of 22%, indicates incomplete decarboxylation, resulting in a moderately acidic fuel that requires upgrading to improve stability and shelf life. This biocrude contains short-chain fatty acids and unsaturated hydrocarbons, similar to lipid-derived intermediates from poultry waste, as indicated by its saponification value of 181 mg KOH/g and iodine values of 73. The peroxide value of 9.4 mleq/kg and acidic pH of 5.5 indicate the existence of reactive oxygen species and partial oxidation of organic compounds, potentially making the biocrude unstable over time. The refractive index of 1.39, which is consistent with other lipid-based biocrudes, indicates a moderate level of aromaticity and conjugation. The greater heating value, which is 31.10 MJ/kg, demonstrates the fuel's significant energy potential, approaching that of petroleum diesel (43 MJ/kg). Overall, these findings suggest that poultry waste is a feasible source for generating renewable liquid fuel via HTL. However, to improve the fuel's combustion performance and ensure compatibility with existing petroleum infrastructure, light catalytic upgrading or hydrodeoxygenation is required to reduce acidity, viscosity, and oxygen content.

**Table 5: Thermal and Physical Transition Properties of Poultry-Waste-Derived Biocrude**

| Property | Unit | Value | Standard |
|---|---|---|---|
| Flash Point | °C | 128 | ASTM D93 |
| Fire Point | °C | 155 | ASTM D92 |
| Pour Point | °C | –5.5 | ASTM D97 |
| Cloud Point | °C | 4 | ASTM D2500 |
| Melting Point | °C | 19 | ASTM D87 (Modified) |
| Aniline Point | °C | 53 | ASTM D611 |

The flash point of biocrude obtained from poultry waste is 128 °C, much higher than that of petroleum diesel, which fluctuates between 60 and 80 °C. This greater flash point indicates that the biocrude is low in volatility and less flammable at room temperature. This higher flash point is due to the presence of high-molecular-weight and oxygen-rich components such as long-chain fatty acids, esters, and phenolic derivatives. These chemicals take more energy to evaporate and burn. Furthermore, the fire point, which is 155 °C and slightly greater than the flash point, suggests that once ignited, the biocrude burns steadily, consistent with its thick and fragrant properties. The biocrude's cold flow qualities include a pour point of -5.5 °C and a cloud point of 4 °C. Because of the unsaturated and branched hydrocarbon chains, the oil remains semi-fluid even at temperatures near freezing. However, the slightly positive cloud point indicates that wax crystallization begins at lower temperatures, which may cause flow issues during cold storage or pumping. To overcome this issue, combine the biocrude with lighter hydrocarbons or use cold-flow additives. The melting point of 19 °C indicates that the biocrude is semi-solid at room temperature, which is typical for bio-oils derived from animal waste. This is owing to the complex mix of paraffins, aromatics, and fatty acid derivatives produced by the breakdown of lipids. Finally, the aniline point of 53 °C serves as an important indicator of both aromatic concentration and solvent behavior.

**Table 6: Comparison of Biocrude and Hydrochar Properties from HTL of Poultry Waste**

| Feedstock | HTL Conditions | Biocrude Yield (%) | Hydrochar / Solid (%) | HHV (MJ/kg) | C (%) | H (%) | N (%) | O (%) | S (%) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Poultry waste | 300 °C, 10 MPa, 30 min | **21.15** | **20.18–24.78** | **31.10** | **67.26** | **8.15** | **5.13** | **18.96** | **0.50** | *This study* |
| Chicken manure | 300 °C, 30 min | 18.6 | 19.3–24.6 | ~32–33 | 66–69 | 8–9 | 4–6 | 17–20 | < 1 | Chen et al., 2020a |
| Animal manure | optimized HTL | up to ~22 | ~20–28 | 28–32 | 58–70 | 7–9 | 4–7 | 16–24 | < 1 | Kumar et al., 2020 |
| Chicken manure | 300 °C, 30 min | 18.6 | 19.3–24.6 | 32 | 66 | 8 | 6 | 17 | <1 | Elliott et al., 2015 |
| Chicken manure | direct HTL | ~20–25 | – | 31–34 | 65–70 | 8–10 | 4–7 | 15–20 | < 1 | Li & Long, 2019 |
| Chicken manure | two-stage HTL | ~32–38 | – | 34–38 | 70–74 | 9–10 | 2–4 | 10–15 | < 1 | Vadlamudi et al., 2024 |
| Municipal solid waste / general biomass review | Literature summary ranges | Usually 10–30 | Usually 15–30 | 24–36 | Variable | Variable | Variable | Variable | Variable | Zhang et al., 2024 |

In this study, the biocrude yield ranged from 12.14 to 21.15 %, which is consistent with the range reported for direct HTL of poultry and animal manures, which is typically between 12 and 25 %. The hydrochar yield, which ranged between 20.18 and 24.78 wt%, is consistent with previous research, demonstrating the increased char production from protein-rich feedstocks (Chen et al., 2020a; Kumar et al., 2020). The biocrude's HHV of 31.10 MJ $kg^{-1}$ is similar to other poultry-derived biocrudes, which typically range between 31 and 34 MJ $kg^{-1}$, indicating efficient carbon densification. The elemental makeup, with 67.26% carbon, 8.15% hydrogen, and 5.13% nitrogen, is consistent with prior observations. However, recent two-stage HTL methods have produced slightly higher yields and nitrogen reductions (Vadlamudi et al., 2024). Overall, these findings support HTL as a promising waste-to-energy alternative for organic waste in developing nations (Zhang et al., 2024).

### 3.6 FTIR Analysis of Biocrude

The FTIR spectrum of the biocrude obtained from poultry waste shows some important functional groups, as shown in Figure 3. The broad absorption peaks at 3858.4 $cm^{-1}$ and 3639.7 $cm^{-1}$ are linked to O–H stretching vibrations of hydroxyl groups, hinting at the partial retention of alcohol and phenolic compounds that usually come from the lignocellulosic and protein parts of poultry waste. The bands found between 2953.9–2855.1 $cm^{-1}$ are associated with C–H stretching vibrations of alkanes and aliphatic chains, indicating an increase in saturated hydrocarbons due to hydrogenation and decarboxylation. Moreover, the weak yet noticeable band at 2130.2 $cm^{-1}$ signifies C≡C stretching of alkynes, which are intermediates created during the thermal cracking and secondary reforming of fatty acid derivatives. The peaks appearing at 1996.0 and 1979.2 cm⁻¹ reflect C=C stretching vibrations of aromatic hydrocarbons, confirming the processes of aromatization and deoxygenation that improve fuel stability and calorific value. A prominent C=O stretching band at 1729.5 cm⁻¹ points to the presence of carbonyl functional groups, mainly found in esters, ketones, and aldehydes. The peaks ranging from 1600.9 to 1509.6 cm⁻¹ are indicative of C=C aromatic stretching and N–H bending, suggesting that nitrogenated aromatics are likely formed from the breakdown of proteins and amino acids. Additionally, the bands around 1459.3 and 1377.3 cm⁻¹ correspond to $CH_2$ and $CH_3$ bending vibrations, showcasing the aliphatic backbone of the biocrude.

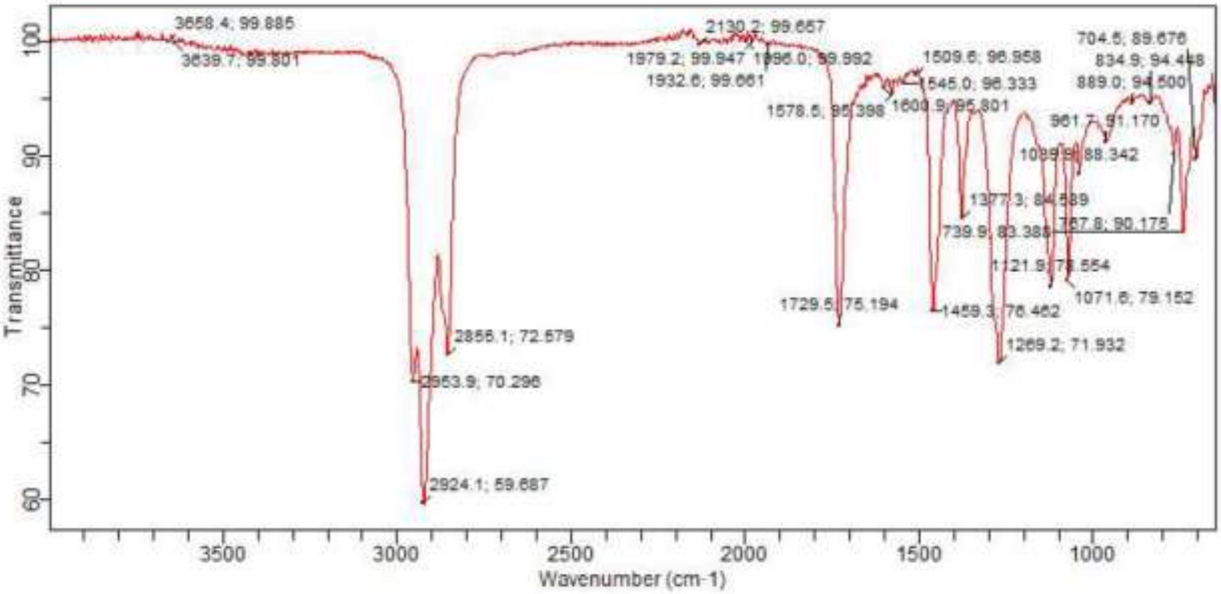

**Figure 3: FTIR Analysis of the Biocrude Derived from Poultry Waste**

The medium-intensity bands between 1269.2 and 1071.6 cm⁻¹ are associated with C–O stretching vibrations from alcohols, esters, and ethers, reflecting the partial oxygenation that's typical of HTL oils. In the impression region (961.7–704.5 cm⁻¹), you can see multiple C–H bending peaks linked to vinyl, trans-alkene, and aromatic structures, confirming the presence of both aliphatic and aromatic hydrocarbons. The spectral features observed here align with those reported by Leng et al. (2022), Chen et al. (2020b), and Neveux et al. (2014), who noted similar changes in biocrudes from protein- and lipid-rich biomasses.

## 4.0 Conclusion

The conclusions are as follows:

1. The HTL of poultry waste with a batch reactor effectively converted organic-rich poultry residues into biocrude and hydrochar. The findings indicated that poultry is a viable feedstock for biofuel production, helping to recycle waste while also producing sustainable energy.
2. The investigation into the effects of temperature on yield and quality revealed that temperature plays an important role in determining biocrude yield and composition. It was established that at a temperature of 300 ºC, the maximum yield of biocrude was obtained.
3. A number of analyses, including proximate, ultimate, FTIR, and TGA, provided useful insights into the physicochemical and fuel properties that occur during HTL. The biocrude had higher quantities of carbon and hydrogen, high oxygen and nitrogen, and a higher heating value, comparable to conventional petroleum fuels. Meanwhile, the hydrochar showed improved porosity, lower ash content, and higher aromaticity in the FTIR spectra, indicating its potential as a solid fuel or adsorbent material.
4. As a result of high oxygen and nitrogen content, bio-oil produced from HTL of poultry waste should be upgraded through hydrotreatment (hydrodeoxygenation and hydrodenitrogenation) with $H_2$ or a catalyst to minimize oxygen and nitrogen before utilization as a transportation and heating fuel.

5. The study shows that utilizing HTL on poultry waste produces energy-rich biocrude and recoverable hydrochar. This indicates an excellent opportunity for large-scale biofuel production in Nigeria, where poultry farming generates a significant amount of organic waste. However, there are challenges to overcome, such as high costs of capital, the need for hydrogen for upgrading, the logistics of collecting feedstock, and regulating nitrogen levels in the biocrude.
6. Future studies should aim to scale up the process, integrate renewable hydrogen sources, explore in-situ catalytic upgrading, and conduct techno-economic modeling. This will aid in optimize energy recovery, lowering operational costs, and assessing environmental implications, allowing for the effective implementation of HTL-based waste-to-energy systems in Nigeria.

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