

An investigation of pyrolysis kinetics in microwave-assisted conversion of oil palm shell and activated carbon for sustainable bio-oil production

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Abstract

This study explores microwave (MW) pyrolysis of oil palm shell (OPS) blended with activated carbon (AC) to produce bio-oil, focusing on the pyrolysis kinetics and the effect of different feedstock ratios. Three OPS mixtures (70:30, 75:25, and 80:20) were analyzed at a constant temperature of 400°C. Gas chromatography-mass spectrometry (GC-MS) revealed that acetic acid, phenol, and other oxygenated compounds were dominant in the resulting bio-oils. Pyrolysis kinetics were modeled using a first-order reaction approach, with rate constants and activation energies determined for each blend. The 75:25 ratio yielded the highest bio-oil content and exhibited the most favorable kinetic performance, showing strong alignment between experimental and simulated data ($R^2 = 0.758$). The study also examined the impact of pyrolysis temperatures (400°C, 500°C, and 600°C) at the fixed 75:25 ratio, demonstrating that temperature plays a key role in both enhancing bio-oil yield and altering its chemical composition.

Keywords: Microwave pyrolysis, Pyrolysis kinetics, Oil palm shell, Activated carbon, Bio-oil production

1. Introduction

The growing global demand for energy and sustainable waste management has sparked significant interest in alternative energy sources. Biomass, which can be carbon-neutral and easily sourced from agricultural waste, wood, and grass, offers a promising approach to producing biofuels and chemicals while reducing environmental impact [1, 2]. Thailand, as an agricultural country, holds great potential for biomass energy production. Among the locally available biomass sources, oil palm shell (OPS) is abundant as a byproduct of the palm oil industry, making it an ideal feedstock for bio-oil production due to its carbon-rich composition. However, optimizing bio-oil yield and quality requires refining the pyrolysis process, and including activated carbon (AC) as an additive has proven effective [3-5].

Pyrolysis, the thermal decomposition of biomass at high temperatures (300-900°C) in the absence of oxygen [6], produces bio-oil, biochar, and non-condensable gas [7]. Microwave (MW) pyrolysis has emerged as a superior method due to its rapid heating, energy efficiency, and uniform heat distribution, which enhances bio-oil quality and reduces unwanted byproducts [8, 9]. However, the effects of combining oil palm shell (OPS) with activated carbon (AC), particularly on bio-oil composition, remain underexplored. Although there is extensive research on microwave-assisted pyrolysis of biomass, most studies focus on other types of biomass and seldom examine OPS blended with AC. As an abundant agricultural byproduct in Southeast Asia, OPS is often underutilized. Studies on OPS pyrolysis without microwave absorbers, such as AC, have shown promise for bio-oil production, but the combined use of OPS and AC in microwave pyrolysis settings remains relatively unexplored. This study addresses this gap by investigating the pyrolysis kinetics and bio-oil composition of different OPS ratios under controlled microwave pyrolysis conditions. Optimizing this process enhances both the efficiency and quality of bio-oil production, positioning OPS as a sustainable feedstock. This approach not only improves bio-oil yield but also opens opportunities for tailoring bio-oil properties for industrial applications. Additionally, insights from this research contribute to advancing biomass conversion methods aligned with sustainable energy objectives.

This study examines the effect of choice of OPS:AC mixture ratio (70:30, 75:25, or 80:20) on bio-oil composition through MW pyrolysis at a constant temperature of 400°C and the effect of different MW pyrolysis temperatures (400, 500, and 600°C) with the mixture ratio fixed at 75:25. Using Gas Chromatography-Mass Spectrometry (GC-MS), the chemical composition of the bio-oil is analyzed to identify valuable compounds with industrial applications, such as phenolics, furans, and hydrocarbons. Additionally, kinetic modeling plays a critical role in predicting biomass decomposition under various conditions. Given the complexity of biomass pyrolysis where thousands of reactions occur simultaneously, thermogravimetric analysis (TGA) has traditionally been used to study

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pyrolysis kinetics [10]. In this research, a custom MW pyrolyzer with weight monitoring and temperature control was developed to better understand the kinetics of the process.

This work contributes to improving the efficiency and sustainability of bio-oil production, aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). By converting waste biomass into valuable biofuels and chemicals, this study supports promoting clean energy, reducing fossil fuel dependence, cutting greenhouse gas emissions, and fostering innovation in green technology and sustainable industry practices.

2. Materials and methods

2.1 Materials

In this study, oil palm shells (OPS) were obtained from Southern Palm (1978) Co., Ltd., located in Phunphin, Surat Thani, Thailand. Commercial-grade activated carbon (AC), made from coconut shells, was used as a catalyst and microwave absorber. The OPS was ground and sieved to achieve a particle size smaller than 5 mm, then oven-dried at 105°C to bring the moisture content down to around 8% by weight. Once dried, the OPS was sealed in zip-lock plastic bags to preserve the desired moisture level.

2.2 Experimental set-up

The experiments were conducted using a household multimode microwave (MW) oven with an output of 800 W at a frequency of 2.45 GHz. Modifications were made to the microwave by removing the turntable base and creating a 25 mm hole at the top. An ON-OFF control system was built using an Arduino UNO microcontroller, based on the Atmega328P, which was connected to a type-K thermocouple placed into the sample via a quartz reactor. The microcontroller sent signals to a solid-state relay (SSR), functioning as an ON-OFF switch for the microwave's power. The system allowed for temperature regulation by setting maximum and minimum thresholds. During the process, real-time temperature data were displayed and recorded on a personal computer (PC) through a USB connection. To minimize noise when switching the microwave on and off, copper ingots were used for electrical grounding of both the microwave and thermocouples. The quartz reactor, a flask-shaped container with a volume of 250 ml, had internal and external diameters of 23 mm and 32 mm, respectively, and a height of 140 mm. Teflon corks with three 7 mm holes for glass tubes were used to seal the reactor. One hole accommodated a bent glass tube for N₂ flushing, connected to a rotameter with a valve for flow control. Another hole held a straight glass tube with a thermocouple probe inside a metal sheath to reduce interference, while the final hole was used to vent pyrolysis gases through a long glass tube to the condensation system.

2.3 Method

Before the pyrolysis run, the reactor was flushed with N₂ at a flow rate of 2 LPM for 2 min to ensure an inert atmosphere with oxygen removed, and the continued flushing facilitated the movement of pyrolysis products to the condensation section. The quartz reactor was supported on a digital balance, which measured the sample weight during the MW pyrolysis process and sent the weight data to the PC. After the process, the system was flushed with N₂ for another 2 min to cool it down, and liquid products were collected from the condensing system. In this experiment, the mixture ratio of OPS to AC was varied among 70:30, 75:25, and 80:20, with a fixed total sample weight of 300 grams for each run. The MW power was set at 800 W for a pyrolysis time of 35 min. The target temperatures were set at 400, 450, 500, 550, and 600°C. These temperatures were selected carefully, guided by the thermal decomposition behavior of the biomass samples, specifically oil palm shell (OPS) and activated carbon (AC). Preliminary thermogravimetric analysis (TGA) revealed key decomposition stages for OPS within the range of 300–600°C [11]. To capture the effects of these stages on bio-oil yield and composition, specific temperatures were set for the microwave pyrolysis experiments. These temperature settings allowed for detailed observation of how the decomposition process varies at each stage, influencing both the kinetics and the chemical profile of the resulting bio-oil. Therefore, Figure 1 shows a schematic diagram of the MW pyrolysis system used in this study.

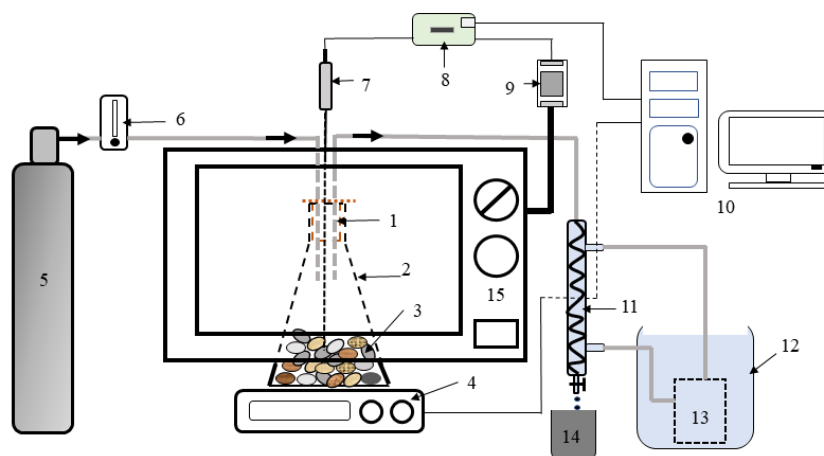


Figure 1 Schematic diagram of the experimental microwave pyrolysis system (1: Teflon lip, 2: quartz reactor, 3: mixture sample, 4: digital balance, 5: nitrogen tank, 6: rotameter, 7: thermocouple, 8: microcontroller unit, 9: solid-state relay, 10: PC, 11: the condenser unit, 12: water bath, 13: water pump, 14: bio-fuel collector, and 15: microwave oven).

After microwave pyrolysis, the products were weighed, and the yields for the three phases: solid, liquid, and gas were calculated using Eq. (1). To clarify, the yield of bio-oil was quantified by weighing the quartz reactor, bio-oil collector, and relevant apparatus components both before and after each experimental run. This method ensured accurate measurement of the bio-oil produced. Additionally, the oil residual on the condensate pipe was taken into account for the total bio-oil yield. The pipe was carefully cleaned, and any remaining oil was collected and weighed to include in the yield calculations. These procedures were followed consistently to improve the precision of the bio-oil yield data. In this study, two sets of the liquid (bio-oil) samples were sent to the Office of Scientific Instrument and Testing (OSIT) at Prince of Songkla University, Hat Yai campus, for chemical composition analysis using GC-MS. The first set of bio-oil samples was obtained from pyrolysis at a fixed temperature of 400°C, with the mixture ratios of oil palm shell (OPS) to activated carbon (AC) set at 70:30, 75:25, and 80:20. The second set was produced at different pyrolysis temperatures (400°C, 500°C, and 600°C), while maintaining a constant mixture ratio of 75:25.

$$\text{Gas yield (\%)} = 100 - (\text{Liquid yield (\%)} + \text{Solid yield (\%)}) \quad (1)$$

2.4 Reaction kinetics and simulation scheme

In this study, the reaction kinetics of oil palm shell (OPS) during microwave (MW) pyrolysis were analyzed using the Kissinger method [12, 13]. The kinetics of reactions involving the transformation of solids into solids and gases can generally be described by Eq. (2).

$$\frac{dx}{dt} = Ae^{-E_a/RT}(1-x)^n \quad (2)$$

$$x = \frac{m_0 - m_t}{m_0 - m_f} \quad (3)$$

where dx/dt is the rate of mass change, m_0 and m_f are the initial and final masses of the sample, respectively, m_t is sample mass at time t , and n is the empirical order of the reaction. This includes the Arrhenius equation for the rate constant k as described in Eq. (4).

$$k = A \exp\left(\frac{-E_a}{RT}\right) \quad (4)$$

In this context, A represents the rate constant's pre-exponential or frequency factor, E_a is the activation energy (kJ/mol), R is the universal gas constant ($8.314 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$), and T denotes the absolute temperature (K). The solid-state pyrolysis kinetics of biomass followed the general reaction rate equation (Eq. 2). For MW pyrolysis, the kinetics are modeled by a first-order ordinary differential equation (ODE). The 4th-order Runge-Kutta (RK) method was employed to numerically solve this ODE, with the reaction order empirically set to 1 ($n = 1$). The kinetic parameters were examined within the following ranges: activation energy (E_a) between 31,550 and 58,040 J/mol [14], with a step size of 10 J/mol, and the pre-exponential factor (A) varied from 6.40 to 68.40 1/s [14], with increments of 0.1/s. The initial temperature was set at 313K. These numerical simulations were used to identify the parameters that best matched the experimental data, which were averaged at each target temperature (400°C, 450°C, 500°C, 550°C, and 600°C) for each OPS mixture ratio (70:30, 75:25, and 80:20). The fit quality was determined using the coefficient of determination (R^2) and root mean square error (RMSE), as defined in Eq. (5).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_{sim,i} - X_{exp,i})^2} \quad (5)$$

where $X_{exp,i}$ and $X_{sim,i}$ refer to the experimental and simulated mass fraction remaining, respectively, and N is the number of data points.

3. Results

3.1 Microwave pyrolysis performance and temperature profiles

The microwave (MW) pyrolysis system controlling and monitoring the pyrolysis of samples maintained the target temperature with a good accuracy, having $\pm 20^\circ\text{C}$ fluctuation due to the ON/OFF cycling of heating, as shown in Figure 2. The figure depicts the temperature profiles for the mixture ratios OPS:AC of 70:30, 75:25, and 80:20 shown respectively in the top, the middle, and the bottom panels. An estimated slope is presented in each panel, indicating the rate of change of temperature, i.e. the heating rate to the highest temperature setpoint. As the fraction of OPS increased the heating rate got slower because OPS is only a weak MW power absorber [15, 16]. Xiong et al. [17] studied the effects of heating rate on pyrolysis product yields and on the bio-oil transformation during pyrolysis, which is crucial for effective utilization.

3.2 Numerical simulation of pyrolysis kinetics

The pyrolysis kinetics of solid biomass followed the general reaction rate equation (Eq. 2). This dynamic process was modeled using a first-order ordinary differential equation (ODE). To solve the ODE numerically, the 4th order Runge-Kutta (RK) method, known for its high accuracy, was applied with the reaction order empirically set to 1 ($n = 1$). Simulation parameters were adjusted iteratively to achieve the best match with experimental data for each mixture ratio. These iterations aimed to maximize the coefficient of determination (R^2) while minimizing the root mean square error (RMSE). After identifying the optimal parameters, the MW pyrolysis kinetics were compared between the simulation results and the experimental data, as presented in Figure 3. For the 70:30 mixture ratio,

the best fit was obtained with a pre-exponential factor (A) of 7.8 s^{-1} and an activation energy (E_a) of $39,540 \text{ J/mol}$, yielding an R^2 of 0.621 and an $RMSE$ of 0.024 . Similarly, for the 75:25 ratio, the values of A , E_a , R^2 , and $RMSE$ were 7.6 s^{-1} , $39,340 \text{ J/mol}$, 0.758 , and 0.018 , respectively. For the 80:20 ratio, the corresponding values were 13.2 s^{-1} , $54,370 \text{ J/mol}$, 0.741 , and 0.016 .

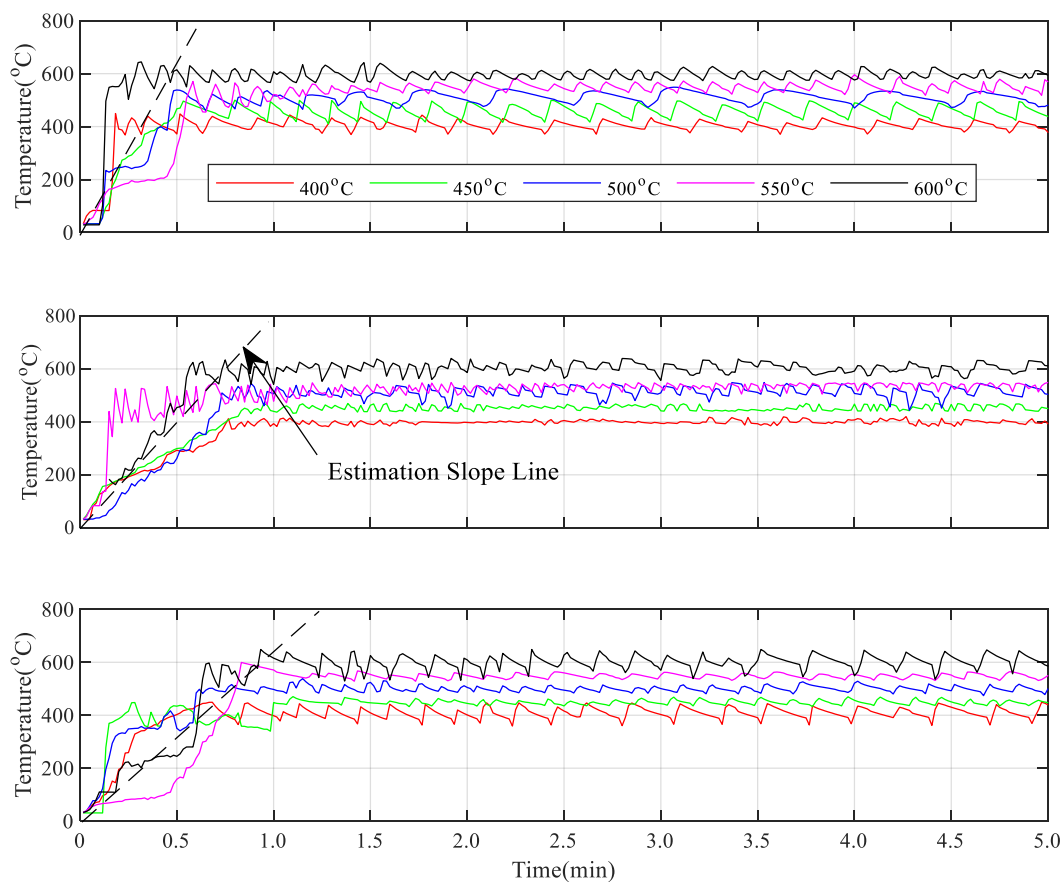


Figure 2 Temperature profiles with a function of time in MW pyrolysis. The top, middle, and bottom panels are respectively for the OPS:AC mixture ratios 70:30, 75:25, and 80:20.

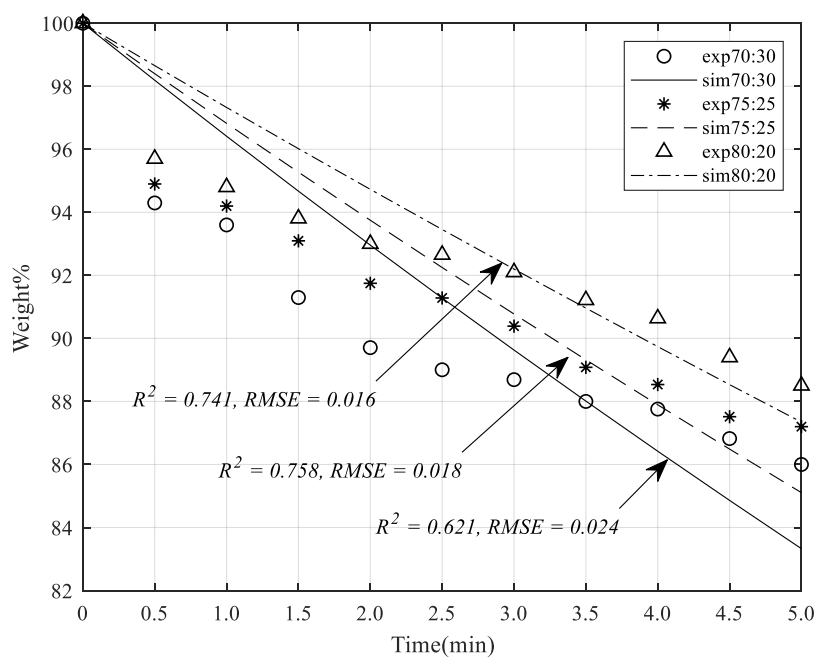


Figure 3 The simulated and experimental sample weights versus a pyrolysis time for OPS with AC of POFA as MWAb, at each MW power level.

Figure 3 illustrates that the microwave pyrolysis kinetics descended for the mixture ratios in the order 70:30, 75:25, and 80:20. This trend correlates with the heating rates of each mixture ratio, as shown in Figure 2. However, it is important to note that the

simulation results did not perfectly match the experimental data, likely due to the heating rate being controlled by the temperature regulation system, which was set at 400, 450, 500, 550, and 600°C. Despite this, the R^2 values ranging from 0.621 to 0.758 fall within an acceptable range.

3.3 Product yields

The pyrolysis process produces three types of products: the solid phase (biochar), the liquid phase (bio-oil), and the gas phase (syngas). The yields (%) of these products were calculated and are presented in Figure 4. Biochar accounted for the largest portion, with yields ranging from 55% to 90%, due to this being a case of slow pyrolysis. This process is influenced by key factors such as temperature, solid residence time, heating rate, and biomass particle size [2, 18]. During pyrolysis, the vapor time is comparatively long (5 to 30 min), allowing elements in the gas phase to interact and react with each other [19, 20]. The second major product is bio-oil, consisting of condensed vapor from the pyrolysis process, with yields between 3% and 10%. Bio-oil, or pyrolysis oil, contains a variety of oxygenated molecules, including carbonyls, carboxyls, and phenolic compounds [16, 21, 22]. It should be noted that the bio-oil should not be used directly to describe the total liquid yield, as the liquid phase includes both bio-oil and water content. In this study, water content was not separated from the bio-oil; thus, the bio-oil yield measurements reflect the total liquid phase rather than pure bio-oil yield. In the next section, the top five chemical components of bio-oil, analyzed via GC-MS in this study, are discussed. Notably, the bio-oil yield (%) in this study was lower than in a previous study conducted by our lab, which reported yields around 30%. This difference is likely due to minor syngas leakage occurring at the joints and connectors of the glass tubing during microwave pyrolysis, leading to a higher syngas yield (%) than in previous studies, with values ranging from 3% to 43%. To address this potential source of variation in the liquid yield, all samples were processed under carefully controlled conditions, and repeated trials were conducted to ensure consistency in yield data and product composition. Despite the minor leakage, the primary focus remained on investigating the liquid and solid products, and the results were validated through multiple trials to confirm reproducibility.

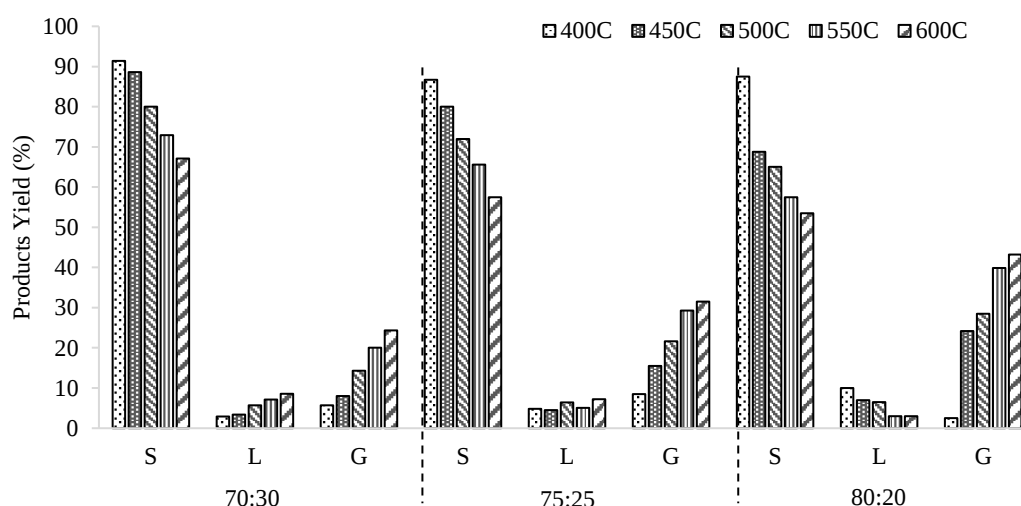


Figure 4 The yields (%) from MW pyrolysis, shown by their phases (S: solid, L: liquid, and G: gas) grouped by mixture ratio in feedstock.

3.4 Chemical composition of bio-oil by GC-MS

The testing report shows the GC analysis utilized a VF-WAXms column (30 m × 250 μm × 0.25 μm) with a set oven temperature program, starting at 70°C and increasing to a maximum of 250°C at a rate of 2.5°C/min. The sample injection volume was 1 μL, and the injector was set to a split mode with a 100:1 split ratio to ensure optimal sample introduction. In the MS analysis, an electron ionization (EI) source was operated at 70 eV with a scan range from 35 to 500 m/z. The ion source and quadrupole temperatures were maintained at 230°C and 150°C, respectively, to achieve effective compound ionization and separation. The data on chemical compositions presented in this study are expressed as relative abundances, not absolute quantities, as focus on comparing the relative chemical profiles of bio-oil samples. Therefore, the chemical compositions of bio-oil characterized by GC-MS are discussed. The first study focused on the influence of the mixture ratio between oil palm shell (OPS) and activated carbon (AC) at a fixed 400°C temperature. The top five dominant chemical components are depicted in Figure 5. For the mixture ratio (OPS:AC) 70:30, the pyrolysis produced significant amounts of acetic acid (37.2%), contributing over one-third of the bio-oil. This suggests a strong breakdown of biomass into simple organic acids, a characteristic of biomass pyrolysis when lignocellulosic materials like OPS are involved [22, 23]. The appearance of cis-3-Methoxy-5-(4) (24.8%) suggests some variations in lignin breakdown products, potentially influenced by the comparatively high AC content. The presence of this compound indicates a shift towards methoxy-substituted phenols, which are commonly formed during slow pyrolysis [24]. Phenols (~8.5%) remain consistent, indicating the influence of lignin decomposition in the bio-oil, with some catalytic effects from AC promoting their formation. For the ratio 75:25 (OPS:AC), the high proportion of OPS likely enhances the efficiency of pyrolysis, leading to a higher production of acetic acid (55.7%). This suggests more effective breakdown of hemicellulose and cellulose. The formation of benzaldehyde (19.8%), an aromatic compound, highlights lignin decomposition, suggesting that the presence of AC facilitates the breakdown of lignin into valuable aromatic chemicals [23]. The moderate levels of phenols and propanoic acid are consistent with lignocellulosic biomass pyrolysis, with the catalytic effect of AC influencing the pathways for acid production and aromatic formation. Regarding the last ratio 80:20 (OPS:AC), the higher OPS content

(80%) promotes the production of bio-oil, while the relatively lower amount of AC (20%) allows for more typical biomass-derived compounds like acetic acid and phenols. However, the presence of 1-chloroethyl acetate (43.4%) suggests that even with a higher OPS content, some catalytic reactions are occurring, potentially due to impurities or interactions with the activated carbon. However, the lower acetic acid yield in comparison to the 75:25 case indicates a moderate breakdown of cellulose and hemicellulose, likely due to the reduced influence of the catalytic effects of AC. In summary, the results highlight the crucial role of the OPS proportion in determining both the quantity and quality of bio-oil produced. A moderate OPS content (75:25) appears to optimize the production of valuable compounds like acetic acid and benzaldehyde, while a higher AC content (70:30) leads to more diverse and complex chemical structures. These findings suggest that adjusting the mixture ratio can be a key tool in tailoring bio-oil composition for specific industrial applications, such as fuel production or chemical extraction.

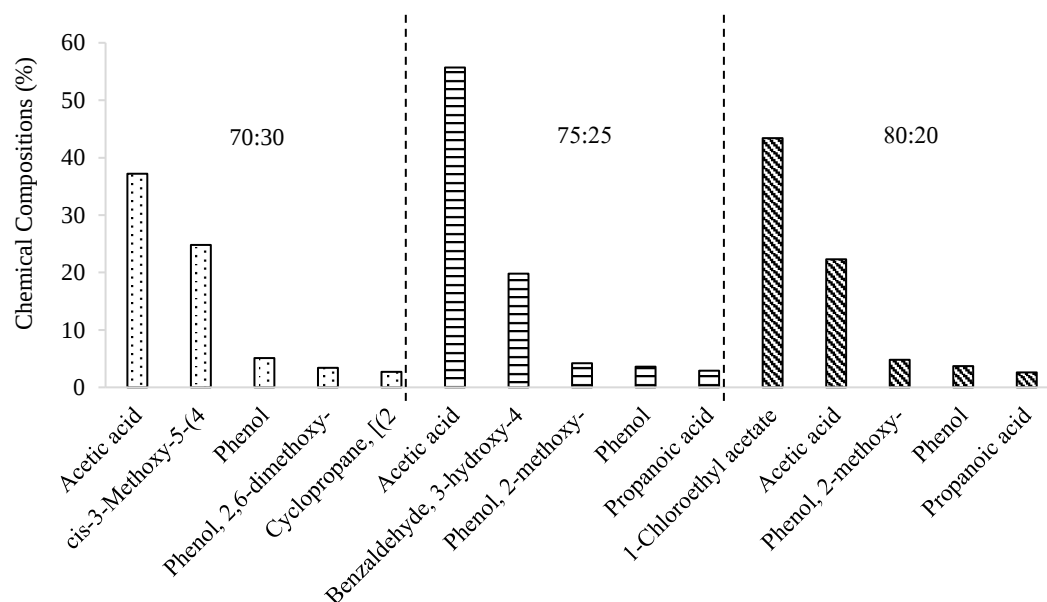


Figure 5 Chemical compositions of bio-oils as determined by GC-MS from MW pyrolysis at 400°C with mixture ratios 70:30, 75:25, and 80:20 in feedstock.

The next study focused on the influence of the pyrolysis temperature, set at 400, 500, and 600 °C, at the fixed 75:25 (OPS:AC) mixture ratio. The top five chemical components are depicted in Figure 6. At the relatively low 400°C temperature, the dominant compound is acetic acid (55.7%), which suggests significant decomposition of cellulose and hemicellulose [25]. The presence of benzaldehyde (19.8%) indicates partial lignin breakdown, contributing to aromatic compounds [23]. The bio-oil also contains smaller amounts of phenolic compounds like phenol (3.6%) and 2-methoxy-phenol (4.2%), indicating the preservation of lignin-derived structures. Propanoic acid (2.9%) adds to the acidic content, possibly from the breakdown of hemicellulose [25, 26]. Therefore, the bio-oil is dominated by acids, particularly acetic acid, with a moderate amount of aromatic compounds from lignin. This temperature favors the formation of simpler oxygenated compounds and acids. At 500°C, acetic acid remains the dominant compound (45.6%), but its concentration is notably lower than at 400°C. There is a significant increase in phenolic compounds, such as 2-methoxy-phenol (21.3%) and phenol (3.2%), indicating more extensive breakdown of lignin at this higher temperature [27, 28]. A new compound, 5-(2-(1,4-Dioxaspiro)) [4, 5] (4.7%), appears, suggesting the formation of more complex oxygenated compounds. Therefore, at 500°C, there is a shift towards producing more phenolic compounds, which may enhance the bio-oil's energy content. This temperature promotes both acid and aromatic compound formation, with more complex structures emerging compared to 400°C. At the last 600°C temperature, the chemical composition changes significantly. Methyl 3-hydroxy-2(p) (32.2%) becomes the dominant compound, indicating further degradation of biomass into more complex oxygenated species. Benzoic acid (26.4%) also appears in higher concentrations, pointing to advanced lignin decomposition. The concentration of acetic acid drops sharply to 3.5%, while phenolic compounds (e.g., 2-methoxy-phenol, 4.7%) remain present but at similar levels to the lower temperatures. 1H-Pyrazol, 1,3,5-trimethyl (2.9%) is a new nitrogen-containing compound that emerges at this high temperature: so, at 600°C, there is a clear transition towards the production of more complex compounds like benzoic acid and nitrogen-containing molecules. The lower acetic acid content at higher temperatures suggests that elevated temperatures promote the breakdown of simpler oxygenated compounds, leading to the formation of more advanced and potentially higher-value chemicals. These findings highlight the significant impact of pyrolysis temperature on the chemical profile of bio-oil. While lower temperatures favor simpler oxygenated compounds like acetic acid, which may be suitable for specific applications, higher temperatures encourage the formation of a broader range of complex compounds. At elevated temperatures, the bio-oil contains larger aromatic and phenolic molecules, enhancing its potential for diverse industrial uses. These complex compounds serve as valuable precursors for high-value chemicals in industries such as pharmaceuticals, adhesives, and resins. Furthermore, the presence of diverse aromatic structures increases the bio-oil's stability and energy density, making it more suitable for fuel applications where a higher energy content is advantageous. Thus, higher pyrolysis temperatures not only expand the versatility of bio-oil for chemical extraction but also improve its viability as a renewable energy source.

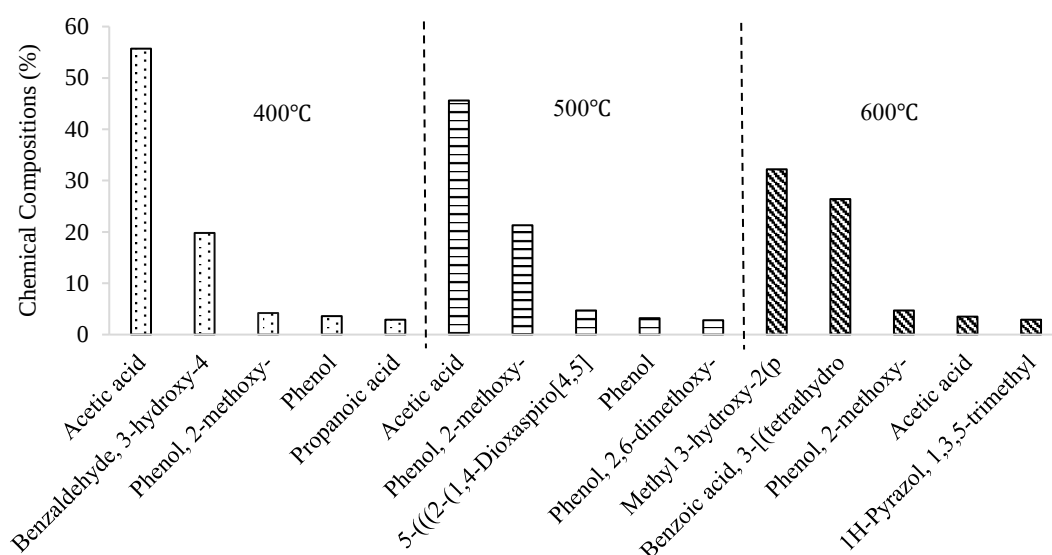


Figure 6 Chemical compositions (showing top five components) as determined by GC-MS of bio-oils from the pyrolysis temperatures 400, 500, and 600°C, while maintaining a 75:25 (OPS:AC) mixture ratio in the MW pyrolysis.

4. Discussion

The results of this study demonstrate that microwave-assisted (MW) pyrolysis of oil palm shell (OPS) mixed with activated carbon (AC) is an efficient method for bio-oil production, with the mixture ratio and temperature playing critical roles in determining yield and chemical composition. When comparing these findings with other research, our study aligns with previous work that highlights the advantages of MW pyrolysis, such as rapid heating rates and energy efficiency, over conventional pyrolysis techniques. The optimal ratio of 75:25 OPS produced the highest bio-oil yield and exhibited favorable pyrolysis kinetics, with a strong correlation between experimental and simulated data ($R^2 = 0.758$). This agrees with studies showing that AC enhances pyrolysis by improving heat distribution and acting as a catalyst in breaking down biomass. However, unlike conventional pyrolysis where longer reaction times are needed, the MW pyrolysis process demonstrated faster reaction rates, which can be advantageous in industrial applications aiming to optimize processing times. Our study also confirmed that temperature significantly influences the chemical profile of bio-oil, with higher pyrolysis temperatures (500°C and 600°C) leading to a shift toward more complex chemical structures, such as phenolics and hydrocarbons. These results are consistent with studies that emphasize the role of temperature in maximizing bio-oil quality and diversity of chemical compounds. Especially, phenolic compounds are considered relevant to the energy content of bio-oil due to their high carbon and hydrogen content, which contributes to a greater calorific value. As complex aromatic structures, phenolics tend to have higher energy densities than simpler oxygenated compounds typically found in bio-oil. Additionally, the presence of phenolic compounds can enhance the stability of bio-oil and improve its potential as a fuel, as these compounds are less reactive with oxygen than other oxygenated groups. Therefore, a higher concentration of phenolic compounds generally indicates a bio-oil with improved energy content and suitability for energy applications.

One limitation of this study is that the syngas yield was not deeply explored, despite its higher production at elevated temperatures. Future research could investigate the optimization of syngas recovery, which would further improve the energy efficiency of MW pyrolysis. Additionally, a focus on integrating this process with circular economy principles, such as utilizing the biochar byproduct in agriculture, could enhance the sustainability of biomass conversion. In conclusion, MW pyrolysis of OPS and AC provides an effective pathway for bio-oil production, offering significant potential in reducing reliance on fossil fuels. By refining the feedstock ratio and temperature, the process can be further optimized for industrial applications, contributing to the development of cleaner energy solutions.

5. Conclusions

This study investigated the microwave-assisted (MW) pyrolysis of oil palm shell (OPS) blended with activated carbon (AC) to enhance bio-oil production, focusing on pyrolysis kinetics and chemical composition. Three OPS ratios 70:30, 75:25, and 80:20 were tested at a fixed pyrolysis temperature of 400°C. Gas chromatography-mass spectrometry (GC-MS) analysis revealed acetic acid, phenol, and other oxygenated compounds as the main components in the bio-oil. The pyrolysis kinetics were modeled using a first-order reaction rate, with the 75:25 mixture achieving the best model fit and the highest alignment with experimental data ($R^2 = 0.758$). Additionally, the impact of pyrolysis temperature (400°C, 500°C, and 600°C) on bio-oil composition was examined at the 75:25 mixture ratio, showing that higher temperatures significantly affect the chemical profile and can increase bio-oil yield. These findings underscore the efficiency of MW pyrolysis in bio-oil production and its potential to contribute to sustainable energy solutions.

The primary motivation behind this research was to optimize bio-oil yield and quality by investigating how blending OPS with AC affects the MW pyrolysis process. As a widely available agricultural byproduct, OPS offers significant potential for bio-oil production, while AC serves as both a microwave absorber, enhancing heating efficiency, and a catalyst, influencing the decomposition pathways. Kinetic analysis demonstrated that adjusting the OPS ratio had a substantial effect on activation energy and reaction rates, which in turn impacted the yield and chemical makeup of the bio-oil. The 75:25 ratio provided the most favorable kinetic parameters and bio-oil yield, indicating it as an optimal balance between feedstock and microwave absorber. These results suggest that feedstock ratio adjustments are an effective strategy for controlling pyrolysis kinetics and customizing bio-oil properties for industrial applications.

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