



Hydrothermal Liquefaction of Palm Tree Waste Using CNT/Silica Nanocomposites: Effects of Process Conditions, Energy Recovery, and Compositional Analysis with Perspectives on SDG 7

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Received: 01.07.2025 Accepted: 03.09.2025 Published: 30.12.2025

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ABSTRACT

Palm trees are mainly cultivated in tropical and subtropical regions for fruit and date production, which in turn generates a substantial amount of agricultural residue. In this study, the sustainable processing of palm tree waste was explored via catalytic hydrothermal liquefaction (HTL) experiments. The HTL process was carried out with varying temperatures from 240 to 340 °C, a reaction time of 60 min, a solvent-to-biomass ratio of 75 g/L to 200 g/L, and a catalyst load of 0.1 to 0.5 wt.% at a pressure of 20 bar. The recovered bio-oil was analyzed using proximate and ultimate analyses, GC–MS, and FTIR, while the biochar was characterized by SEM and FTIR. The maximum bio-oil yield of 28.9 wt.% was obtained at 300 °C, a catalyst loading of 0.3 wt.%, and a biomass-to-solvent ratio of 175 g/L. The carbon content was 52.78 wt.% in the bio-oil and 78.49 wt.% in the biochar, with higher heating values (HHVs) of 30.86 MJ/kg and 25.58 MJ/kg, respectively. The bio-oil contained aliphatic and aromatic compounds, oxyacids, and hydrocarbons such as octadecane and hexadecane. The biochar exhibited high porosity and has the potential to serve as an effective adsorbent with broad environmental applicability. This study paves way for sustainable waste management, eco-friendly practices and green initiatives

Keywords: Hydrothermal liquefaction; Palm tree waste; Bio-oil; Biochar; Biomass; Agricultural waste.

1. INTRODUCTION

Green energy research has garnered global attention, owing to the need to combat climate change and reduce greenhouse gas (GHG) emissions, since fossil fuels contribute over 75% of worldwide GHG release. Fossil fuel usage causes natural habitat degradation, water contamination, and climate instability (Barbir *et al.* 1990). Agricultural waste can be converted into biofuels and biogas through processes like anaerobic digestion and thermochemical conversion processes (Khan *et al.* 2023). The hydrothermal liquefaction (HTL) technique converts wet biomass into bio-crude oil under high temperature and high pressure. HTL supports sustainable energy solutions, waste reduction, and efficient biofuel production, all of which are in line with the SDG goals on promoting the use of bioresources (Yiin *et al.* 2022). Palm trees are cultivated globally in tropical and subtropical regions for their fruits, oil, and other by-products. These trees produce a significant amount of

waste, such as leaves, trunks, fruit bunches, and shells (Mathias *et al.* 2024). Date palm leaves and trunks are used in papermaking, biochar, and activated carbon, whereas oil palm waste is utilized for the production of bio composites and biodiesel (Malki *et al.* 2023; Tahir *et al.* 2020). High-temperature, high-pressure conditions created by HTL treatment convert complex organic matter into bio-oil (Mukundan *et al.* 2022; Thamarai *et al.* 2025). This method produces a valuable biofuel, in addition to offering an environmentally responsible way to dispose of palm debris (Su *et al.* 2023; Hamed *et al.* 2023). The study provides a perfect forum for investigating and sharing developments in this sustainable strategy, highlighting the importance of using HTL to transform palm tree waste into bio-oil for a more environmentally friendly and effective use of bioresources (Ayodele *et al.* 2022). Catalysts help convert biomass into bio-oil by speeding up chemical reactions at lower temperatures, which maximizes yields and uses less energy (Guran, 2018). Hydrothermal

liquefaction (HTL) of palm trees converts biomass into bio-oil and hydrochar under a temperature range of 300–390 °C and high pressure, frequently in subcritical or supercritical water conditions. Majorly, product yield depends upon the parameters, such as temperature, catalyst load, reaction time, and feedstock type (Ciuffi *et al.* 2021; Ghadge *et al.* 2022). This study aligns with Sustainable Development Goals (SDGs) by advancing the renewable energy sector, reducing dependency on fossil fuel reserves, and managing agricultural waste, contributing to environmental protection and economic development.

The novelty of this study is to effectively utilize palm tree waste for the production of bio-oil through a hydrothermal process. The impact of CNT-based silica nanocomposites is investigated, and their effect on HTL product distribution is estimated. In addition, the distribution of HTL products in association with process conditions is analyzed. Further, this study will pave the way for futuristic approaches in the effective processing of the palm tree agriculture sector for valuable product production.

2. MATERIALS AND METHODS

2.1 Biomass Collection and Characterization

Palm tree waste samples (trunk, empty fruit bunches (EFB), fronds, and palm leaf ribs) were washed, sun-dried for 24 hours before being used in the experiments. The dried samples were ground and screened by the VAZ 1600 S Rotary Shredder to less than 2 mm. Samples were dried using an oven at 378 K overnight to remove moisture. The weight loss behavior of the biomass was estimated by Thermogravimetric (TGA) analysis. The Proximate and Ultimate analyses were carried out according to ASTM standards (Arun *et al.* 2018).

2.2 Catalyst Synthesis and Characterization

The MWCNTs/SiO₂ nanocomposites were prepared by the hydrothermal synthesis method for catalyst application in the hydrothermal reactor. 50 mg (20 wt.%) of MWCNTs were dissolved in 40 ml of distilled water with 45 minutes of ultrasonic vibration, and 0.7 g (80 wt.%) of (SiO₂) was dissolved in 30 ml of sulfuric acid (H₂SO₄) in 0.5 N solution. Next, the two solutions (MWCNTs and silicone dioxide) were mixed in one container with stirring for 60 minutes until a homogenous solution was obtained. After stirring, the blended suspension was transferred to a container heated at a temperature of 160 °C for 8 hours. The autoclave was in normal condition; it was cooled to ambient temperature. The final product was centrifuged, and the precipitates were carefully cleaned with ethanol and

distilled deionized water before being dried at 80 °C for 2 hours. The SiO₂ and MWCNTs were synthesized under the same procedure as SiO₂/MWCNT nanocomposites. The final products were gathered and further characterized. Catalysts help convert biomass into bio-oil by speeding up chemical reactions at lower temperatures, which maximizes yields and uses less energy (Marimuthu, 2025; Guran, 2018).

2.3 Instrumentation Analysis of Catalyst

A Field emission scanning electron microscope (SUPRA 55VP FE-SEM) was used to examine the surface morphology of the prepared material. To examine the internal structure and shape of the composite, a TALOS F200S G2 High-resolution scanning transmission electron microscope (HR-STEM) was employed at an accelerating voltage of 200 kV with EDAX for the elemental composition analysis. For HR-STEM analysis, the samples were prepared by depositing an aqueous suspension onto a copper grid of 300 mesh covered with a skinny, lacey carbon layer. Using the Fourier transform infrared spectroscopy (ATR FT-IR) Jasco 6600 instrument, the samples were analyzed in the range of 4500-500 cm⁻¹ spectra. In addition, XRD patterns of the synthesized SiO₂/MWCNT were analyzed using an ARL EQUINOX 3000 X-ray Diffractometer with a CPS120 detector. The analysis was employed using CuK α (λ = 0.15405 nm) and was conducted over an angle range of 10° to 100°. Raman analysis was performed using a Renishaw in Via Confocal Raman microscope, UK.

2.4 Hydrothermal Liquefaction of biomass

HTL experiments were performed in a 5 L capacity closed stainless high-pressure reactor (SS 316) at different temperatures between 240 to 340 °C, with a biomass-to-solvent ratio of 75 to 200 g/L, and a catalyst load of 0.1 to 0.5 wt.%. Water was used as a solvent for 60 minutes under a pressure of 20 bar. The reactor is designed to handle a maximum pressure of 200 bar and a temperature of 420 °C with an auto-cooling unit. Throughout the entire process, the reactants were stirred at a constant speed of 650 rpm under a nitrogen environment. In between the set of experiments, the reactor was cleaned by rinsing and heated with water at a temperature of 240 °C. After the heated experiments, the reactor was switched off and allowed to cool down.

2.5 HTL Products Recovery

After the HTL experiments, the biomass was converted into highly viscous dark-brown bio-crude, and it was recovered from the reactor and mixed with Dichloromethane (DCM) to extract bio-oil. The mixture

was allowed to settle down for phase separation in a separating funnel. Unreacted and excess solvent were recovered using a rotary evaporator from the bio-oil at 45 °C. The product yield was calculated using Equ. (1) and (2) (Arun *et al.* 2020). The HHV value (calorific value) of bio-oil was calculated as per Eq. (3).

$$\text{Bio - oil yield (wt. \%)} = \frac{\text{Mass of bio-oil (g)}}{\text{Mass of biomass (g)}} \times 100 \quad \dots (1)$$

$$\text{Gas phase yield (wt. \%)} = 100 - (\text{Bio - oil} + \text{Aqueous phase} + \text{Biochar}) \quad \dots (2)$$

$$\text{HHV} \left(\frac{\text{MJ}}{\text{kg}} \right) = (0.338 * C) + (1.428 * \left(H - \frac{O}{8} \right)) + (0.095 * S) \quad \dots (3)$$

2.6 HTL Products Characterization

2.6.1 Proximate and Ultimate Analysis

The proximate analysis was done in accordance with ASTM D 7582-10. The composition of biomass (fixed carbon, moisture, volatile matter, and ash contents) was estimated. The ultimate analysis of the products was performed using a CHNS/O Analyzer (Thermo-Fisher).

2.6.2 Gas Chromatography Analysis

Gas chromatography technique under the reported conditions (Kashimalla *et al.* 2023) was used to analyze the composition of bio-oil. The flame ionization detector (FID) has a major role in predicting the hydrocarbon profile for the bio-oil. Helium is the carrier gas with 1 mL/min as flow rate and the sample injection temperature was 260 °C. The column was fitted with an Agilent 7683B auto-injector, HP-5 section (100 m × 320 μm × 0.25 μm) with a flame ionization detector (FID). The initial temperature of the column was 40 °C and increased to 250 °C at a rate of 5 °C/min and held at the final temperature for 5 min.

2.6.3 FTIR Analysis

FTIR spectroscopy (SHIMADZU IR Prestige 21 instrument) was used to analyze the bio-oil and biochar. A Nicolet 5700 FT-IR spectrometer equipped with a Ge crystal ATR attachment (Omni Sampler Nexus) was fitted for the analysis. The samples were scanned over the spectra from 400 cm⁻¹ to 4000 cm⁻¹ (Singh *et al.* 2015).

2.6.4 SEM Analysis

The physical morphology of the surface of biochar has been analyzed by using a scanning electron microscope SUPRA 55VP FE-SEM. Initially, the morphology of the precursor and the biochar were

vacuum-dried for a whole night at about 105 °C before SEM analysis. They were examined at a 3 kV accelerating voltage. To prepare the samples for SEM, no conductive coating was used (Singh *et al.* 2015).

3. RESULTS AND DISCUSSION

3.1 Biomass Characterization

In order to produce a higher amount of bio-oil, it is important to analyze and understand the composition of biomass (Rajagopal *et al.* 2021). The biomass had moisture (14.78%), ash (6.28%), volatile (54.29%) and fixed carbon (24.65%) content. Biomass had carbon, hydrogen, nitrogen, sulfur, oxygen, HHV, H/C (2.48), and O/C (0.64) as 47.28%, 9.81%, 1.08%, 0.89%, 40.94%, 22.68 MJ/kg, respectively. The lower ash content in the biomass was an indication of low salt deposition in the plant tissue. A study with olive tree pruning waste (OPW) showed cellulose, hemicellulose, and lignin compositions of 38.18 %, 15.17 %, and 34.84 % respectively. Further, the OPW had a moisture content of 3.08 %, ash content of 3.17 %, VM content of 77.24 % and FC content of 16.51 % (Öcal *et al.* 2024). A study with oil palm blended waste showed carbon, hydrogen, nitrogen, and oxygen content of 47.51 %, 5.30%, 0.81% and 46.38% respectively. The biomass had HHV of 19.04 MJ/kg, moisture of 6.77 %, VM of 72.01 %, FC of 16.40% respectively (Parthasarathy *et al.* 2024).

3.2 TGA Analysis

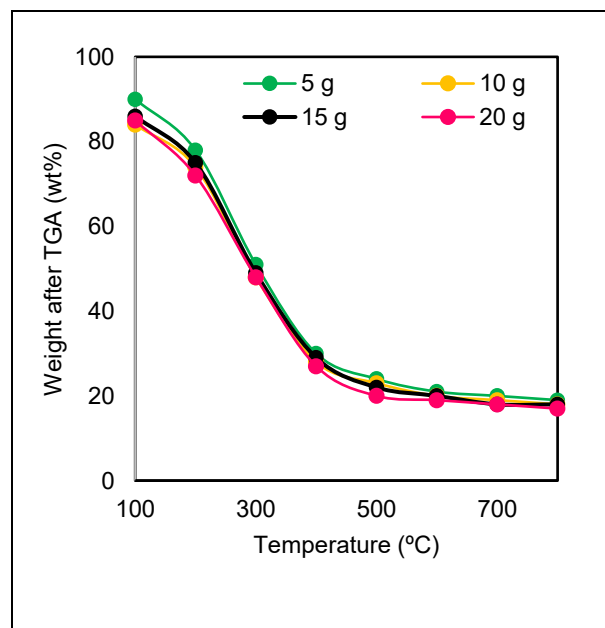


Fig. 1: TGA of biomass

TGA helps to forecast the thermal stability of palm tree waste biomasses and their pyrolytic behavior.

It has three steps over the experiments in accordance with the existing literature (Abnisa *et al.* 2013). In the first stage (100 °C and 300 °C), the free moisture and loosely bound water molecules of the bio-macromolecules were evaporated and thus causing the initial weight loss of the biomass. In the second stage (300 °C to 500 °C), the volatile compounds (proteins, carbohydrates, triglycerides, extracts, cellulose, hemicellulose, and lignin) were degraded. In the last stage (above 500 °C),

the left-out organic compounds were oxidized. The entire process has been performed over a wide range of temperatures of 100 °C to 800 °C. Biomass degradation rates were highest at 15 °C/min compared to other heating rates. According to the results of TGA, at 600 °C, there was a weight difference of 21% (5 °C/min), 20% (10 °C/min), 20% (15 °C/min), and 19% (20 °C/min), as shown in Figure 1.

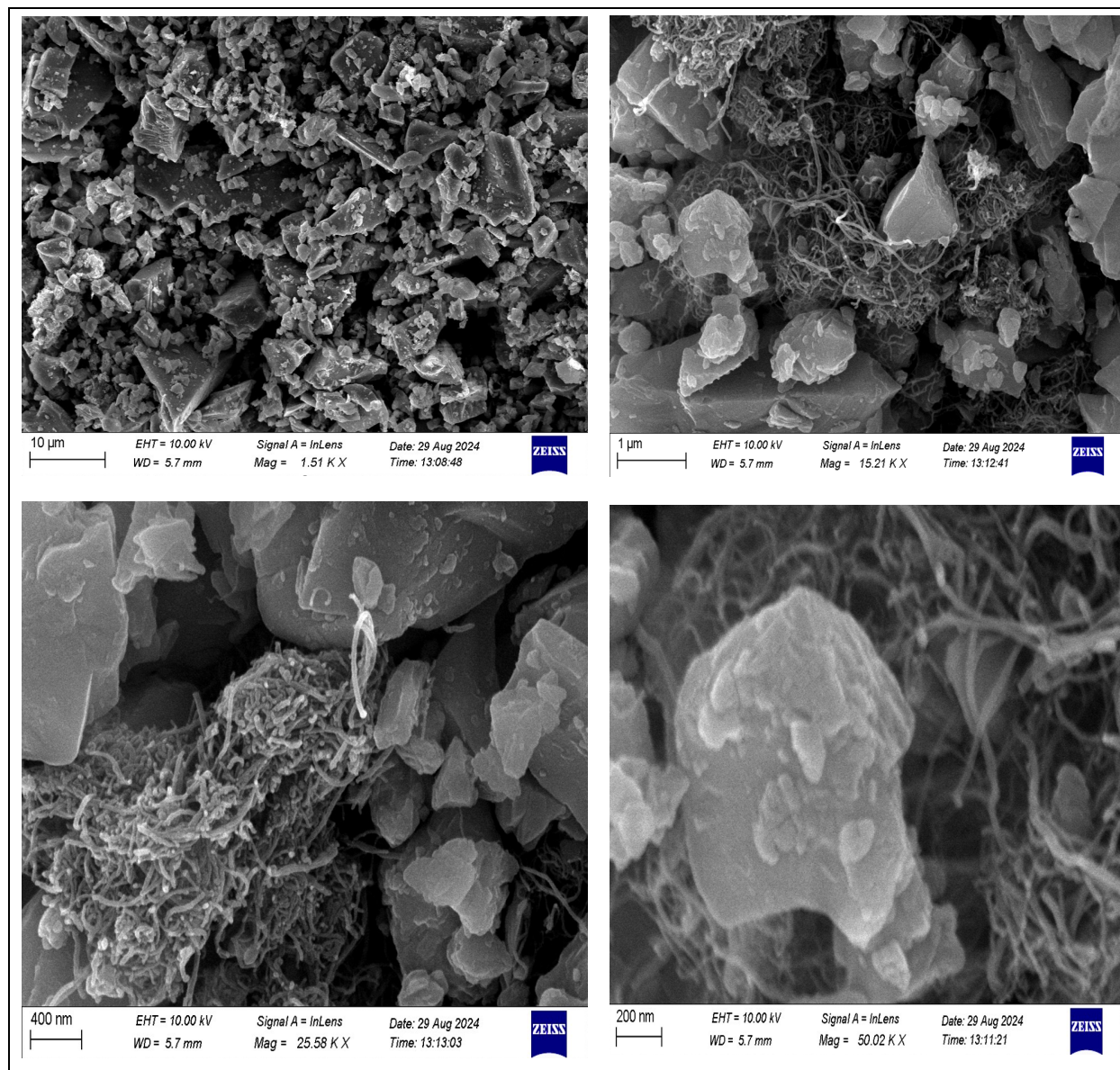


Fig. 2: Surface morphological characterization of MWCNT/silica composites

3.3 Catalyst Characterization

3.3.1 FE-SEM Analysis

FE-SEM analysis verified the existence of MWCNT and SiO₂ (Figure 2). SiO₂ nanoparticles are spherical in shape, which further supports their

homogeneity and structural integrity (Kim *et al.* 2008). SEM analysis provides the material properties and microstructures across diverse fields. The SEM results provide insights into the high spatial resolution, topographical, and large depth field through electron-sample interactions.

3.3.2 TEM

TEM micrographs of silica-coated MWCNTs show the morphology and structural features (Dillon *et al.* 2015). The homogeneous distribution of silica around the nanotubes is highlighted in the representative TEM images of the MWCNT/silica nanocomposite shown in Figure 3(a). Effective composite production is indicated by the micrographs, which verify good interfacial bonding between the MWCNTs and the silica matrix. Figures 3(b) and 3(c) show the matching sizes, and the measured average diameter of the MWCNTs was 22.5 nm. Furthermore, the EDAX spectrum of the synthesized composite is shown in Figure 3(d), indicating the presence of silica and MWCNTs. The composite material's crystalline nature is further confirmed by the Selected Area Electron Diffraction (SAED) pattern, which is displayed in Figure 3(e)

3.3.3 FT-IR

The synthesized MWCNT/SiO₂ composite, analyzed using FTIR spectroscopy to identify the functional groups present, confirmed the bonding interactions essential for material formation. The obtained spectrum, shown in Figure 4, exhibits several characteristic peaks corresponding to different molecular vibrations (Zeng *et al.* 2017). A peak at 649 cm⁻¹ was attributed to C-Cl stretching (alkyl halides), while the 1043 cm⁻¹ peak corresponded to C-F stretching (alkyl

halides). The presence of an ether (-C-O-C) functional group was confirmed by the peak at 1218 cm⁻¹, and the 1404 cm⁻¹ peak indicated CH₃ bending vibrations. A peak at 2300 cm⁻¹ corresponded to C≡N stretching, confirming the presence of nitrile groups. Additionally, alkene-related vibrations were observed at 2894 cm⁻¹ (C-H stretch) and 1997 cm⁻¹ (=C-H stretch), indicating the presence of unsaturated carbon bonding. The broad peak at 3305 cm⁻¹ was assigned to O-H stretching (alcohols), confirming the presence of hydroxyl groups.

3.3.4 XRD

X-ray diffraction (XRD) patterns of the synthesized MWCNT/SiO₂ composite confirmed its crystalline structure (Fig. 5) and the presence of SiO₂ and MWCNTs through distinct diffraction peaks. The JCPDS card numbers 75-1621 (C) and 89-2749 (SiO₂) correlate to the observed peaks at 24°, 44°, 58°, 64°, 78°, and 97° (2θ), which correspond to particular crystallographic planes (hkl). In particular, overlapping peaks from C (01-14) and Si (11-20) are represented at 44°, but the peak at 24° corresponds to Si (1 0 -10). Moreover, Si (20-20) and C (11-20) are represented by the peaks at 58° and 64°, respectively. Si (21-30) and C (02-24) are represented by the peaks at 78° and 97°, respectively (Sulistianti *et al.* 2017; Duan *et al.* 2023).

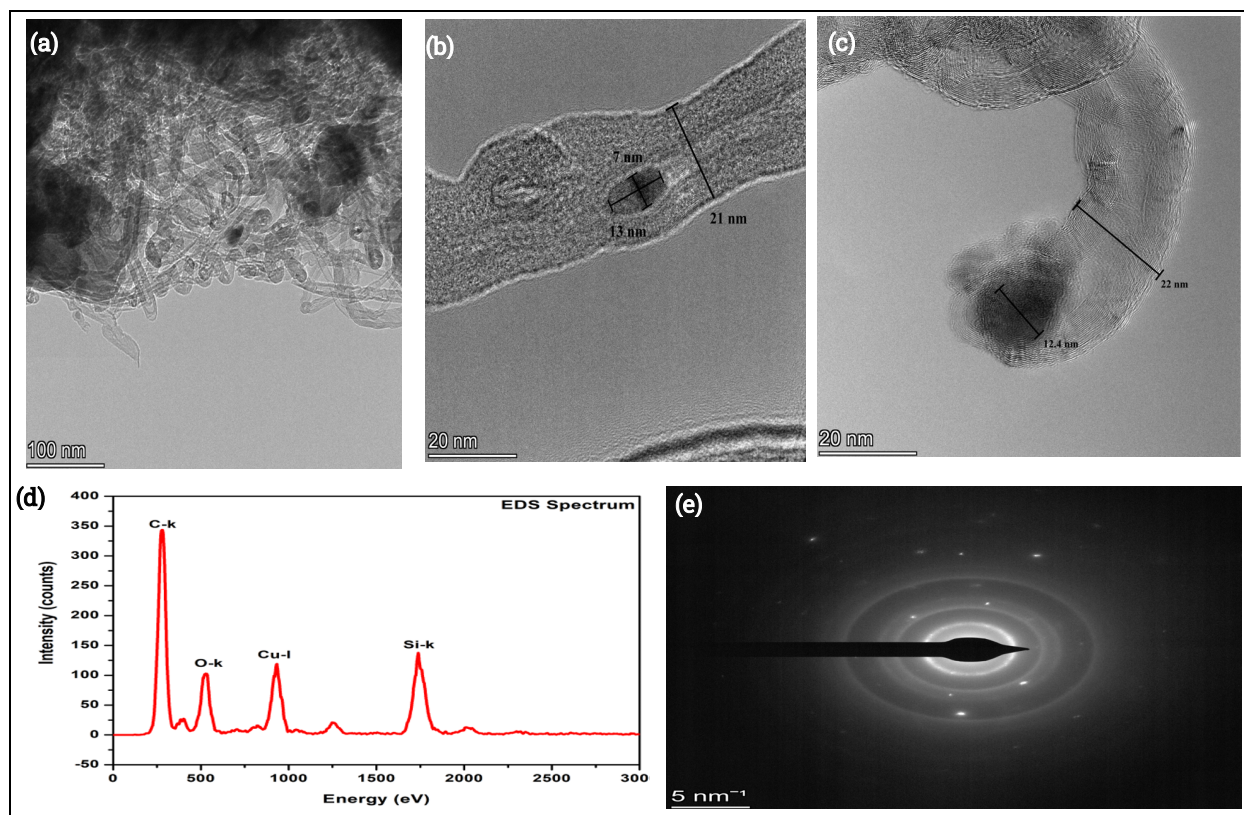


Fig. 3: TEM characterization of MWCNT/silica composites

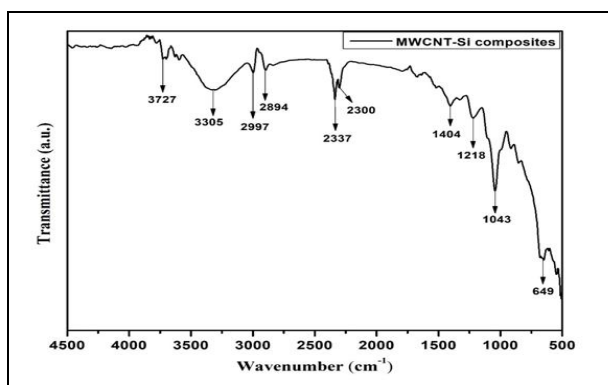


Fig. 4: FT-IR spectrum of MWCNT/silica composites

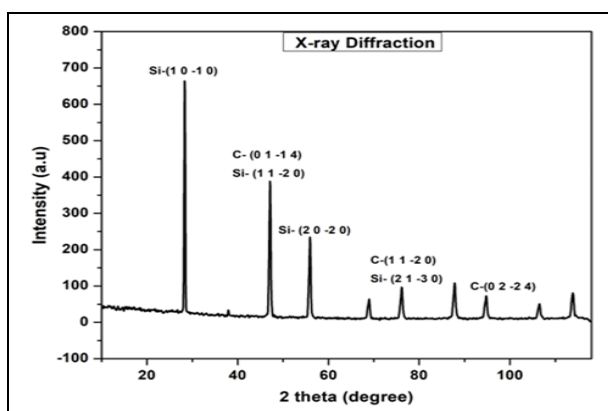


Fig. 5: XRD patterns of MWCNT/silica composite

3.3.5 RAMAN

The MWCNT/silica composite's Raman spectrum is shown in Figure 6, highlighting important vibrational modes connected to the structural elements of the material. The presence of Si-O-Si bonding within the composite is indicated by the detected peaks at 287 cm^{-1} , 498 cm^{-1} , and 512 cm^{-1} , which correspond to the distinctive vibrational modes of silica (SiO_2). Furthermore, the signal at 927 cm^{-1} indicates interactions between the silica matrix and the multi-walled carbon nanotubes (MWCNTs), maybe as a result of composite creation or surface functionalization (Dillon *et al.* 2015).

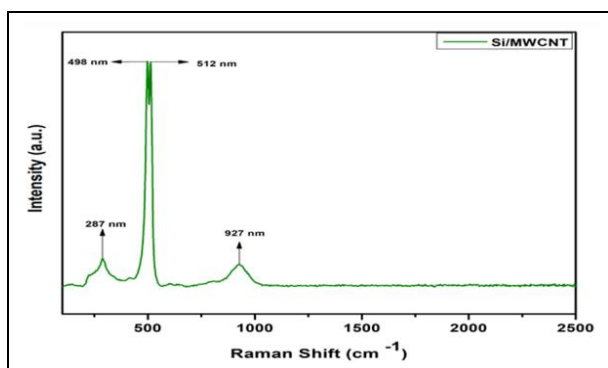


Fig. 6: Raman spectrum of MWCNT/silica composite

3.4 Hydrothermal Experiments

3.4.1 Role of Temperature

Degradation of biomass depends upon certain components such as temperature, solvent, pressure, and biomass-to-solvent proportion. The temperature at which the biomass breaks down varies for each particular component of the biomass. In the case of higher temperature, it leads to gas product generation, or if the temperature is lower, it causes improper biomass degradation (Brindhadevi *et al.* 2021). The highest bio-oil yield of (21.6%) at a temperature of 300 $^{\circ}\text{C}$ was shown in Fig. 7. In addition, biochar, gaseous phase, and aqueous phase were found to be 16%, 30.1%, and 31.9%, respectively. Gaseous products formation resulted from the conversion of low molecular volatile compounds present in the bio-oil to gas products (Valle *et al.* 2018).

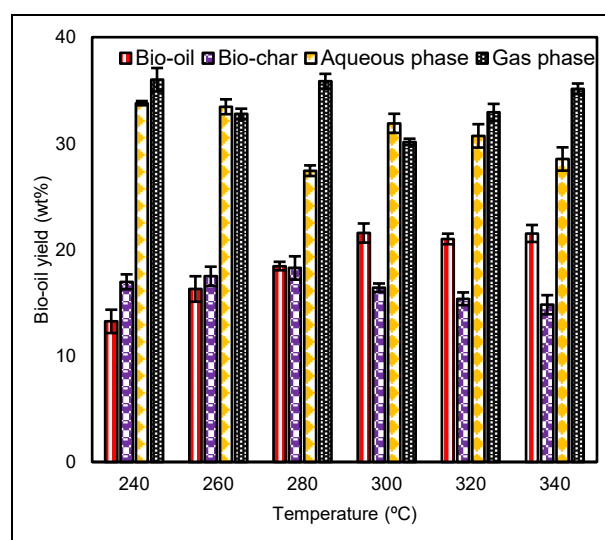


Fig. 7. Effect of temperature on HTL products yield

3.4.2 Effect of Biomass Load

The effect of biomass concentration on bio-oil yield was studied at varying biomass loading rates (75–200 g/mL) at 300 $^{\circ}\text{C}$ for one hour. The results are shown in Fig. 8. The maximum bio-oil yield was 23.1 wt.% with a biomass load of 175 g/L of solvent. The by-products produced under the same conditions were 13.5 wt.% biochar, 28.2 wt.% aqueous phase, and 35.2 wt.% gaseous phase. A subsequent increase in biomass loading rate to 200 g/mL showed a 22.8 wt.% decrease in bio-oil yield. Biomass load influences the bio-oil formation from the HTL process (Ravichandran *et al.* 2022). In a study, a 1:10 ratio of biomass to water resulted in bio-oil yield at 20 min; however, for a 1:30 ratio, it showed higher bio-oil yield in 40 min (Prasakti *et al.* 2019). The higher the proportion of biomass-to-water ratio, the lower the bio-oil yield (Arun *et al.* 2018b).

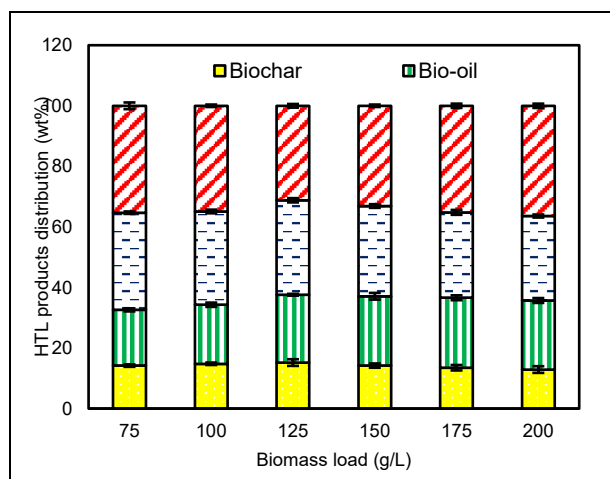


Fig. 8: Effect of biomass load on HTL product yield

3.4.3 Effect of Catalyst Load

An assessment on the synthesized catalysts to increase bio-oil proportion was conducted at 300 °C using 125 g of biomass that contained varying catalyst loads (0.1–0.5 wt.%). The results (Fig. 9) demonstrate that the addition of a catalyst has influenced the bio-oil yield at 300 °C. An increase in bio-oil yield of 28.9% was observed with 0.3 wt.% catalyst load, whereas the yield slightly decreased to 28.6% at a catalyst load of 0.4 wt.%. Increase in catalyst load beyond 0.3 wt.% does not greatly influence the bio-oil yield; however, it resulted in increased biochar and gaseous phase formation. The alkaline or acidic nature provided by the catalyst in the HTL process defines the effect of catalyst load on bio-oil yield (Ong *et al.* 2024). An increase in catalyst load concentration influences the bio-oil yield with less oxygen content, and in turn, this provides high calorific value bio-oil (Sharma *et al.* 2021).

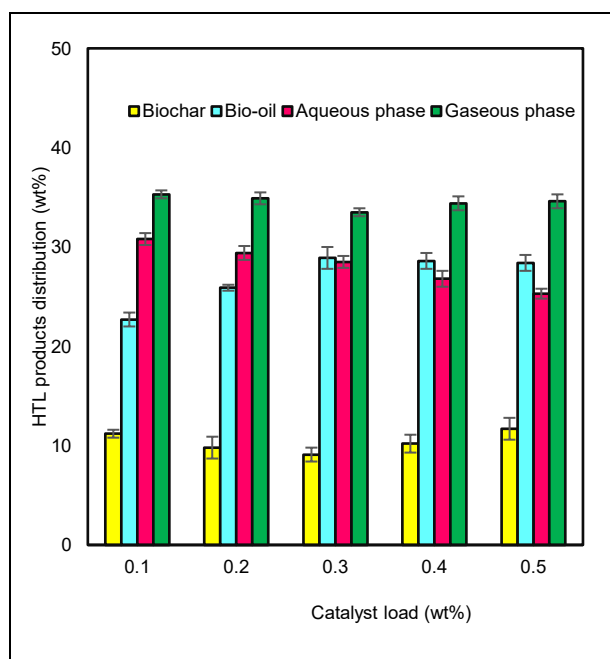


Fig. 9: Effect of catalyst load on HTL product yield

3.5 HTL Products Analysis

3.5.1 Elemental Analysis

Elemental analysis and calorific value analysis are the most important factors that define the quality and usage of bio-oil and biochar produced from the HTL process. The bio-oil and biochar were subjected to elemental analysis. The carbon, hydrogen, nitrogen, sulfur, oxygen, HHV, H/C (3.01 and 0.26), and O/C (0.47 and 0.18) of bio-oil and biochar were found to be 52.78%, 13.28%, 0.47%, 0.18%, 33.29%, 30.86 MJ/kg and 78.49%, 1.74%, 0.34%, 0.23%, 1.92%, 25.58 MJ/kg, respectively. The higher the calorific value, the higher the fuel quality, and it directly influences the energy recovery process with economic advantages.

3.5.2 GC-MS Analysis of Bio-oil

GC-MS analysis was used to determine the composition of the bio-oil (Fig. 10). The most important factors that define the quality of bio-oil from GC-MS analysis are the oxygen-containing compounds, HTL process conditions, and biomass composition. Most of the chemicals found in the bio-oil were documented based on previous research (Arun *et al.* 2021). The key compounds that are identified from bio-oil are categorized as phenols, ketones, aldehydes, furans, esters, hydrocarbons, and organic acids. The chemical composition of the produced bio-oil is categorized into hydrocarbons, esters, oxyacids, and others (Ahmed *et al.* 2023). The fractional percentage of hydrocarbons rose from 62% to 65% at 0.1 wt.% to 0.3 wt.% of different biomass loads. Furthermore, the hydrocarbons in the bio-oil decreased to 58% when the biomass load was increased to 0.4 wt.%. The proportion of furfurals, carboxylic acids, aldehydes, and other substances decreased from 8 weight per cent to 14 wt.%, 7 wt.%, and 13 wt.% in the bio-oil. The following literature reported similar results of palm tree waste bio-oil (Abnisa *et al.* 2013).

3.5.3 FTIR Analysis

FTIR analyses of both bio-oil (Fig. 11) and biochar (Fig. 12) depict the presence of functional groups in the surface of the biochar and bio-oil. Bio-oil had functional groups at 2352 cm^{-1} corresponding to C-O stretching, 1952 cm^{-1} and 1865 cm^{-1} corresponding to C=O stretching due to alkenes, 1336 cm^{-1} corresponding to C-H bending vibrations, and 975 cm^{-1} due to C-H deformation attributed to aromatics. In biochar, it had peaks at 2987 cm^{-1} , 2969 cm^{-1} , and 2900 cm^{-1} , corresponding to C-H stretching attributing alkanes, 2358 cm^{-1} and 2325 cm^{-1} corresponding to C-O stretching due to the presence of alcohols and carboxylic acids, and 1393 cm^{-1} corresponding to C-H bending vibrations.

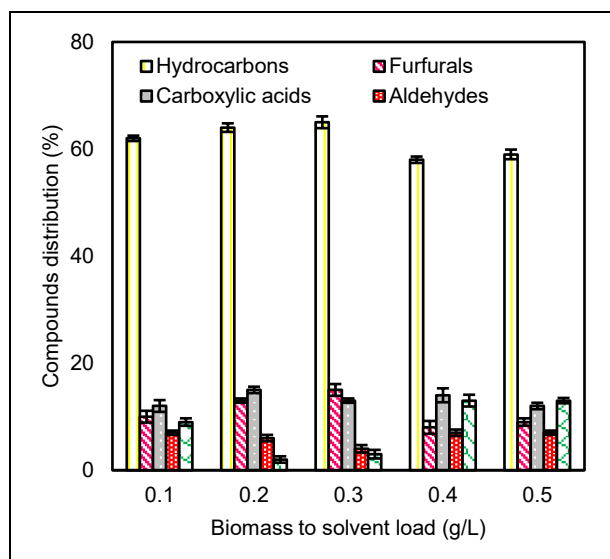


Fig. 10: GC-MS analysis of bio-oil

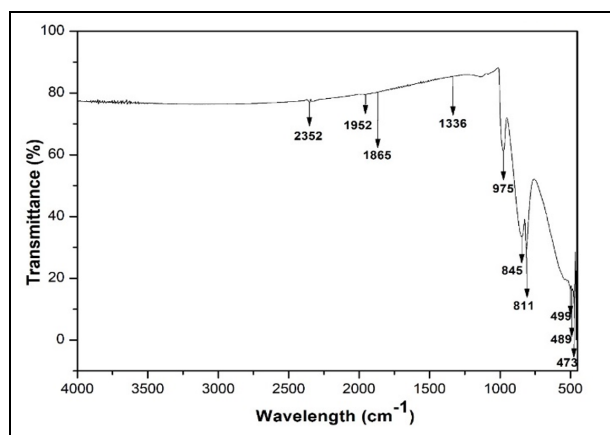


Fig. 11: FTIR spectra of bio-oil

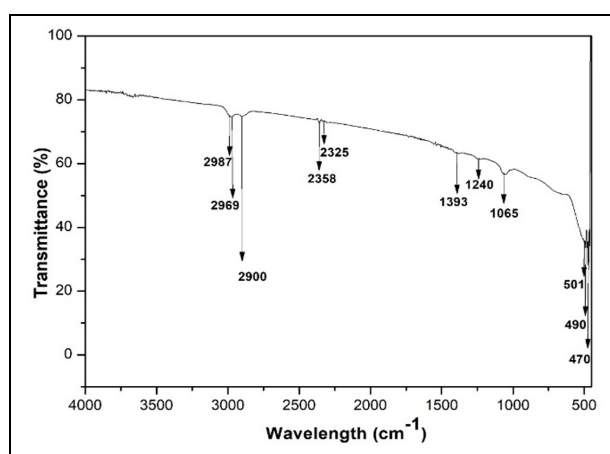


Fig. 12: FTIR spectra of biochar

3.5.4 SEM Analysis of Biochar

From the SEM analysis of biochar (Fig. 13), it was evident that the operating temperature influences the

surface properties like surface pore volume, size, and area. Formation of pores in the surface of the biochar helps in trapping or reacting to a greater extent. The specific pore volume of the biochar was $0.57 \text{ cm}^3/\text{g}$, surface area of $517.4 \text{ m}^2/\text{g}$, with the average pore diameter of 3.82 nm . The presence of rod-like structures in the SEM image would have been attributed to the mixed palm tree biomass, since it had trunk, EFB, fronds, and palm leaf ribs. The chances of recovering and reusing of catalyst from the biochar are explored in recent studies. This enhances the economic and environmental sustainability of the biofuel production from waste biomass. The specificity, synthesis method, and composition of the catalyst define the degree of recovery from the biochar (Pérez *et al.* 2015). The lifespan and cost-effectiveness improvement routes need to be explored in the future for a greener and sustainable mode of operations on a large scale.

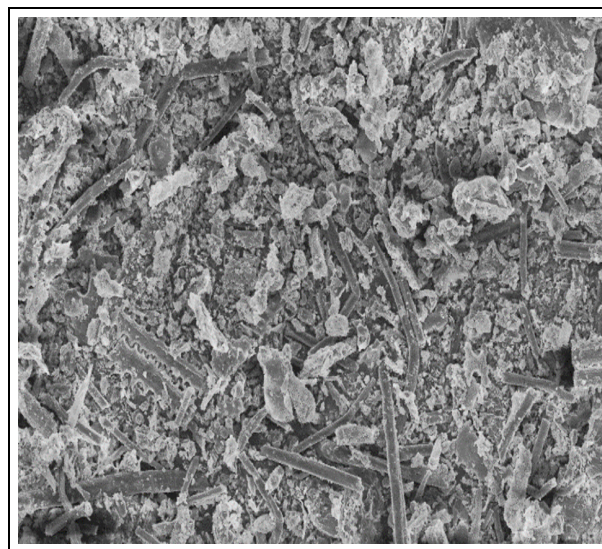


Fig. 13: SEM analysis of biochar

4. CONCLUSION

In this study, the palm tree debris was hydrothermally liquefied for the production of bio-oil and biochar under varying conditions. The maximum bio-oil yield was 28.9 wt.% was obtained at 300°C with a catalyst loading of 0.3 wt.% and a biomass-to-solvent ratio of 175 g/L. Bio-oil had a carbon content of 52.78 wt.%, and biochar had 78.49 wt.%. HHV of bio-oil was 30.86 MJ/kg , and for biochar it was 25.58 MJ/kg . The biochar will serve as a better adsorbent, catalyst support material, and electrode material based on the surface properties. This study will further contribute to the welfare of the agriculture and food sector in accordance with the SDGs.

ACKNOWLEDGEMENT

The authors wish to thank Sathyabama Institute of Science and Technology for the support.

AUTHOR CREDIT STATEMENT

C. Marimuthu and J. Jayakanth contributed to writing the original draft; J. Arun provided supervision and conceptualization; Salim Al Jadidi carried out the investigation; S. Naveen was responsible for data curation and investigation; and D. Ramachandran and K. Viswanathan contributed resources.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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