

TECHNICAL FEASIBILITY OF CHARCOAL-WASTE ENGINE OIL-WATER SLURRY FOR SUSTAINABLE SYNGAS PRODUCTION IN PAKISTAN

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Abstract

In recent years, the demand for alternative fuel sources in Pakistan has increased significantly. Concurrently, large quantities of waste engine oil are generated, creating both, environmental challenges and opportunities for energy recovery. This study evaluates the technical feasibility of utilizing a charcoal-waste engine oil-water slurry mixture as a feedstock for the syngas production through gasification. Five different slurries were prepared using varying ratio of charcoal to waste engine oil, along with water and additives. Proximate analyses were conducted to determine the moisture content, volatile matter, ash, and fixed carbon, while ultimate analysis assessed elemental composition to estimate potential syngas yields. The results indicate that increasing the proportion of waste engine oil leads to higher volatile matter content and improved energy density. Conversely, increasing the charcoal fraction enhances fixed carbon content while maintaining stable combustion characteristics. Among the tested samples, Sample 4 demonstrated the best overall performance, exhibiting highest higher heating value of 26.77 MJ/kg and lower heating value of 24.91 MJ/kg. Sample 1 was identified as second most promising candidate due to its high heating value (26.42 MJ/kg), elevated fixed carbon content, and balanced fuel properties. Overall, finding suggest that charcoal-waste engine oil- water slurry fuels possess sufficient energy density, combustion stability, and favorable elemental composition, making them a viable and sustainable feedstock for syngas production via gasification.

INTRODUCTION

Rapid urbanization, population growth, and industrialization are significantly increasing glable energy demand [1-3]. Historically, this demand have been met primarily through fossil fuels such as oil, coal, and natural gas [4-6]. However, the extensive use of these resources has led to serious environmental challenges, including global warming, air pollution, greenhouse gas emissions,

and the depletion of non-renewable resources [7-9]. These concerns have intensified the global search for sustainable, economically viable, and environmentally friendly energy alternatives [10-12]. Among the emerging solutions, fuel blending, biomass-based fuels, and waste-to-energy technologies have gain considerable attention [13-15]. One particularly promising yet problematic waste stream is waste engine oil (WEO), which is

generated from used petroleum-based lubricants [16–18]. In Pakistan, improper disposal practices such as discharging WEO into rivers, soil, and the Arabian Sea pose serious environmental and ecological risks [19–21]. Various approaches for utilizing WEO, including direct combustion, pyrolysis, and blending with diesel, have been explored [22–24]. Charcoal, a carbon-rich material produced via biomass pyrolysis, offers advantages such as a high calorific value and relatively low ash content [25–27]. However, its high fixed carbon content and solid nature limit its direct applicability in modern combustion and gasification systems, where pumpable and flowable fuels are preferred [28–30]. Nevertheless, due to its renewable origin and favorable carbon combustion, charcoal and other biomass-derived materials have been widely investigated for gasification processes [31–34]. Despite these advances, research on developing stable slurry fuels combining charcoal, waste engine oil, and water remains limited. Key challenges include insufficient understanding of slurry stability and sedimentation behavior, limited data on rheological and flow properties during handling and transport, and a lack of comprehensive evaluation of combustion performance and emissions characteristics [35–38]. In this context, formulating a homogeneous slurry from charcoal, WEO and water presents a promising approach to address both energy production and waste management challenges [39–41]. Therefore, this study focuses on the formulation, characterization, and potential application of charcoal-WEO-water slurry fuel as a viable feedstock for syngas production, industrial heating, and other thermal applications [42–45].

This study aims to address environmental challenges associated with the petroleum and automobile industries by exploring the reuse of WEO as an alternative energy resource. The research focuses on evaluating the technical feasibility of utilizing WEO as a component of feedstock in gasification processes for synthetic gas (syngas) production, thereby enabling safe and environmentally sustainable energy generation. Five slurry samples were prepared, each consisting of charcoal, waste engine oil, water, and a quantity of

additives. The compositions of samples were varied by adjusting the ratios of charcoal and waste engine oil. Proximate analysis, ultimate analysis, and heating value assessment were conducted for each sample. Based on experimental results, conclusions were drawn regarding the suitability and feasibility for syngas production. This finding suggests that this approach has significant potential to contribute to environmental sustainability by industrial waste into a cost-effective and cleaner energy source.

Materials and methods

Materials and laboratory equipment were utilized in this study for the preparation, stabilization, and characterization of charcoal-waste engine oil-water (ChWEO) slurry samples. The selection of materials and the choice of analytical instruments were carefully made to ensure reliable testing conditions, accurate measurements, and consistent data generation.

2.1 Selection of Materials

Three primary components were used in the preparation of the ChWEO slurry samples: charcoal, WEO, and water. Charcoal was selected as the solid component due to its high carbon content, porous structure, and relative cleaner combustion characteristics compared to other solid fuels. It serves as the carbon source, playing a crucial role in syngas formation during the gasification process. To ensure uniformity and consistent behavior during analysis, the charcoal was ground to achieve a uniform particle size, facilitating homogeneity within the slurry. The charcoal used in this study was sourced locally from villages surrounding Khairpur Mirs, Sindh, Pakistan (See Fig.1). WEO was utilized as liquid fuel component and primary energy carrier in the slurry. WEO is a denser fuel containing a concentration of combustible hydrocarbons, making it suitable for energy recovery applications. The WEO was collected locally subjected to filtration to remove impurities, including metal particles, and residual water, ensuring improved quality and consistency for experimental use (See Fig.1). Water was incorporated into the slurry to reduce the viscosity and enhance fluidity. This

contributed to improve mixing, better homogeneity, and enhanced pumping characteristics of the slurry. In addition to the main components, small amounts of additives namely Tween-80, xanthan gum, and sodium

lignosulfonate were introduced. These additives were used to improve the stability, emulsification, rheological properties of the slurry, preventing phase separation and enhancing overall performance during handling and analysis.



Fig.1 Charcoal and waste engine oil (WEO)

2.2 Sample compositions

Five slurry sample with varying compositions were prepared to investigate the influence of component ratios on the fuel properties of the ChWEO. The compositions were systematically selected to achieve an optimal balance between slurry's stability, flow characteristics, and overall energy content, while remaining within practical and acceptable limits. .

2.3 Sample preparations

The slurry samples were prepared under controlled laboratory conditions at Department of Petroleum and Natural Gas Engineering, Mehran University of Engineering and Technology SZAB Campus Khairpur Mirs (See Fig. 2). The following procedure was adopted:

- (1) Drying of charcoal: The collected charcoal samples were dried in an oven at 105°C for 2 hours to remove inherent moisture. This step ensured that the added water content in a slurry remained controlled and consistent.
- (2) Grinding and sieving: The dried charcoal was ground and sieved to obtain a fine particle size (preferable below 150 μm). This was done to

ensure homogeneous distribution within the slurry, effective interaction between solid and liquid phases, minimize sedimentation, and enhance flow behavior.

- (3) Filtration of waste engine oil: Waste engine oil, obtained from local automobile repair shops, was filtered using a fine mesh sieve followed by whatman filter paper. This process remove dust, metallic particles, and sludge, ensuring that the energy contribution primarily originated from hydrocarbons without interference from impurities.

- (4) Preparation of additive solution: Measured quantities of different additives, including Tween-80, xanthan gum, sodium lignosulfonate, were dissolved in a small amount of water to form a uniform additive solution.

- (5) Blending process: Predetermined amounts of charcoal, water and waste engine oil were accurately measured using a digital weighing balance. These components were then mixed in mechanical mixer and stirred at a speed of approximately 800-1000 rpm for about 20 minutes until a smooth and consistent slurry was formed. The prepared additive solution was gradually

added during the mixture process to enhance stability and uniformity.

(6) Observation and labeling: Each slurry sample was visually inspected for uniformity, consistency and absence of phase separation. The samples were then transferred into an airtight containers, properly labeled and prepared for subsequent analysis.

(7) Storage and handling: The prepared samples were stored in a cool, dry environment to prevent contamination and degradation. . All samples were kept in airtight containers and were not opened prior to testing. Before analysis, each sample was thoroughly stirred to ensure a uniform distribution of components.



Fig.2 ChWEO slurry samples.

Experimental tests and methodology

To evaluate the fuel characteristics and technical feasibility of the prepared ChWEO slurry for syngas production, a series of standard tests were conducted. These included proximate analysis, ultimate analysis and determination of higher heating value (HHV) and lower heating value (LHV). These analyses are essential for characterizing fuel behavior and assessing its suitability as a gasification feedstock. .

3.1 Proximate analysis

Proximate analysis was performed on each slurry sample to determine key composition parameters, including moisture content, volatile matter, ash content and fixed carbon. These parameters provide an initial assessment of fuel quality and combustion behavior. The tests were conducted in accordance with relevant ASTM standard to ensure accuracy, consistency and comparability of results.

3.1.1 Moisture Content (ASTM D3173)

1. Approximately 2–3 g of well-mixed slurry sample was accurately weighed using an electronic balance with a precision of ± 0.001 g.
2. The sample was placed in a pre-weighed and pre-dried crucible
3. The crucible containing the sample was heated in a moisture oven at 105°C for 1 hour to remove all moisture content.
4. After drying, the crucible was cooled in a desiccator and the dried sample was then reweighed.
5. Moisture content was calculated using the following equation:

$$\text{Moisture (\%)} = \frac{W_{\text{initial}} - W_{\text{dried}}}{W_{\text{initial}}} \times 100 \quad \text{.....(1)}$$

3.1.2 Volatile Matter (ASTM D3175)

1. The moisture-free sample obtained from the previous test was placed in a covered silica crucible.
2. The crucible was introduced into a preheated muffle furnace and heated at 950 °C for 7 minutes under controlled conditions.
3. After heating, the crucible was carefully removed and cooled in a dessicator. The crucible was then reweighed.
4. Volatile matter was determined based on the loss in weight during high-temperature heating.

Volatile Matter (%) =

$$\frac{W_{dried} - W_{residue}}{W_{initial}} \times 100 \dots\dots\dots(2)$$

3.1.3 Ash Content (ASTM D3174)

1. The residue obtained after the volatile matter determination was placed in an uncovered crucible.
2. Then crucible was then heated in the muffle furnace at 750 °C until constant weight was achieved, ensuring complete combustion of all combustible material.
3. After heating, the crucible was cooled in a desiccator to room temperature and reweighed.
3. Ash content was calculated as:

$$\text{Moisture (\%)} = \frac{W_{Ash}}{W_{initial}} \times 100 \dots\dots\dots(3)$$

3.1.4 Fixed Carbon (By Difference)

Fixed carbon was not measured directly but was calculated analytically using the difference method from the results of proximate analysis. The fixed carbon content was determined using the following relationship:

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture} + \text{Volatile Matter} + \text{Ash} \dots\dots\dots(4)$$

3.2 Ultimate analysis

Ultimate analysis was conducted to determine the elemental composition of the fuel samples in terms carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). This analysis is essential for understanding the chemical structure combustion behavior, and energy potential of the prepared slurry fuels. In this study, an X-ray fluorescence (XRF) spectrometer was employed for

elemental characterization. The instrument provides rapid and precise determination of elemental composition in both solid and slurry-based samples without extensive chemical pre-treatment. The obtained elemental data were used to evaluate the fuel quality and assess the suitability of the ChWEO slurry for gasification and syngas production applications. The details of procedure is given below:

1. A small quantity (approximately 1–2 mg) of air-dried slurry sample was prepared and carefully placed in the XRF spectrometer's sample holder.
2. The instrument was calibrated using standard reference materials to ensure accurate and reliable elemental detection.
3. The sample was then subjected to x-ray irradiation, causing the constituent element to emit secondary (fluorescent) x-rays.
4. The emitted x-rays were detected and analyzed to determine the relative elemental composition of C, H, N and S.
5. The oxygen content was not directly measured and was calculated by difference using the following relation:

$$\text{Oxygen (\%)} = 100 - (C + H + N + S) \dots\dots\dots(5)$$

All elemental compositions were reported on a weight-percentage (wt%) basis.

3.3 HHV and LHV heating value estimations

HHV and LHV of each slurry sample were estimated using a weighted average approach based on the mass fractions of charcoal and WEO. The calculations were performed to evaluate the overall energy potential of the prepared ChWEO slurry fuels. The details of procedure is given below:

1. Standard HHV values for the individual components were obtained from literature sources i.e. charcoal: approximately 30 MJ/kg and WEO: approximately 42 MJ/kg
2. The mass fraction of charcoal and WEO in each slurry sample was determined based on the formulation of the mixture.
3. The overall HHV of each sample was calculated using the weight average equation:

$$HHV_{sample} = (W_{charcoal} \times HHV_{charcoal}) + (W_{WEO} \times HHV_{WEO} \dots\dots\dots)(6)$$

Where W represents the mass fraction of each component.

4. The LHV was estimated by accounting for moisture content losses. A simplified moisture correction approach was applied as follows:

$$LHV = HHV - \text{Moisture (\%)} \dots\dots\dots(7)$$

Where:

Moisture = Moisture by Weight (%)

Results and Discussion

4.1 Proximate analysis

Proximate analysis was conducted to determine the fuel properties of the prepared ChWEO slurry samples including MC, VM, AC, and FC. These parameters play a critical role in defining combustion efficiency, ignition characteristics, and overall gasification performance of the fuel. Fig 3 provides insight into how variations on slurry composition influences these key fuel properties. In general, MC affects the energy efficiency and ignition delay, while VM contributes to flame stability and combustion reactivity. AC presents the non-combustible fraction, which can negatively impact gasification efficiency by causing slagging or operational issues. FC, on the other hand, is directly associated with the solid carbon available for sustained energy release and syngas formation. The observed trends in proximate analysis demonstrate the suitability of the ChWEO slurry as a potential feed stock for gasification-based energy production, depending on the optimized balance of its constituent components.

4.1.1 Influence on water content

From shown in Fig 3, MC of the slurry samples ranged from 2.32% to 6.63%. Sample 3 exhibited the lower MC (2.32%), indicating higher combustion efficiency and reduced energy losses associated with moisture evaporation during the initial heating phase. In contrast, Sample 5 recorded the highest MC (6.63%), which may negatively affect thermal efficiency due to additional energy required for water evaporation prior to combustion. MC plays a significant role in

determining slurry stability and handling characteristics. While excessive moisture can dilute the fuel concentration and reduce heating value, extremely low moisture levels may affect slurry flow ability and pumping performance. Therefore, an optimal moisture range is necessary to balance stability and energy efficiency. Based on the observed results, Sample 2 and Sample 3 demonstrated comparatively favorable moisture levels, making them more suitable candidates for gasification applications in terms of both stability and energy performance.

4.1.2 Effect on volatile material

VM significantly influences the ignition behavior, flame stability and overall combustion reactivity of fuel. As illustrated from Fig 3, the VM content of the slurry sampled ranged from 21.58% to 28.21%. Sample 5 exhibited the highest VM content (28.21%), indicating rapid ignition characteristics and enhanced release of volatile compounds during the pyrolysis stage. This behavior can promote quicker flame propagation and improved initial combustion reactivity. In contrast, Sample 2 recorded the lowest VM value (21.58%), suggesting relatively slower ignition but improved thermal stability during combustion. Although higher VM content enhances ignition and flame development, it may reduce combustion control and stability. Conversely, the lower VM contributes to more controlled and stable combustion behavior but may require higher ignition energy. Based on the observed trends, Samples 1 and 2 exhibit faster ignition behavior due to their higher VM content. The selection of an optimal sample therefore depends on the desired balance between ignition speed and combustion stability for gasification applications.

4.1.3 Impact on ash content

As illustrated in figure 3, AC plays a significant role in determining gasifier efficiency, operational stability and slag formation. Lower AC generally indicates cleaner combustion, improved reactor performance, and reduced solid residue formation. Among the tested samples, Sample 4 exhibited the lowest AC (7.35%), making it more suitable for cleaner fuel utilization and minimizing

residue-related issue during gasification. In contrast, Sample 3 showed the highest AC (10.50%), which may lead to increase solid waste generation, higher maintenance requirements, and potential operational challenges such as fouling or slugging in the reactor system. Overall, lower AC is considered beneficial for syngas production as it enhances process efficiency and reduces operation disruptions. Therefore, samples with reduced ash fractions are more favorable for efficiency and sustainable gasification performance.

4.1.4 Impact on fixed carbon

Fixed carbon represents the solid combustible fraction of the fuel that contributes to sustained

energy release during combustion and gasification. As shown in Fig 3, the FC content of the slurry ranged from 61.63% and 66.10%. Sample 2 exhibited the highest FC content (66.10%), indicating strong energy potential and favorable conditions for sustained and enhanced syngas production. In contrast, Sample 3 recorded the lowest FC value (61.63%), which is consistent with its comparatively higher ash and VM content. Higher FC content generally contributes to improved combustion stability and increase energy yield during gasification. Based on the results, Samples 1 and 2 demonstrate more favorable FC levels, making them better suited for efficient and stable syngas generation applications

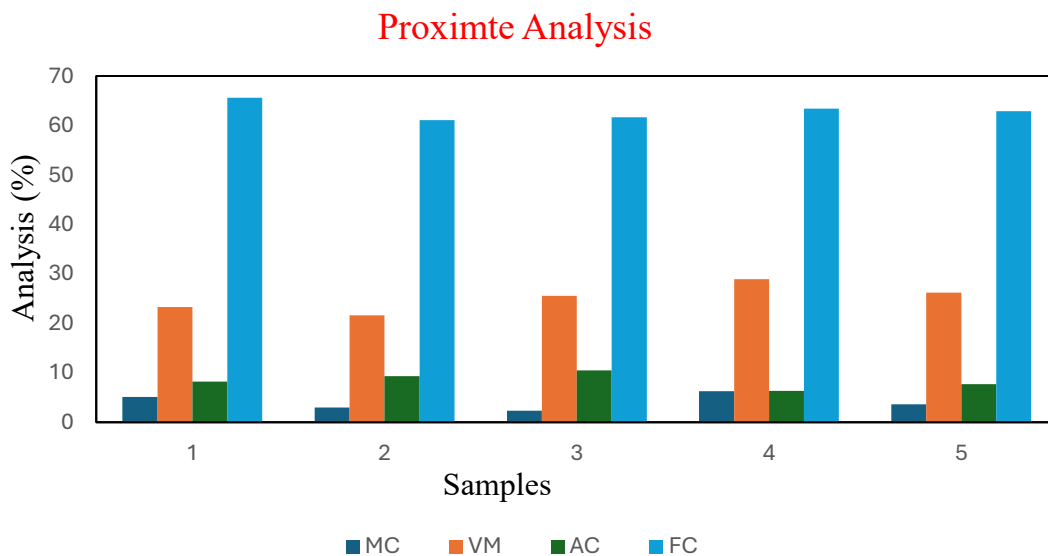


Fig.3. Proximate analysis of all ChWEO samples.

4.2 Ultimate analysis

The elemental composition of the slurry samples including C, H, N, S, and O was determined through ultimate analysis. The elemental constituents are directly related to syngas yield, heating value, and emission characteristics of the fuel.

4.2.1 Impact on hydrogen and carbon content

Theoretical syngas yield and heating values are strongly influenced by the C and H content of the

fuel. With the highest hydrogen and highest carbon, Sample 4 exhibited the highest H content (10.6%) and C content (74.9%), indicating superior energy potential and a strong capacity for efficient syngas generation. In contrast, sample 2 recorded comparatively lower values (C = 68.2%, H = 6.1%), which corresponds to its reduced heating value and lower expected syngas yield. H contributes significantly to H₂ production, thereby improving the quality and calorific value of the resulting syngas, while higher carbon

content enhances the formation of CO and CO₂ during the gasification process. Consequently, an optimal balance of these elements is essential for efficient conversion. Based on the results (See Fig.4), Sample 4 demonstrates the most favorable characteristics for syngas production, owing to its high C and H content, which collectively enhance its energy output and gasification efficiency.

4.2.2 Impact on sulfur and nitrogen content

As shown in Fig. 4, the N and S contents of all slurry samples remained consistently low across the tested range. N values varied between 0.43% and 0.46%, while S content ranged from 0.35% to 0.40%. The relatively low concentrations of N and S are environmentally favorable, as they indicate a reduced potential for nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions during combustion or gasification. These pollutants are typically associated with environmental and health concerns, making their minimization an important factor in fuel evaluation. The observed values are well below typical emission-critical thresholds, highlighting the environmental

acceptability of the ChWEO slurry as a fuel. These results further emphasize the sustainability benefits of utilizing charcoal and WEO as feedstock materials, contributing to waste valorization and cleaner energy production.

4.2.3 Effect on oxygen level

As shown in Fig. 4 the O content ranged from 13.7% to 24.9% across the slurry samples. Sample 2 exhibited the highest O content (24.9%), indicating a greater extent of oxidized compounds within the fuel matrix, which may be associated with reduced energy density and increase inherent oxygenated species. processes. In contrast, sample 4 recorded the lowest O content (13.7%), suggesting a higher proportion of combustion elements such as C and H. This lower oxygen is generally favorable, as it corresponds to higher energy density and improved fuel quality for gasification applications. Overall, a lower O content is considered beneficial for syngas production, as it typically enhances the calorific value and improves the overall efficiency of the fuel during thermal conversion processes.

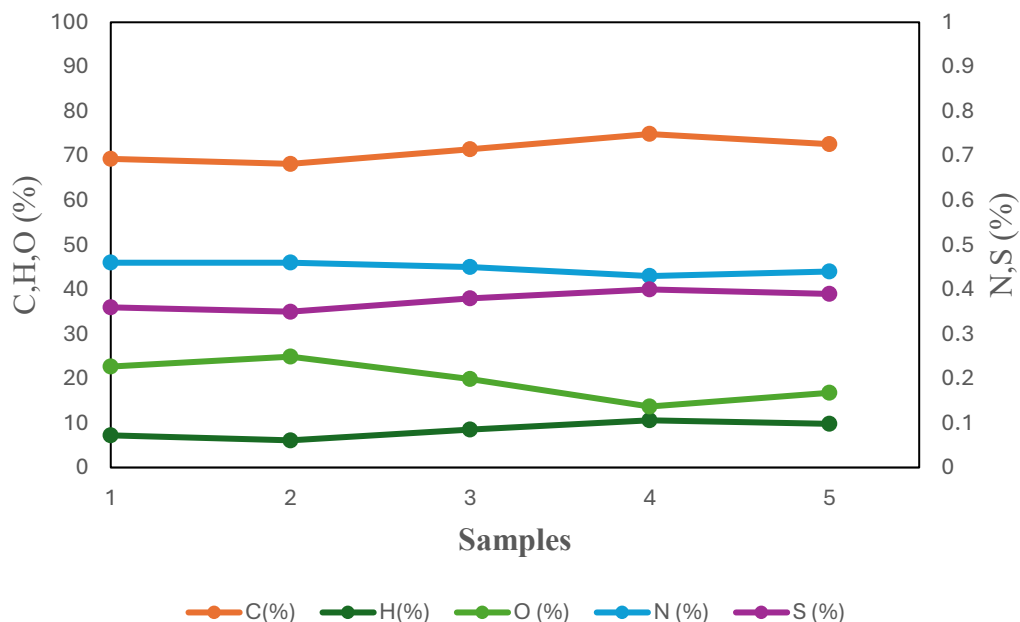


Fig.4. Proximate analysis of all samples.

4.3 Heating values (HHV AND LHV)

The heating values of the slurry samples were calculated using the elemental composition obtained from ultimate analysis, along with the mass fractions of charcoal and WEO in each

sample. These parameters were used to estimate the overall energy content of the fuel mixtures.

4.3.1 Impact on high heating value (HHV)

As illustrated Figure 5, the HHV value of the slurry samples ranged from 23.96 and 26.77 MJ/kg. Sample 4 exhibited the highest HHV (26.77 MJ/kg), which can be attributed to its higher proportion of WEO, a component rich in combustible hydrocarbons and thus possessing a

high energy content. In contrast, Sample 2 recorded lowest HHV, reflecting its comparatively lower C and H content, which are the primary contributors to fuel calorific value. This trend clearly highlight the significant role of WEO in enhancing the overall energy content of the slurry. The results confirm that increasing the fraction of

WEO in the slurry leads to higher calorific values, thereby improving the fuel's suitability for energy generation and gasification applications.

4.3.2 Low heating value (LHV) impact

As shown in Figure 5, the LHV value of the slurry samples ranged from 22.36 to 24.91 MJ/kg. Sample 4 exhibited the highest LHV (24.91 MJ/kg), indicating superior new energy output even after accounting for moisture related energy losses. This reflects its favorable composition, particularly its higher hydrocarbon contents and lower oxygen fraction. In contrast, the Sample 2 recorded the lowest LHV, which can be attributed to its relatively higher O content and lower H concentration. Increased O content typically reduces the effective calorific value of a fuel, while lower H content limits its energy contribution. Overall, the results demonstrate that samples with higher WEO content and optimized elemental composition tend to yield improved LHV values, enhancing their suitability for efficient energy generation and gasification applications.

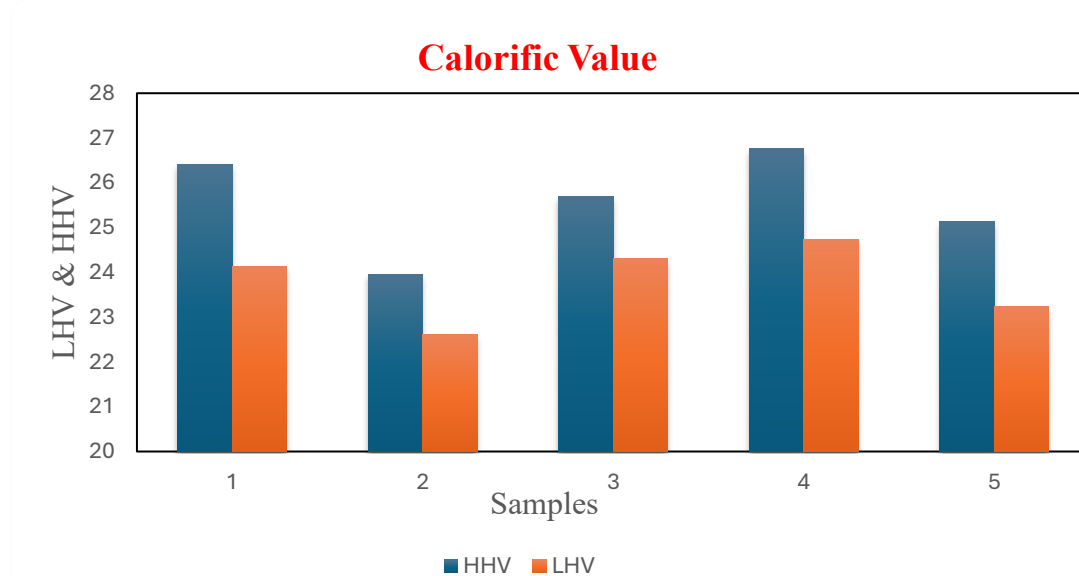


Fig 5. Combined HHV & LHV of all samples.

Conclusions

This study evaluated the technical feasibility of utilizing ChWEO slurry as an alternative feedstock for syngas production. The following conclusion can be drawn:

Proximate analysis indicated that increased charcoal content enhanced FC, contributing to stable combustion behavior, while higher WEO content reduced ash and increased VM. The obtained ranges are comparable to conventional biomass and waste derived fuels. Supporting the viability of ChWEO as an alternative energy source.

Ultimate analysis indicated that the higher C and H contents significantly contributed to increased syngas yield and calorific value. While low N and S levels suggested reduced environmental impact due to lower NO_x and Sox emissions. O content showed an inverse relationship with energy density, where lower oxygen fractions resulted in improved fuel quality.

The heating value analysis further confirmed that the inclusion of WEO substantially enhances the energy content of the slurry. Among the tested samples, Sample 4 consistently exhibited the highest HHV and LHV, along with favorable elemental composition, making it the most suitable candidate for efficient syngas generation. In contrast, samples with lower C and H content and higher O fraction demonstrated reduced energy performance.

Overall, the finding demonstrate that ChWEO slurry is a promising, cost-effective, and environmentally suitable alternative fuel. This study highlights the potential of converting industrial waste. Particularly WEO, into valuable energy resources through gasification, thereby contributing to waste management and clean energy production.

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Declarations

Conflict of interest: The authors declare no competing interests.

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