

Effect of microwave pyrolysis temperature on liquid yield from low-rank coal using $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalysts

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ABSTRACT

Low-rank coal (LRC) offers substantial reserves as an alternative energy source, but its low calorific value and high moisture content limit direct combustion. This study investigated the effect of microwave-assisted pyrolysis temperature (550 °C, 600 °C, and 650 °C) and reaction time (60 and 120 minutes) on the liquid yield of sub-bituminous LRC, using a microwave pyrolysis reactor (800 W, 2.45 GHz) combined with $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalysts at a 2% w/w ratio. Proximate and ultimate analyses characterised the feedstock, while SEM, FTIR, and GC-MS characterised the pyrolysis liquid product. Each condition was tested once, and results were analysed descriptively rather than through replicate-based statistics. The highest liquid yield, 46.5%, was obtained at 600 °C and 120 minutes using the Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalyst, exceeding the 40.0% achieved with $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ under identical conditions. Yield increased from 550 °C to 600 °C due to enhanced thermal cracking, then declined at 650 °C due to secondary cracking reactions. FTIR indicated stronger aromatic and sulfur-related functional-group signals, and SEM revealed a denser, more homogeneous char morphology for the activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ system, while GC-MS showed phenolic compounds dominating the liquid product at the optimum condition for both catalysts (59.68-78.54% of total peak area). These results demonstrate that microwave-assisted pyrolysis with $\text{Fe}_2(\text{SO}_4)_3$ -based catalysts effectively converts low-rank coal into a phenol-rich pyrolysis liquid, with the Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalyst providing superior performance at 600 °C and 120 minutes.

Keywords: activated carbon; $\text{Fe}_2(\text{SO}_4)_3$ catalyst; liquid yield; low-rank coal; microwave pyrolysis; phenolic compounds

INTRODUCTION

The global energy crisis, coupled with growing concern over climate change, continues to drive the diversification of energy sources worldwide. Global primary energy consumption increases at 1-2% per year, while oil and natural gas reserves continue to decline (Mohr, 2021). Coal remains the largest fossil energy reserve, with proven world reserves reaching 1,074,108 million tonnes (Plc, 2021). Amid tightening oil supply, coal continues to dominate power generation in many developing countries, including Indonesia, which has abundant coal reserves and long-term production potential. Optimising coal utilisation, particularly by converting it into liquid fuel, therefore represents an urgent energy strategy.

Low-rank coal (LRC), comprising sub-bituminous and lignite types, accounts for a global reserve of 320,469 million tonnes (PLC, 2021). Despite this abundance, the direct utilisation of LRC as fuel faces serious constraints, including high moisture content (often above 30%), low calorific value, relatively high ash and sulfur content, and low combustion efficiency, resulting in high pollutant emissions and uncompetitive operating costs when burned directly. Thermal conversion technologies such as

pyrolysis offer a relevant solution to upgrade LRC into higher-value energy products, namely liquid fuel, syngas, and char (Sardi et al., 2022).

Microwave-assisted pyrolysis (MAP) is one such technology that has developed rapidly, using electromagnetic radiation at 2.45 GHz as a direct internal heat source. Unlike conventional heating, which transfers heat from the material surface inward, microwave heating generates heat directly within the material through interaction with polar molecules, resulting in a faster heating rate, more uniform heat distribution, and higher energy efficiency (Miura et al., 2000; Sardi et al., 2023).

Product distribution during pyrolysis-liquid, solid (char), and gas-is strongly governed by reaction temperature: low temperatures favour char formation, an optimal temperature maximises liquid yield, while excessive temperatures promote secondary cracking reactions that reconvert liquid products into light gases (Ruslan et al., 2025). Catalysts play a critical role in this process. TiO_2 offers high thermal stability and an active surface that promotes hydrocarbon cracking and reforming reactions (Z. Zhang et al., 2013), while activated carbon provides a much

larger specific surface area, offering more active sites for decomposition reactions and acting as a catalyst support (Sardi et al., 2022). $\text{Fe}_2(\text{SO}_4)_3$ plays a dual role as a cracking accelerator and sulfur receptor that stabilises the liquid product (Zhou et al., 2019). Combining metal- or carbon-based catalysts with $\text{Fe}_2(\text{SO}_4)_3$ has been shown to enhance both thermal decomposition rate and pyrolysis product quality (Ren et al., 2018; Sardi et al., 2022).

Several previous studies have examined microwave-assisted coal pyrolysis. (Sardi et al., 2022) reported that activated carbon+ $\text{Fe}_2(\text{SO}_4)_3$ and HZSM-5+ $\text{Fe}_2(\text{SO}_4)_3$ catalysts increased bio-oil production from LRC, while Sardi et al. (2024) demonstrated that reservoir rock and activated carbon additives actively contribute to bio-oil synthesis during MAP. (Y. Zhang et al., 2020) showed that K_2CO_3 , CaCl_2 , and $\text{Fe}_2(\text{SO}_4)_3$ catalysts influence MAP product composition. In the broader biomass pyrolysis literature (Habibi et al., 2025), published in this journal, rice-husk pyrolysis oil is similarly reported to be dominated by phenolic compounds with fuel-additive potential, underscoring that oxygen-rich lignocellulosic feedstocks generally favour phenolic product

formation during pyrolysis. Nevertheless, studies specifically investigating the effect of MAP temperature on liquid yield using a combined $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalyst system remain limited. (Sardi et al., 2022) demonstrated the effectiveness of activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ for LRC bio-oil production, while (Ruslan et al., 2025) examined an $\text{Fe}_2(\text{SO}_4)_3$ -based catalyst combination in LRC MAP; however, neither study directly compared these two catalyst systems under identical operating conditions, and a systematic determination of the optimum temperature across the 550–650 °C range has not been comprehensively addressed for either system. This gap forms the primary justification for the present study. Its specific novelty lies not in either catalyst individually, but in the head-to-head comparison of $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ under identical feedstock, reactor, and operating conditions across three systematic temperature levels, supported by comprehensive product characterisation through SEM, FTIR, and GC-MS.

Based on this background, the present study aims to analyse the effect of microwave pyrolysis temperature (550, 600, and 650 °C) on the liquid

yield of sub-bituminous LRC, to determine the optimum operating temperature, and to evaluate the role of $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalysts in improving the quality of the resulting pyrolysis liquid product.

METHODE

This experimental research was conducted at the Energy Laboratory, Research Centre for Energy Materials, Nanotechnology and Materials Research Organisation, National Research and Innovation Agency (BRIN), B.J. Habibie Science and Technology Park, Serpong, South Tangerang, Indonesia.

The feedstock was sub-bituminous low-rank coal (LRC) from the Bobong Formation, North Taliabu Island, North Maluku, sieved to 16-mesh particle size. The catalysts were commercial TiO_2 and activated carbon, each combined with an $\text{Fe}_2(\text{SO}_4)_3$ receptor synthesised from iron waste (lathe and welding workshop scrap) reacted with H_2SO_4 solution. We used nitrogen gas (N_2) as an inert atmosphere to prevent oxidation during pyrolysis.

LRC was dried in an oven equipped with an oxygen blower at 105-110 °C and 40-60 psi for 12 hours, crushed, and sieved using a rotary vibrating screen to 16 mesh. Feedstock

characterisation included proximate analysis (moisture: ASTM D3173-17; ash: ASTM D3174-12; volatile matter: ASTM D3175-17; fixed carbon: ASTM D3172-13) and ultimate analysis (total sulfur: ASTM D4239-18; carbon/hydrogen/nitrogen: ASTM D5373-16; oxygen: ASTM D3176-15).

TiO_2 and activated carbon catalysts were calcined by heating 200 g of mineral overnight at 120 °C to remove bound moisture, storing for 12 hours in a desiccator, then calcining at 500 °C for 3 hours under an air flow rate of 1.2 L/h, followed by cooling under N_2 at the same flow rate to 50 °C. The $\text{Fe}_2(\text{SO}_4)_3$ receptor was synthesised by reacting 42 g of Fe powder with 50 mL H_2SO_4 in 250 mL distilled water at 75 °C until the Fe powder dissolved, after which the solution was cooled and filtered. The $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ catalysts were prepared by mixing 250 mL of FeSO_4 and 250 mL of 0.5 N H_2SO_4 , heating with stirring at 930 rpm to 90 °C, introducing 20 g of catalyst (TiO_2 or activated carbon) with an air flow of 4 L/min for 100 minutes at constant temperature, then filtering and oven-drying the product at 100 °C. The initial reaction of metallic Fe with H_2SO_4 yields ferrous sulfate (FeSO_4) in solution; the subsequent oxidation to the ferric form, $\text{Fe}_2(\text{SO}_4)_3$,

was promoted by the continuous air flow (4 L/min) introduced during the 90 °C impregnation step, which supplies dissolved oxygen to oxidize Fe^{2+} to Fe^{3+} . This acid-dissolution/air-oxidation route follows established procedures for preparing $\text{Fe}_2(\text{SO}_4)_3$ -based pyrolysis catalysts. The compound identity of the resulting Fe-sulfate phase was not independently confirmed by XRD or an equivalent structural technique in this study; the $\text{Fe}_2(\text{SO}_4)_3$ designation used throughout this paper is therefore based on the synthesis stoichiometry and established literature precedent rather than direct structural verification, and should be interpreted accordingly (see Study Limitations).

We performed pyrolysis using a microwave-assisted pyrolysis reactor equipped with a furnace, a distillation column with bubble-cap trays, a condenser, and a cooling system, powered by an Electrolux EMM2308X

microwave unit (800 W output, 220 V, 2.45 GHz magnetron frequency). LRC, catalyst, and receptor were weighed at a 2% w/w catalyst and 2% w/w receptor ratio relative to LRC and loaded into the reactor. Pyrolysis was carried out at three temperatures (550, 600, and 650 °C) and two reaction times (60 and 120 minutes) under N_2 atmosphere. The 550/600/650 °C values refer to the reactor setpoint controlled by the microwave unit's built-in temperature controller; this study did not separately log thermocouple placement, heating ramp rate, or nitrogen flow rate during the reaction (see Study Limitations). We separated the liquid product from each tray and measured its volume, while weighing the char. We further separated the liquid product and tar using a separating funnel and filter paper.

Product yields were calculated using Equations (1)–(3):

$$Y_{\text{Liquid}} = \frac{m_{\text{cairan}}}{m_{\text{feed}}} \times 100\% = \frac{m_{\text{tray I}} + m_{\text{tray II}} + m_{\text{tray III}} + m_{\text{tray end}}}{m_{\text{LRC}}} \times 100\% \quad (1)$$

$$Y_{\text{char}} = \frac{m_{\text{char}}}{m_{\text{feed}}} \times 100\% = \frac{m_{\text{char}}}{m_{\text{LRC}}} \times 100\% \quad (2)$$

$$Y_{\text{syngas}} = 100\% - Y_{\text{cairan}} - Y_{\text{char}} \quad (3)$$

Syngas yield (Equation 3) was obtained by mass-balance difference rather than direct gas-phase analysis, and therefore represents an aggregate of non-condensable gases together

with any unaccounted mass losses (e.g., handling losses or residual moisture). Liquid product characterisation was performed at the optimum condition (600 °C, 120

minutes) for both catalyst systems, comprising SEM analysis of LRC and char surface morphology, FTIR analysis for functional group identification, and GC-MS analysis for compound composition. Each temperature-time combination was tested once; all yield data were therefore analysed descriptively and presented in tables and figures to determine the optimum operating condition.

RESULT AND DISCUSSION

Feedstock Characterization

The sub-bituminous LRC used in this study, sourced from the Bobong Formation, North Taliabu Island, North Maluku, was characterised through proximate and ultimate analysis, as summarised in Table 1.

Table 1. Proximate and Ultimate Analysis of the Sub-Bituminous LRC

Parameter	Value (%)	Standard
Moisture (M)	6.54	ASTM D3173-17
Ash (A)	11.86	ASTM D3174-12
Volatile Matter (V)	43.56	ASTM D3175-17
Fixed Carbon (FC)	38.05	ASTM D3172-13
Carbon (C)	74.75	ASTM D5373-16
Hydrogen (H)	6.87	ASTM D5373-16
Nitrogen (N)	0.76	ASTM D5373-16
Sulfur (S)	5.40	ASTM D4239-18
Oxygen (O)	12.21	ASTM D3176-15

The high volatile matter (43.56%), well above the low-rank coal threshold (>30%), indicates a substantial potential for thermal conversion within the 550–650 °C pyrolysis range. The relatively high oxygen content (12.21%) points to

high thermal reactivity, as oxygenated functional groups such as phenols, ketones, and ethers degrade readily at moderate pyrolysis temperatures. The comparatively high sulfur content (5.40%) provides the technical basis for employing $\text{Fe}_2(\text{SO}_4)_3$, which,

based on literature precedent, is expected to function not only as a cracking accelerator but also as a sulfur receptor that stabilises the liquid product against excess sulfur contamination (Zhou et al., 2019); this study did not perform a direct sulfur-balance measurement to confirm the receptor function.

Effect of Temperature and Catalyst on Liquid Yield

Table 2 presents the liquid, char, and syngas yields obtained for both catalyst systems across the three temperatures and two reaction times, while Figure 1 illustrates the corresponding temperature trends. Each value represents a single-run measurement.

Table 2. Product Yield of Microwave Pyrolysis with $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ Catalysts

Temp. (°C)	Time (min)	Liquid- TiO2 (%)	Liquid- AC (%)	Char- TiO2 (%)	Char- AC (%)	Syngas- TiO2 (%)	Syngas- AC (%)
550	60	34.0	35.5	46.5	47.0	19.5	17.5
550	120	36.5	38.5	44.5	44.5	19.0	17.0
600	60	38.0	43.0	40.5	37.5	21.5	19.5
600	120	40.0	46.5	39.0	34.5	21.0	19.0
650	60	36.5	41.0	41.5	38.5	22.0	20.5
650	120	37.5	44.0	40.5	36.5	22.0	19.5

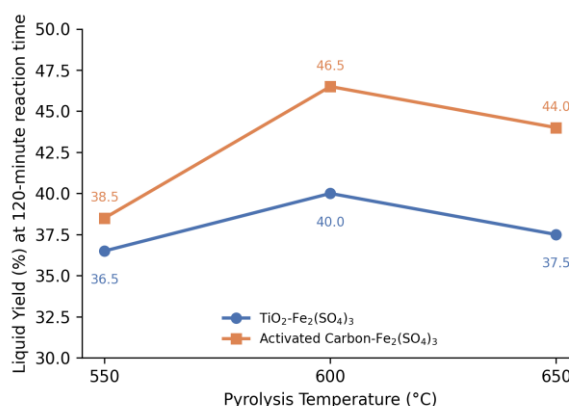


Figure 1. Liquid Yield as a Function of Temperature for $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ Catalysts at 120-Minute Reaction Time.

Values are single-run measurements; error bars are not shown as replicate runs were not performed (see Study Limitations). For both catalysts, liquid yield increased from 550 to 600 °C and declined at 650 °C. With $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$, the yield rose from 34.0% to 38.0% (60 min) and from 36.5% to 40.0% (120 min) between 550 and 600 °C, then fell to 36.5–37.5% at 650 °C. The activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ system followed the same pattern but at consistently higher values, peaking at 46.5% (600 °C, 120 min) versus 40.0% for $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ under identical conditions—an absolute difference of 6.5 percentage points, equivalent to a 16.25% relative improvement. This rise-then-fall trend reflects the balance between primary and secondary cracking: at 600 °C, thermal energy is sufficient to cleave C-C and C-O bonds in the coal macromolecule, maximising tar and liquid formation, whereas at 650 °C, intensified secondary cracking

reconverts part of the liquid into char and light gas, consistent with the findings of Ruslan et al. (2025) that temperatures above 600 °C in microwave pyrolysis promote vapour reforming and secondary cracking that reduce liquid yield.

Extending the reaction time from 60 to 120 minutes increased liquid yield by 2–2.5% for $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and by 3–3.5% for activated carbon- $\text{Fe}_2(\text{SO}_4)_3$, a smaller effect than temperature, confirming temperature as the dominant operating parameter. The larger time-dependent gain for activated carbon may be attributed to its much higher specific surface area; activated carbon typically exhibits BET surface areas of 500–1500 m^2/g versus 50–150 m^2/g for TiO_2 (Sardi et al., 2022). Mechanistically, TiO_2 behaves as a Lewis acid catalyst that accelerates primary cracking of long hydrocarbon chains into lower-molecular-weight, condensable species (Z. Zhang et al., 2013), while the larger active-site density of

activated carbon promotes more extensive cracking and reforming of volatile matter released from the coal matrix (Sardi et al., 2022). BET measurements were not performed on the specific catalyst batches used in this study, so this explanation should be regarded as consistent with, rather than directly confirmed by, the present dataset (see Study Limitations). Notably, the highest liquid yield (46.5%) numerically exceeds the initial LRC volatile matter content (43.56%, Table 1). This apparent excess should be interpreted with caution: the proximate analysis (Table 1) was performed on an as-received basis, whereas the liquid yield in Table 2 was calculated relative to the as-fed LRC mass without normalising to the same analytical basis, and the collected liquid may also include condensed moisture and other

components not derived directly from volatile matter. The apparent liquid yield exceeding the measured volatile-matter fraction may therefore reflect differences in analytical basis and/or the incorporation of condensed water and secondary reaction products, rather than definitive proof of a specific reaction mechanism between volatile fragments and moisture vapour. Based on the complete dataset in Table 2, the optimum operating condition for maximising liquid yield is 600 °C and 120 minutes using the activated carbon-Fe₂(SO₄)₃ catalyst.

Functional Group

Characterisation (FTIR)

Table 3 summarises the FTIR spectra of the liquid product obtained under the optimum conditions (600 °C, 120 min) for both catalyst systems.

Table 3. FTIR Functional Group Identification of the Liquid Product

Wavenumber (cm ⁻¹)	Functional Group	Intensity, TiO ₂ - Fe ₂ (SO ₄) ₃	Intensity, AC- Fe ₂ (SO ₄) ₃	Assigned Compound
3300	O-H (phenolic, H- bonded)	Weak- Moderate	Weak	Phenol
2583	S-H (thiol)	Moderate	Strong	Sulfur- containing compound (thiol/mercaptan)

Wavenumber (cm-1)	Functional Group	Intensity, TiO2- Fe ₂ (SO ₄) ₃	Intensity, AC- Fe ₂ (SO ₄) ₃	Assigned Compound
1675	Aromatic C=C	Moderate	Strong	Benzene, naphthalene
625	C-O	Moderate	Strong	Ether, phenol

The weak O-H band near 3300 cm-1 in both catalyst systems indicates a relatively low concentration of free hydroxyl (phenolic/alcoholic) groups in the liquid product compared with the other functional groups detected, consistent with the trend reported by Sardi et al. (2022) for a similar catalyst system. In contrast, the S-H stretching band near 2583 cm-1 (Lin-Vien et al., 1991), together with the aromatic C=C (1675 cm-1) and C-O (625 cm-1) bands, is markedly stronger for activated carbon-Fe₂(SO₄)₃, indicating a higher concentration of sulfur-containing and aromatic species and corroborating the higher liquid yield

obtained with this catalyst (46.5% versus 40.0%, Table 2). These spectral features are consistent with a liquid product containing phenols, sulfur-containing compounds, and aromatic hydrocarbons, in line with the coal's sulfur (5.40%) and oxygen (12.21%) content (Table 1), and are consistent with the aromatic sulfonate compound class subsequently identified by GC-MS (Table 4).

Surface Morphology (SEM)

SEM analysis compared the surface morphology of the raw LRC with char from both catalyst systems at the optimum temperature (600 °C), as shown in Figure 2.

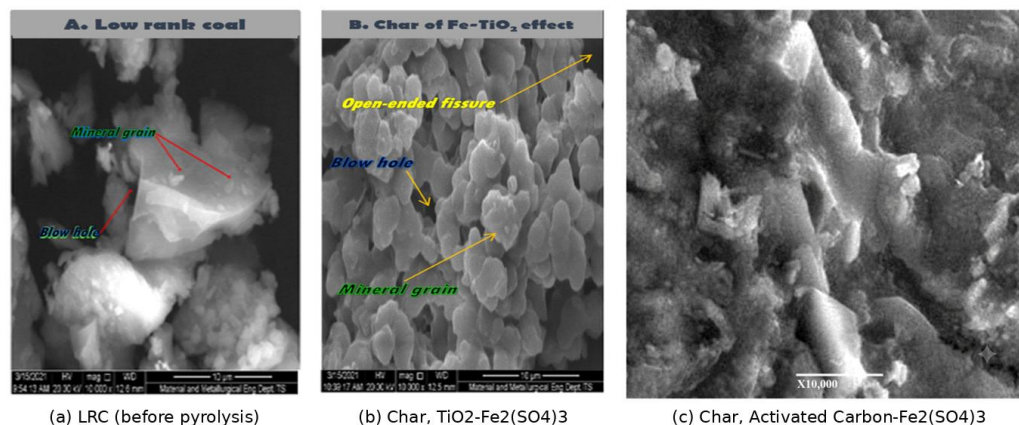


Figure 2. SEM Morphology of (a) Raw LRC, (b) Char from $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$, and (c) Char from Activated Carbon- $\text{Fe}_2(\text{SO}_4)_3$ (600 °C, 10,000× Magnification)

The raw LRC (Figure 2a) shows a loose surface with open pores and visible mineral grains, with a representative feature size of approximately 150 μm estimated from visual inspection. After pyrolysis at 600 °C, char from both catalysts (Figures 2b-c) shows visibly larger representative feature sizes—approximately 215 μm for $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ and 205 μm for activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ —consistent with interparticle agglomeration during devolatilization, in line with the trend reported by (Sardi et al. 2022) for a comparable catalyst system. These values are single-image visual estimates rather than statistically averaged particle-size distributions (see Study Limitations). Blow-hole

structures on both chars develop into open-ended fissures, consistent with intensive volatile release at 600 °C. The activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ char displays a comparatively denser, more homogeneous surface with more evenly distributed blow holes than the $\text{Fe}_2(\text{SO}_4)_3$ char, consistent with its higher liquid yield under the same conditions.

Chemical Composition (GC-MS)

We performed GC-MS analysis under the optimum conditions (600 °C, 120 min) for both catalysts. We grouped individual compounds identified in the original chromatograms by chemical class, as summarised in Table 4.

Table 4. GC-MS Compound Classes in the Liquid Product at the Optimum Condition (600 °C, 120 min)

Compound Class	Area, TiO ₂ -Fe ₂ (SO ₄) ₃ (%)	Area, AC-Fe ₂ (SO ₄) ₃ (%)
Phenolics (phenol and methylated derivatives)	59.68	78.54
Aromatic sulfonate (benzenesulfonic acid deriv.)	12.58	13.83
Carboxylic acids	9.10	n.d.
N-aromatic compounds	7.14	n.d.
Ether/alkene	8.36	n.d.
Cycloalkane	3.13	n.d.
Cyclic alkane/amine/ketone (minor)	n.d.	5.66

n.d. = not detected as a significant peak area in the corresponding chromatogram.

Phenolic compounds dominate the liquid product under optimal conditions for both catalyst systems, accounting for 59.68% of the total peak area for TiO₂-Fe₂(SO₄)₃ and 78.54% for activated carbon-Fe₂(SO₄)₃. This phenolic dominance is consistent with the coal's oxygen content (12.21%, Table 1) and aligns with Sardi et al. (2022) and Ruslan et al. (2025), who reported similar Fe₂(SO₄)₃-based catalyst systems yielding phenol-dominated liquid products from LRC, given that lignin-

related structures in low-rank coal are the primary precursor of phenolic species through ether- and ester-bond cleavage. Habibi et al. (2025) also reported comparable phenolic dominance in pyrolysis oil from an oxygen-rich lignocellulosic feedstock (rice husk), supporting the generality of this pathway across oxygenated carbonaceous feedstocks. Activated carbon-Fe₂(SO₄)₃ produced a substantially higher total phenolic fraction (78.54%) than TiO₂-Fe₂(SO₄)₃ (59.68%), whereas the TiO₂ system showed a broader compound distribution, including carboxylic acids (9.10%) and N-

aromatic compounds (7.14%) that were not significant in the activated carbon product. This suggests that activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ has higher selectivity toward phenolic compound formation, likely because its pore structure favours directed deoxygenation, whereas the Lewis acid sites on TiO_2 promote a more diverse cracking pathway (Z. Zhang et al., 2013).

Overall, the FTIR, SEM, and GC-MS characterisation results are complementary: FTIR and GC-MS both point to a higher concentration of aromatic and sulfur/oxygen-containing species in the activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ liquid product, while SEM shows a correspondingly denser char morphology for the same system. Together, these independent lines of evidence support the conclusion that activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ provides a consistent performance advantage over TiO_2 - $\text{Fe}_2(\text{SO}_4)_3$ for converting LRC into a phenol-rich pyrolysis liquid. These findings complement Ruslan et al. (2025) on Fe- TiO_2 -based catalyst combinations by providing systematic optimum-temperature data across the 550–650 °C range, along with a direct comparison against an activated-carbon-based catalyst system.

Study Limitations

Several aspects of the experimental design constrain the interpretation of

these results and are stated explicitly here for transparency:

- No catalyst-free (blank) pyrolysis run was included; consequently, the fractional contribution of the catalysts relative to non-catalytic thermal decomposition of LRC could not be isolated, and the reported yield advantage of the catalysed runs should be read against this baseline gap.
- The $\text{Fe}_2(\text{SO}_4)_3$ receptor's compound identity was inferred from synthesis stoichiometry and air-mediated $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ oxidation rather than confirmed by XRD or an equivalent structural technique.
- Reported specific-surface-area values for TiO_2 and activated carbon are literature-typical ranges, not BET measurements performed on the exact catalyst batches used in this study.
- Each temperature-time condition was run once; results are reported as single-point, descriptive measurements without replicate-based error bars or formal statistical testing (e.g., ANOVA).
- Syngas yield (Equation 3) was obtained by mass-balance difference rather than direct gas-phase analysis.
- SEM particle/feature sizes represent visually representative estimates from the available micrographs rather than a statistically averaged size distribution.

- GC-MS characterisation was performed only at the optimum condition (600 °C, 120 min) for both catalysts; compositional trends at other temperatures or the 60-minute reaction time were not assessed.

These limitations do not undermine the central comparative finding—that activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ consistently outperforms $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ under the tested conditions—but they do bound the mechanistic and quantitative claims that can be drawn from a single-run, exploratory dataset. Future work should incorporate a no-catalyst control, replicate runs with statistical analysis, BET surface-area characterisation of the specific catalyst batches, and direct structural confirmation of the $\text{Fe}_2(\text{SO}_4)_3$ phase.

CONCLUSION

Microwave pyrolysis temperature affected the liquid yield of low-rank coal, increasing from 550 to 600 °C and declining at 650 °C; the optimum condition was 600 °C for 120 min. Because the design was single-run and descriptive, this pattern is reported as an observed trend rather than a statistically confirmed effect. Under the optimum condition, activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ achieved the highest liquid yield (46.5%), exceeding $\text{TiO}_2\text{-Fe}_2(\text{SO}_4)_3$ (40.0%), consistent with its larger specific surface area. GC-MS confirmed that phenolic compounds dominated the liquid product for both catalysts (59.68% and 78.54%, respectively), while SEM and FTIR provided complementary morphological and functional-group evidence for this

phenol-rich product rather than independent confirmation. Both catalysts are consistent with the cracking-accelerator and sulfur-receptor role reported in the literature for $\text{Fe}_2(\text{SO}_4)_3$ -based systems, though sulfur-balance measurements were not performed to confirm this function. Overall, activated carbon- $\text{Fe}_2(\text{SO}_4)_3$ offers superior performance for producing a phenol-rich pyrolysis liquid from low-rank coal, within the exploratory scope of this study.

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