

One-step microwave pyrolysis of sago bark waste for rapid pyrolytic oil production: a response surface methodology approach

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Abstract

Purpose – This study employed microwave pyrolysis using palm kernel shell activated carbon (POAC) as an absorber to maximize the output of pyrolytic oil from sago bark (SB).

Design/methodology/approach – Using a central composite rotatable design in response surface methodology (RSM), 17 experiments were conducted to examine the combined effects of temperature, sample mass and



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POAC loading. The physicochemical characteristics were thoroughly studied, and the main components of the resulting oil were identified by gas chromatography–mass spectrometry (GC–MS) analysis.

Findings – In the microwave pyrolysis at 400 °C, the addition of 35% POAC increased the oil output to 29.63%. The oil's calorific value was 21 MJ/kg, density was 2 g/cm³ and the phenolic compounds accounted for 57.6% of the oil content.

Practical implications – The findings demonstrate an efficient way to convert sago bark waste (SBW) into pyrolytic oil through an optimized process. Pyrolytic oil's characterization offers insights into the specific refining processes for its potential utilization as a sustainable biofuel.

Originality/value – This research is a distinct exploration of the application of POAC as an additive to optimize the pyrolytic oil yield. The optimized synthesis and the characterization of the oil demonstrate POAC benefits as an absorber and highlight the potential of SB as a bio-oil feedstock.

Keywords Biomass, Bio-oil, Microwave pyrolysis, Pyrolytic oil, Response surface methodology

Paper type Research article

1. Introduction

Global energy consumption has significantly increased as a result of rapid industrialization and population growth (Badza *et al.*, 2024). Despite dominating the energy landscape for more than a century, fossil fuels, though dominant for over a century, pose major challenges due to their limited availability and significant environmental impacts, such as carbon emissions and global warming (Foong *et al.*, 2024). To support sustainable development, the Paris Agreement sets a target for a worldwide commitment to reduce greenhouse gas emissions and keep global warming below 2 °C, ideally 1.5 °C, by 2100 (Imran-Shaukat *et al.*, 2025a). Despite initiatives to meet these goals, reliance on fossil fuels remains a significant challenge (Fang *et al.*, 2024). According to the International Energy Agency, between 30 and 40% of the energy used worldwide comes from oil alone (Kashif *et al.*, 2024). The rapid population growth in recent years has significantly driven up global energy demand (Palla *et al.*, 2024). With increasing ecological degradation, pollution and resource depletion, renewable energy is emerging as a crucial alternative to fossil fuels (Yue *et al.*, 2024). Renewable energy sources include hydropower, geothermal, solar and biomass (Palla *et al.*, 2024).

Biomass is the fourth-largest renewable energy source under the waste-to-energy strategy, accounting for 14% of global energy consumption and reinforcing its role in the global energy matrix (Muniyappan *et al.*, 2023). Resources derived from non-food sources, such as lignocellulosic materials (wood, plants and leaves) and carbohydrates from crops and vegetables (Allende *et al.*, 2023a). It also includes organic, industrial and household waste, algae and municipal waste, which are all considered biomass (Shahnouri *et al.*, 2024). Various thermochemical techniques – such as gasification, hydrolysis, liquefaction, pyrolysis and hydrothermal carbonization—are employed to convert biomass and solid waste into sustainable fuels and energy products (Badza *et al.*, 2024; Sidabutar *et al.*, 2024). Key biomass conversion technologies include direct combustion (Palla *et al.*, 2024), gasification (Qiu *et al.*, 2024), liquefaction, hydrolysis (Badza *et al.*, 2024), torrefaction (Sidabutar *et al.*, 2024) and pyrolysis (Kashif *et al.*, 2024).

Pyrolysis, a thermochemical process carried out in an inert or low-oxygen atmosphere, is particularly appealing due to its low pollutant emissions and diverse product yield (Fernández *et al.*, 2024). Depending on the properties of the feedstock and the process parameters, particularly temperature and residence time, it can yield three distinct products: solid char, liquid fuel and syngas (Hanafi *et al.*, 2024a). Pyrolysis is typically conducted at temperatures between 400 °C and 1,200 °C to optimize the product yield and quality (Allende *et al.*, 2023a). Higher temperatures generally enhance syngas production, whereas lower temperatures favor char formation, depending on the feedstock type (Fang *et al.*, 2024). Pyrolysis of biomass at approximately 500 °C primarily yields bio-oil as the main product (Makepa *et al.*, 2023). Each pyrolysis product holds distinct value and serves specific functions across various applications (Hanafi *et al.*, 2024b).

During pyrolysis, biomass undergoes a series of reactions, including the breaking of large molecular bonds, polymerization of small molecules and isomerization, ultimately forming low molecular weight volatile components such as bio-oil, gas and char (Ke *et al.*, 2024; Wahi

et al., 2022). The primary constituents of bio-oil include organic acids, aromatics, acetone, acetic acid, methanol and tar, which can be further processed into biofuels (Fang *et al.*, 2024). The combustion of biofuels has been shown to emit fewer pollutants (SO_x, NO_x and NH₃) compared to conventional fossil fuels (Banchapattanasakda *et al.*, 2023). Moreover, biofuel combustion can result in zero or even negative net CO₂ emissions, as the CO₂ released during combustion may be offset by the CO₂ absorbed during photosynthesis, thereby reducing the overall greenhouse effect (Hanafi *et al.*, 2024a, b).

Conventional pyrolysis involves heating biomass using external sources such as hot air, gases, or other heating elements to facilitate thermal decomposition through conduction, convection, or radiation (Kashif *et al.*, 2024). However, slow and uneven heat transfer can become a limitation of this process, resulting in fluctuating yields of bio-oil, syngas and char, as well as inconsistent product quality (Foong *et al.*, 2024). Microwave-assisted pyrolysis has emerged as an alternative heating method, offering simple operation with rapid on/off control, thereby enhancing both product yield and quality (Fernández-González *et al.*, 2020). Microwave heating generates heat through molecular friction, as polar molecules within the target material (such as feedstock and absorber) rapidly rotate in response to the oscillating electromagnetic field (Kashif *et al.*, 2024). This absorbed energy is uniformly distributed by converting electromagnetic energy into molecular motion through dielectric loss (Suresh *et al.*, 2021). Compared to conventional heating methods, this technique offers significant advantages, including uniform and rapid internal heating, accelerated reaction kinetics and improved overall energy efficiency, making it a promising option for commercial applications (Badza *et al.*, 2024).

The sago palm (*Metroxylon sagu*) is a plant well-suited to tropical regions and typically grows in aquatic environments where other crops struggle due to poor soil and drainage conditions (Susanto *et al.*, 2024). It is a significant source of dry starch, producing yields up to ten times higher than those of other starchy crops such as potatoes or cassava (Fetriyuna *et al.*, 2024). Annually, between 25,000 and 40,000 tons of sago products are exported from Sarawak, Malaysia, to various countries (Khairunnisa *et al.*, 2021). The three main by-products of sago starch production are sago bark (SB), fibrous pith residue and sago wastewater (Fathi *et al.*, 2022). For every ton of sago flour produced, approximately 0.75 tons of SB are generated as solid waste (Susanto *et al.*, 2024). Malaysian sago factories produce over 20,000 tons of SB annually, which is typically disposed of through open burning or by dumping into rivers (Khairunnisa *et al.*, 2021). These disposal practices can worsen pollution, harm aquatic life and degrade the broader ecosystem (Susanto *et al.*, 2024). To address this issue, waste-to-energy conversion has emerged as a sustainable strategy that supports the circular economy and offers environmental benefits (Muniyappan *et al.*, 2023).

In microwave-assisted pyrolysis of biomass feedstock, electromagnetic waves with frequencies between 300 MHz and 300 GHz are applied (Fang *et al.*, 2024). By optimizing the process, biomass feedstocks can be converted into higher-quality bio-oil or biochar with improved energy efficiency and reduced waste generation (Ke *et al.*, 2024). To enhance process efficiency and product selectivity in microwave-assisted pyrolysis for bio-oil synthesis, precise control of pyrolysis temperature, microwave power and biomass particle size is essential (Xaba *et al.*, 2020). The size of biomass particles affects heat transfer efficiency and reaction kinetics in microwave-assisted pyrolysis; smaller particles typically enable more uniform heating, which promotes faster decomposition and may lead to higher bio-oil yields (Fernández *et al.*, 2024). Carbon rich materials, such as biochars and activated carbons, have been found to be effective microwave absorbers due to their high minerals content, oxygen concentration and acidic functional groups (Hanafi *et al.*, 2024a). Systematic optimization of these parameters can result in improved energy efficiency, enhanced product yields and better control over pyrolysis reactions (Mahfud *et al.*, 2024).

One-variable-at-a-time (OVAT) optimization is a traditional technique in which one parameter is varied while keeping the others constant. This approach overlooks the interactive effects of multiple variables and requires a large number of experimental runs to optimize each

parameter individually (Imran-Shaukat *et al.*, 2023). In contrast, statistical experimental designs such as response surface methodology (RSM) allow simultaneous optimization of all process parameters (Makepa *et al.*, 2023). By generating an optimal experimental matrix that accounts for interaction effects, RSM minimizes the number of experimental runs, thereby reducing operational costs and labor, making it a valuable tool for efficient process optimization (Mahfud *et al.*, 2024).

Effective valorization techniques are essential in response to the increasing generation of sago bark waste (SBW) and the growing demand for sustainable energy alternatives. This study aims to design and optimize a one-step microwave-assisted pyrolysis process for converting SBW into pyrolytic oil. To achieve this, RSM will be employed to optimize key process parameters, including SBW mass, pyrolysis temperature and the absorber-to-biomass ratio (percentage of palm kernel shell activated carbon (POAC)), in order to maximize pyrolytic oil yield. Furthermore, the study will assess the physicochemical properties of the resulting oil to evaluate its potential as a sustainable energy source. The findings are expected to advance bio-oil production technology by enhancing yield, improving quality and increasing overall process efficiency, thereby promoting the sustainable utilization of agricultural waste.

2. Material and methods

2.1 Material

In this study, shredded SB was collected from the Ubom Sago Factory, Dalat, Sarawak, Malaysia. The bark was thoroughly washed with tap water and then was oven-dried at 105 °C for 24 h. The dried bark was subsequently ground and sieved to particle size <3 cm, packed in plastic containers and labeled as SBW.

2.2 Characterization of SBW

Thermogravimetric analysis (TGA) was used to determine the proximate composition of SB biomass, including moisture and volatile contents, using a Thermogravimetric Analyzer (Mettler Toledo, TGA/SDTA851c). Approximately 10 mg of SB was placed in a 20 mL alumina crucible and heated in a thermobalance at a rate of 10 °C/min under a nitrogen atmosphere. The TGA-DTG curves were plotted with temperature on the X-axis and mass percentage (%) on the Y-axis to identify the primary degradation stages and the optimal temperature range for microwave-assisted pyrolysis. In addition to assessing the thermal stability of the SB sample, moisture content was determined based on mass loss at 110 °C, while volatile content was estimated from the mass loss occurring between 150 °C and 500 °C. Ash content was determined by combusting the SB in a muffle furnace at 950 °C for 10 min (Racero-Galaraga *et al.*, 2024). Fixed carbon content was calculated as the difference between the initial sample mass and the total mass of moisture, volatile matter and ash (Khelfa *et al.*, 2020). A CHNS elemental analyzer (Model: FlashEA1112 CHNS) was used to determine the carbon, hydrogen, nitrogen and sulfur contents in the SB sample.

2.3 Microwave-assisted pyrolysis of SBW

The experimental setup for the microwave-assisted pyrolysis of SBW is illustrated in Figure 1. A modified household microwave oven (MW71 C, Samsung) with a maximum output power of 700 W and an operating frequency of 2.54 GHz was used to carry out the pyrolysis process (Wahi *et al.*, 2020). The upper chamber of the microwave oven was modified by attaching a quartz container to an oil collector to efficiently capture the pyrolysis products (Aziz *et al.*, 2017). A quartz container with a height of 100 mm and an inlet diameter of 120 mm was used to hold the SBW sample during the experiment. The SBW was placed in the microwave oven cavity subjected to both drying and pyrolysis in a single-step process.

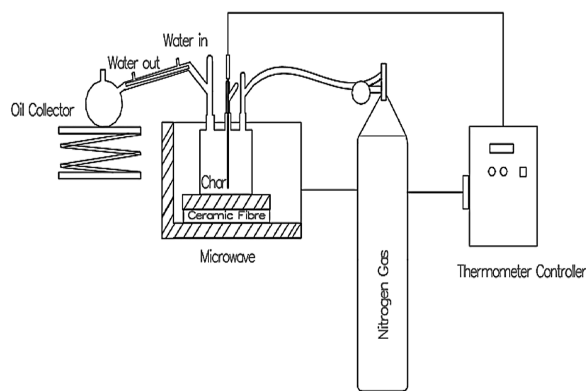


Figure 1. Experimental set up for microwave-assisted pyrolysis of SBW. **Source(s):** Authors’ own work

An electronic temperature regulator controlled the magnetrons of the microwave oven, enabling temperature adjustment by switching them on and off (Hanafi *et al.*, 2024a). To maintain an inert pyrolysis environment and prevent combustion, a gas inlet with a valve was installed above the reactor to introduce nitrogen gas (N_2), effectively purging oxygen (O_2) from the system (Allende *et al.*, 2023b). During pyrolysis, the resulting volatile compounds were condensed using a cooling system and collected in a round-bottom flask for storage (Mahfud *et al.*, 2024). To ensure accurate measurement of the pyrolytic oil yield, residual oil adhering to the quartz container and condenser was rinsed with dichloromethane (DCM) and transferred into sample bottles. The solvent was then evaporated using a rotary evaporator (Hei-Vap Value, Heidolph, USA) at 39.6 °C, leaving behind pure pyrolytic oil (Sun *et al.*, 2023).

2.4 Experimental design

To explore and optimize the influence of different factors on SBW-based pyrolytic oil yield, an RSM approach with a Central Composite Rotatable Design (CCRD) was used. The CCRD was preferred due to its predictive capability to incorporate the highest polynomial order with significant terms in the mathematical model requiring only a limited set of experimental data, and it has the ability to provide precise response predictions; CCRD was chosen (Yassin *et al.*, 2023). The effect of three independent variables, including SBW mass (factor A), POAC loading (factor B) and temperature (factor C), was studied on the response (pyrolytic oil yield) as a dependent variable. The ranges of the independent variables have been described in Table 1. The pyrolysis was set to be carried out for 15 min, and the process efficiency was calculated from the mass changes of the solid and liquid fractions before and after the pyrolysis (Fodah *et al.*, 2022).

Previous studies on the pyrolytic oil synthesis process using biomass substrate were utilized to determine the ranges for factor A (sample mass) (Khelfa *et al.*, 2020; Wallace *et al.*, 2019) and factor B (POAC loading) (Ke *et al.*, 2024; Xaba *et al.*, 2020). While the range for

Table 1. Range of factors for pyrolytic oil synthesis via CCRD

Factors	Unit	−1	0	+1
SBW mass	g	5	10	15
POAC loading	wt.%	35	55	75
Temperature	°C	350	375	400

Source(s): Authors’ own work

factor C (temperature) was determined through TGA (Ke *et al.*, 2024). Full factorial CCRD was developed with Design Expert software (Version 13.0, Stat-Ease Inc., MN, USA). There were five levels for each factor: high (+1), low (−1), center (0) and two axial points at ± 1.68179 . Based on standard CCRD principles, the axial points ($\alpha = \pm 1.68179$) along with the CCRD factor levels were selected to ensure rotatability, enhance predictive accuracy and maintain uniform variance across the design space. The values for different levels were adjusted as necessary, based on experimental limitations and insights from preliminary trials. Table 2 shows that 17 experimental runs based on CCRD for three parameters were carried out. These runs include eight factorial experiments, six axial points and three center points. The total number of experiments was determined using Equation (1):

$$N = 2^n + 2n + n_c = 2^3 + 2(3) + 3 = 17 \quad (1)$$

The CCRD for this study provided a comprehensive framework for analyzing the measured response (the percentage of pyrolytic oil yield), with eight factorial points, six axial points and three central points. The mathematical model from CCRD was selected because it ensures the accuracy and reliability of the model by incorporating the highest polynomial order with statistically relevant terms while reducing aliasing effects (Yassin *et al.*, 2023).

A second-order polynomial model was employed to predict the response surface and analyze the effects of process parameters on pyrolytic oil yield. The mathematical model used to represent the response surface for all parameters is given in Equation (2) (Badza *et al.*, 2024).

$$Y_i = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11} + b_{22} + b_{33} + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (2)$$

where x_1 , x_2 and x_3 are linear effects, x_1x_2 , x_1x_3 and x_2x_3 are interaction effects, b_0 , b_1 , b_2 and b_3 are the coefficients of offset term, and b_{12} , b_{13} , b_{23} are the interaction coefficients.

Equation (3) and Equation (4) were employed to calculate mass yield of the pyrolytic oil and the average of pyrolytic oil yield, respectively, to determine actual yield produce for each experimental run (Mahfud *et al.*, 2024).

Table 2. Parameters for microwave-assisted pyrolysis for bio-oil synthesis from SBW

Standard	Practical run	Factor A: SBW mass (g)	Factor B: POAC loading (wt.%)	Factor C: Temperature (°C)
7	1	5	75	400
8	2	15	75	400
6	3	15	35	400
12	4	10	88.6	375
15	5	10	55	375
14	6	10	55	417
16	7	10	55	375
11	8	10	21.4	375
10	9	18.41	55	375
5	10	5	35	400
17	11	10	55	375
13	12	10	55	333
3	13	5	75	350
4	14	15	75	350
2	15	15	35	350
9	16	1.59	55	375
1	17	5	35	350

Source(s): Authors' own work

$$\text{Mass yield of pyrolytic oil} = \frac{\text{Mass of pyrolytic oil}}{\text{Mass of SBW}} \times 100 \quad (3)$$

$$\text{Average of pyrolytic oil} = \frac{\text{PO}_1 + \text{PO}_2 + \text{PO}_3}{3} \quad (4)$$

where PO₁, PO₂ and PO₃ stand for the mass yields of pyrolytic oil from experiments 1, 2 and 3, respectively.

2.5 Characterization of SBW-based pyrolytic oil (SPO)

The moisture and volatile content of SPO was determined using a Protech Oven (Model FAC-50) by drying the samples at 105 °C for 24 h. The calorific value of the SPO was measured using a Parr 6,400 auto-calculating bomb calorimeter, in accordance with ASTM D240 (Banchapattanasakda *et al.*, 2023). The pH of the SPO was determined using a pH meter (Martini instrument, Mi 150). The density of the SPO was calculated as the ratio of its mass to its volume. The functional groups in the SPO were analyzed using FTIR spectroscopy (Thermo Scientific Nicolet Is10 FTIR Spectrometer). The chemical composition of the SPO was analyzed using gas chromatography–mass spectrometry (GC–MS) (Agilent 7,890 series GC with a 5975 MS detector). A 1 µL sample of SPO was dissolved in 999 µL of dichloromethane prior to analysis. The samples were injected into the injection port (250 °C) in a splitless configuration. The column temperature was initially set at 40 °C, then raised to 100 °C at a rate of 20 °C/min, and finally increased to 250 °C at 8 °C/min, with a solvent delay time of 3 min. The ion source was set to 250 °C with a 70-eV ionization potential (Muniyappan *et al.*, 2023). The peaks were identified by comparison with the National Institute of Standards and Technology (NIST) library. Quantification based on peak area (%), was carried out for chemical compounds, including phenols, aldehydes, ketones, monoaromatic compounds, esters, ethers, alcohols and amines.

3. Results and discussion

3.1 Thermal decomposition behavior of SBW

Lignocellulosic biomass (wood chips, bark, sawdust, stems, husks, etc.) predominantly comprises 30–50% cellulose, 20–40% hemicellulose and 10–20% lignin, along with small quantities of inorganic minerals and water (Ke *et al.*, 2024). Thermal decomposition of these major components of lignocellulosic biomass occurs within distinct temperature ranges, such as hemicellulose decomposing between 180 °C and 285 °C, cellulose breaking down between 285 °C and 365 °C, and lignin, which is the most thermally stable component, decomposing at higher temperatures, from 365 °C to 500 °C (Foong *et al.*, 2024). Consequently, the thermal degradation of SBW occurred in three stages, as illustrated in Figure 2. In the initial stage, moisture content decreased as the temperature increased from room temperature to 140 °C (Badza *et al.*, 2024). During the second stage (140–380 °C), hemicellulose, cellulose and lignin decompose into volatile components, including gases and SPO (Palla *et al.*, 2024; Vaštyl *et al.*, 2022). Since overall thermal decomposition of SBW took place when the temperature exceeded 400 °C, it was anticipated that the conversion of SBW into SPO would predominantly take place between 140 and 380 °C, with complete cellulose degradation and char formation initiating thereafter (Wu *et al.*, 2023).

3.2 Physiochemical characteristics of SBW

The proximate analysis of SBW revealed the composition as 74.6% volatile matter, 15.3% fixed carbon, 8.2% moisture content and 1.9% ash content. These values are comparable to those reported in previous studies, such as 62.61% volatile matter, 22.90% fixed carbon, 8.35% moisture content and 6.15% ash content (Wahi *et al.*, 2022), as well as 81.4% volatile

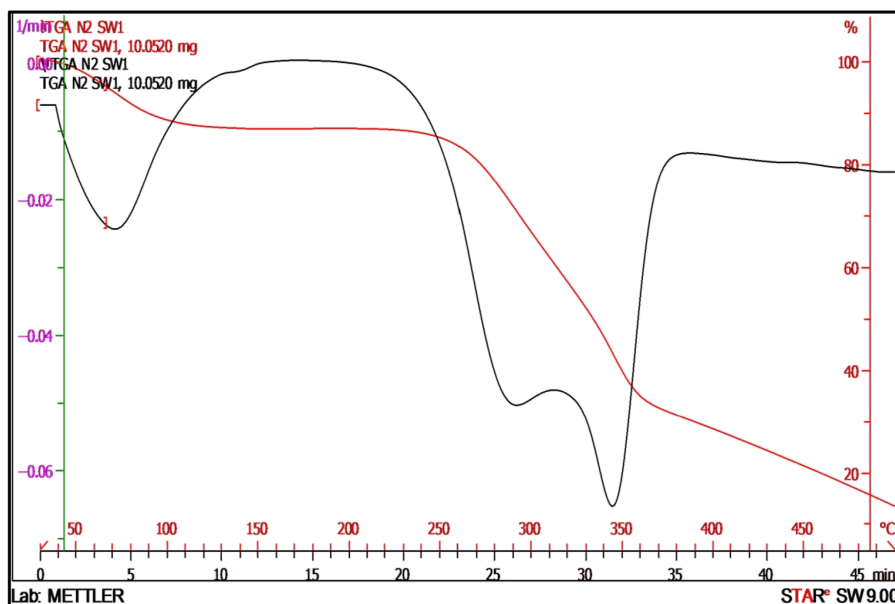


Figure 2. Thermogravimetric curve (TG) and derivative thermogravimetric (DTG) curve for SBW. **Source(s):** Authors' own work

matter, 18.7% fixed carbon, 4.9% moisture and 1.3% ash content (Siruru *et al.*, 2019). For comparison, pine sawdust has been reported to contain 78.19% volatile matter, 14.24% fixed carbon, 7.29% moisture content and 0.28% ash content (Makepa *et al.*, 2023), while cocoa pod husk comprises 59.8% volatile matter, 17.1% fixed carbon, 11.5% moisture content and 11.1% ash content (Vaštýl *et al.*, 2022).

The high volatile matter content indicates high suitability of SBW for pyrolysis and getting converted into pyrolytic oil through the breakdown of volatile organic components (Khelfa *et al.*, 2020). As larger proportions of volatile content in the feedstock indicate the decomposition will result in bio-oil and syngas (Palla *et al.*, 2024). While the fixed carbon content of the biomass describes the presence of carbon-based organic compounds along with other elements rather than present as pure carbon in the biomass (Racero-Galaraga *et al.*, 2024). Fixed carbon and calorific value are connected because during combustion, carbon bonds are broken, releasing energy as heat (Khelfa *et al.*, 2020). The moisture content of SBW is significantly lower than 12%, meaning that it has no considerable impact on the amount of heat necessary for pyrolysis to remove excess moisture (Palla *et al.*, 2024). Additionally, the low ash content also reduces residue buildup and related operational issues, making SBW a useful feedstock to produce bio-oil via pyrolysis (Hanafi *et al.*, 2024b).

In this study, the ultimate analysis of SBW revealed the following elemental composition: 40.51% carbon, 53.75% oxygen, 5.51% hydrogen and 0.25% nitrogen. Consequently, the H/C ratio was found to be 0.14, and the O/C ratio was found to be 1.3. These values are comparable to those reported in a previous study, which found 39.13% carbon, 50.76% oxygen, 5% hydrogen, 1.46% nitrogen, a 1.3 O/C ratio and a 0.13 H/C ratio (Wahi *et al.*, 2022). CHNS contents of SBW are also comparable with sugarcane bagasse, which was found to have 41.93% carbon, 53.39% oxygen, 5.47% hydrogen and 0.21% oxygen (Allende *et al.*, 2022). The H/C molar ratio of 0.13, lower than 0.3 indicates a high degree of aromatic compounds present in the feedstock (Imran-Shaukat *et al.*, 2025b). The O/C molar ratio of 1.3 indicates the presence of oxygen-containing heterocyclic organic compounds, as moisture content is

markedly low, as reported in proximate analysis (Liu *et al.*, 2024a). Some of the available oxygen definitely takes part in thermal decomposition of the feedstock and execution of oxidation reactions of structural components and conversion to bio-oil (Vaštyl *et al.*, 2022).

A feedstock's Low Heating Value (LHV), also known as its net calorific value, refers to the amount of heat generated during complete combustion, excluding the latent heat of water vaporization (Allende *et al.*, 2023a). The LHV of SBW was found to be 12.92 MJ/kg, which is comparable to other recently studied biomass wastes such as 12.0 MJ/Kg for cocoa pod husk (Vaštyl *et al.*, 2022), 13.86 MJ/Kg for sugarcane bagasse (Allende *et al.*, 2022), 16.71 MJ/Kg for raw corn stover (Fodah *et al.*, 2022), 25.2 MJ/Kg for food waste and 28.4 MJ/Kg for wood chips (Allende *et al.*, 2024). Despite its comparatively lower LHV, SBW has been successfully utilized microwave pyrolysis for the production of pyrolytic oil (Aziz *et al.*, 2017; Wahi *et al.*, 2020). This is attributed to its lignocellulosic composition, which includes 44% cellulose, 22.8% hemicellulose and 29.4% lignin (Siruru *et al.*, 2019). These components contribute differently during pyrolysis based on conditions: cellulose and hemicellulose primarily facilitate the formation of liquid and gaseous products, while lignin mainly contributes to the production of char, a solid by-product (Kashif *et al.*, 2024).

3.3 Optimized synthesis of SPO

The SPO yield (an average of triplicate experiments) obtained from microwave-assisted pyrolysis of SBW under various experimental conditions, as optimized using the CCRD method, is summarized in Table 3.

The experimental data presented in Table 3 reveals significant variability in SPO yields during microwave-assisted pyrolysis of SBW with POAC as the absorber. The highest SPO yield of 29.63 wt.% was observed in Run 3, using 15 g of SBW, 35 wt.% POAC loading, and a temperature of 400 °C. These results can be attributed to the excellent microwave absorption capacity of POAC, which enhanced localized heating and promoted efficient biomass decomposition (Fodah *et al.*, 2022). Moreover, the optimized experimental conditions facilitated better energy transfer and increased volatile release, both critical factors for maximizing the liquid product yield (Fernández *et al.*, 2024). These results suggest that a

Table 3. Experimental factors and observed responses for SPO synthesis

Standard	Practical run	SBW mass (g)	POAC loading (%)	Temperature (°C)	Average yield (wt.%)	Predicted yield, (wt.%)	Standard deviation
7	1	5	75	400	3.5	6.71	3.77
8	2	15	75	400	19.05	16.64	7.95
6	3	15	35	400	29.63	24.97	10.94
12	4	10	88.6	375	0.55	−1.35	0.55
15	5	10	55	375	15.5	17.87	1
14	6	10	55	417	27.75	28.91	4.55
16	7	10	55	375	19	17.87	1
11	8	10	21.4	375	0	3.29	0
10	9	18.41	55	375	11	18.46	0.6
5	10	5	35	400	0	1.1	0
17	11	10	55	375	19.35	17.87	3.9
13	12	10	55	333	22.95	23.19	1.95
3	13	5	75	350	0.55	4.22	0.32
4	14	15	75	350	11.6	9.51	4.4
2	15	15	35	350	24.85	20.65	5.15
9	16	1.59	55	375	0	−6.07	0
1	17	5	35	350	0	1.42	0

Source(s): Authors' own work

higher SBW mass combined with an optimized POAC loading at 400 °C can enhance SPO yield. The increased SBW mass provided a larger substrate for pyrolysis, while POAC acted as a microwave absorber, facilitating efficient energy transfer and promoting biomass thermal decomposition, thus increasing oil yield by improving biomass decomposition efficiency (Fang *et al.*, 2024; Fodah *et al.*, 2022).

In contrast, three experiments – Run 10 (5 g SBW, 35 wt.% POAC, 400 °C), Run 8 (10 g SBW, 21.4 wt.% POAC, 375 °C) and Run 17 (10 g SBW, 35 wt.% POAC, 350 °C) – produced no SPO yield (0 wt.%). This can be attributed to incomplete thermal decomposition or insufficient microwave energy absorption due to the low biomass mass. The lack of a sufficient substrate for pyrolysis likely limited the generation of volatile compounds, leading to negligible oil formation (Syed *et al.*, 2023). Similarly, Run 16 (1.59 g SBW, 55 wt.% POAC, 375 °C) exhibited discrepancies, with a predicted yield of –6.07 wt.% and an experimental yield of 0 wt.%. This discrepancy suggests potential experimental uncertainties, such as unaccounted material losses due to condensation or incomplete thermal degradation of the biomass (Ethaib *et al.*, 2020).

A general trend was observed across the experimental runs indicating that increasing the SBW mass, especially when coupled with optimized POAC loading, enhanced SPO yields. For instance, Run 15 (15 g SBW mass, 35 wt.% POAC loading, 350 °C) achieved an SPO yield of 24.85 wt.%, while Run 2 (15 g SBW mass, 75 wt.% POAC loading, 400 °C) resulted in a yield of 19.05 wt.%. These findings suggest that POAC, as a microwave absorber, significantly influences biomass conversion efficiency by improving localized heating and facilitating the breakdown of SBW into volatile components (Ethaib *et al.*, 2020).

However, the results also indicate that the optimization of both SBW mass and POAC loading is essential for maximizing oil yields. Excessively high POAC loading does not necessarily lead to higher yields. For example, Run 1, which utilized 75 wt.% POAC loading, did not produce the highest yield. This could be due to energy dissipation effects, where excessive POAC absorbed too much microwave energy, reducing the effective heating of the biomass (Badza *et al.*, 2024). These findings emphasize the importance of achieving a balanced biomass-to-absorber ratio to optimize SPO production efficiency.

As shown in the TGA analysis in Figure 2, cellulose and hemicellulose undergo thermal decomposition within the temperature range of 200–360 °C, while lignin decomposes at higher temperatures between 350 and 450 °C. In this study, the production of SPO from SBW was observed at temperatures ranging from 350 to 400 °C. Increasing the pyrolysis temperature generally enhances SPO yield, primarily due to the accelerated degradation of lignin and minimized mass transport limitations, which facilitate the rapid release of volatiles (Fernández *et al.*, 2024).

3.4 Process optimization using response surface methodology

The relationship between SPO yield and three independent parameters – SBW mass, POAC loading and temperature – was investigated using statistical modelling. The model coefficients, namely the R² and F-values, and significant probabilities were used to evaluate the significance of the studied parameters. Second order polynomial model was obtained for the oil yield based on Equation (5).

$$Y = 614.66 + 3.2A + 1.4B - 3.57C - 0.17A^2 - 0.015B^2 + 0.0046C^2 - 0.035AB \\ + 0.0093AC + 0.0014BC \quad (5)$$

where Y represents the SPO yield, while A, B and C are the coded terms for SBW mass, POAC loading and temperature, respectively. The regression model and its associated terms have been summarized in Table 4. The linear term of sample mass (A) significantly influenced the SPO yield, as indicated by its high F-value of 26.21. While POAC loading (B) had no noticeable effect in linear form, its quadratic term (B²) was identified as an important

Table 4. ANOVA for the regression model and respective model term for SPO yield

Source	Sum of squares	Degree of freedom	Mean of square	F-value	p-value	
<i>Model</i>	1726.52	9	191.84	6.93	0.0092	Significant
A	726.05	1	726.84	26.21	0.0014	
B	26.06	1	26.03	0.9408	0.3644	
C	39.60	1	39.59	1.43	0.2708	
A ²	192.06	1	192.12	6.93	0.0337	
B ²	402.73	1	564.35	14.54	0.0066	
C ²	94.40	1	94.40	3.41	0.1074	
AB	97.16	1	97.16	3.51	0.1032	
AC	10.76	1	10.76	0.3887	0.5528	
BC	3.95	1	3.95	0.1425	0.7170	
<i>Residual</i>	193.88	7	27.70			
Lack of Fit	184.81	5	36.96	8.16	0.1128	Not significant
Pure error	9.07	2	4.53			
<i>Correlation total</i>	1920.40	16				

Source(s): Authors' own work

parameter, with an F-value of 14.54. Similarly, the quadratic term of SBW sample mass (A²) also played a noticeable role, with an F-value of 6.93.

The adequacy of the response surface model for predicting SPO yield was evaluated using the actual vs. predicted yield plot (Figure 3). The quadratic model was suggested as the best fit, with a statistically significant sequential *p*-value of 0.0065 and an adjusted R² of 0.7692, indicating that approximately 76.92% of the variability in SPO yield is explained by the model. Additionally, the lack of fit *p*-value (0.1128) was not significant, confirming that the model adequately describes the experimental data without systematic error. However, the predicted R² of 0.2571 suggests some deviation between predicted and actual values, indicating that while the model captures the overall trend, external factors such as biomass composition variability, energy transfer efficiency, or secondary reactions may contribute to the remaining unexplained variance. The actual vs. predicted plot further validates the model's performance, as most data points align with the diagonal reference line, demonstrating a reasonable correlation between experimental and predicted values. Slight deviations at higher or lower yield values indicate minor prediction errors, potentially due to interaction effects not fully accounted for in the quadratic model. Overall, the results confirm that the selected model provides a reliable approximation for SPO yield prediction while highlighting areas for further optimization to improve predictive accuracy.

The correlation between the predicted and actual values of SPO yield is illustrated in Figure 4. The analysis of variance (ANOVA), conducted using Design Expert software, indicates that the regression model exhibits a predicted R² value of 0.8991 and an adjusted R² value of 0.7693. This level of agreement suggests that the model captures the overall trends in the data reasonably well and demonstrates acceptable predictive accuracy (Badza *et al.*, 2024). While the difference between the predicted and adjusted R² values points to some degree of model complexity or residual variability, such discrepancies are not uncommon in pyrolysis-related experimental systems (Anoopkumar *et al.*, 2023; Rios-Del Toro *et al.*, 2021).

Furthermore, the regression model was developed by incorporating all relevant process variables-SBW mass, POAC loading and pyrolysis temperature-based on literature evidence and preliminary trials. The inclusion of these significant factors contributed to maintaining model robustness, as removal of such parameters typically reduces the model's explanatory power (Rios-Del Toro *et al.*, 2021). The reasonable agreement between predicted and experimental values supports the model's utility for process optimization and its practical applicability in maximizing bio-oil yield from SBW, consistent with findings reported in other

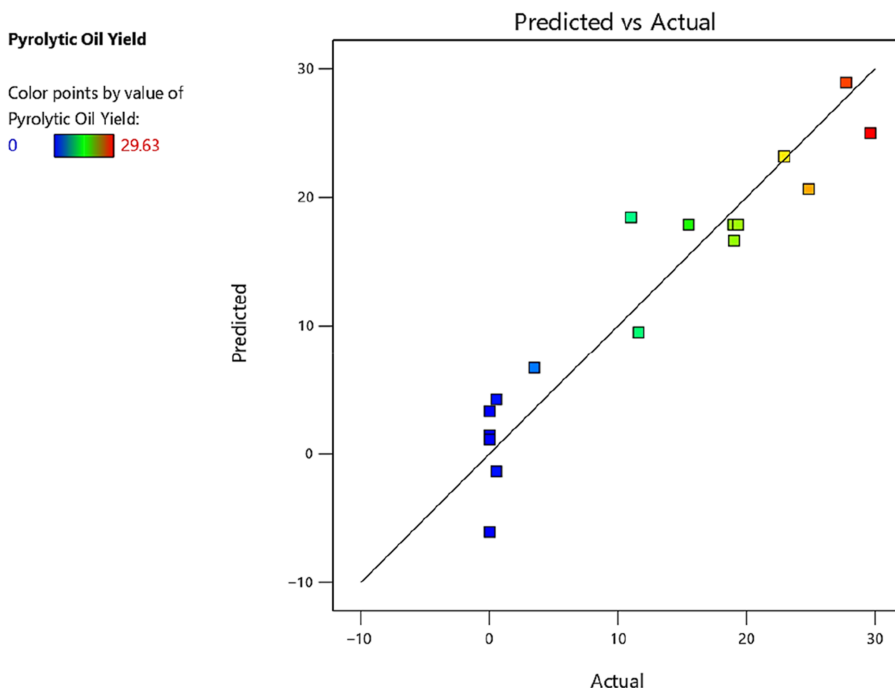


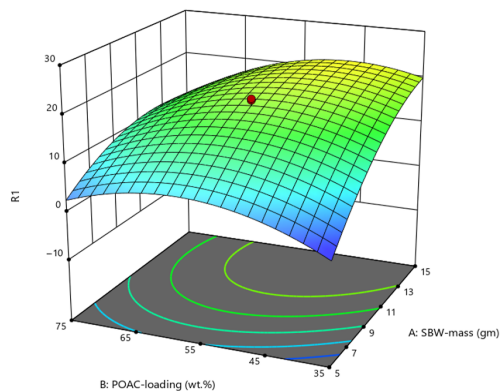
Figure 3. Predicted vs actual optimized yield of SPO from SBW. **Source(s):** Authors' own work

biomass valorization studies (Muniyappan *et al.*, 2023). Minor discrepancies between predicted and actual pyrolytic oil yields have been observed, which are common in biomass pyrolysis studies due to experimental variability and system complexities (Anoopkumar *et al.*, 2023). Such variations can arise from factors including feedstock heterogeneity, microwave energy distribution and measurement uncertainties (Fernández *et al.*, 2024). To enhance predictive accuracy, further replication of experiments and refinement of process parameters are recommended, as supported by previous optimization research (Badza *et al.*, 2024; Mahfud *et al.*, 2024; Xaba *et al.*, 2020).

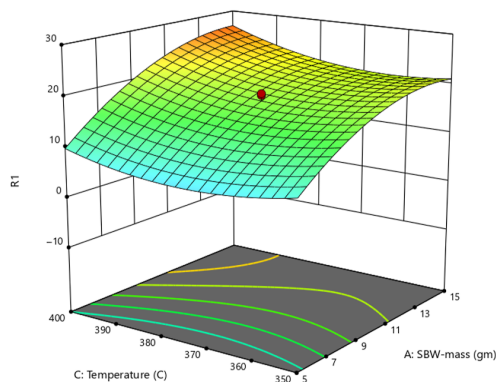
The three-dimensional response surface plots for pyrolytic yield demonstrate the influence of the process parameters and their interaction on pyrolytic yield, as shown in Figure 4.

The combined effect of mass and POAC loading on pyrolytic yield is illustrated in Figure 4 (a), with the surface plotted at a fixed temperature of 375 °C. Pyrolytic yield increases gradually with the increase in mass and POAC loading. The response surface clearly indicates that higher mass and POAC loading are favorable for producing pyrolytic yield from SB. The increasing POAC loading enhances the heating rate (Mahfud *et al.*, 2024), which accelerates the thermal cracking of SB, leading to the release of more volatiles and an increase in the overall pyrolytic yield. The findings are in agreement with prior studies, which have reported that higher microwave absorbent loading accelerates heating, thereby improving the efficiency of biomass conversion (Fernández *et al.*, 2024; Lozano Pérez *et al.*, 2024).

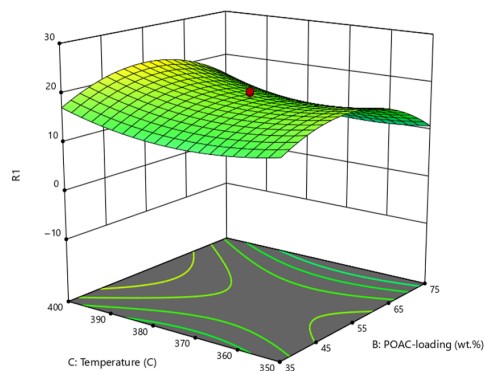
Increasing mass and POAC loading inside the microwave can quickly raise the temperature and remove non-condensable volatiles from the reaction zone. Consequently, the biomass can release more volatiles with an increase in reaction temperature (Ke *et al.*, 2024). The increase in volatile production can enhance pyrolytic yield by reducing biochar yield (Rios-Del Toro *et al.*, 2021). Similar observations were reported by Xaba and colleagues (Xaba *et al.*, 2020). The combined effect of SBW mass and temperature at a fixed POAC loading of 55



(a)



(b)



(c)

Figure 4. 3D interaction plots showing the effects of (a) SBW sample mass and POAC loading, (b) SBW sample mass and temperature, and (c) POAC loading and temperature on SPO yield. **Source(s):** Authors' own work

wt.% is depicted in Figure 4(b). The results show that increasing both parameters led to a higher SPO yield. At elevated temperatures, biomass undergoes more efficient thermal decomposition, releasing a greater amount of volatile compounds, which enhances oil

production (Palla *et al.*, 2024). Unlike conventional slow pyrolysis, where excessive heating can induce secondary thermal cracking and degrade the pyrolytic oil into non-condensable gases, microwave-assisted pyrolysis operates within a shorter reaction time (FOONG *et al.*, 2024). This rapid heating in thermal pyrolysis minimizes secondary cracking effects, ensuring a higher retention of SPO (Fang *et al.*, 2024). These findings highlight the importance of precisely controlling reaction temperature to optimize oil yield while minimizing unwanted side reactions (Hanafi *et al.*, 2024b).

Figure 4(c) illustrates the interactive effect of POAC loading and temperature on SPO yield. The results suggest that increasing both variables generally enhances oil production. However, beyond a certain POAC loading threshold, a decline in yield is observed. This phenomenon is likely due to excessive heat generation within a short time frame, which promotes secondary cracking of volatile components, leading to the formation of heavy tar and carbonaceous residues (Sun *et al.*, 2023). Secondary cracking occurs when high temperatures cause the breakdown of previously formed products, which not only reduces the overall yield of oil but also generates undesirable by-products like tar and coke (Liu *et al.*, 2024b). Therefore, while higher POAC loading can improve initial yields, it is crucial to optimize this variable to prevent excessive thermal degradation and ensure efficient heat transfer. Maintaining the optimal POAC loading is essential to maximize SPO yield and minimize side reactions that compromise product quality.

3.5 Physical characteristics of SPO

The dark brownish color of SPO is compatible with the previously reported appearance of bio-oils derived from biomass pyrolysis, which shows the presence of complex hydrocarbons and oxygenated compounds (Allende *et al.*, 2023a). The SPO exhibited 56.3% volatile and moisture content because of the drying temperature of 105 °C. This can also be because of the release of both free water and reaction water during the decomposition of biopolymers in the lignocellulosic biomass (Badza *et al.*, 2024).

The elemental composition of SPO was found to be 53.7% oxygen, 40.51% carbon, 5.51% hydrogen and 0.25% nitrogen. These values are comparable to those reported for pyrolytic oil produced from microwave pyrolysis of mushroom spent compost, which contained 39.7% oxygen, 52.33% carbon, 7.55% hydrogen and 0.32% nitrogen (Shahnouri *et al.*, 2024). Similarly, the proximate analysis of SPO revealed a volatile content of 74.6%, fixed carbon of 15.3%, moisture content of 8.2% and ash content of 1.9%. These are also in reasonable agreement with the values reported for mushroom spent compost pyrolytic oil, which include 8.87% fixed carbon content and 0.2% ash (Shahnouri *et al.*, 2024). The carbon and fixed carbon contents are attributed to the applied microwave power (Lam *et al.*, 2017), which transferred energy to the SBW and generated greater heat within the biomass (Lawai *et al.*, 2024). This elevated thermal energy promoted effective carbonization, resulting in a pyrolytic oil with moderate carbon and fixed carbon (Lam *et al.*, 2017). This indicates that SBW is ideally suited for SPO production, as feedstocks with elevated fixed carbon content often increase biochar yield, while those with high volatile content promote the generation of liquid and gaseous products (Allende *et al.*, 2024).

The density of SPO was found to be 2 g/cm³ which is relatively high compared to other bio-oils. For example, SPO produced from *Chlorella* sp. algae has a density of 1.01 g/cm³ (Mahfud *et al.*, 2024), and waste cooking oil-derived bio-oil has a lower density of 0.899 g/cm³ (Banchapattanasakda *et al.*, 2023). This elevated density of SPO suggests that it may contain a higher proportion of heavier molecules or that its molecular structure contributes to greater compactness compared to bio-oils derived from other biomass sources (Silos-Llamas *et al.*, 2023). The total acid content of SPO was found to be 168 mg KOH/g, indicating high acidity with a pH of 3. This is notably higher compared to bio-oil derived from *Triplochiton scleroxylon* sawdust, which exhibited an acid value of 47 mg KOH/g (Badza *et al.*, 2024). Similarly, waste cooking oil-derived bio-oil had a comparatively lower acid value of 126.78 mg KOH/g

(Banchapattanasakda *et al.*, 2023). The higher acid value of SBW-based bio-oil suggests a greater presence of acidic compounds, which could limit its application as a fuel due to the potential for corrosion of engine components, storage tanks and pipes (Badza *et al.*, 2024).

The calorific value of SPO produced through microwave-assisted pyrolysis was found to be 21.41 MJ/kg, which is within the range of previously reported biomass-derived pyrolytic oils. For instance, the bio-oil derived from fast pyrolysis of rice husk exhibited a calorific value of 13.83 MJ/Kg (Fu *et al.*, 2020), and bio-oil from furfural residue ranged from 19.61 to 22.02 MJ/kg (Liu *et al.*, 2024a). However, the calorific value is lower than that of waste cooking oil-derived bio-oil (39.07 MJ/kg) and biodiesel (>42.00 MJ/kg), which have higher hydrocarbon content and lower oxygenated compounds (Banchapattanasakda *et al.*, 2023). These variations highlight the influence of feedstock composition and pyrolysis conditions on the energy potential of bio-oils, with SBW-based bio-oil exhibiting competitive calorific properties among lignocellulosic biomass sources. However, its direct use may not be beneficial, and thus it requires further processing to enhance its properties and make it suitable for commercial applications (Aziz *et al.*, 2017).

3.6 Chemical composition

The chemical composition of SPO was studied by FTIR analysis as well as GC–MS analysis.

3.6.1 FTIR analysis. The FTIR spectra for SPO has been presented in Figure 5. The FTIR spectrum of the SPO reveals the presence of several key functional groups. A strong, broad absorption band between 3,300 and 3,600 cm^{-1} is attributed to O–H stretching, indicating the presence of water or phenol group (Xaba *et al.*, 2020). Peaks between 3,000 and 2,800 cm^{-1} are characteristic of C–H stretching in aliphatic hydrocarbons, suggesting the presence of alkane groups (Muniyappan *et al.*, 2023). A distinct absorption peak in the range of 1,750–1,700 cm^{-1} is attributed to C=O stretching, which is commonly associated with carbonyl-containing compounds such as ketones, aldehydes, esters and carboxylic acids (Banchapattanasakda *et al.*, 2023). The peak at 1,550–1,500 cm^{-1} corresponds to N–O bending vibrations, indicative

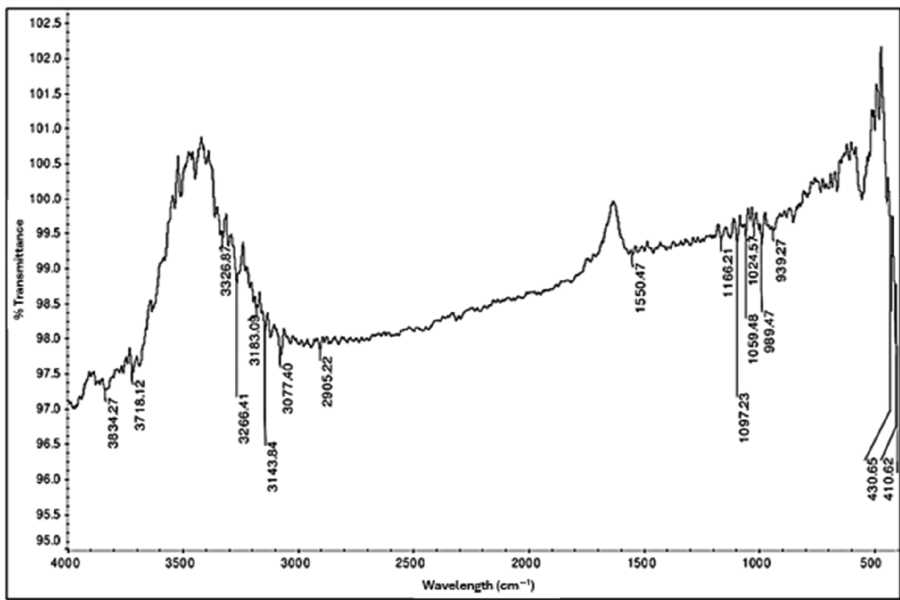


Figure 5. FTIR spectra for SPO. Source(s): Authors’ own work

of the presence of nitro (NO_2) groups in nitrogenous compounds (Xaba *et al.*, 2020). Peaks in the $1,470\text{--}1,350\text{ cm}^{-1}$ region are typically associated with C–H bending vibrations in alkanes (Banchapattanasakda *et al.*, 2023). Lastly, the peaks between 915 and 650 cm^{-1} are attributed to out-of-plane bending vibrations of C–H bonds, characteristic of aromatic compounds (Hanafi *et al.*, 2024b). Overall, the FTIR analysis suggests that SPO contains a complex mixture of alcoholic and aliphatic hydrocarbons, with notable oxygenated and nitrogenous functional groups.

3.6.2 GC–MS analysis. The presence of organic compounds in the SPO was determined using GC–MS analysis, revealing a diverse composition of chemical species (Banchapattanasakda *et al.*, 2023). The SPO comprises a broad spectrum of organic compounds, including aldehydes, ketones, sugars, carboxylic acids, esters, phenolics, guaiacols, hydrocarbons and furan derivatives (Fu *et al.*, 2020). These compounds contribute to the chemical and physical properties of the oil, influencing its potential applications in various industries (Xaba *et al.*, 2020). The detailed composition is summarized in Table 5.

Among the identified compounds, monoaromatic compounds were the most dominant, accounting for 57.6% of the total composition. The major phenolic constituents include 2,6-dimethoxyphenol (11.15%), 2-methoxyphenol (7.42%) and 4-methylphenol (7.12%). The high concentration of these phenolic compounds indicates significant lignin-derived contributions to the pyrolytic oil with potential for application in robust combustion engines like slow- and medium-speed diesel engines with enhancement of physicochemical properties to meet the criteria (Khelifa *et al.*, 2020; Wahi *et al.*, 2020). Fourier Transform Infrared (FTIR) spectroscopy further confirmed the presence of phenolic groups, reinforcing the GC–MS results (Liu *et al.*, 2024a). Aldehydes constituted 8.02% of the oil, with notable compounds such as 5-methylfurfural (6.01%) and 3,5-dimethoxy-4-hydroxycinnamaldehyde (1.08%) (Mahfud *et al.*, 2024). Ketones, contributing 11.68% to the composition, included 1-(2,6-dihydroxy-4-methoxyphenyl)butan-1-one (3.55%) and 2-hydroxy-3-methyl-2-cyclopenten-1-one (2.7%), which are often associated with the degradation of cellulose and hemicellulose fractions (Banchapattanasakda *et al.*, 2023). Esters accounted for 5.57% of the oil composition, with bis(2-ethylhexyl) benzene-1,2-dicarboxylate (3.12%) being the most abundant (Badza *et al.*, 2024).

Furthermore, anhydrous sugars such as 6-ethyl-3-propionyl-2,3-dihydropyran-2,4-dione (1.61%) were identified, indicating the partial decomposition of carbohydrate fractions during pyrolysis (Mahfud *et al.*, 2024). Other minor constituents included ethers, amines and alcohols. The ether fraction was represented by 1,2,3-trimethoxybenzene (4.45%), whereas the amine fraction contained 1-(Dimethylamino)pyrrole (0.93%) (Yue *et al.*, 2024). The presence of these nitrogen-containing compounds suggests the decomposition of proteinaceous materials in the feedstock (Liu *et al.*, 2024a). Alcohols, such as 4-hydroxy-3-methoxyphenylethylethanol (1.01%), were also detected, further contributing to the overall complexity of the oil's chemical profile (Badza *et al.*, 2024). The diverse chemical composition of pyrolytic oil underscores its potential as a viable raw material for fuel production. However, further refining and upgrading processes may be necessary to enhance its stability, efficiency and commercial viability for energy applications.

4. Conclusion

The optimization and characterization of sago pyrolytic oil produced through microwave-assisted pyrolysis, utilizing palm kernel shell activated carbon as a microwave absorber, demonstrated significant enhancements in both heating efficiency and oil yield. The presence of the absorber facilitated extensive pyrolytic cracking, leading to improved oil recovery. CCRD in RSM successfully optimized the process parameters, predicting an optimal yield of 29.63% under controlled conditions. Chemical analysis revealed a high phenolic content (57.6%), indicating potential for use in robust combustion engines like slow- and medium-speed diesel engines, which require fuels with lower acidity and water content than the current pyrolytic oil.

Table 5. Relative proportions (% area) of the SPO

Chemical compounds	Chemical formula	Area (%)
<i>Aldehydes</i>		
5-methylfurfural	C ₉ H ₁₀ O ₂	6.01
3,5-dimethoxy-4-hydroxycinnamaldehyde	C ₁₁ H ₁₂ O ₄	1.08
4-hydroxy-3-methoxybenzaldehyde	C ₈ H ₈ O ₃	0.55
3-(4-hydroxy-3-methoxyphenyl)prop-2-enal	C ₁₀ H ₁₀ O ₃	0.38
	<i>Total</i>	8.02
<i>Ketones</i>		
1-(2,6-dihydroxy-4-methoxyphenyl)butan-1-one	C ₁₁ H ₁₄ O ₄	3.55
2-hydroxy-3-methyl-2-cyclopenten-1-one	C ₆ H ₈ O ₂	2.7
1-(4-hydroxy-3,5-dimethoxyphenyl)ethanone	C ₁₀ H ₁₂ O ₄	2.18
4-acetylphenylbenzene	C ₁₅ H ₁₄ O	1.90
Acetophenone	C ₈ H ₈ O	0.37
2,3-dihydro-1-indanone	C ₉ H ₈ O	0.37
	<i>Total</i>	11.68
<i>Monoaromatic Compounds</i>		
2,6-dimethoxyphenol	C ₈ H ₁₀ O ₃	11.15
2-methoxyphenol	C ₇ H ₈ O ₂	7.42
4-methylphenol	C ₇ H ₈ O	7.12
2-methylphenol	C ₇ H ₈ O	5.91
2-methoxy-5-methylphenol	C ₈ H ₁₀ O ₂	5.00
1,2,3-Trimethoxybenzene	C ₉ H ₁₂ O ₃	4.45
2-methoxy-4-(2-propenyl)phenol	C ₁₀ H ₁₂ O ₂	4.45
1,2,3-trimethoxy-5-methylbenzene	C ₁₀ H ₁₄ O ₃	3.34
2,6-dimethoxy-4-(2-propenyl)phenol	C ₁₁ H ₁₄ O ₃	3.23
4-ethyl-2-methoxyphenol	C ₉ H ₁₂ O ₂	2.55
2,4-dimethylphenol	C ₈ H ₁₀ O	2.16
4-ethylphenol	C ₈ H ₁₀ O	1.11
2-methoxy-4-propylphenol	C ₁₀ H ₁₄ O ₂	0.93
2,4-di-tert-butylphenol	C ₁₄ H ₂₂ O	0.89
2,6-dimethylphenol	C ₈ H ₁₀ O	0.60
4,4'-methylethynylbis[2,6-dimethoxyphenol]	C ₁₇ H ₂₀ O ₆	0.49
1,1'-biphenyl-2',3',4'-trimethoxy-6-hydroxymethyl	C ₁₆ H ₁₈ O ₄	0.47
2-ethylphenol	C ₈ H ₁₀ O	0.40
2,6-bis(1,1-dimethylethyl)-4-methylphenol	C ₁₅ H ₂₄ O	0.38
	<i>Total</i>	57.60
<i>Esters</i>		
Bis(2-ethylhexyl) benzene-1,2-dicarboxylate	C ₁₈ H ₁₈ O ₂	3.12
11-methyl-octadecanoate	C ₁₉ H ₃₆ O ₂	1.15
9-octadecenoic acid, methyl ester	C ₁₉ H ₃₆ O ₂	0.46
Dimethyl 3-methyl-4-propyl-2,4-hexadienedioate	C ₁₁ H ₁₄ O ₄	0.44
Bis(trimethylsilyl) methylphosphonate	C ₉ H ₁₂ O ₄ P	0.4
	<i>Total</i>	5.57
<i>Ether</i>		
1,2,3-trimethoxybenzene	C ₉ H ₁₂ O ₃	4.45
<i>Anhydrous sugars</i>		
6-ethyl-3-propionyl-2,3-dihydropyran-2,4-dione	C ₁₀ H ₁₂ O ₄	1.61
<i>Amine</i>		
1-(Dimethylamino)pyrrole	C ₆ H ₁₀ N ₂	0.93
2,5-Dimethoxy-4-ethylamphetamine	C ₁₃ H ₂₁ NO ₂	0.35
	<i>Total</i>	1.28
<i>Alcohols</i>		
4-hydroxy-3-methoxyphenylethylethanol	C ₉ H ₁₂ O ₃	1.01
Source(s): Authors' own work		

However, the physicochemical properties indicate that upgrading and refining are essential to improve stability, energy density and overall fuel quality. This underscores the importance of additional processing to optimize performance and expand its use in sustainable energy systems.

The deployment of this optimized microwave pyrolysis system at a commercial scale offers promising environmental and economic benefits. By valorizing sago bark waste – a readily available agricultural byproduct – into pyrolytic oil, the process supports waste minimization and renewable energy generation. The use of palm kernel shell-based activated carbon, itself a biomass-derived material, further enhances the system's sustainability. Commercial adoption could reduce reliance on fossil fuels, promote circular economic practices in agricultural regions and create new economic opportunities in rural biomass valorization chains.

References

- Allende, S., Brodie, G. and Jacob, M.V. (2022), "Energy recovery from sugarcane bagasse under varying microwave-assisted pyrolysis conditions", *Bioresource Technology Reports*, Vol. 20, 101283.
- Allende, S., Brodie, G. and Jacob, M.V. (2023a), "Breakdown of biomass for energy applications using microwave pyrolysis: a technological review", *Environmental Research*, Vol. 226, 115619.
- Allende, S., Brodie, G. and Jacob, M.V. (2023b), "Energy recovery from pumpkin peel using microwave-assisted pyrolysis", *Energies*, Vol. 16 No. 18, p. 6438.
- Allende, S., Brodie, G. and Jacob, M.V. (2024), "Microwave pyrolysis of various wastes and analysis of energy recovery", *Bioresource Technology Reports*, Vol. 26, 101821, Elsevier Ltd.
- Anoopkumar, A.N., Reshmy, R., Aneesh, E.M., Madhavan, A., Kuriakose, L.L., Awasthi, M.K. and Pandey, A. (2023), "Progress and challenges of microwave-assisted pretreatment of lignocellulosic biomass from circular bioeconomy perspectives", *Bioresource Technology*, Vol. 369, 128459.
- Aziz, S.M.A., Wahi, R., Ngaini, Z., Hamdan, S. and Yahaya, S.A. (2017), "Esterification of microwave pyrolytic oil from palm oil kernel shell", *Journal of Chemistry*, Vol. 2017, 8359238.
- Badza, K., Raïssa, K.R., Karole, T.T.R., Philemon, Z.B. and Benoit, N.M. (2024), "Optimal bio-oil production using *Triplochiton scleroxylon* sawdust through microwave-assisted pyrolysis", *Bioenergy Research*, Vol. 17, pp. 2362-2373.
- Banchapattanasakda, W., Asavatesanupap, C. and Santikunaporn, M. (2023), "Conversion of waste cooking oil into bio-fuel via pyrolysis using activated carbon as a catalyst", *Molecules*, Vol. 28 No. 8, p. 3590.
- Ethaib, S., Omar, R., Kamal, S.M.M., Biak, D.R.A. and Zubaidi, S.L. (2020), "Microwave-assisted pyrolysis of biomass waste: a mini review", *Processes*, Vol. 8 No. 9, p. 1190.
- Fang, H., Hai, L., Xie, R., Yuan, J. and Zhang, Q. (2024), "Progress in the study of microwave pyrolysis technology and its influencing factors", *Journal of Materials Science and Chemical Engineering*, Vol. 12 No. 10, pp. 30-61.
- Fathi, N.K.M., Bukhori, M.F.M., Abdullah, S.M.A.A., Wahi, R., Zailani, M.A. and Gopal, M.M.R. (2022), "Effect of sago bark biochar application on *Capsicum annuum* L. Var. *Kulai* growth and fruit yield", *Malaysian Applied Biology*, Vol. 51 No. 3, pp. 127-135.
- Fernández, I., Pérez, S.F., Fernández-Ferreras, J. and Llano, T. (2024), "Microwave-assisted pyrolysis of forest biomass", *Energies*, Vol. 17, p. 4852.
- Fernández-González, R., Martín-Lara, M.A., Blázquez, G., Tenorio, G. and Calero, M. (2020), "Hydrolyzed olive cake as novel adsorbent for copper removal from fertilizer industry wastewater", *Journal of Cleaner Production*, Vol. 268, 121935.
- Fetriyuna, F., Murniani, S., Letsoin, A., Radix, I., Jati, A.P. and Purwestri, R.C. (2024), "Potential of underutilized sago for bioenergy uses", Vol. 14 No. 1, pp. 144-150.
- Fodah, A.E.M., Ghosal, M.K. and Behera, D. (2022), "Microwave-assisted pyrolysis of agricultural residues: current scenario, challenges, and future direction", *International journal of Environmental Science and Technology*, Vol. 19, pp. 2195-2220.

- Foong, S.Y., Low, F., Yek, P.N.Y., Yang, Y.A.N., Meng, L., Keey, L.R. and Verma, M. (2024), "Production of value-added biochar and bio-oil from microwave co2 pyrolysis of medium-density fiberboard waste", *Journal of Sustainability Science and Management*, Vol. 19 No. 6, pp. 75-84.
- Fu, P., Zhang, A., Luo, S., Yi, W. and Zhang, Y. (2020), "Comparative study on the catalytic steam reforming of biomass pyrolysis oil and its derivatives for hydrogen production", *RSC Advances*, Vol. 10 No. 22, pp. 12721-12729.
- Hanafi, N.H.M., Rozali, S. and Ibrahim, S. (2024a), "A review of the application of microwave-metal interactions on the microwave-metal-assisted pyrolysis (MMAP)", *Biomass Conversion and Biorefinery*, Vol. 14, pp. 13611-13628.
- Hanafi, N.H.M., Rozali, S. and Ibrahim, S. (2024b), "Empty fruit bunch derived biochar synthesized via microwave-metal-assisted pyrolysis and its potential as solid biofuel", *Biomass Conversion and Biorefinery*, Vol. 15, pp. 3771-3788.
- Imran-Shaukat, M., Wahi, R. and Ngaini, Z. (2023), "Optimization of copper, lead and nickel ions adsorption by *Melia azedarach* activated carbon: a response surface methodology approach", *Arabian Journal for Science and Engineering*, Vol. 48 No. 7, pp. 9047-9068.
- Imran-Shaukat, M., Haghani, H., Apaiyakul, R., Gao, H., Liang, Z., Tontiwachwuthikul, P. and Sema, T. (2025a), "Efficient catalytic regeneration of amine-based solvents in CO₂ capture: a comprehensive meta-analysis", *Separation and Purification Technology*, Vol. 359 No. 1, 130434.
- Imran-Shaukat, M., Wahi, R. and Ngaini, Z. (2025b), "Bio-based activated carbon for Cu(II), Ni(II), and Pb(II) ions aqueous sequestration: physiochemical characterization, isotherms, and kinetics", *International Journal of Environmental Science and Technology*, Vol. 22, pp. 3763-3786.
- Kashif, M., Ahmad, F., Cao, W., Zhao, W., Mostafa, E. and Zhang, Y. (2024), "Experimental study on microwave pyrolysis of Eucalyptus camaldulensis leaves: a promising approach for bio-oil recovery", *Frontiers of Chemical Science and Engineering*, Vol. 18 No. 10, p. 115.
- Ke, L., Zhou, N., Wu, Q., Zeng, Y., Tian, X., Zhang, J. and Fan, L. (2024), "Microwave catalytic pyrolysis of biomass: a review focusing on absorbents and catalysts", *Npj Materials Sustainability*, Vol. 2 No. 24, pp. 1-20.
- Khairunnisa, N., Fathi, M., Abd, S.M., Abdullah, A., Fhaizal, M., Bukhori, M. and Wahi, R. (2021), "Physicochemical properties of sago bark biochar and its potential as plant growth media", *Malaysian Journal of Analytical Sciences*, Vol. 25 No. 4, pp. 622-636.
- Khelfa, A., Rodrigues, F.A., Koubaa, M. and Vorobiev, E. (2020), "Microwave-assisted pyrolysis of pine wood sawdust mixed with activated carbon for bio-oil and bio-char production", *Processes*, Vol. 8 No. 11, pp. 1-12.
- Lam, S.S., Liew, R.K., Wong, Y.M., Azwar, E., Jusoh, A. and Wahi, R. (2017), "Activated carbon for catalyst support from microwave pyrolysis of orange peel", *Waste and Biomass Valorization*, Vol. 8 No. 6, pp. 2109-2119.
- Lawai, V., Ngaini, Z., Farooq, S., Wahi, R. and Bhawani, S.A. (2024), "Microwave-assisted molecularly imprinted polymer synthesis for chemometric and rebinding mechanism of drug release applications", Vol. 35 No. 1, pat.6291.
- Liu, Y., Zhou, C., Siyal, A.A., Liu, C., Zhang, Y., Fu, J. and Yun, H. (2024a), "Comparative microwave catalytic pyrolysis of cellulose and lignin in nitrogen and carbon dioxide atmospheres", *Journal of Cleaner Production*, Vol. 437, 140750.
- Liu, Z., Xie, M., Zhou, T., Yang, J., Yang, Y., Liu, T. and Dai, S. (2024b), "A review on liquid fuel produced from microwave-assisted pyrolysis of plastic waste", *Process Safety and Environmental Protection*, Vol. 187, pp. 833-844, Institution of Chemical Engineers.
- Lozano Pérez, A.S., Lozada Castro, J.J. and Guerrero Fajardo, C.A. (2024), "Application of microwave energy to biomass: a comprehensive review of microwave-assisted technologies, optimization parameters, and the strengths and weaknesses", *Journal of Manufacturing and Materials Processing*, Vol. 8 No. 3, p. 121.
- Mahfud, M., Qadariah, L., Haqqyana, H. and Aswie, V. (2024), "Optimization bio-oil production from chlorella sp. through microwave-assisted pyrolysis using response surface methodology", *Green Energy and Resources*, Vol. 2 No. 1, 100057.

- Makepa, D.C., Chihobo, C.H., Ruziwa, W.R. and Musademba, D. (2023), "Microwave-assisted pyrolysis of pine sawdust: process modelling, performance optimization and economic evaluation for bioenergy recovery", *Heliyon*, Vol. 9 No. 3, e14688.
- Muniyappan, D., Lima, G.R., Pereira, A.O., Gopi, R. and Ramanathan, A. (2023), "Multivariate combined optimization strategy and comparative life-cycle assessment of biomass and plastic residues via microwave co-pyrolysis approach towards a sustainable synthesis of renewable hydrocarbon fuel", *Journal of Environmental Chemical Engineering*, Vol. 11 No. 6, 111436.
- Palla, S., Surya, D.V., Pritam, K., Puppala, H., Basak, T. and Palla, V.C.S. (2024), "A critical review on the influence of operating parameters and feedstock characteristics on microwave pyrolysis of biomass", *Environmental Science and Pollution Research*, Vol. 31, pp. 57570-57593.
- Qiu, B., Wang, Y., Zhang, D. and Chu, H. (2024), "Microwave-assisted pyrolysis of biomass to high-value products: factors assessment, mechanism analysis, and critical issues proposal", *Chemical Engineering Journal*, Vol. 498, 155362.
- Racero-Galaraga, D., Rhenals-Julio, J.D., Sofan-German, S., Mendoza, J.M. and Bula-Silvera, A. (2024), "Proximate analysis in biomass: standards, applications and key characteristics", *Results in Chemistry*, Vol. 12, 101886.
- Rios-Del Toro, E.E., Chi, H., González-Álvarez, V., Méndez-Acosta, H.O., Arreola-Vargas, J. and Liu, H. (2021), "Coupling the biochemical and thermochemical biorefinery platforms to enhance energy and product recovery from *Agave tequilana* bagasse", *Applied Energy*, Vol. 299, 117293.
- Shahnouri, S.A., Taghizadeh-Alisaraei, A., Abbaszadeh-Mayvan, A. and Tatari, A. (2024), "Catalytic microwave pyrolysis of mushroom spent compost (MSC) biomass for bio-oil production and its life cycle assessment (LCA)", *Biomass Conversion and Biorefinery*, Vol. 14 No. 9, pp. 9949-9965.
- Sidabutar, R., Irvan, Trisakti, B., Gusty, N.D., Syahputra, M.R., Saputra, B.W. and Alexander, V. (2024), "Towards low-cost and sustainable biochar production based on empty fruit bunch: effect of pelletization, microwave power, residence time, and mass on biochar quality for commercial approach", *Case Studies in Chemical and Environmental Engineering*, Vol. 10, 100929.
- Silos-Llamas, A.K., Sudibyo, H., Hernández-Montoya, V., Meredith, W. and Durán-Jiménez, G. (2023), "Fast pyrolysis of agricultural residues: reaction mechanisms and effects of feedstock properties and microwave operating conditions on the yield and product composition", *Journal of Analytical and Applied Pyrolysis*, Vol. 175, 106217.
- Siruru, H., Syafii, W., Wistara, I.N.J. and Pari, G. (2019), "Characteristics of *Metroxylon rumphii* (pith and bark waste) from seram island, Maluku, Indonesia", *Biodiversitas*, Vol. 20 No. 12, pp. 3517-3526.
- Sun, J., Tao, J., Huang, H., Ma, R. and Sun, S. (2023), "Promotion of bio-oil production from the microwave pyrolysis of cow dung using pretreated red mud as a bifunctional additive: parameter optimization, energy efficiency evaluation, and mechanism analysis", *Environmental Research*, Vol. 236 No. 2, 116806.
- Suresh, A., Alagusundaram, A., Kumar, P.S., Vo, D.V.N., Christopher, F.C., Balaji, B. and Viswanathan, V. (2021), "Microwave pyrolysis of coal, biomass and plastic waste: a review", *Environmental Chemistry Letters*, Vol. 19, pp. 3609-3629.
- Susanto, B., Tosuli, Y.T., Cahyadi, A., Nami, H., Surjosatyo, A. and Alandro, D. (2024), "Characterization of sago tree parts from sentani, Papua, Indonesia for biomass energy utilization", *Heliyon*, Vol. 10 No. 1, e23993.
- Syed, N.R., Zhang, B., Mwenya, S. and Aldeen, A.S. (2023), "A systematic review on biomass treatment using microwave-assisted pyrolysis under PRISMA guidelines", *Molecules*, Vol. 28 No. 14, p. 5551.
- Vaštyl, M., Jankovská, Z., Cruz, G.J.F. and Matějová, L. (2022), "A case study on microwave pyrolysis of waste tyres and cocoa pod husk; effect on quantity and quality of utilizable products", *Journal of Environmental Chemical Engineering*, Vol. 10 No. 1, 106917.
- Wahi, R., Yahaya, S.A., Lam, S.S., Abdul Aziz, S.M. and Ngaini, Z. (2020), "Esterification of microwave induced pyrolytic oil from sago bark waste", *Waste and Biomass Valorization*, Vol. 11 No. 7, pp. 3653-3663.

- Wahi, R., Zuhaidi, N.F.Q., Yahaya, S.A., Lam, S.S., Imran-Shaukat, M., Aziz, S.M.A. and Ngaini, Z. (2022), "Engineered microwave biochar from sago bark waste for heavy metals adsorption", *Materials Today: Proceedings*, Vol. 57, pp. 1403-1414.
- Wallace, C.A., Afzal, M.T. and Saha, G.C. (2019), "Effect of feedstock and microwave pyrolysis temperature on physio-chemical and nano-scale mechanical properties of biochar", *Bioresources and Bioprocessing*, Vol. 6 No. 1, p. 33.
- Wu, Y., Gui, Q., Zhang, H., Li, H., Li, B., Liu, M. and Chen, Y. (2023), "Effect of biomass components' interaction on the pyrolysis reaction kinetics and small-molecule product release characteristics", *Journal of Analytical and Applied Pyrolysis*, Vol. 173, 106039.
- Xaba, S.A., Igberase, E., Osayi, J., Seodigeng, T. and Osifo, P.O. (2020), "Optimization of primary sewage sludge and coal lignite by microwave assisted pyrolysis for the production of bio-oil", *Environmental Technology*, Vol. 42 No. 5, pp. 1-35.
- Yassin, K.E., El-Rehem, F.H., Amin, R. and Sobhy, A. (2023), "Separation of pyritic sulfur from ultrafine coal by pyrolysis and wet high magnetic separation", *International Journal of Coal Preparation and Utilization*, Vol. 43 No. 10, pp. 1759-1771, Taylor and Francis Ltd.
- Yue, W., Hu, Y., Yu, Z., Zhan, J. and Ma, X. (2024), "Microwave-assisted catalytic rapid pyrolysis of soybean straw for the preparation of high-value indole-rich bio-oils", *Journal of Analytical and Applied Pyrolysis*, Vol. 181, 106634.

Further reading

- Mohamed, B.A., Bi, X., Li, L.Y., Leng, L., Salama, E.S. and Zhou, H. (2021), "Bauxite residue as a catalyst for microwave-assisted pyrolysis of switchgrass to high quality bio-oil and biochar", *Chemical Engineering Journal*, Vol. 426, 131294.

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