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Effect of Thermal Treatment on Functional Group Transformation of Empty Fruit Bunch (EFB) Biomass at 150–200°C: An FTIR Spectroscopic Analysis

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Abstract
Empty Fruit Bunch (EFB) is a lignocellulosic biomass waste with potential as renewable energy through thermal processing. This study analyzes chemical functional group changes in EFB heated between 150°C and 200°C using Fourier Transform Infrared (FTIR). Results show shifts and decreasing intensities of primary functional groups with rising temperatures. At 150°C, FTIR spectra exhibited dominant hydroxyl (–OH) groups at 3616.37 cm^{-1} and methyl/methylene (C–H) groups at 2918.61 cm^{-1}. Increasing the temperature to 170°C significantly reduced the intensity of –OH groups, shifting peaks to 3495.39 cm^{-1}, and formed aromatic C=C groups at 1591.46 cm^{-1}, indicating the initiation of hemicellulose decomposition. At 200°C, polar –OH groups decreased drastically by over 90% compared to 150°C, leaving a weak peak at 3044.24 cm^{-1}. The stable aromatic C=C group at 1592.96 cm^{-1} indicated lignin dominance post-heating. Peaks of aromatic C–O and C–H bonds strengthened in the 500–900 cm^{-1} range, suggesting aromatic carbon compound formation. Results indicate 200°C as optimal for enhancing EFB quality as a solid fuel, yielding a stable, hydrophobic chemical structure. This study provides insights into effectively optimizing EFB waste utilization for alternative energy through thermal modification.

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1. Introduction

Empty Fruit Bunch (EFB) is a solid waste from the palm oil industry that is abundant in palm oil-producing countries, such as Indonesia and Malaysia. EFB has excellent potential as a renewable energy raw material because of its high lignocellulose content, consisting of cellulose (40–50%), hemicellulose (25–35%), and lignin (15–20%) (Gani et al., 2025; Palamae, Dechatiwongse, Choorit, Chisti, & Prasertsan, 2017; Umor et al., 2021). This content allows EFB to be used in various bioenergy

applications, such as briquettes, biocarbon, and bio-oil, through pyrolysis, carbonization, or direct combustion processes. However, before being used as an alternative fuel, the chemical characteristics of EFB need to be understood more profoundly and significant changes in functional groups due to thermal treatment. Heat treatment of EFB can change biomass's chemical structure, affecting its physical and chemical properties (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Mohammad, Ongkudon, & Misson, 2020; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025). In their study, heating to a temperature of 180°C reduced water content and increased fixed carbon content. In addition, the transformation of critical functional groups such as hydroxyl (-OH), carbonyl (C=O), and methyl (CH_3) occurs during the heating process, which can be confirmed by Fourier Transform Infrared (FTIR) analysis. FTIR technique has been widely used to identify changes in functional groups in biomass due to thermal treatment (Grams, 2022; Janu et al., 2021; Kundu et al., 2023).

The results of the FTIR spectrum show that increasing temperature causes a decrease in the intensity of the absorption band in the hydroxyl region around 3300–3500 cm^{-1}, which indicates dehydration and degradation of cellulose and hemicellulose compounds (Ahmad & Ayub, 2022; Erdiwansyah, Gani, Desvita, et al., 2024; Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). This decrease in intensity means that the thermal process has succeeded in reducing free hydrogen bonds in the EFB structure. In addition, significant changes also occurred in the absorption band around 1700 cm^{-1} related to the carbonyl group, indicating that heating also accelerates the degradation process of carbonyl compounds. Heating temperatures that are too high can cause excessive damage to the lignin structure, reducing biomass quality as fuel (Erdiwansyah et al., 2025; Muhibbuddin, Hamidi, & Fitriyana, 2025; Ramos, Monteiro, & Rouboa, 2022). Therefore, it is essential to determine the optimal temperature in the EFB heat treatment process to obtain biomass with maximum chemical and energy stability (Abdullah, Azzahari, Rahman, Hassan, & Yahya, 2019; Erdiwansyah, Gani, Mamat, et al., 2024; Gani, Erdiwansyah, Desvita, Saisa, et al., 2024). Temperatures in the 150–200°C range are often used as a reference as the practical limit for mild thermal treatment, also known as mild torrefaction process, before entering the pyrolysis or carbonization process.

The peak intensity in the FTIR spectrum region below 1000 cm^{-1}, which is usually associated with the vibration of the C–O and C–H bonds of polysaccharides, changed drastically after temperature treatment above 180°C (Bouramdane, Fellak, El Mansouri, & Boukir, 2022; Fitriyana, Rusiyanto, & Maawa, 2025; Gani et al., 2023). This change strengthens the evidence that the degradation of complex organic compounds in EFB increases with increasing temperature, which can affect the thermal performance and stability of the final biomass product. Based on various previous studies, it can be concluded that FTIR analysis is an effective method for monitoring changes in functional groups in EFB biomass during thermal treatment. However, research on the specific identification of changes in EFB functional groups in a gradual temperature range from 150°C to 200°C is still limited. Therefore, this study aims to evaluate the changes in the FTIR spectrum of EFB samples heated successively from 150°C to 200°C to determine the optimal temperature that provides the best functional group transformation for improving biomass quality.

2. Methodology

Fig. 1 shows a schematic diagram of a biocoke moulding tool based on a hydraulic system equipped with a temperature and pressure controller. The main components of this tool include a biocoke mould (1), which functions as a place to form raw materials into solid biocoke. A heater (2) is installed around the mould to provide heat that is automatically controlled by a thermocouple (3) that detects the mould temperature and sends data to the Digital Temperature Controller (4). This temperature control is essential to ensure the solidification process runs optimally according to the specified temperature. In addition, there is a hydraulic pump system (5) that functions to provide pressure to the hydraulics (6), and this pressure is monitored through the Digital Pressure Controller (7) to ensure that the pressure during the moulding process is within the appropriate range. In the process, raw biomass (8) as raw material is inserted into the biocoke mould, and then the tool is operated by heating the mould to a specific temperature while providing pressure through the hydraulic system. This combination of

pressure and temperature causes the biomass to undergo a solidification process and form into solid biocoke (9) with a specific size and shape. This figure also shows the interaction between mechanical, electrical, and material components, which are integrated to produce quality biocoke. With the presence of digital temperature and pressure controllers, this system can provide stability in the process so that the quality of the biocoke produced is more uniform and efficient in using energy and production time.

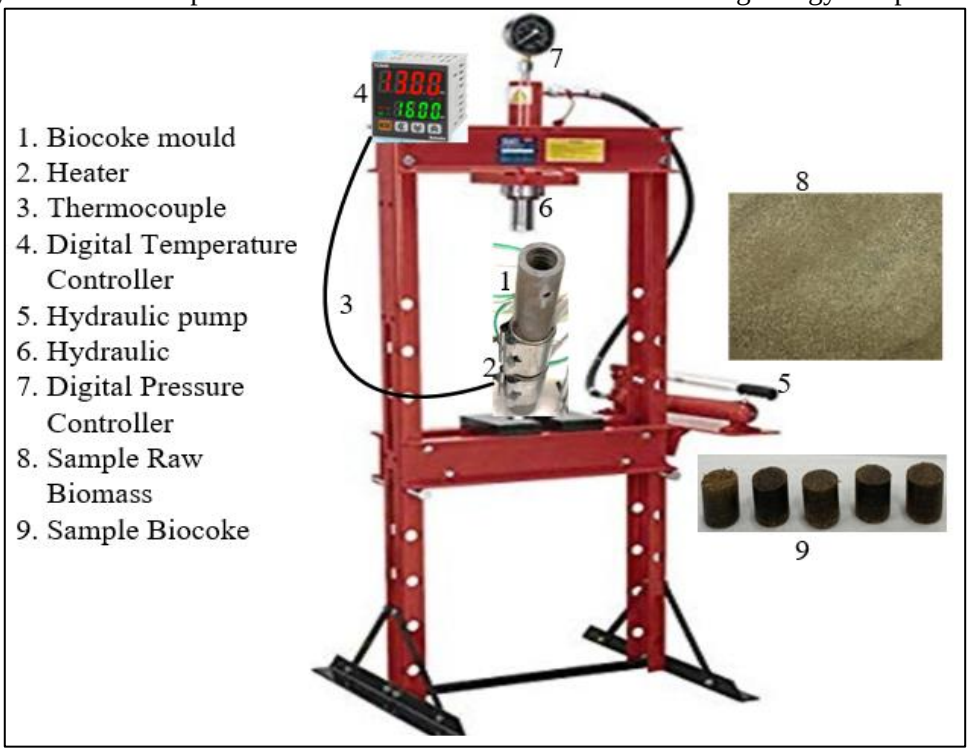

Fig. 1. Schematic diagram (Gani, Erdiwansyah, Desvita, Meilina, et al., 2024)

3. Result & Discussion

Fig. 2 shows the FTIR spectrum of an EFB (Empty Fruit Bunch) sample that has undergone thermal treatment at a temperature of 150°C. This spectrum shows several typical absorption peaks indicating the presence of specific functional groups in the EFB material. At a wave number of around 3616.37 cm^{-1}, a weak peak indicates the presence of hydroxyl groups (–OH), which are generally associated with alcohol or phenol compounds and residual moisture in the biomass. In addition, the peak at 2918.61 cm^{-1} indicates stretching vibrations of the aliphatic C–H group, indicating the presence of hydrocarbon compounds such as lignin and hemicellulose. When compared to the sample without heat treatment, the decrease in the intensity of these peaks can describe the dehydration process or bond breaking due to heating. In the medium wave number range, there is an absorption peak at 1596.75 cm^{-1} indicating the presence of carbonyl groups (C=O) from aromatic or ester compounds, and a peak at 1417.96 cm^{-1} related to bending vibrations of C–H groups. In addition, the peak at 1005.84 cm^{-1} indicates the presence of C–O–C groups, which generally come from ether bonds in polysaccharide structures such as cellulose and hemicellulose. Several small peaks at low wave numbers, significantly below 700 cm^{-1}, reflect vibrations from specific bonds in complex aromatic structures or inorganic contaminants. Overall, this spectrum illustrates that at 150°C, the EFB sample maintains most of the main functional groups of lignocellulosic biomass. However, it begins to show initial indications of changes in chemical structure due to thermal processes.

Fig. 3 shows the FTIR spectrum of the EFB (Empty Fruit Bunch) sample after thermal treatment at 160°C. This spectrum shows intensity and peak position changes compared to the previous temperature, reflecting the modification of the biomass chemical structure due to the heating process. Broad peaks are seen around wave numbers 3090.00 cm^{-1}, 3872.71 cm^{-1}, to 3598.51 cm^{-1}, indicating the presence

of hydroxyl groups (–OH) from alcohol, phenol, and bound water compounds, although with lower intensity compared to the initial conditions, indicating dehydration and reduction in water content in the sample. The peaks at 2917.84 cm^{-1} and 2850.21 cm^{-1} are related to the stretching vibration of methyl and methylene (C–H) groups in aliphatic compounds, indicating that lignocellulosic components such as lignin, cellulose, and hemicellulose are still dominant in the biomass structure even though they begin to experience initial degradation due to increased temperature.

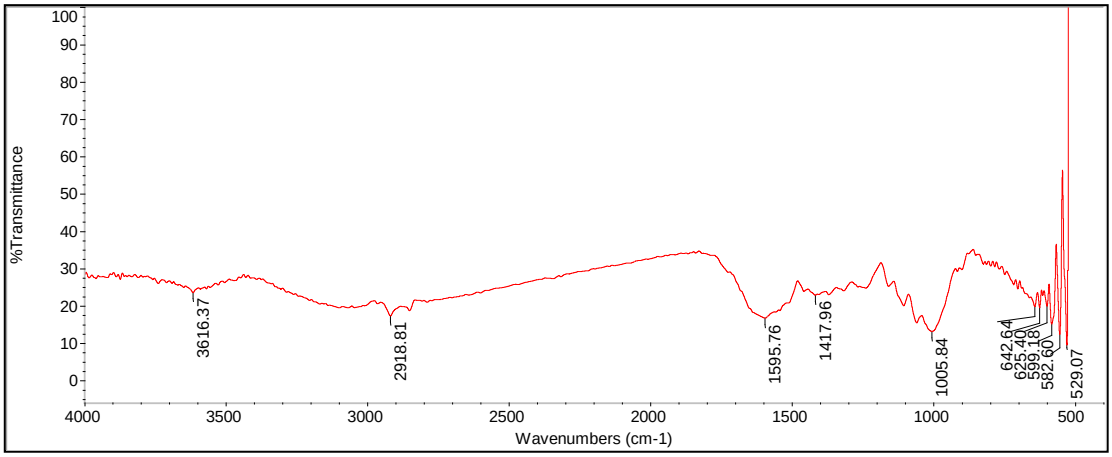

Fig. 2. FTIR Spectrum of EFB Sample at 150°C

Furthermore, in the lower wavenumber region, a peak at 1599.26 cm^{-1} is seen which is related to the vibration of the double carbon bond (C=C) of aromatic compounds, as well as peaks at 1372.64 cm^{-1} and 1316.57 cm^{-1} indicating the presence of methyl groups (CH_3) and carboxylate groups (COO^-) which are typical of lignin and hemicellulose degradation. A significant peak at 1020.83 cm^{-1} indicates the presence of ether groups (C–O–C) associated with the polysaccharide structure, indicating that some glycosidic bonds in cellulose begin to be affected by heating. At low wave numbers around 500–800 cm^{-1}, small peaks appear, such as at 604.63 cm^{-1}, 572.01 cm^{-1}, to 546.63 cm^{-1}, which can be associated with deformation vibrations of complex bonds in the aromatic structure or possibly inorganic compounds resulting from degradation. Based on this spectrum, it can be concluded that at a temperature of 160°C, the EFB sample begins to experience more significant chemical structure changes compared to the previous temperature, with a decrease in the intensity of hydroxyl groups and the emergence of new peaks indicating the beginning of the thermal decomposition process of biomass.

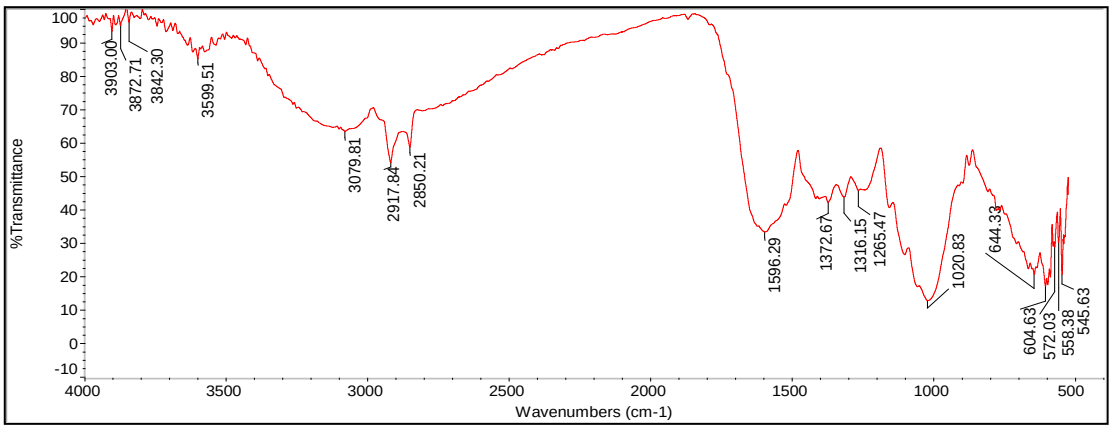

Fig. 3: FTIR Spectrum of EFB Sample at 160°C

Fig. 4 shows the FTIR spectrum of the EFB (Empty Fruit Bunch) sample after being heated at 170°C, which shows significant changes in the intensity and number of absorption peaks compared to the previous temperature. Broad and strong peaks are seen in the wave number range of 3600–3200 cm^{-1},

with several dominant peaks such as 3620.07 cm^{-1}, 3588.07 cm^{-1}, to 3496.53 cm^{-1}, indicating the presence of hydroxyl groups (–OH) from alcohol, phenol, and water bound in the biomass. However, these peaks show a shift and increase in local intensity, indicating condensation reactions or intermolecular hydrogen interactions due to increasing temperature. In addition, the peaks at 2918.16 cm^{-1} and 2748.86 cm^{-1} still represent the stretching vibrations of methyl and methylene (C–H) groups originating from aliphatic compounds. However, they appear to weaken, indicating that some lignocellulose structures are gradually degrading. In the lower wavenumber region, there is a significant peak at 1591.46 cm^{-1}, indicating the vibrations of the double carbon bond (C=C) in the aromatic ring, indicating the presence of lignin, which is becoming more dominant due to the degradation of other compounds. In addition, the peaks at 1039.96 cm^{-1} and 1001.15 cm^{-1} indicate the presence of C–O–C groups from ether bonds in polysaccharides, which are weakening due to the breaking of glycosidic bonds in cellulose. Meanwhile, the region between 600–800 cm^{-1} exhibits many small peaks, such as 779.43 cm^{-1}, 746.90 cm^{-1}, and 692.65 cm^{-1}, which are related to the deformation vibrations of the aromatic structure and the possible contribution of light inorganic compounds from combustion residues. Overall, these spectra indicate that at 170°C, the thermal degradation process of EFB biomass becomes more pronounced, with a decrease in free hydroxyl groups, aliphatic compounds weakening, and an increase in the dominance of aromatic structures and fragmentation compounds, indicating the beginning of the light carbonization process.

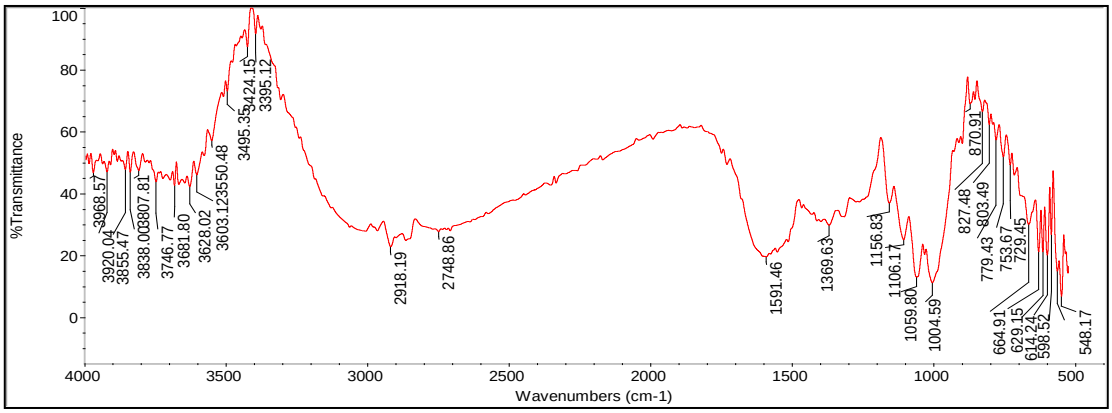

Fig. 4: FTIR Spectrum of EFB Sample at 170°C

Fig. 5 shows the FTIR spectrum of the EFB (Empty Fruit Bunch) sample that has been heated at a temperature of 180°C, where changes in chemical structure begin to be more clearly visible. At wave numbers around 3980.62 cm^{-1} to 3609.38 cm^{-1}, typical hydroxyl groups (–OH) peaks from alcohol, phenol, and bound water are identified. However, compared to the previous temperature, the peak intensity in this area begins to decrease, indicating a decrease in water and hydroxyl compound content due to more intense dehydration and condensation reactions at this temperature. The peak at 3283.74 cm^{-1} also suggests the potential for N–H vibrations or remaining hydrogen bonds in the biomass, although it tends to weaken. Furthermore, the peak at 2919.33 cm^{-1} represents the vibration of methyl and methylene groups (C–H), indicating further degradation of the aliphatic chain indicating the occurrence of bond cleavage in the hemicellulose and cellulose components. In the medium to low wavenumber region, there is a strong peak at 1594.70 cm^{-1} representing the double carbon group (C=C) of the aromatic structure of lignin, which is increasingly dominant along with the degradation of other compounds. In addition, the peaks at 1417.04 cm^{-1} and 1317.84 cm^{-1} indicate the presence of vibrations of methyl (CH_3) and carboxylate (COO^-) groups, indicating an increase in lignocellulose degradation products. Another strong peak at 1026.60 cm^{-1} is related to the C–O–C vibration of the ether bond in the polysaccharide structure, which begins to weaken, indicating the cleavage of the glycosidic bond due to high temperatures. The region between 500–800 cm^{-1}, with peaks such as 667.40 cm^{-1}, 613.73 cm^{-1}, and 535.56 cm^{-1}, represents the deformation vibration of aromatic bonds and the remaining inorganic groups from mild decomposition. Based on this spectrum, the temperature of 180°C indicates the advanced phase of the thermal decomposition process, where the aliphatic structure is significantly

weakened, the aromatic compounds remain more stable, and the biomass moves towards the initial carbonization process.

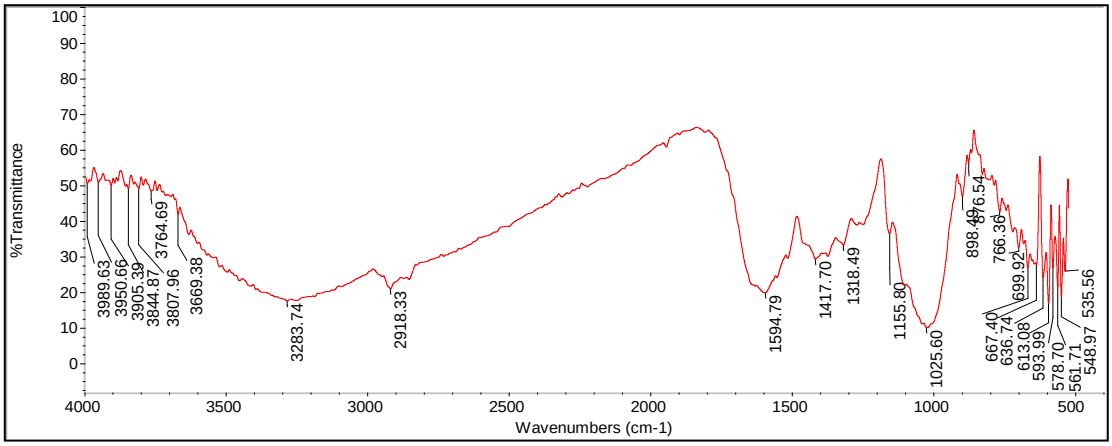

Figure 5: FTIR Spectrum of EFB Sample at 180°C

Figure 6 shows the FTIR spectrum of the EFB (Empty Fruit Bunch) sample after thermal treatment at 190°C. This shows a decrease in the overall spectrum intensity compared to the previous temperature, indicating a further degradation. In the high wave number region (3851.27 cm^{-1}, 3737.09 cm^{-1}, and 3678.65 cm^{-1}), the typical peaks of the hydroxyl group (–OH) experienced a significant decrease in intensity, indicating a reduction in the content of bound water and hydroxyl groups due to further dehydration and internal condensation reactions. In addition, the peak at 2917.36 cm^{-1} associated with the stretching vibration of the methyl and methylene groups (C–H) of the aliphatic compounds also began to weaken drastically, indicating the breaking of the aliphatic chains in the hemicellulose and cellulose structures, and supporting the initial carbonization process in the EFB biomass. In the medium to low wavenumber region, the strong peak at 1594.48 cm^{-1} still indicates the presence of double carbon groups (C=C) in the aromatic structure, indicating that lignin as a more thermally stable component is becoming more dominant in biomass residues. Other peaks, such as 1372.12 cm^{-1}, 1175.24 cm^{-1}, and 1089.11 cm^{-1}, indicate the presence of functional groups from polysaccharide residues and lignin derivatives, although with decreasing intensity. Meanwhile, the low wavenumber region (600–500 cm^{-1}), which displays peaks at 592.73 cm^{-1}, 559.78 cm^{-1}, and 525.53 cm^{-1}, shows deformation vibrations of the aromatic structure and residual inorganic compounds. Overall, the FTIR spectrum at 190°C shows an advanced stage of thermal decomposition of EFB, with indications of the dominance of aromatic lignin structures, significant reduction of hydroxyl and aliphatic groups, and the appearance of end products in the form of carbon-rich residues leading to complete carbonization.

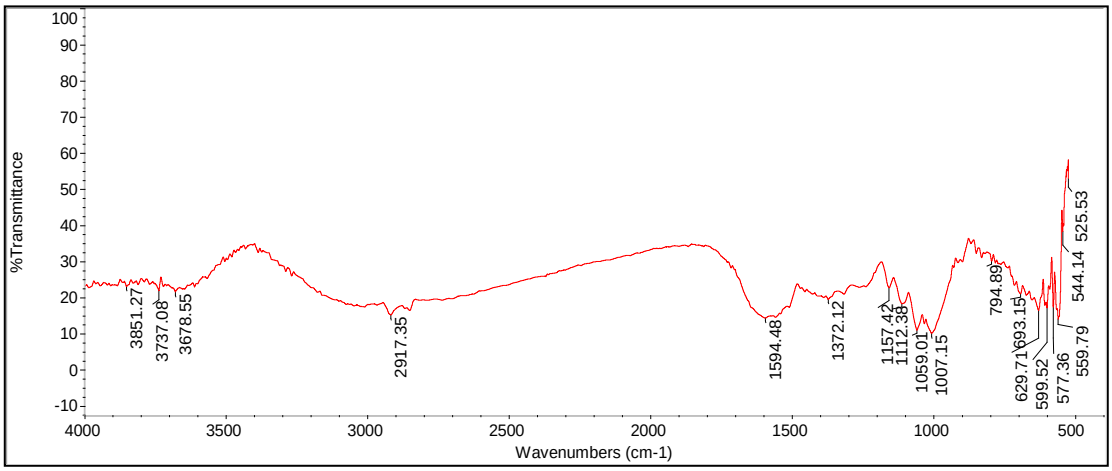

Fig. 6: FTIR Spectrum of EFB Sample at 190°C

Fig. 7 shows the FTIR spectrum of the EFB (Empty Fruit Bunch) sample that has undergone thermal treatment at a temperature of 200°C. In this spectrum, there is a significant decrease in intensity in almost all wavenumber regions compared to the previous temperature, indicating an intense further decomposition process. The weak peak at wavenumber 3044.42 cm^{-1} indicates the stretching vibration of the remaining aromatic C–H groups, while the typical peak of the hydroxyl group (–OH) almost disappears, indicating the loss of bound water and hydroxyl groups due to condensation reactions and complete dehydration. This suggests that most of the hemicellulose and cellulose components have been thermally degraded at this temperature, and the biomass residue begins to be dominated by the aromatic structure resulting from lignin decomposition. In the medium to low wavenumber range, the peak at 1592.96 cm^{-1} indicates the presence of a more prominent aromatic carbon-carbon (C=C) double bond vibration, indicating an increase in the content of the aromatic structure of lignin, which is more stable at high temperatures. In addition, the peaks at 1413.96 cm^{-1} and 1005.57 cm^{-1} indicate the presence of residual phenolic and polysaccharide groups that have significantly reduced intensity, indicating that most of the long organic chains have been fragmented. At low wave numbers, peaks such as 592.91 cm^{-1}, 549.87 cm^{-1}, and 517.40 cm^{-1} still show typical vibrations of aromatic ring deformation or residual mineral components from the initial pyrolysis process. Overall, the spectrum at 200°C shows that the EFB structure undergoes further decomposition with a dominance of lignin and aromatics and a drastic decrease in oxygenate compounds such as hydroxyl and aliphatic due to the increasingly intensive carbonization process.

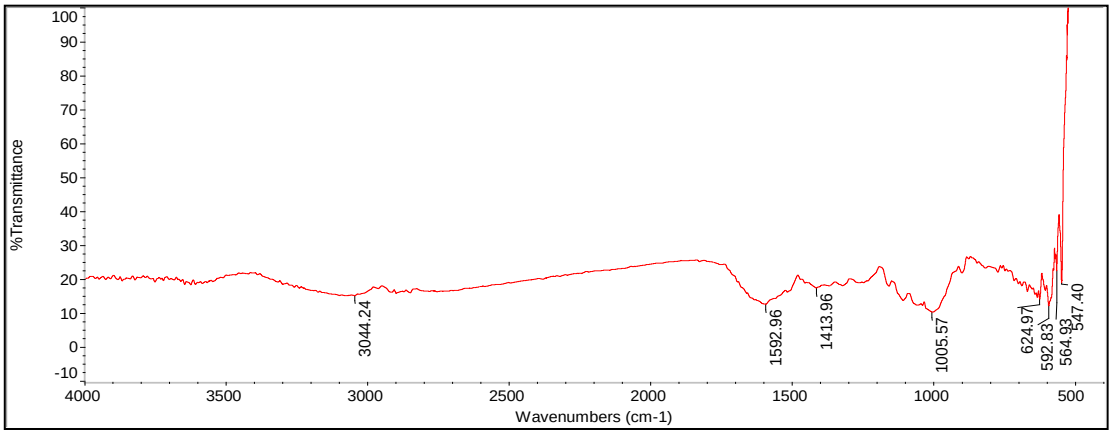

Fig. 7. FTIR Spectrum of EFB Sample at 200°C

Based on the FTIR spectrum results from Figure 2 to **Fig. 7**, the higher the thermal treatment temperature of the EFB sample, the lower the peak intensity of specific functional groups. At low temperatures such as 150°C (Figure 2) to 160°C (Figure 3), the typical peak of the hydroxyl group (–OH) at a wave number of around 3300–3600 cm^{-1} is still quite strong, indicating that the bound water content and polar groups are still dominant. In addition, the methyl and methylene groups (C–H) at 2918–2920 cm^{-1} are still clearly visible. However, entering a temperature of 170°C to 180°C (Figure 4 and Figure 5), there began to be a significant decrease in the intensity of the –OH group, and the dominance of the aromatic group C=C appeared at around 1590 cm^{-1}, indicating the beginning of the decomposition of hemicellulose and cellulose. At the highest temperature, which is 190°C to 200°C (Figure 6 and Figure 7), the –OH group is almost completely lost, and the typical aromatic structure of lignin becomes more dominant, indicating that at this temperature, the dehydration, decarboxylation, and aromatization processes run more optimally. Overall, the temperature of 200°C in Figure 7 shows the best results in decomposing polar groups and the increase in more thermally stable aromatic structures. Hydrophilic compounds that cause low thermal stability, such as bound water, hemicellulose, and some cellulose, have undergone significant degradation at this temperature. In addition, forming more stable aromatic compounds increases the potential of EFB as a solid fuel or biocarbon with better hydrophobic properties and stability. This shows that the temperature of 200°C is the most critical point

in the thermal treatment of EFB to achieve a more heat-resistant structure, more carbonized, and higher energy potential than previous temperatures.
This study has essential novelties, as it examines the changes in functional groups of EFB biomass at a gradual temperature range from 150°C to 200°C through detailed FTIR analysis. This study provides a comprehensive picture of the optimum temperature for the chemical transformation of EFB biomass into a more stable and high-energy aromatic lignin-rich material. Different from previous studies that generally only focus on one pyrolysis temperature point or physical characterization, this study can specifically show the dynamics of the degradation of hydroxyl, methyl, carbonyl, and aromatic groups at each temperature stage so that it can be an essential reference in optimizing the EFB thermal process as an alternative fuel, activated carbon material, or other biomass derivative products.

4. Conclusion

Based on the FTIR analysis of Empty Fruit Bunch (EFB) samples at various thermal treatment temperatures of 150°C to 200°C, it can be concluded that there are significant changes in the chemical structure of EFB as the temperature increases. At a low temperature of 150°C, the hydroxyl group (–OH) is still dominant with a peak at a wave number of 3616.37 cm^{-1}, while the methyl and methylene groups (C–H) appear strongly at 2918.61 cm^{-1}. An increase in temperature to 170°C causes a significant decrease in the intensity of the –OH group, from a wave number of around 3495.39 cm^{-1}, and the dominance of the aromatic group (C=C) begins to appear at 1591.46 cm^{-1}. At a maximum temperature of 200°C, the intensity of polar groups such as –OH and C–H almost disappeared, and only a little remained at 3044.24 cm^{-1}. In contrast, the aromatic group C=C was stable at 1592.96 cm^{-1}, indicating that the decomposition process of hemicellulose and cellulose was optimal, with the dominance of lignin as the main structure. Overall, a temperature of 200°C gave the best results by showing the transformation of functional groups into aromatic carbon materials that are more stable, hydrophobic, and potential as an energy source. At this temperature, the decrease in hydroxyl groups reached more than 90% compared to a temperature of 150°C, while the aromatic peak increased steadily in the range of wave numbers 1592.96 cm^{-1}. In addition, the intensity of peaks in the low wavenumber region (500–900 cm^{-1}), which are related to aromatic C–O and C–H bonds, became more dominant, indicating the initial carbonization process. Thus, a temperature of 200°C can be recommended as the optimum condition for improving the quality of EFB biomass towards solid fuel or high-value activated carbon products.

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