EXPLORING A LOW-COST APPROACH FOR SEPARATING BIO-CRUDE FROM HYDROTHERMALLY LIQUIFIED FAECAL SLUDGE WITHOUT SOLVENT: A SUSTAINABLE ENERGY AND WASTE MANAGEMENT APPROACH

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ABSTRACT

Fossil fuels are unsustainable as they are non-renewable. Despite the increasing consumption, the reserves of fossil fuels remain finite, necessitating the search for alternative fuel sources. Among these, faecal sludge emerges as a viable fuel source, especially considering the global population will reach 8 billion by 2022, with many people living in underdeveloped regions where sanitation is a pressing challenge. Hydrothermal liquefaction (HTL) of faecal sludge holds promise as a sustainable solution to address both sanitation issues and the looming shortage of fossil fuels. Through this process, bio-crude can be obtained as a valuable product. Studies have demonstrated that hydrothermal liquefaction of faecal sludge yields a substantial percentage of crude, making it a potential renewable energy resource. Bio-crude production from faecal sludge addresses the sanitation problem prevalent in underdeveloped countries, providing a sustainable and environmentally friendly waste management solution. Also, the bio-crude can serve as an alternative to fossil fuels, reducing dependency on finite and environmentally damaging resources. Despite the promising aspects of hydrothermal liquefaction, separating crude from the solution remains challenging due to the conventional use of costly solvents. The reliance on solvents increases the overall cost of the process and poses potential environmental hazards. Therefore, there is a pressing need to explore low-cost and solvent-free methods for separating bio-crude from the faecal sludge liquified product. This thesis aims to develop a low-cost and environmentally friendly bio-crude separation process, eliminating the use of solvents by investigating innovative separation techniques. For this, faecal sludge samples underwent the Hydrothermal Liquefaction process, and three distinct centrifugal speeds—6000, 9000, and 12000 rpm—were employed to separate crude. The assessment of the produced bio-crude quality involved analysing A-factor, C-factor, Vitrinite Reflectance (VR%), Kerogen Type, Maturation Scheme, T_{Fluid}, T_{Burial}, Specific Gravity, and API° Gravity, using Fourier Transform Infrared Spectroscopy (FTIR). Additionally, the production quantity was measured in terms of barrels of bio-crude per metric ton of faecal sludge. The production rates at 6000, 9000, and 12000 rpm were determined as 4.73, 4.33, and 4.36 barrels per metric ton, respectively. Considering the fuel quality, energy consumption, and production rates, separating crude at 12000 rpm was identified as the optimal condition for industrial-scale production. The successful implementation of such a process would make bio-crude production from faecal sludge economically viable and socially beneficial, which could address both the sanitation challenges and the growing energy demand.

Keywords: *Waste-to-energy, Hydrothermal Liquefaction (HTL), Faecal sludge, Biocrude oil, Solvent-free Separation.*

1. INTRODUCTION

As of 2023, the Earth is home to a global population of 8 billion people, with projections indicating that this number will surge to 9.8 billion by 2050, exhibiting a growth rate of 0.84% since 2022. This rapid population expansion poses a significant challenge as it necessitates a substantial amount of fossil fuels to meet the world's increasing energy demands. The issues stemming from this surge include the depletion of fossil fuel reserves, escalating costs, inadequate supplies, and environmental pollution.

For instance, in 2019, gasoline consumption in Bangladesh was estimated to reach 4,000 barrels per day, marking a 35% rise from 2017, as the US Energy Information Administration reported. British Petroleum's evaluation of global energy trends highlights a growing oil demand, exceeding 1.6 million barrels per day, while the world's oil production lags behind at just 0.4 million barrels per day. Moreover, the combustion of fossil fuels contributes to rising global temperatures and greenhouse gas emissions. Consequently, developing alternative energy sources, such as biomass-derived crude oil and biofuels, becomes imperative. Biomass resources like wood scraps, energy crops, macroalgae, field crops, waste products, and municipal and animal waste, among others, can be harnessed to produce fuel or chemicals.

Most of the global population resides in underdeveloped countries with prevalent sanitation problems. Research indicates that worldwide, approximately 600-700 million tons of solid waste and 250-300 million tons of faecal sludge are not managed environmentally sustainably (Hossain et al., 2022). Currently, 2.4 billion people lack access to improved sanitation facilities, with an additional 946 million still practicing open defecation. Sub-Saharan Africa and Southern Asia bear the brunt of these sanitation challenges, hosting the least-covered nations (World Health Organization (WHO) & United Nations Children's Fund (UNICEF), 2015).

Sub-Saharan Africa's 2021 population is estimated to be around 1.13 billion, while Southern Asia is expected to have about 1.97 billion people. Together, these regions encompass over half of the world's total population. Given that most countries in these regions are still developing, the expensive and often burdensome management of their primary energy source, crude oil, prompts the exploration of converting waste materials into viable energy sources.

Various types of waste are generated, including solid waste from homes and cities, which encompasses food scraps, paper, plastic, glass, and metal, as well as industrial and construction debris like concrete, bricks, and wood. Additionally, liquid waste from homes, businesses, and other establishments, including wastewater and sewage, also contributes to the waste challenge. Hazardous waste, such as chemicals, batteries, electrical equipment, and medical waste, poses risks to both human health and the environment. Organic waste, like food scraps, grass clippings, and electronic waste (e-waste) from obsolete or damaged electrical devices, further compound the waste issue. Considering the sanitation crisis and the looming oil scarcity, our primary focus will revolve around both solid and liquid waste, with special emphasis on human sludge.

While solid waste contains a relatively low percentage of water (15-40%), the technological advancements in waste-to-energy facilities in countries like Sweden and Brazil are already making a difference. However, the high moisture content in sewage sludge presents a challenge, necessitating innovative approaches to convert this material into biofuels.

In simple terms, Bangladesh is a developing country facing significant challenges. Like many other developing nations, it grapples with a severe sanitation problem. Most of the population lacks access to adequate sanitary facilities, particularly in rural areas and urban slums. This results in insufficient faecal sludge management in these regions. The sewage sludge generated in these areas is often poorly treated and controlled. For example, in Khulna, only 24.5% of sludge is disposed of properly, while in Dhaka, this figure is just 30.6% (Opel et al., 2012). In 2019, only 59% of the population had access to improved pit latrines, flush toilets, or basic sanitation. Rural areas had even lower sanitation coverage, at 46%.

Furthermore, more than a quarter of the global population still practices open defecation, especially in rural areas (World Bank, 2020).

Hygiene and sanitation have emerged as critical global concerns. The United Nations General Assembly adopted the Sustainable Development Goals (SDGs) in 2015, which include two key objectives in this area: Goal 3, "Good Health and Well-being," and Goal 6, "Clean Water and Sanitation." However, a significant portion of the world's population still lives below the poverty line, lacking access to adequate sanitation facilities, which poses a major obstacle to achieving these goals.

Another important SDG is Goal 7, "Affordable and Clean Energy." Currently, the high price of crude oil is beyond the financial reach of many people. Goal 13, "Climate Action," emphasises the importance of addressing climate issues. Inadequate sanitation not only disrupts daily life but also has adverse environmental impacts. Goal 15, "Life on Land," also relies on several elements, including sanitation and a sustainable energy source.

The lack of proper treatment for human faeces poses health risks, as various pathogens found in faeces can contaminate water and lead to various illnesses. Human faeces composting has proven effective in reducing harmful bacteria and maintaining a healthy carbon-to-nitrogen ratio. Additionally, anaerobic digestion is used for biogas production from faeces, although it is a time-consuming process in both composting and anaerobic digestion. In contrast, pyrolysis, which requires high temperatures (>400°C) and energy-intensive drying of wet waste, has gained attention.

Hydrothermal liquefaction (HTL) has emerged as a promising alternative, allowing the direct conversion of wet waste into bio-crude oil at temperatures of 200-350°C and pressures of 5-20 MPa, as shown in Figure 1. HTL also eliminates microorganisms in the faecal feedstock due to its high-temperature process. HTL stands out from oil extraction and pyrolysis in two key ways: it doesn't require drying of the feedstock, making it suitable for wet biomass with a total solid (TS) content of 10-25%, and it can convert not only lipids but also proteins and carbohydrates into bio-crude oil. Research has shown that swine manure can be converted into bio-crude oil with a maximum oil yield of 24.2% and a higher heating value (HHV) of 36.05 MJ/kg. High-temperature fermentation (HTL) can also mitigate the environmental impact of swine manure by deactivating antibiotic-resistant genes and blocking their release into the environment.

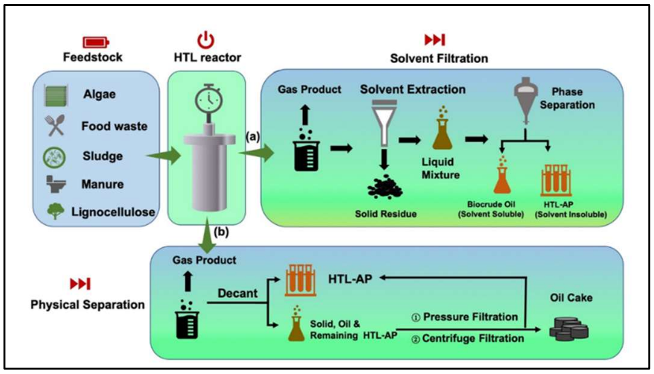

Figure 1: HTL Process (Watson et al., 2020)

The objectives of this study are to produce bio-crude from faecal sludge using the HTL method, separate bio-crude at different centrifugal speeds without using solvents, and analyse the effects of the separation process. Every day, the world's crude oil, a fossil fuel that takes a long time to form naturally, becomes scarcer. Conversely, its demand continues to rise. If this research successfully identifies an alternative source of oil and develops a process that accelerates production while reducing costs, it could significantly improve this situation. This study aims to create a sustainable, cost-effective waste-to-energy conversion method that is environmentally friendly.

2. METHODOLOGY

2.1 Faecal Sludge Collection and Characterization

The faecal sludge used in this study was collected from the second chamber of a septic tank located in the residential area of Khulna University of Engineering & Technology (KUET). The collected faecal sludge was promptly stored at a temperature of 4°C overnight to maintain its integrity. Subsequently, the raw faecal sludge was homogenised through blending and prepared for further analysis, as shown in Figure 2.

Proximity analysis and ultimate analysis were performed on the faecal sludge to characterise its composition, and the results are presented in Table 1. Proximity analysis involved determining the moisture content, volatile matter, and ash content. First, the sample's weight was recorded and heated at 106 °C for 1 hour. After heating, the weight was measured again, and the difference was used to calculate the moisture content. The dried sample was then subjected to heating at 550 °C in a muffle furnace for 1 hour, and its weight was measured once more to calculate the volatile matter content. Subsequently, the sample was heated at 850 °C for 15 minutes, and the difference in weight from the previous stage was used to calculate the fixed carbon content, with the remainder being the ash content. The H/C_{eff} Ratio was calculated using Equation 1 to predict coke formation during hydrothermal liquefaction (HTL) reaction, determining the feasibility of converting biomass into hydrocarbons (Zhang et al., 2011).

$$\frac{H}{C_{eff}} = \frac{H-2O}{C} \tag{1}$$

Where H, C, and O represent the mole percentage of hydrogen, carbon, and oxygen, respectively, based on the analysis.

Table 1: Proximate and Ultimate Composition of Faecal Sludge (FS)

	Components	Unit	Value
Proximate Composition	Moisture Content	% of Weight	88.20
	Total Solids, TS	% of Weight	11.85
	Volatile Matter	% of Weight	6.63
	Ash Content	% of Weight	4.65
	Fixed Carbon	% of Weight	0.52
Ultimate Composition	Carbon, C	% of Weight	27.95
	Hydrogen, H	% of Weight	3.79
	Nitrogen, N	% of Weight	1.13
	Oxygen, O	% of Weight	27.95
	H/C	Molar Ratio	1.44
	O/C	Molar Ratio	0.65
	N/C	Molar Ratio	0.10
	H/C_{eff}	-	0.25
	Chemical Formula	-	$CH_{1.74}O_{0.75}N_{0.04}$
	HHV	MJ/kg	10.48

Here, Volatile Matter, Ash Content, Fixed Carbon, C, H, N, and HHV are reported on a dry basis. O content was calculated by difference:

$$O\ (wt\%) = 100 - Sum\ of\ (C, H, N, Ash) \tag{2}$$

$$Fixed\ Carbon\ (FC), \% = 100 - Sum\ of\ (\%VM, \%MC, \%AC) \tag{3}$$

2.2 Sample Preparation

For each trial, a 12 mL sample was prepared with a composition of 10% faecal sludge and 90% water on a weight basis, as shown in Figure 3. To prepare each sample, 1.2 grams of faecal sludge were weighed and placed in a test tube. Subsequently, 10.8 mL of water was added, and the mixture was thoroughly shaken to ensure proper blending. A vortex machine was employed to homogenise each sample further, with each sample undergoing 5 minutes of vortexing. These prepared samples were then used for Hydrothermal Liquefaction.

2.3 Hydrothermal Liquefaction (HTL)

The hydrothermal liquefaction (HTL) experiments were conducted using a stainless steel (SS304) 25 mL batch reactor with a working volume of 10 mL. For each HTL run, 10 mL of faecal sludge (FS) was directly added to the reactor. The reactor was then securely sealed using a copper gasket and steelhead, as shown in Figure 4 and Figure 5. Subsequently, the sealed reactor was placed inside a Carbolite ESF 12/2 furnace model located in Bamford, Sheffield, as shown in Figure 6. The HTL experiment was carried out at a temperature of 300 ± 10 °C, with a heating rate of 65 °C per minute. Once the temperature reached 300 °C, the timer was initiated, and each experiment was allowed to proceed for a duration of 60 minutes (Dandamudi et al., 2020). After one hour of heating, the reactor was quenched by immersing it in a water bath at approximately 25 °C for cooling.


Figure 2: Faecal Sludge after Collection


Figure 3: Sample Preparation


Figure 4: HTL Reactor

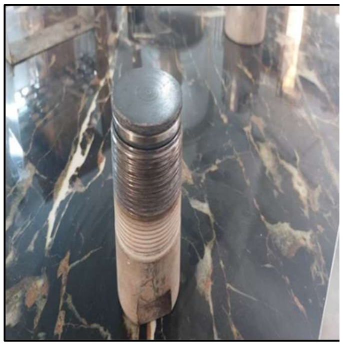
Figure 5: HTL Reactor with Copper Gasket and Steelhead

2.4 Separation of Product

Previous Studies reported that the separation process can be done by either using a solvent like DCM or without solvent by higher centrifugal force (Khalekuzzaman et al., 2024; Adnan et al., 2023). In this study, the reactor opened after cooling the reactor, and the product was carefully transferred into 15 mL centrifuge tubes. To ensure thorough mixing, the sampling tube was vortexed for 5 minutes. Subsequently, the product mixture, which included biocrude, biochar, and an aqueous phase, was subjected to centrifugation using a NUVE NF 800/800R multi-purpose benchtop centrifuge at 6000 rpm for 5 minutes, effectively separating each layer of the product, as shown in Figure 7 (Hossain et al., 2022).

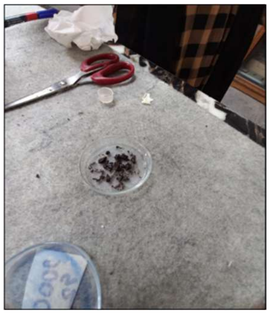

Figure 6: Carbolite ESF 12/2, Bamford, Sheffield Model Furnace

Figure 7: Centrifuge Machine and Its Operational Settings

Figure 8: Aqueous Phase and Bio-crude and Bio-char

The aqueous phase was immediately extracted once the centrifuge process was completed. Since no solvent was used, the biocrude was extracted using a 5 mL syringe. The biochar was collected using a spatula, as shown in Figure 8. This same separation process was repeated for the subsequent two HTL runs, with centrifugal speeds of 9000 rpm and 12000 rpm being utilised for separation in those instances.

2.5 Analytical Method

2.5.1 Elemental Analysis of Physicochemical Composition

The elemental composition (C, H, N, and O) of biomass and biocrude samples was determined using a CE-440 elemental analyser from Exeter Analytical Inc., USA. Standard methods were employed for the determination of total solids (TS), moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC) in biomass samples, following the ASTM D3172 standard (ASTM D3172-13, 2021). The higher heating value (HHV) of biomass samples was calculated using a bomb calorimeter and compared to the HHV obtained from elemental analysis. Empirical equations (Equations 4-7) were used to calculate the percentages of carbon (C), hydrogen (H), oxygen (O), and HHV based on the values obtained from elemental analysis (Parikh et al., 2007).

$$C(\%) = 0.635FC + 0.460VM - 0.095AC \tag{4}$$

$$H(\%) = 0.0590C + 0.0605M + 0.010A0C \tag{5}$$

$$O(\%) = 0.340 + 0.469 \times 0.023AC \tag{6}$$

$$HHV_{Biomass}(MJ/kg) = 0.3536FC + 0.1559VM - 0.0078AC \tag{7}$$

The physicochemical compositions of the samples were examined using a HACH DR6000 spectrophotometer (Hach, USA) and a UDK 129 Kjeldahl Distillation Unit (Velp, Italy), following standard methods for the analysis of water and wastewater (APHA, 2005; Hasan et al., 2021).

2.5.2 Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis was conducted on biocrude and aqueous phase samples to identify vibrations, chemical compounds, and functional groups (Hasan et al., 2022). A Shimadzu (IRTracer-100) spectrophotometer was used to perform FTIR analyses at room temperature, covering spectra ranging from 800 cm^{-1} to 4000 cm^{-1} with a resolution of 2 cm^{-1}. The collected IR data were converted from transmittance units to absorbance percentages and analysed using MS Excel, irAnalyze-RAMalyze (Lab-Cognition GmbH & Co. KG), and OriginPro 2020.

2.5.3 Biocrude Oil Quality Assessment by A-Factor and C-Factor

The A-Factor (aliphatic/aromatic bands) and C-Factor (carbonyl/aromatic bands) were calculated from FTIR spectra of biocrude samples separated at different centrifugal speeds. Peak heights at specific wavenumbers (2930 cm^{-1}, 2860 cm^{-1}, 1705 cm^{-1}, and 1630 cm^{-1}) were used to calculate the A-Factor and C-Factor (Ganz & Kalkreuth, 1991).

$$A - Factor = \frac{2930\ cm^{-1} + 2860\ cm^{-1}}{2930\ cm^{-1} + 28\quad cm^{-1} + 1630\ cm^{-1}} \tag{8}$$

$$C - Factor = \frac{1705\ cm^{-1}}{1705\ cm^{-1} + 1630\ cm^{-1}} \tag{9}$$

2.5.4 Thermal Maturity of Biocrude Oil, Parent Kerogen Type, and Paleotemperature

The thermal maturity of biocrude oil, parent kerogen type, and paleotemperature were determined using an A-Factor vs C-Factor vitrinite reflectance equivalent grid diagram. Vitrinite reflectance (VR%) was used to categorise biocrude maturity stages. Equations (10) and (11) were employed to calculate T_{Fluid} fluids and e T_{Burial} based on VR%.

$$T_{Fluid} = ln(VR\%) + 1.19/0.00782 \tag{10}$$

$$T_{Burial} = ln(VE\%) + 1.68/0.0124 \tag{11}$$

3. RESULTS

3.1 Biomass Characterisation

Table 1 provides the proximate and ultimate characterisation of faecal sludge (FS). The proximity analysis revealed an organic matter/volatile matter concentration of 6.63 percent in FS, which is relatively high due to its 4.65% ash content and 0.52 percent fixed carbon content. The higher heating value (HHV) of FS was determined to be 10.48 MJ/kg, which is in line with previous research (Mugerwa et al., 2019). The H/C_{eff} ratio, calculated from elemental analysis, was found to be 0.25. Prior studies have suggested that if the H/C_{eff} ratio of biomass is less than 0.2, it has a significant potential for coke formation (Zhang et al., 2011).

3.2 FTIR Analysis of Bio-Crude, Bio-Char and Aqueous Phase Separated at 6000 Rpm

FTIR analysis was conducted to analyse the functional groups, vibration modes, and spectral strength of bio-crude and bio-char that were separated at a centrifugal speed of 6000 rpm for 5 minutes, as shown in Figure 9. The analysis revealed peaks between 2800 cm^{-1} and 3000 cm^{-1} and 1350 cm^{-1} to 1460 cm^{-1}, representing medium peaks related to C-H stretching, specifically -CH3 and -CH3 vibrations. This suggests the presence of long-chain aliphatic hydrocarbons. Furthermore, there is an absorbance peak in the range of 1020 cm^{-1} to 1100 cm^{-1}, indicating the presence of alcohol and phenol compounds due to C-O stretching. Another peak between 1590 cm^{-1} to 1800 cm^{-1} suggests C=O vibration, indicating the presence of ketones, aldehydes, carboxylic acids, and esters functional groups (Feng et al., 2018).

FTIR analysis of the aqueous phase, separated at 6000 rpm for 5 minutes, was also conducted to determine functional groups and spectral characteristics, as shown in Figure 10. The analysis revealed peaks at 2850 cm^{-1} and 2922 cm^{-1}, indicating the presence of C-H stretching. Another peak at 1654 cm^{-1} suggests the presence of C=O vibration, indicating the presence of ketones, aldehydes, carboxylic acids, and esters functional groups. Additionally, an absorption peak at 1018 cm^{-1} indicates the presence of alcohol and phenol compounds. Furthermore, a peak at 3628 cm^{-1} suggests O-H stretching in water molecules. However, the FTIR spectra show that at 6000 rpm, the bio-crude and bio-char are not fully separated from the aqueous phase, indicating that the result is not valid for further discussion.

3.3 FTIR Analysis of Bio-Crude, Bio-Char and Aqueous Phase Separated at 9000 Rpm

FTIR analysis was conducted on bio-crude and bio-char separated at a centrifugal speed of 9000 rpm for 5 minutes, as presented in Figure 11. Similar to the previous analysis, peaks in the range of 2800 cm^{-1} to 3000 cm^{-1} and 1350 cm^{-1} to 1460 cm^{-1} were observed, indicating C-H stretching. Moreover, a peak between 1590 cm^{-1} to 1800 cm^{-1} suggested C=O vibration, indicating the presence of ketones, aldehydes, carboxylic acids, and esters functional groups.

FTIR analysis of the aqueous phase separated at 9000 rpm for 5 minutes is presented in Figure 12. The analysis revealed peaks at 1647 cm^{-1}, indicating the presence of C=O vibration and suggesting the presence of ketones, aldehydes, carboxylic acids, and esters functional groups. Additionally, peaks at

3238 cm^{-1} and 3388 cm^{-1} indicated O-H stretching in water molecules. These FTIR analyses at 9000 rpm demonstrate better separation of bio-crude and bio-char from the aqueous phase compared to the 6000 rpm separation. This indicates improved validity for further discussions regarding the composition of the separated products.

3.4 FTIR Analysis of Bio-Crude, Bio-Char and Aqueous Phase Separated At 12000 Rpm

FTIR analysis was conducted on bio-crude and bio-char separated at a centrifugal speed of 12000 rpm for 5 minutes, as shown in Figure 13. Similar to previous analyses, peaks between 2800 cm^{-1} to 3000 cm^{-1} and 1350 cm^{-1} to 1460 cm^{-1} were observed, indicating C-H stretching, specifically -CH3 and -CH3 vibrations. Additionally, a peak between 1560 cm-1 and 1800 cm-1 suggests C=O vibration, indicating the presence of ketones, aldehydes, carboxylic acids, and esters functional groups.

FTIR analysis of the aqueous phase separated at 12000 rpm for 5 minutes is presented in Figure 14. The analysis revealed a peak at 1647 cm^{-1}, indicating the presence of C=O vibration and suggesting the presence of ketones, aldehydes, carboxylic acids, and esters functional groups. A peak at 3385 cm^{-1} also indicates O-H stretching in water molecules.

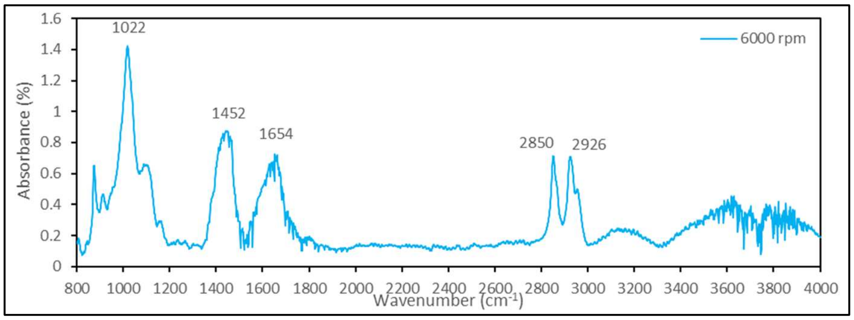

Figure 9: FTIR Spectra of Bio-Crude and Bio-Char Separated at 6000 Rpm with Correction for CO_2 Contamination

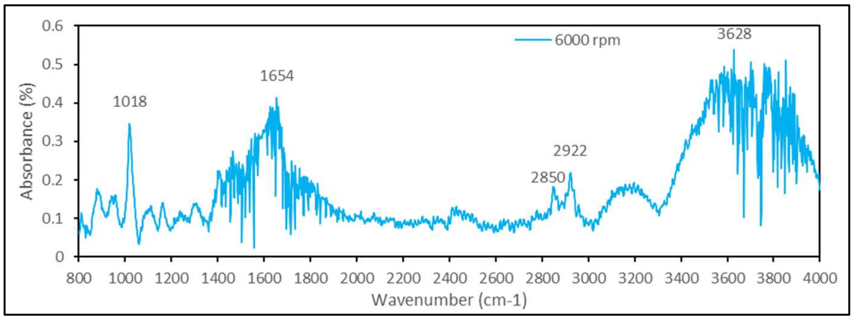

Figure 10: FTIR Spectra of Aqueous Phase Separated at 6000 Rpm with Correction for CO_2 Contamination

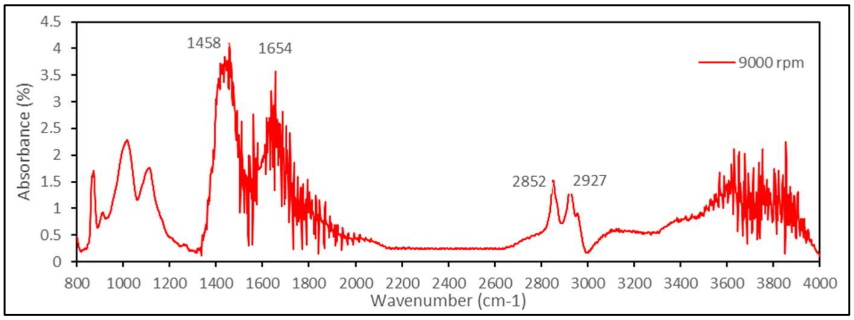

Figure 11: FTIR Spectra of Bio-Crude and Bio-Char Separated at 9000 Rpm with Correction for CO_2 Contamination

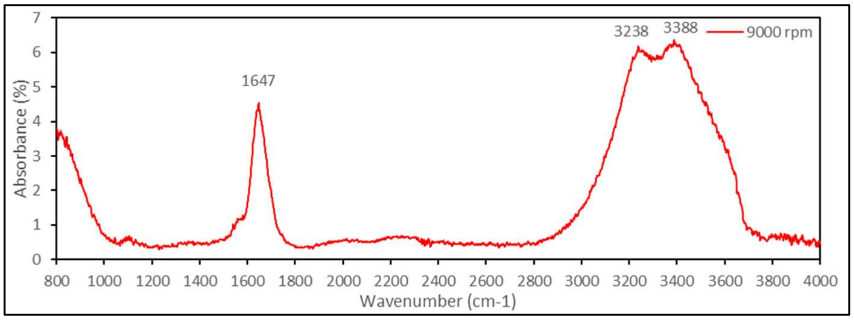

Figure 12: FTIR Spectra of Aqueous Phase Separated at 9000 Rpm with Correction for CO_2 Contamination

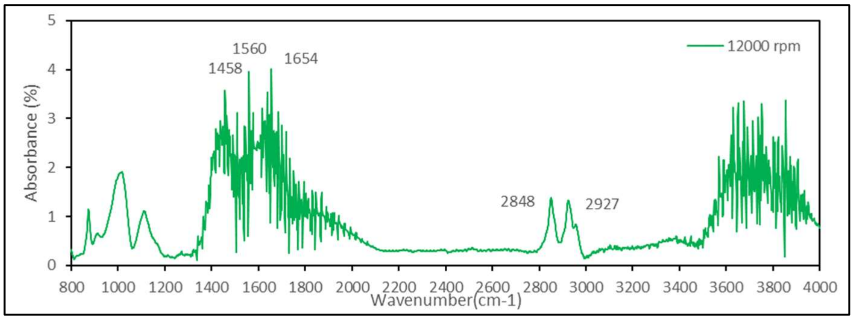

Figure 13: FTIR Spectra of Bio-Crude and Bio-Char Separated at 12000 Rpm with Correction for CO_2 Contamination

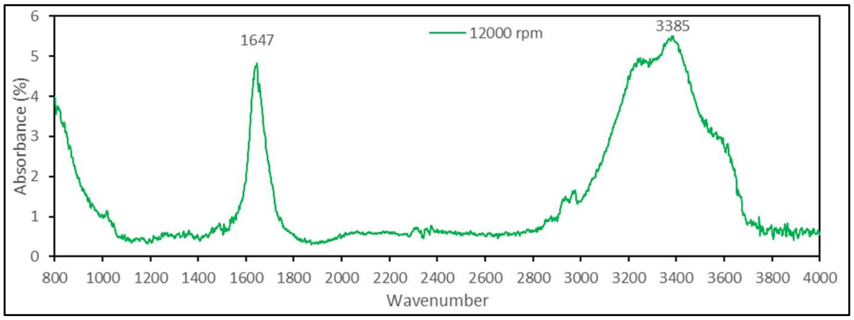

Figure 14: FTIR Spectra of Aqueous Phase Separated at 12000 Rpm with Correction for CO_2 Contamination

3.5 Comparison of Graphs

In a combined figure (Figure 15), bio-crude and bio-char separated at both 9000 rpm and 12000 rpm are presented, and Figure 16 shows the aqueous phase separated at these two speeds. It is evident that the separation is more effective at 12000 rpm compared to 9000 rpm. The FTIR spectra indicate improved separation of products at the higher centrifugal speed. These results suggest that using a higher centrifugal speed (12000 rpm) is more effective in separating the bio-crude and bio-char from the aqueous phase, making it a preferable choice for further discussions and analyses.

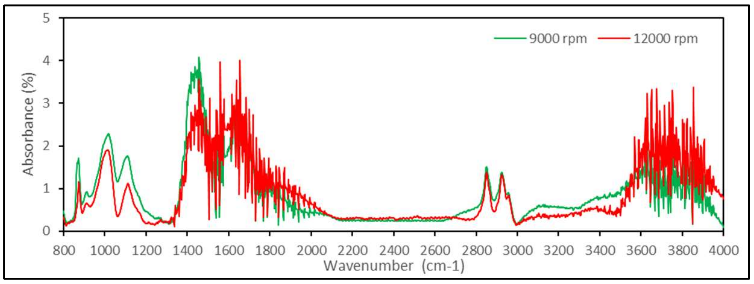

Figure 15: FTIR Spectra of Bio-Crude and Bio-Char Separated at 9000 Rpm & 12000 Rpm with Correction for CO_2 Contamination

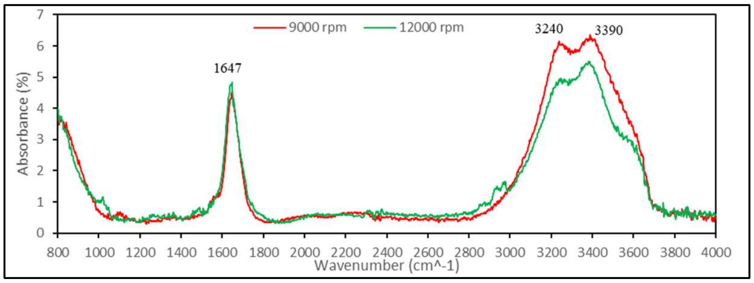

Figure 16: FTIR Spectra of Aqueous Phase Separated at 9000 Rpm & 12000 Rpm with Correction for CO_2 Contamination

3.6 Bio-Crude Characteristics

A-Factor and C-Factor were calculated for the samples separated at different centrifugal speeds and are presented in Table 2. These factors are important for determining the composition and characteristics of the bio-crude and bio-char. The values are different for each separation speed, indicating variations in the composition of the separated products.

Table 2: A-Factor and C-Factor Determined from FTIR Spectra of Bio-Crude and Bio-Char

Sample Type	**Peak Height (Absorbance %)**				**Parameters**	
	2930 cm^{-1}	**2860 cm^{-1}**	**1705 cm^{-1}**	**1630 cm^{-1}**	**A-Factor**	**C-Factor**
6000 Rpm	0.75348	0.62458	0.31637	0.58746	0.70112	0.35003
9000 Rpm	2.35493	2.35456	1.84570	1.98463	0.70353	0.48186
12000 Rpm	2.65478	2.4157	1.56478	1.95648	0.72158	0.44438

The paleotemperature, kerogen type, and thermal maturity of the samples were calculated based on vitrinite reflectance (VR%) and are shown in Table 3. The results reveal differences in thermal maturity and kerogen type for the separated products at different centrifugal speeds, as shown in Figure 17.

Table 3: Paleotemperature Estimations Derived from FTIR Spectra of Bio-Crude and Bio-Char

Sample Type	**Vitrinite Reflectance (VR%)**	**Kerogen Type**	**Maturation Scheme**	T_{Fluid}	T_{Burial}
6000 Rpm	0.68	II	Early mature	102.86	104.38
9000 Rpm	0.48	II	Premature	58.32	76.29
12000 Rpm	0.55	II	Premature	75.72	87.27

Table 4 presents the characteristics of the bio-crude separated at different centrifugal speeds. It includes the specific gravity (SG), API° gravity, and barrels of bio-crude per metric ton. These values provide information about the quality and quantity of the bio-crude. The figure shows the variation in specific gravity and API° gravity among the samples and the projected volume of bio-crude per metric ton. According to the data, the SG of the separated bio-crude ranges from 1.33 to 1.47, with the highest value observed at 9000 rpm. The API° gravity varies from -25.10 to -35.54, again with the most extreme value at 9000 rpm. The projected volume of bio-crude per metric ton ranges from 4.27 to 4.73 barrels, with the highest value observed at 6000 rpm.

Table 4: Characteristics of Bio-Crude

Sample Type	Specific Gravity (SG)	API° Gravity	Barrels of Bio-Crude per Metric Ton
6000 rpm	1.33	-25.10	4.73
9000 rpm	1.47	-35.54	4.33
12000 rpm	1.44	-33.33	4.36

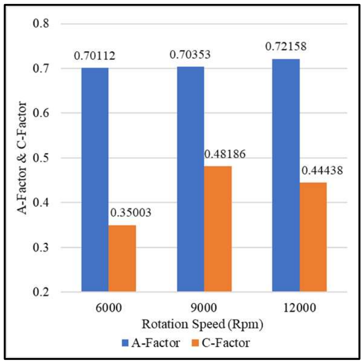

Figure 17: A-Factor and C-Factor

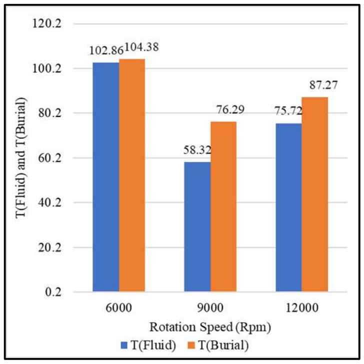

Figure 18: $\boldsymbol{T_{Fluid}}$ and $\boldsymbol{T_{Burial}}$

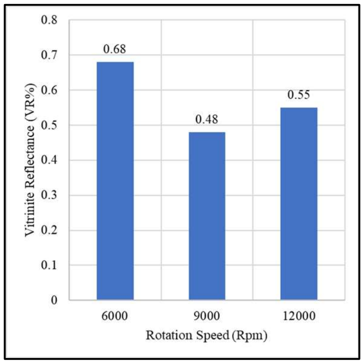

Figure 19: Vitrinite Reflectance

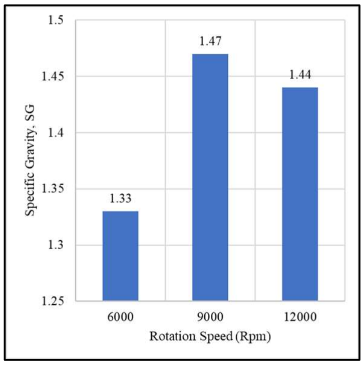

Figure 20: Specific Gravity (SG)

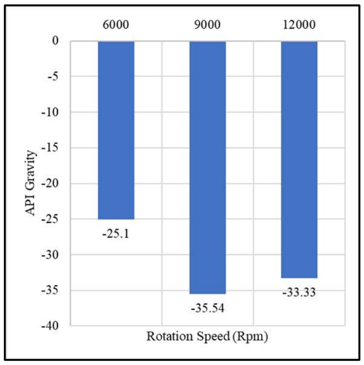

Figure 21: API° Gravity

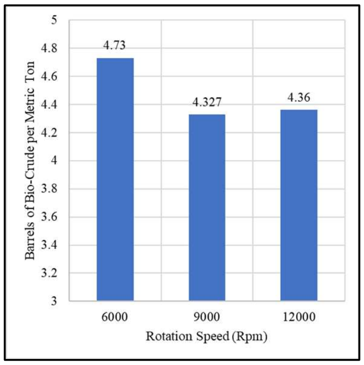

Figure 22: Barrels of Bio-Crude per Metric Ton

4. CONCLUSIONS

The research indicates that Bio-Crude obtained at 6000 rpm has the lowest Specific Gravity (SG) and the highest API° gravity. These characteristics make it suitable for easy transport and storage. However, this Bio-Crude also has lower energy content and higher emissions. Moreover, at 6000 rpm, the separation of aromatic compounds (AP) from Bio-Crude is incomplete, making this speed unsuitable for real-life or large-scale Bio-Crude production.

In contrast, both 9000 rpm and 12000 rpm achieve complete separation of AP from Bio-Crude. Although 9000 rpm appears slightly better than 12000 rpm in terms of SG and API° gravity, the quantity of Bio-Crude obtained at 9000 rpm is less than that obtained at 12000 rpm. A lower API° gravity and specific gravity at 12000 rpm centrifugal speed suggest more efficient separation and superior fuel quality compared to 9000 rpm. Also, the production rate at 12000 rpm is higher. Despite the increased energy consumption and advanced technology requirements, separation at 12000 rpm emerges as the preferred and optimal choice for bio-crude production, surpassing both 6000 rpm and 9000 rpm options.

Therefore, the conclusion is that 12000 rpm is the more suitable and acceptable speed for practical use and large-scale industrial production.

If implemented in real life, it could provide access to low-cost fuel and improved sanitation systems for many people, leading to a healthier environment. Nevertheless, it's important to note that higher centrifugal speeds can enhance separation but consume more power. Thus, the need for more energy-efficient devices or instruments should be considered, especially as the research was conducted on a small scale. Further research is required, and the effects of temperature and pressure on this process should also be explored.

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