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ORIGINAL RESEARCH ARTICLE

Valorization and physicochemical characterization of municipal solid waste gasification tar derived aliphatic hydrocarbon-rich oils

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ABSTRACT

BACKGROUND AND OBJECTIVES: Municipal solid waste gasification generates tar as a persistent by-product, posing operational and environmental challenges due to its viscosity, instability, and high content of various hydrocarbons. Previous studies demonstrated that the principal constituents of tar were predominantly aliphatic hydrocarbon compounds. The study objectives were to investigate the valorization potential and evaluate the physicochemical properties of the oil fraction derived from tar waste through pyrolysis process from gasification plant of Surakarta landfill, Indonesia.

METHODS: Conversion of tar into aliphatic hydrocarbon-rich oils using a sequential re-pyrolysis method at temperatures ranging from 350–700 degrees Celsius. The physical properties of the pyrolysis products, specifically temperature, viscosity, and density, were determined, while their chemical compositions were evaluated using gas chromatography and infrared spectroscopy. The results of the physicochemical tests were then analyzed and evaluated with those of commercial oil products.

FINDINGS: Pyrolysis produced three liquid fractions based on the sequential re- pyrolysis: tar pyrolysis 1, 2, and 3. Liquid yields of approximately 65–70 weight percent at 500–550 degrees Celsius. Mass spectrometry analysis revealed aliphatic hydrocarbons (alkane–alkene) contents of 86.65, 45.58, and 46.76 percent in tar pyrolysis oil-1, 2, and 3 samples. The identified aliphatic hydrocarbons ranged from 8–21, 12–43, and 9–20 carbon atoms in the respective fractions. The infrared spectra consistently displayed characteristic aliphatic carbon-hydrogen stretching vibrations, thereby confirming that the resulting products are rich in aliphatic hydrocarbons. The produced oils exhibited densities of 801.3–875.4 kilograms per cubic meter and viscosities of 2.304–2.956 centistokes at 40 degrees Celsius, indicating potential for liquid-fuel and hydrocarbon-material applications, although the relatively low flash point of 40–62 degrees celsius requires further upgrading for improved product stability.

CONCLUSION: Sequential re-pyrolysis demonstrated the potential to convert tar into aliphatic hydrocarbon-rich oils, with tar pyrolysis oil-3 showing the highest aliphatic hydrocarbon content (86.65 percent) and a C8–C21 carbon-chain range. The findings demonstrate that tar pyrolysis oil-3 exhibits the highest aliphatic content among the evaluated products, suggesting its viability as an intermediate hydrocarbon feedstock for subsequent upgrading. Further fractionation, upgrading, and scale-up studies are required to determine its suitability for specific fuel or hydrocarbon-material applications.

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INTRODUCTION

An escalating municipal solid waste (MSW) crisis is currently being experienced in Indonesia. Approximately 43.458 million tons (Mt) of municipal solid waste were generated in 2023, with an average annual increase of 2–3 percent (%) attributed to urbanization, population growth, and changing consumption patterns (KLH, 2023). Urban centers such as Jakarta, Surabaya, and Bandung contribute significantly to this problem, generating over 1,500–2,500 tons per day (t/d) of waste each city (Himawanto, 2021). Waste sorting at the source and landfill management have been continuously pursued, yet more than 50% of waste still ends up in landfills. Landfill overburdening exerts significant adverse environmental impacts; furthermore, excessive reliance on landfilling creates spatial constraints and leads to the depletion of valuable energy resources embedded within municipal waste streams (Khan *et al*., 2022). Waste management challenges are increasingly being addressed through waste-to-energy (WtE) technology, while greater energy independence is simultaneously being promoted. One such technology, gasification, is increasingly gaining attention as an integrated solution for managing large amounts of waste while recovering energy (Wang *et al.,* 2023a). The national strategic framework incorporates the development of WtE facilities via eco-friendly technologies, aiming to expedite landfill waste management across 12 major urban centers through thermal applications pursuant to Presidential Regulation No. 35 of 2018. The thermal conversion of waste into electrical energy using gasification technology has been implemented in the city of Surakarta, with a processing capacity of 545 t/d and an electrical output of 8 MegaWatts (MW) (Sonjaya, 2021; Wasita, 2023). MSW gasification has emerged as a promising thermochemical technology for converting heterogeneous municipal waste into valuable energy. The primary product of gasification is synthetic gas (syngas), consisting of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), which is then converted into electricity. This methodological approach corresponds with the expanding global prioritization of sustainable WtE systems, which serve to curtail landfill diversion volumes while efficiently converting waste streams into secondary energy sources (Im-Orb *et al.*, 2016; Niu *et al.*, 2013). However, one of the most persistent and technical issues in MSW gasification is the formation of tar, a complex mixture of heavy hydrocarbons. Previous studies concerning tar generation from waste gasification indicate that the condensate consists primarily of polycyclic aromatic hydrocarbons, including benzene, naphthalene, and toluene (Blanco *et al.*, 2012; Etutu *et al.*, 2016; Pio *et al.*, 2021; Tursunov *et al.*, 2020), as well as aliphatic hydrocarbons including alkanes and alkenes (Chancelice *et al*., 2020; Ni *et al.*, 2013). Tar typically exhibits physical properties characterized as a viscous liquid–solid material, dark brown to black in color, and possessing a distinctive odor (Huang *et al*., 2015). Tar production not only reduces gasification efficiency but also causes operational issues such as pipeline blockages, equipment fouling, reduces the quality of syngas, and catalyst deactivation, ultimately increasing system downtime and maintenance costs (Chan *et al.*, 2020; Pio *et al.*, 2021; Rios *et al.*, 2018). Tar generation occurs during the pyrolysis and partial oxidation phases of the gasification, wherein MSW constituents, including food waste, paper, plastic, and biomass, undergoes thermochemical degradation under sub-stoichiometric oxygen environments (Qin *et al*., 2010). At lower temperatures below 1000 degrees Celsius (°C), these volatile intermediate compounds fail to completely convert into light gases, leading to the polymerization and condensation of heavier hydrocarbons. This phenomenon is predominantly observed in fixed-bed reactors, which are characterized by lower operating temperatures and nonuniform thermal distribution relative to fluidized-bed or fixed-bed

alternatives (Čespiva *et al.*, 2020; Pio *et al.*, 2021). Other influencing factors include feedstock composition, residence time, heating rate, and the presence or absence of a catalyst. The incorporation of cracking catalysts, including dolomite, olivine, or nickel-based formulations, substantially diminishes tar formation by accelerating secondary gas-phase reactions (Anis and Zainal, 2011). Tar has a fairly high calorific value, ranging from 30 to 40 megajoule per kilogram (MJ/kg). Tar has the potential to be used as a valuable alternative energy source through thermal cracking and compound purification. Tar contains fuel compounds such as paraffin and olefin hydrocarbons (Ni *et al*., 2013; Satyro *et al*., 2023). In a previous study, total paraffin–olefin (alkane–alkene) compounds of 64.80 weight (wt) % in the solid tar extract and 65.98 wt% in the liquid tar extract were reported for tar produced from waste gasification at the Putri Cempo Surakarta Landfill (Ridwan *et al*., 2026). These compounds exhibit strong potential as alternative aliphatic hydrocarbon-based oils for value-added applications, provided that their processing methodologies align with circular economy principles in WtE management (Satyro *et al*., 2023). Thermal cracking is an effective method for breaking complex hydrocarbon bonds (Anis and Zainal, 2011). Based on the abundance of this potential, tar is converted into aliphatic-rich hydrocarbons oil fraction contained alkane-alkene (paraffin-olefin) compound. Liquid aliphatic hydrocarbon condensate is successfully recovered by regulating the system temperature to match the boiling point range of alkane-alkene fractions, utilizing high-temperature thermal cracking as the primary method for converting tar into aliphatic hydrocarbon oil (Niu *et al*., 2024). Temperature variation analysis is employed to determine the optimal paraffin yield percentage (Drissi *et al*., 2019). The resulting oil fraction is then subjected to specification testing and compared with commercial oil products or materials. This study focuses on the conversion of tar and the analysis of liquid fraction products. In parallel, significant quantities of tar are continuously generated as a by-product of MSW gasification at the Putri Cempo Landfill in Surakarta, Indonesia, with a tar yield of approximately 0.7 wt% (Sonjaya, 2021). To address this gap, this study investigates the conversion of real MSW-derived tar into oil light aliphatic hydrocarbon fractions through a sequential pyrolysis process. In contrast to prior investigations dependent on model compounds, this study examines actual tar recovered from an operational landfill gasification facility, thereby offering practical insights under realistic operational conditions. The novelty of this study lies in three key aspects: i) the use of real landfill-derived tar as feedstock, enabling potential of tar upgrading under practical operating conditions; ii) the application of sequential pyrolysis to selectively enhance light aliphatic hydrocarbon fractions; and iii) potential application regarding evaluate the physicochemical analysis of light aliphatic hydrocarbon fractions. Integrating tar valorization technology with MSW gasification systems can potentially mitigate environmental impacts while advancing responsible waste management practices. The findings of this study can serve as a basis for future evidence-based policy-making regarding the responsible implementation of waste-to-energy processes at the Surakarta Landfill gasification plant in Indonesia. This study strives to realize of sustainable development goals (SDGs), particularly SDGs 7 (affordable and clean energy), SDGs 9 (industry, innovation and infrastructure), and SDGs 12 (responsible consumption and production). This study aims to investigate the valorization of tar derived from MSW gasification at the Putri Cempo landfill into light aliphatic-rich hydrocarbon oil fractions through sequential re-pyrolysis process, as well as to evaluate its physicochemical properties. This study was carried out at the MSW gasification plant at Putri Cempo Landfill, Surakarta and environmental engineering laboratory of Univeristas Sebelas Maret, Surakarta, Indonesia during the period of 2025–2026.

MATERIALS AND METHODS

Material preparation

The material used for conversion into light aliphatic hydrocarbon-*rich* oil fractions was tar, which was generated as a by-product of the MSW gasification process at Putri Cempo Landfill, Surakarta, Indonesia. The landfill was designated as the case study site, wherein the generated tar was maintained within a covered storage facility featuring a dedicated collection basin. Approximately 128,000 liters (L) of tar based on storage capacity, had accumulated at the source location and was expected to increase with the continuation of large-scale MSW gasification operations. Tar samples were collected from the by-product storage tank via grab sampling method (Fig. 1). The tar was continuously generated during steady-state operations utilizing a gasification feedstock characterized by consistent properties. Prior to thermal conversion, the collected raw tar was homogenized by mechanical stirring at 300 revolutions per minute (rpm) for 10–15 minutes (min) to obtain a more uniform viscosity and composition (Abatzoglou *et al.,* 2000). The homogenized tar was subsequently used as the feedstock for the sequential pyrolysis process.

Conversion of tar through sequential re-pyrolysis

Prior to thermal conversion, the moisture content of the tar was reduced directly under oxygen-limited conditions in a sealed fixed-bed reactor. Approximately 1000 grams (g) of raw tar was loaded into a crucible and positioned inside the reactor. Subsequently, the reactor was hermetically sealed to prevent the ingress of atmospheric oxygen (Dabai *et al*., 2014). The loaded tar was initially heated to 100–150 °C and maintained at this temperature for 30–60 min. to facilitate the evaporation and removal of residual moisture. After drying, the tar was heated at 10 degrees Celsius per minute (°C/min) to target temperatures ranging from 350 to 700 °C (Abatzoglou *et al*., 2000). Pyrolysis was performed under oxygen-limited conditions in a sealed fixed-bed reactor in the absence of an external carrier or purge gas, with each target temperature maintained for 30 min. Sequential re-pyrolysis was implemented to continuously enhance volatilization and thermal cracking, thereby generating lighter hydrocarbon fractions and condensable liquid products (Fig. 2). The temperature range was selected to evaluate progressive thermal cracking, with 350–450 °C facilitating the volatilization of lighter constituents and temperatures exceeding 600 °C promoting secondary cracking and C–C bond scission (Zhou *et al*., 2019; Drissi *et al*., 2019). The vapors generated during pyrolysis were directed through a continuously flowing cooling-water condensation system, where the condensable products were cooled and recovered as liquid fractions. The sequential re-pyrolysis approach was implemented to assess the thermal conversion of tar into lighter hydrocarbon fractions and to identify the temperature range responsible for the generation of aliphatic-rich liquid products (Wang *et al.,* 2025). The pyrolysis experiments were conducted in duplicate at each temperature re-pyrolysis to improve the reliability and reproducibility of the obtained product yields light hydrocarbon. Furthermore, the re-pyrolysis operation facilitated the generation of distinct heavy and light fractions, which subsequently underwent comparative physicochemical and compositional evaluations (Gholami *et al*., 2021).

Physicochemical analysis of oil fraction

The physical properties analyzed included density, kinematic viscosity, flash point, and pour point (ASTM International, 2021). The chemical compositions were characterized using gas chromatography–mass spectrometry (GC–MS) and Fourier-transform infrared spectroscopy (FT-IR), respectively (Table 1). The chemical composition of the liquid products was characterized using a Shimadzu GCMS-QP2010 SE system with a column temperature range of 50–270 °C, a heating rate of 10 °C/min, and helium as



Fig. 1: Tar (by-product) MSW gasification in Putri Cempo landfill, Surakarta

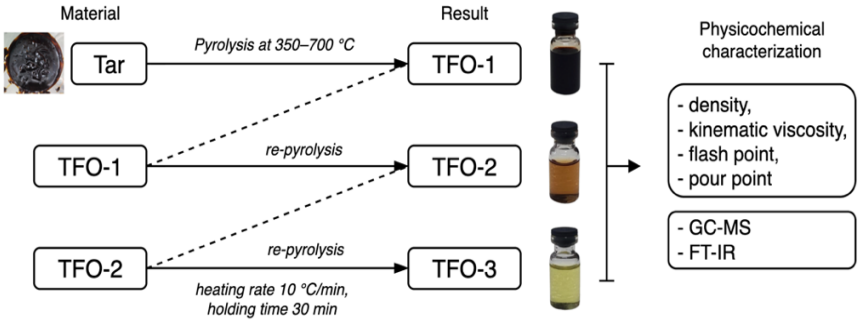

Fig. 2: Schematic diagram of the sequential re-pyrolysis process for tar-derived products and subsequent physicochemical characterization (Note: Tar Pyrolysis Oil-1 (TFO-1), TFO-2, and TFO-3)

Table 1: Physicochemical characterization parameters and analytical methods

Parameter	Unit	Method	Analytical principle
Physical testing			
Density	Kilogram per cubic meter (kg/m^3)	ASTM D4052-22	Oscillating U-tube
Kinematic viscosity	Centistokes (cSt)	ASTM D445-23	Capillary flow-time
Flash point	°C	ASTM D93-20	Pensky–Martens closed cup
Pour point	°C	ASTM D5853-17a	Controlled cooling and flowability
Chemical testing			
Chemical (Organic volatil) compound	Peak area (%)	GC-MS/MS	GC separation and MS/MS detection
Chemical bonds	Wavenumber /cm	FT-IR/IR	Infrared molecular vibration

the carrier gas at 1.7 milliliter per minute (mL/min). Compounds were identified by comparison with mass spectral library matching, and their relative peak areas were utilized to evaluate hydrocarbon fraction distributions. Functional groups were characterized using a Thermo Scientific Nicolet iS10 FT-IR spectrometer with KBr sample preparation. The resulting spectra were evaluated according to characteristic absorption bands to identify major chemical bonds and functional groups (Wang *et al*., 2023b).

RESULTS AND DISCUSSION

This study investigated the potential valorization of MSW gasification tar from the Putri Cempo Landfill, Surakarta, Indonesia, through sequential re-pyrolysis to obtain aliphatic hydrocarbon-rich oil fractions. The physicochemical and chemical properties of the resulting liquid products were assessed to determine the effects of pyrolysis temperature and successive re-pyrolysis stages. Furthermore, these findings offer valuable insights into the prospective recovery of distinct heavy and

lighter aliphatic hydrocarbon fractions from gasification-derived tar as a secondary resource.

Existing characteristics of tar from gasification plant, Surakarta landfill

The main product in the gasification of MSW pellet feedstock at Putri Cempo Landfill with a fixed bed downdraft gasifier produces syngas with a composition of CO (24.78%), CO_2 (18.65%), H_2 (15.6%), and CH_4 (4.06%) at an air fuel ratio (AFR) of 0.3 at 600–750 ^oC (Sonjaya, 2021). Downdraft fixed-bed gasifiers typically generate significantly lower tar yields than updraft and fluidized-bed configurations. The tar examined in this study was derived from steady-state gasification operations, with the RDF maintaining consistent characteristics prior to entering the gasifier (Sonjaya, 2021). Gravimetric tar yields as low as 0.7 wt% have been reported in pilot-scale and parametric studies under optimal superficial velocity conditions and specific reactor configurations (Bhavanam and Sastry, 2011). Tar management at the Surakarta landfill is currently handled through large storage ponds. Moreover, tar frequently deposits within system ducts, pipelines, and associated equipment, as its susceptibility to low-temperature cooling and solidification leads to severe operational blockages (Rakesh and Dasappa, 2018). A tar yield of 0.7 wt% is applied to the gasification of 545 t/d or 545,000 kilograms per day (kg/d) of waste at the Surakarta Landfill, representing a low-to-medium value commonly reported for fixed-bed downdraft reactors processing municipal solid waste under stable operating conditions (Bhavanam and Sastry, 2011). Based on this fraction, the estimated daily tar production reaches 3,815 kg/d, indicating that even at relatively low yields, tar accumulation from municipa-scale operations generates substantial condensate volumes, thereby supporting the technical feasibility of evaluating its potential as an upgrading feedstock for paraffinic (Bhavanam and Sastry, 2011). Based on the analysis of tar compounds in Surakarta landfill using gas chromatography–mass spectrometry (GC-MS), the majority of the content is dominated by aliphatic hydrocarbons in the form of alkanes and alkenes (Table 2). Alkanes and alkenes and their derivatives have been identified as hydrocarbons with carbon atom (C) lengths ≥ C_{13-33} (Ridwan *et al.,* 2026). Previous studies have established that aliphatic hydrocarbon, including paraffins and olefins, are prevalent within tar, originating from the thermal degradation of lignocellulose and complex hydrocarbon compounds during pyrolysis or carbonization (Huang *et al.*, 2015). Other detected compounds were predominantly derivatives of aliphatic hydrocarbons, including alcohols, carboxylic acids, and ethers. In contrast, the proportion of aromatic compounds identified was very low (Table 2). This finding provides an initial basis for further thermal conversion through sequential re-pyrolysis, enabling the selective transformation of heavier hydrocarbon components into lighter aliphatic-rich hydrocarbons oil fractions.

Field observations at Putri Cempo fall within this range. To provide a conservative but realistic assessment, the operational tar formation is approximately at 0.7 wt% (Sonjaya, 2021). Based on the waste gasification process that produces and its associated tar yield, the daily tar production of the gasification plant at the Surakarta landfill is calculated as shown in Eq. 1 (Wang *et al*., 2023a):

$$M_{tar} = M_{msw} \times Y_{tar} \quad (1)$$

Where: M_{tar} tar formation (kg/d); M_{msw} MSW/feed stock (kg/d); Y_{tar} tar yield (kg/kg).

$$M_{tar} = 545{,}000 \text{ kg/d} \times 0.007$$
$$M_{tar} = 3{,}815 \text{ kg/d}$$

Conversion of tar into oil fraction

Sequential re-pyrolysis successfully converted a portion of these heavy molecules into lighter condensable oils. During subsequent thermal treatment, these heavy constituents undergo a

Table 2: Distribution of compounds in tar from MSW Gasification, Surakarta landfill (Ridwan *et al*., 2026)

Compound group	Tar extract		
	Ethyl acetate (%)	Hexane (%)	Heptane (%)
Paraffin (alkane)	22.96	46.37	55.42
Olefin (alkene)	00.00	18.43	10.56
Subtotal aliphatic hydrocarbon	22.96	64.80	65.98
Alcohol	19.29	25.90	31.30
Carboxilic acid	42.08	6.39	-
Aromatic	8.92	2.93	-
Eter	-	-	2.72
Keton	6.76	-	-
Total	100.00	100.00	100.00

progression of volatilization, thermal cracking, dealkylation, and secondary reactions, resulting in continuous shifts in the molecular-weight distribution of the final products (Abatzoglou *et al.,* 2000). Previous studies indicates that elevating thermal severity facilitates the transformation of heavier tar compounds into lighter condensable hydrocarbons, whereas excessive severity can simultaneously accelerate secondary polymerization and char formation (Evans and Milne, 1998). In the present study, sequential re-pyrolysis was therefore applied to promote controlled conversion of the heavy tar matrix into lighter condensable oil fractions while allowing the temperature-dependent evolution of the products to be evaluated. Prior to primary pyrolysis, the raw tar underwent gradual thermal conditioning to minimize the impact of residual moisture. The initial heating step was conducted below approximately 100–120 °C to facilitate the evaporation of physically entrained water while minimizing the occurrence of significant thermal decomposition. This conditioning step was particularly critical because the presence of moisture within the highly viscous tar matrix can significantly affect heat transfer, vapor generation, and the stability of the liquid-phase during subsequent heating. After moisture removal, the temperature was progressively increased to approximately 150–250 °C to facilitate the release of readily volatile constituents before the main cracking reactions occurred at higher temperatures. This stage as a preliminary devolatilization step that stabilizes the feedstock and promotes more consistent thermal conversion (Abatzoglou *et al.,* 2000). Sequential re-pyrolysis was resulting in three liquid fractions representing TPO-1, 2, and 3 (Fig. 3). This re-pyrolysis configuration was engineered to progressively elevate the thermal severity imposed on the tar, thereby promoting the conversion of high-molecular-weight hydrocarbons into lighter condensable fractions. At the lower temperature range, approximately 350–450 °C, the process primarily promoted the volatilization of relatively light and thermally labile constituents, while a considerable proportion of the heavier hydrocarbon matrix remained unconverted. Increasing the pyrolysis temperature enhanced thermal cracking and promoted the cleavage of C–C bonds within the heavier hydrocarbon structures, thereby increasing the formation of lower-molecular-weight vapors that could subsequently be recovered as condensable liquids. In the intermediate temperature range of approximately 500–550 °C, enhanced formation of condensable liquid products is achieved, indicating an optimal balance between heavy tar conversion and the preservation of hydrocarbons within their condensation threshold. At higher temperatures, particularly above 600 °C, more severe secondary cracking may occur, causing a greater fraction of the hydrocarbons to undergo further decomposition into non-condensable gases and other secondary products. Comparable temperature-dependent behavior has been documented during the thermal conversion of

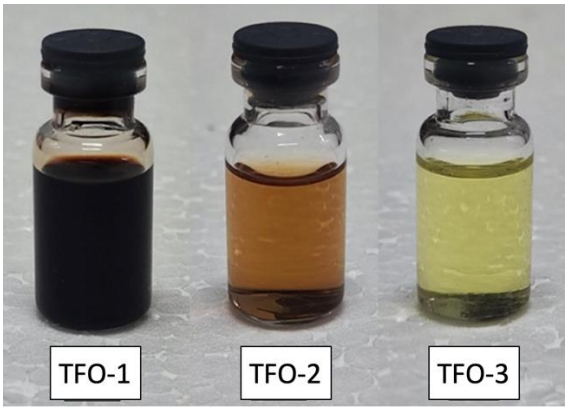

Fig. 3: Tar Pyrolysis Oil (TFO) from the tar sequential re-pyrolysis process (Note: Tar Pyrolysis Oil-1 (TFO-1), TFO-2, and TFO-3)

complex tar and heavy hydrocarbon matrices, wherein elevated temperatures drive both primary cracking and ensuing secondary reactions (Aboelela *et al*., 2023). A favorable temperature range for condensable liquid recovery was observed at 500–550 °C, where liquid production remained relatively high before greater gas-phase conversion occurred at higher temperatures. This trend is consistent with thermal cracking behavior documented for hydrocarbon systems; wherein intermediate temperatures can favor liquid formation while restricting excessive conversion into gaseous products. The implementation of a staged heating strategy enabled precise control over tar thermal conversion across successive temperature ranges, thereby mitigating the excessive polymerization and coke formation typically induced by high-temperature treatment. The resulting products were characterized by relatively high aliphatic hydrocarbon fractions, although further process optimization and upgrading would be required to confirm their potential applications (Aboelela *et al*., 2023; Rios *et al*., 2018). Identical pyrolysis temperature and heating rate were maintained across each successive re-pyrolysis stage. Sequential re-pyrolysis increased the degree of thermal conversion, promoting the transformation of heavier hydrocarbon compounds into lighter fractions. This observation aligns with the enhanced generation of lighter and more volatile hydrocarbon compounds during successive thermal conversion (Heydariaraghi *et al.,* 2016). Consequently, the combined effects of pyrolysis temperature and the number of re-pyrolysis stages establish a robust foundation for assessing the conversion of MSW-derived tar into lighter, aliphatic hydrocarbon-rich liquid fractions (Fig. 3).

Liquid recovery and volumetric characteristics

Experimental findings indicate that the liquid phase constituted the primary product fraction. Accounting for approximately 65–70 wt% of the initial feed based on their density characterization in oil fraction (Table 3). These results indicate that a substantial portion of heavy tar can be converted into recoverable liquid products (Rios *et al*., 2018). Based on the results of the density test on the oil fraction samples, the range obtained was 801.3–875.4 kg/m^3 (Table 7). Based on an assumed liquid recovery of 70 wt%, approximately 0.70 kg of liquid product can be obtained from 1 kg of tar. The corresponding liquid volume was estimated from the measured density using Eqs. 2 and 3 (ASTM International, 2021):

$$m_{liquid} = m_{tar} \times Y_{liquid} = 1\,kg \times 70\,wt\% = 0.70\,kg \quad (2)$$

$$V_{liquid} = \frac{m_{liquid}}{\rho_{liquid}} = \frac{0.70}{875.4} \times 1000 = 0.799\,L \approx 0.80\,L \quad (3)$$

Table 3: Reported tar conversion to oil yields and related research

Feedstock and process	Reactor type	Temperature (°C)	Liquid yield (wt%)	Source
Mixed MSW condensate upgrading	Spiral condenser	450–600	1.2 L from 2 kg (≈60)	Sadewo, 2023
Coal–MSW tar cracking	Fixed-bed catalytic	500–650	55–68	Liu *et al.*, 2017
Stepwise tar pyrolysis	Fixed-bed staged	350–700	65–70	Wang *et al.*, 2025
This study	Fixed-bed staged	350–700	65–70	Ridwan *et al.*, 2027

1 kg tar → 0.70 kg recovered liquid → 0.800 L TFO Where: V_{liquid} is the liquid volume (L), m_{liquid} is the recovered liquid mass (kg), ρ_{liquid} is the liquid density (kg/m³). For the TFO fraction with a density of 875.4 kilograms per meters (kg/m³), the estimated 0.70 kg of recovered liquid corresponds to approximately 0.800 L. Thus, on a standardized basis, 1 kg of tar is estimated to produce approximately 0.800 L of liquid under the assumed 70 wt% recovery. The density of the recovered TFO fractions provides an additional indication of their physical characteristics following sequential re-pyrolysis. Variations in density among the TFO fractions likely originate from distinct molecular composition and hydrocarbon distribution induced by progressive thermal cracking.

The similarity of yields between this study and the stepwise approach reported by Wang *et al.*, (2025) confirms that staged heating effectively prevents premature polymerization, minimizes soot formation, and shifts the product distribution toward lighter hydrocarbons.

1 kg tar → 0.70 kg recovered liquid → 0.800 L TFO (Eqs. 2 and 3), potential daily production, using Eq. 4 (Wang *et al*., 2023a):

$$V_{oil} = M_{tar} \times V_{liquid} \quad (4)$$

Where: V_{oil} daily liquid production (L/d); V_{liquid} liquid recovery yield tar (L/kg)

$V_{oil} = 3{,}815\ \mathrm{kg/d} \times 0.8$

$V_{oil} = 3{,}052\ \mathrm{L/d}$

Physical properties analysis of oil fraction from tar

Oil fraction exhibits a wide range of viscosities, from light to heavy, depending on its specific application. The reference materials used for comparison include paraffin chemical abstracts service (CAS), with the molecular formula $C_nH_2n_2$ (n = 16–24), as well as paraffinic oil 60 and paraffinic oil 95 (Table 4). In addition, the product was also compared with domestic biofuel standards established by Indonesia's Director General of Oil and Gas (Table 5). Paraffin CAS paraffin, commonly as mineral paraffin, is used for analytical purposes due to its high level of purity. Highly purified paraffin, achieving purities of up to 99%, is typically employed in cosmetic, pharmaceutical, and chemical applications, with standard liquid paraffin also demonstrating exceptional stability under ambient conditions (Carlen and Mastrangelo, 2002; Ma *et al.*, 2020). The paraffinic oils 60 and 95 produced by Pertamina are standard products derived from solvent-dewaxed light paraffinic petroleum distillates (CAS No. 64742-56-9). Based on the physicochemical characterization presented in Table 6, the density of the thermally cracked tar fractions ranged from 801.3 to 875.4 kg/m³, while several other properties remained below or outside the applicable reference specifications (Table 7). The comparatively low flash point indicates the presence of volatile hydrocarbons generated via thermal cracking, implying that additional stabilization is essential for applications governed by stringent safety requirements (Sarikoc, 2020). Subsequent upgrading via considered through fractional distillation, hydrotreatment, catalytic treatment, or fuel blending may be implemented to tailor the physical and chemical properties of the recovered liquid (Razavian and Fatemi, 2020; Ula and Kurniadi, 2017). Fractional distillation effectively minimizes light volatile components, whereas

Table 4: Physical properties of paraffin CAS, paraffinic oil 60, and paraffinic oil 95 (Chemwhat, 2025; Pertamina, 2017)

Parameter	Paraffin CAS	Paraffinic Oil 60	Paraffinic Oil 95
Melting point	-24 °C	0 °C	0 °C
Boiling point	300 °C	352 °C	315 °C
Flash point	> 300 °C	> 216 °C	> 211 °C
Density	850 kg/m³ at 20 °C	867.1 kg/m³ at 15 °C	877.6 kg/m³ at 15 °C
Viscosity	–	48.76 cSt at 23 °C	124.1 cSt at 23 °C
Color	White	Liquid, yellow	Liquid, yellow

Table 5: Standard specifications for domestic diesel fuel

Parameter	Unit	Pertamina Dex (B35)*	Dexlite (B35)*	Biodiesel (B40)*
Density	kg/m³	815 – 860	815 – 880	815 – 880
Kinematic Viscosity	cSt	2.0 – 4.5	2.0 – 5.0	2.0 – 5.0
Flash Point	°C, minimum	55	52	52
Pour Point	°C, maximum	18	18	18

*Director general of oil and gas decree No. 447.K/MG.06/DJM/2023 and No. 384.K/MG.06/DJM/2024 concerning standards and quality (specifications) for diesel fuel domestically.

Table 6: Physical properties of oil fraction samples based on re-pyrolysis

Parameter	Method	Unit	Sequental re-pyrolysis		
			PFO-1	PFO-2	PFO-3
Color	-	-	heavy-Dark brown	Medium-brown	light-yellow
Density (15°C)	ASTM D4052-22	kg/m³	875.4	802.1	801.3
Viscosity (40°C)	ASTM D445-23	cSt	2.956	2.404	2.304
Flash Point	ASTM D93-20	°C, minimum	62.0	40.0	45.0
Pour Point	ASTM D5853-17	°C, maximum	-3	+21	+3

Table 7: Comparison of hydrocarbon oil fraction from tar with hydrocarbon oil product

Parameter	Unit	Range of Oil fraction	Commercial Paraffin	Diesel (Domestic)	Result and potential
Density (15°C)	kg/m³	801.3–875.4	780–880	820–850	Close to diesel and paraffin, potential for liquid fuel alternative
Viscosity (40°C)	cSt	2.304–2.956	1.5–3.0	2.0–4.5	Within the operational range, potential for combustion systems
Flash Point	°C	40.0 – 62.3	>60	>52	Too low → safety risk Requires upgrading (distillation/catalytic treatment)
Pour Point	°C	(-3) – (+21)	−10 to 10	−15 to 10	depending on the application

hydrotreatment and catalytic treatment enhance overall hydrocarbon stability. For wax-based applications, blending with microcrystalline wax may improve flexibility and oxidation resistance. Collectively, the physicochemical characterization demonstrates that thermally cracked tar fractions hold promise as intermediate hydrocarbon precursors, although subsequent upgrading remains essential prior to utilization in systems with stringent fuel-quality standards. Fractional distillation, catalytic upgrading, hydrotreatment, and blending can be considered according to the identified property limitations and intended end use (Wang *et al.,* 2022). Additional experimental validation is necessary to establish the most effective upgrading route.

Chemical properties analysis of oil fraction using GC-MS and FT-IR

The GC–MS results provide the relative distribution of compounds based on chromatographic peak areas. The combined results served to assess shifts in hydrocarbon distribution and composition throughout sequential re-pyrolysis (Tables 8 and 9). The three fractions were predominantly composed of

Table 8: Compounds detected by gas chromatography

Peak	TFO-1	Area	TFO-2	Area	TFO-3	Area
	Name	(%)	Name	(%)	Name	(%)
1	2-Isopropyl-1-hexene	0.91	Benzene, 1,3,5-trimethyl- (CAS)	0.96	Benzene, ethyl- (CAS)	0.64
2	Phenol (CAS)	1.82	Phenol, 2-methyl-	1.78	Benzene, 1,2-dimethyl-	1.60
3	1-Decanol (CAS)	2.10	2-propyl-trimethylcyclohexane	2.73	1,8-Nonadiene	0.60
4	Decane (CAS)	1.54	2-Undecene, 4,5-dimethyl-,	1.70	1-Nonene (CAS)	3.82
5	Octane, 3,3-dimethyl-	0.85	4-Dodecene, (Z)-	1.61	Octane (CAS)	4.16
6	1-Octanesulfonyl chloride	4.77	Dodecane (CAS)	1.91	Octane, 2-chloro- (CAS)	1.11
7	Cyclopropane, Octyl-	1.64	tetra propylene	0.90	1-Decene (CAS)	6.63
8	Tetradecane (CAS)	1.34	5,9-dimethyldeca-5,8-diene	2.29	Decane,2,3,5,8, tetramethyl	4.83
9	2-Undecanethiol, 2-methyl-	0.92	Benzene, 1-butyl-	1.29	trans-4-Decene	0.67
10	Benzenemethanol, 4-methyl-	2.32	Benzene, pentyl- (CAS)	1.01	1-Undecene (CAS)	0.84
11	Cyclopropane, Octyl-	4.81	2-Hydroxy-2-phenyl-acetamide	0.98	10-Undecen-1-ol (CAS)	1.22
12	Nony lthiol, isomer mix	8.17	(4E)-4-Dodecene #	2.68	3-Dodecene, (E)-	6.55
13	trans-7-tetradecene	0.91	Naphthalene (CAS)	7.57	Dodecane, 2,6,10-trimethyl	4.16
14	Decane, 2,3,5,8-tetramethyl-	2.29	Tetradecane (CAS)	2.68	1,11-Dodecadiene	0.89
15	2-(2'-Nitro-2'-propenyl)-1-cyclohexanone	1.53	4,5-Dimethyltetrahydro-1,3-oxazine-2-thione	1.11	Cyclopropane, nonyl-	5.92
16	Cyclooctane, 1,4-Dimethyl	1.86	Decane, 2,3,5,8-Tetramethyl-	1.62	Naphthalene	1.39
17	Nonane, 5-(2-Methylpropyl)-	4.12	5-Tetrade Cene, (E)-	3.28	Dodecane, 2,6,10-trimethyl-	4.06
18	1-Heptadecene (CAS)	9.23	Tridecane (CAS)	4.60	4-Dodecene, (Z)-	0.72
19	1-Tridecanol (CAS)	3.16	Isotridecanol-	11.27	1,11-Dodecadiene	0.87
20	3-OCTADECENE, (E)-	7.57	1-UNDECENE, 7-METHYL-	3.79	3-Tetradecene, (Z)-	4.64
21	1,4-Methanonaphthalene,	0.91	1-Heptanol, 2,4-diethyl-	9.62	Tetradecane (CAS)	4.04
22	Umbellulol	0.93	1-Tridecanol (CAS)	2.40	5-Dodecene, (E)-	0.64
23	1-Tridecanol (CAS)	2.33	1-Tridecanol (CAS)	1.94	5-Hydroxy-2-metylpyrimidin	0.68
24	1-Tridecanol (CAS)	1.49	Bicyclo-heptan-3-one, trimethyl	1.48	8-Dodecenol	0.80
25	Bicyclo-heptan-3-one, trimethyl	1.51	1,12-Tridecadiene (CAS)	1.14	3-Tetradecene, (Z)-	4.40
26	5,5-Diethyl-Thiohexan-4-One	1.03	1-Pentadecene (CAS)	5.76	Tetradecane (CAS)	3.69
27	1-Pentadecene (CAS)	6.58	Tetradecane (CAS)	3.49	9-Octadecene, (E)-	3.45
28	Tetradecane (CAS)	3.25	Naphthalene, 1,4-dimethyl-	1.07	Tetradecane (CAS)	3.92
29	Naphthalene, 1,3-dimethyl-	0.94	Benzene, octyl-	1.20	9-Octadecene, (E)-	2.68
30	Naphthalene, 1,5-dimethyl-	0.93	7-HEXADECENE, (Z)-	3.49	Nonadecane	3.76
31	Decane, 2-methyl- (CAS)	1.43	PENTADECANE	3.99	9-Octadecene, (E)-	1.83
32	1-Tridecanol (CAS)	2.85	Naphthalene, 2-ethyl- (CAS)	1.13	Hexadecane	3.63
33	Tetradecane (CAS)	3.89	Isotridecanol-	2.15	9-Octadecene, (E)-	1.13
34	Pyridine-2,4-diol, trimethyl	0.93	1-Tridecanol (CAS)	0.82	Hexadecane	3.06
35	Isodecyl methacrylate	2.24	Isotridecanol-	0.81	9-Eicosene, (E)-	0.67
36	Isotridecanol-	0.97	5-OCTADECENE, (E)-	1.07	Nonadecane (CAS)	2.61
37	7-Hexadecene, (Z)-	1.43	Tetracosane, 3,5,24-trimethyl-	1.87	Nonadecane (CAS)	2.15
38	1-Decanol, 2-hexyl-	2.18	Isotridecanol-	0.80	Heneicosane	1.55
39	Hexadecane (CAS)	1.42				
40	Isotridecanol-	0.89				
Total		**100**	Total	**100**	Total	**100**

Table 9: Hydrocarbon distribution and physical appearance of oil fractions

Fraction	re-pyrolysis stage	Carbon-chain range	Aliphatic hydrocarbon relative peak area (%)	Physical appearance
TFO-1	1 stage	C_9–C_{20}	46.76	Darker/Heavy
TFO-2	2 stages	C_{12}–C_{43}	45.58	Intermediate
TFO-3	3 stages	C_8–C_{21}	86.65	Clearer/Light

aliphatic hydrocarbons, with combined relative peak areas of 46.76% for TFO-1, 45.58% for TFO-2, and 86.65% for TFO-3 (Fig. 4). The aliphatic hydrocarbon class fraction remained relatively similar between TFO-1 and TFO-2 but increased substantially in TFO-3. This elevation indicates that successive re-pyrolysis modifies the hydrocarbon distribution and accelerates the formation of aliphatic hydrocarbon compounds in the final stage. A progressive alteration in physical

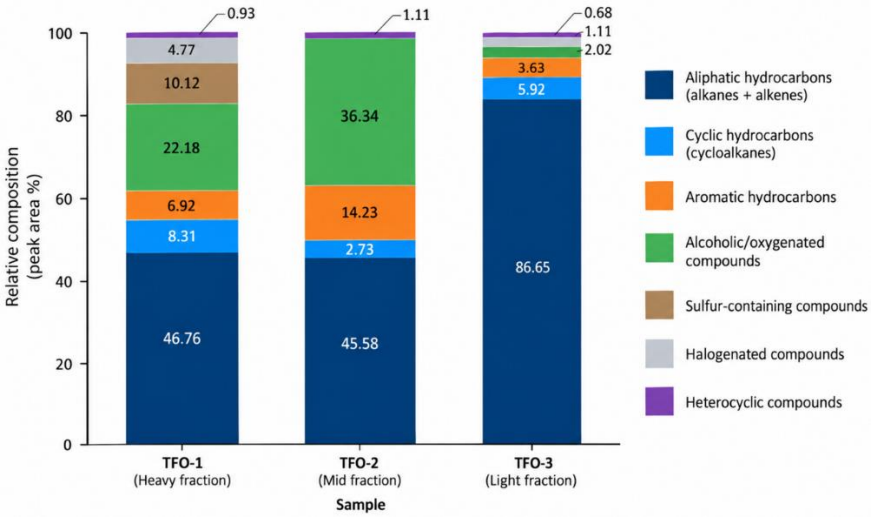

Fig. 4: Relative composition of compound classes identified in TFO-1, TFO-2, and TFO-3 based on GC–MS analysis
(Note: Values are expressed as relative peak area (%). Alkanes and alkenes were combined into a single hydrocarbon class, whereas cycloalkanes were classified separately)

appearance was likewise evident, with the TFO fractions exhibiting increased clarity following sequential re-pyrolysis. Although thermal re-pyrolysis promotes the cleavage of larger hydrocarbon structures into smaller molecules, the extent of this transformation is governed by temperature, residence time, and feedstock composition (Heydariaraghi *et al.,* 2016). However, the visual change alone cannot confirm molecular-weight reduction and is therefore considered a supporting observation. GC–MS results provide evidence of the compound changes, particularly the substantial increase in aliphatic hydrocarbon fraction observed in TFO-3. The broader distribution observed in TFO-2 indicates that intermediate re-pyrolysis did not produce a continuous shift toward shorter-chain hydrocarbons. However, the subsequent increase in the aliphatic hydrocarbon fraction and the narrower carbon-chain range in TFO-3 indicate a substantial change in hydrocarbon distribution during the third stage. Thermal cracking accelerates the breakdown of macromolecular hydrocarbon frameworks and secondary reactions, effectively modifying the distribution of condensable hydrocarbons. Nevertheless, the observed change in color should be regarded as a supporting physical indicator rather than definitive evidence of molecular-weight reduction (Andalia *et al.,* 2025). The GC–MS results, particularly the carbon-chain distribution and aliphatic hydrocarbon composition, provide the primary evidence for evaluating changes in hydrocarbon characteristics. The GC–MS results showed clear changes in the chemical-group distribution during sequential re-pyrolysis (Fig. 4). The aliphatic hydrocarbon fraction increased from 46.76% (TFO-1) and 45.58% (TFO-2) to 86.65% in TFO-3, while the oxygenated fraction decreased to 2.02% in TFO-3. Aromatic compounds accounted for 6.92%, 14.23%, and 3.63% in TFO-1, TFO-2, and TFO-3, respectively. These variations indicate that successive thermal treatment modifies the distribution of condensable compounds, exhibiting the most pronounced aliphatic hydrocarbon enrichment in TFO-3. Thermal cracking drives the decomposition and restructuring of heavier hydrocarbon frameworks via primary and secondary pathways, albeit with the ultimate product composition remaining contingent upon feedstock characteristics and operating conditions (Andalia *et al.,* 2025). The

progressively clearer appearance of the TFO fractions after re-pyrolysis provides a complementary visual indication of changes in the liquid composition, but cannot independently confirm molecular-weight reduction. The presence of sulfur-containing compounds in TFO-1 (10.12% relative peak area) and halogenated compounds in TFO-3 (1.11% relative peak area) should also be considered in evaluating potential applications. These values reflect GC–MS relative peak areas rather than absolute sulfur or halogen concentrations; therefore, direct comparison with fuel specifications necessitates dedicated sulfur and chlorine quantification. Sulfur- and chlorine-containing compounds may contribute to SO_x emissions, corrosion, and other operational concerns during thermal utilization and should therefore be controlled during fuel upgrading (Kusenberg *et al*., 2022; Thi *et al.,* 2021). Among the three fractions, TFO-3 exhibited the highest relative abundance of aliphatic hydrocarbons (86.65%) and the lowest oxygenated fraction (2.02%), indicating its potential as an aliphatic-rich hydrocarbon intermediate for further upgrading. Rather than serving as a direct finished fuel, TFO-3 holds potential for subsequent conversion into marketable fuels or as a substitute material for wax-based products. Fractional distillation, hydrotreatment, catalytic processing, or blending may be considered to improve physicochemical properties and reduce unwanted volatile components or those containing heteroatoms before use in specific end applications (Razavian and Fatemi, 2020; Ula and Kurniadi, 2017). For wax-based applications, advanced formulations incorporating additives such as microcrystalline wax may also be evaluated to optimize product performance. Further evaluation of flash point, viscosity, distillation range, heating value, total sulfur, total chlorine, and other relevant fuel properties is required. Fractional distillation and hydrotreatment have been documented as viable strategies for enhancing the physicochemical characteristics of MSW-derived pyrolysis oils, encompassing flash point, viscosity, and sulfur-related properties (Sarikoc, 2020). The FT-IR spectra in Fig. 5 showed that aliphatic hydrocarbon structures were consistently identified in all TFO fractions (Table 10). Characteristic C–H stretching bands were observed at approximately 2955, 2923, and 2853 /cm, together with CH_2/CH_3 deformation bands near 1456 and 1377 /cm. The band near 721–722 /cm was also consistently detected, supporting the presence of aliphatic hydrocarbon chains (Qiao *et al.,* 2018). These stretching bands indicate that C–H-containing aliphatic structures constitute a major component of TFO fractions, aligning with the high relative abundance of aliphatic hydrocarbons identified by GC–MS. Bands associated with C=C and =C–H vibrations were also identified in all samples. The absorption near 1641–1648/cm can be attributed to C=C stretching, while bands in the approximately 888–992/cm region are associated with =C–H vibrations. he detection of both saturated and unsaturated hydrocarbon-related bands is consistent with the aliphatic hydrocarbon distribution obtained from GC–MS. Overall, FT-IR analysis provided supporting evidence for the chemical changes identified by GC–MS. The prominent aliphatic C–H stretching bands across all TFO fractions indicate a predominance of aliphatic components, whereas the subdued oxygenation signals in TFO-3 align with its lower proportion of oxygen-containing compounds. Nevertheless, FT-IR was used only for structural identification and not for quantitative determination of compound composition or molecular-weight distribution (Mishra *et al.*, 2024; Pannucharoenwong *et al.,* 2026).

Tar based Light hydrocarbon oil fraction potential

These findings demonstrate that successive thermal treatments alter the chemical composition of tar-derived liquids, yielding an intermediate fraction enriched in aliphatic components. TFO-3 exhibited a substantially higher relative abundance of aliphatic hydrocarbons (86.65%) and a lower proportion of

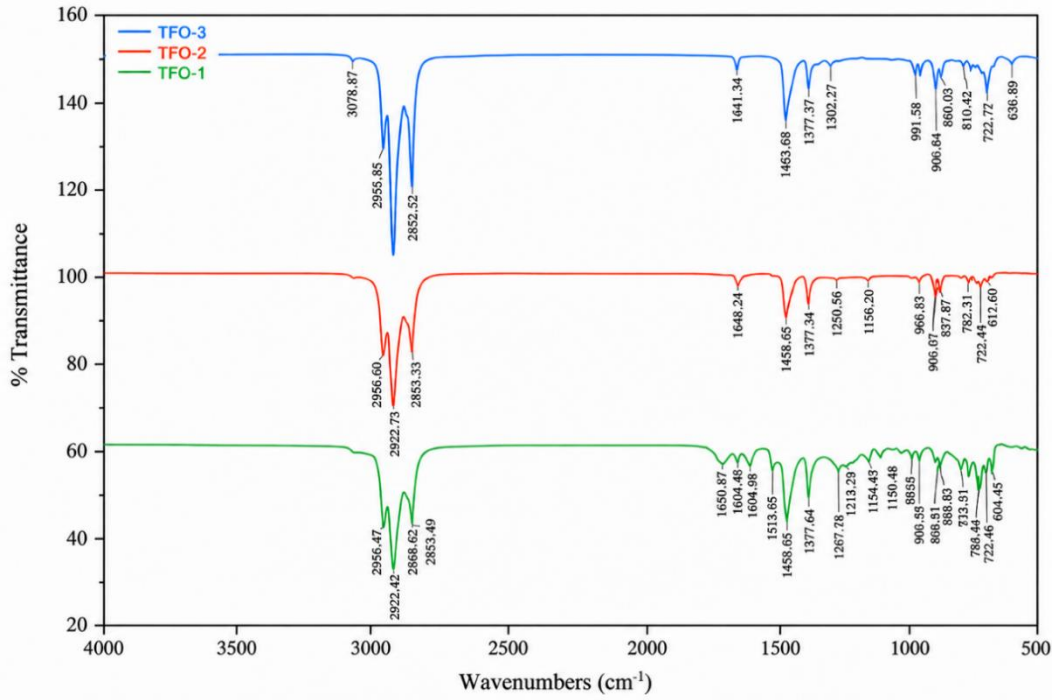

Fig. 5: Infrared spectra of TFO-1, TFO-2, and TFO-3

Table 10: Interpretation of functional groups and compound classifications based infrared spectrum

Compound classification	Functional group	TFO-1 (/cm)	TFO-2 (/cm)	TFO-3 (/cm)	Interpretation	Source
Alkane-Alkene/ Aliphatic hydrocarbons	–CH_3 and –CH_2–	2955.47; 2922.56; 2853.49; 1456.66; 1377.04; 721.46	2955.60; 2922.73; 2853.53; 1458.65; 1377.34; 721.90	2955.85; 2922.73; 2852.52; 1463.68; 1377.37; 721.27	Dominant and consistently identified in all samples	Qiao *et al.*, 2018
	C=C and =C–H	1643.62; 963.55; 908.81; 886–887	1648.24; 966.33; 908.81; 887.67	1641.34; 991.55; 965.10; 908.84; 888.08	Indicated in all samples	Qiao *et al.*, 2018
Aromatic/ cyclic hydrocarbons	Ar–H and aromatic C=C	812.23; 750.54; 668.46	782.31; 733.54	810.42; 781.36; 721.27; 633.98	Indicated, but less prominent than aliphatic structures	Yousef *et al.* 2021
Oxygenated compounds	O–H, C=O, and C–O	1267.88; 1154.27; 1109.99	1269.58; 1155.20	No strong bands in principal region	Weakly indicated in TFO-1 and TFO-2; not prominent in PFO-3	Yousef *et al.* 2021

oxygenated compounds (2.02%) than TFO-1 and TFO-2. Findings from the sequential re-pyrolysis demonstrate that MSW gasification tar serves as a promising feedstock for the recovery of hydrocarbon-rich liquid fractions. Based on estimate a liquid recovery of 70 wt% and an oil density of 875.4 kg/m³, the potential volume of recovered oil fraction was estimated at approximately 3,052 L/d (Eq. 4), equivalent to approximately 1,113,980 L/y or 1,114 m³/y (Fig. 6). This value represents a scenario-based estimate of liquid hydrocarbon recovery and may vary

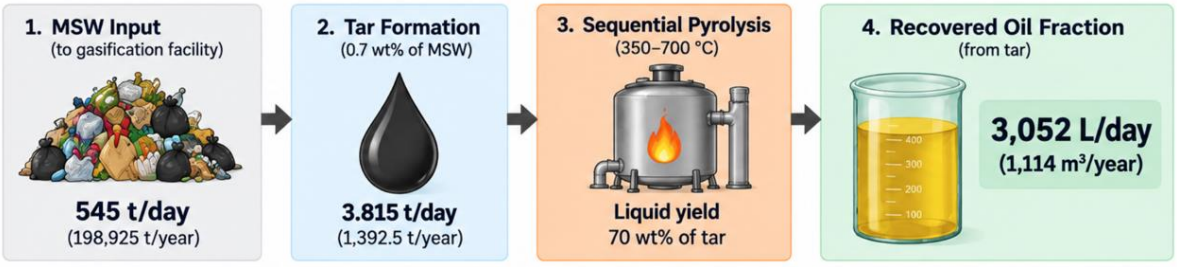

Fig. 6: Potential hydrocarbon oil recovery from tar at the Surakarta landfill

depending on tar composition, pyrolysis conditions, condensation efficiency, and product properties. The recovered liquid is more appropriately evaluated as an intermediate hydrocarbon feedstock rather than applied directly as a fuel. The relatively high aliphatic hydrocarbon content observed in TFO-3 provides a basis for considering applications in fuel-blending components, hydrocarbon feedstocks, or wax material-related formulations after appropriate upgrading. MSW-derived pyrolysis oils typically necessitate post-treatment owing to the unfavorable flash point, viscosities, densities, sulfur contents, and other fuel properties inherent in the crude products. Fractional distillation and hydrotreatment have been reported as practical approaches for improving several of these properties (Faisal *et al.,* 2023). Fractional distillation is recommended as an initial upgrading step to separate light, middle, and heavy boiling fractions. Subsequent evaluations might explore the lighter fraction for fuel-blending applications, whereas heavier fractions can be routed toward further cracking or material utilization. Distillation has been reported to reduce density and viscosity and to improve the characteristics of selected pyrolysis-oil fractions (Wang *et al.,* 2025). Hydrotreatment can subsequently be considered when reduction of unsaturation, sulfur-containing compounds, or other unstable components is required. However, hydrogen consumption, catalyst deactivation, pressure requirements, and process energy demand should be evaluated before scale-up (Osman *et al.*, 2024). Overall, the results support the potential recovery of an aliphatic hydrocarbon-rich intermediate from MSW gasification tar, with TFO-3 showing the most pronounced aliphatic hydrocarbon character.

Environmental implications

The sequential re-pyrolysis of tar provides a potential route for recovering liquid hydrocarbon fractions from a waste stream that would otherwise require further treatment or disposal. From an environmental standpoint, converting tar into an oil fraction minimizes the volume of residual tar requiring direct disposal while simultaneously recovering hydrocarbons as a secondary resource. Pyrolysis has been reported as a waste-valorization pathway capable of recovering energy and material from MSW, although its environmental performance depends strongly on feedstock characteristics and process control (Aswathy and Ramesh, 2026). Furthermore, the contaminants present in MSW–derived tar raise significant environmental concerns. Depending on feedstock composition, pyrolysis systems can generate or concentrate compounds containing sulfur, chlorine, nitrogen, and other contaminants, while emissions such as HCl and SO_2 may require appropriate control. Consequently, the recovered oil should not be regarded as a directly usable fuel without further characterization and, where necessary, upgrading (Javed *et al.*, 2025; Osman *et al.*, 2024). For the obtained TFO fractions, fractional distillation serves as a viable subsequent treatment to separate compounds based on boiling range, while hydrotreatment can be employed to

eliminate sulfur, unsaturated compounds, or other undesirable components. Such upgrading has been reported to improve properties including viscosity, flash point, and sulfur content of MSW-derived pyrolysis oils (Detsios *et al.,* 2024). Overall, the primary environmental benefit of the proposed pathway stems from effective tar reduction and hydrocarbon recovery, rather than from the direct displacement of conventional fuels. The estimated 3,052 L/d oil fraction demonstrates the potential scale of resource recovery. Further assessment through energy balance, emission characterization, contaminant analysis, and life-cycle assessment (LCA) are required to quantify the net environmental benefit. This approach would provide a more robust basis for determining whether sequential re-pyrolysis offers an environmentally preferable pathway for tar management. The recovery of aliphatic hydrocarbon-rich oil fractions from gasification tar supports the relevance of SDG 7, SDG 9, and SDG 12 by demonstrating potential for secondary resource recovery, and waste valorization. Nevertheless, the recovered oil functions primarily as an intermediate product, necessitating further upgrading and characterization prior to its utilization in specific fuel or material applications. Future implementation would also require appropriate product quality standards, emission controls, market mechanisms, and economic incentives to support the utilization of waste-derived hydrocarbon products.

Limitation of this study

This study was conducted at laboratory scale, and therefore, the performance of sequential re-pyrolysis under plant-scale conditions remains to be validated. The estimated oil potential of 3,052 L/d is derived from a scenario-based calculation using assumed tar yield and liquid recovery rates, rather than direct empirical measurements from the gasification facility. Further characterization, including higher heating value, distillation range, sulfur, chlorine, nitrogen, metals, and product stability, is required to determine the suitability of the recovered oil for specific applications. Furthermore, this study did not encompass detailed energy balance, techno-economic evaluations, and LCA. Additionally, fluctuations in MSW composition and gasification operating conditions may influence tar properties and product yield. Therefore, further fractionation and/or catalytic upgrading, together with pilot-scale validation, is recommended to strengthen the assessment of the practical and environmental potential of the recovered hydrocarbon fractions.

CONCLUSION

This study demonstrated the potential valorization of municipal solid waste (MSW) gasification tar from the Putri Cempo Landfill, Surakarta, through sequential re-pyrolysis to obtain aliphatic hydrocarbon-rich liquid fractions. The original tar contained substantial aliphatic hydrocarbons, with combined alkane–alkene contents of 64.80 wt% and 65.98 wt% in the hexane and n-heptane extracts, respectively, indicating potential for further thermal conversion. Sequential re-pyrolysis at 350–700 °C produced condensable liquid fractions, with 500–550 °C identified as a favorable temperature range for liquid recovery under the investigated conditions. The chemical composition underwent significant alteration throughout the sequential re-pyrolysis process. The aliphatic hydrocarbon content was 46.76% in TFO-1, 45.58% in TFO-2, and increased to 86.65% in TFO-3. The alkane content also increased from 20.13% and 20.16% in TFO-1 and TFO-2 to 45.62% in TFO-3. The identified carbon-chain distributions ranged from C9–C20 in TFO-1, C12–C43 in TFO-2, and C8–C21 in TFO-3. The broader carbon range observed in TFO-2 reflects a more extended hydrocarbon distribution, whereas TFO-3 exhibits a comparatively restricted range combined with a maximum alkane–alkene content, collectively confirming its enrichment in aliphatic hydrocarbon. The presence of aliphatic structures was further supported by FT-IR analysis, which

consistently showed characteristic aliphatic C–H stretching bands at approximately 2955–2956, 2922–2923, and 2852–2854 /cm, corresponding to asymmetric and symmetric C–H stretching vibrations of CH_3 and CH_2 groups. Additional absorption bands observed approximately 1456–1464 and 1377 /cm were assigned to CH_2/CH_3 deformation vibrations, whereas signals near721–722 /cm denoted the presence of extended aliphatic hydrocarbon chains. These FT-IR features support the GC–MS results and confirm the predominance of aliphatic hydrocarbon structures in the recovered fractions. The physicochemical characterization showed densities of 801.3–875.4 kg/ m^3 and kinematic viscosities of 2.304–2.956 cSt. The flash points ranging from 40 to 62 °C indicate the presence of relatively volatile components, highlighting the necessity for further treatment in applications requiring stricter alternative fuel or hydrocarbon-material specifications. Fractional distillation, blending, and catalytic or hydrotreatment processes could therefore be considered for subsequent product upgrading. Based on an assumed tar generation rate of 0.7 wt% from 545 t/d of MSW, approximately 3.815 t/d of tar could be generated. Using the liquid recovery basis applied in this study, the potential oil fraction was estimated at approximately 3,052 L/d, equivalent to approximately 1,114 m^3/y. This value reflects a scenario-based potential rather than empirical plant-scale production, depending heavily on tar generation, liquid recovery rates, condensation efficiencies, and product density. sequential re-pyrolysis provides a potential route for recovering aliphatic hydrocarbon-rich liquid products from MSW gasification tar, supporting waste valorization and secondary resource recovery. Further investigations should prioritize pilot-scale validation, product fractionation and upgrading, comprehensive contaminant profiling, energy integration, alongside techno-economic and life-cycle assessments. These developments could strengthen the relevance of the proposed pathway to SDG 7, SDG 9, and SDG 12 through waste-derived resource recovery, technological development, and more efficient utilization of secondary resources.

AUTHOR CONTRIBUTIONS

M. Ridwan conceived and designed, prepared materials, data collection, analytical measurements, drafted manuscript, interpreted results, and edited. P. Setyono conceived and designed, analysis and discussion, reviewed draft, validated and supervised, grant funding, and as corresponding author. M.T.S. Budiastuti performed analysis and discussion, reviewed draft, project administration, and supervision.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest related to the research and funding. All authors have full independence in conducting research and preparing manuscripts without any pressure or influence from third parties.

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ABBREVIATIONS

%	Percent
°C	Degree celsius
°C/min	Degree Celsius per minute
/cm	Per centimeter
≥	Greater than or equal to
–CH₃	Methyl
–CH₂–	Methylene
ρ_{liquid}	Liquid density (kg/m³)
wt %	Weight percentage
AFR	Air fuel ratio
ASTM	American Society for Testing and Materials
C	Carbon atom
C–C	Carbon-carbon single bond
C=C	Carbon-carbon double bond
C–H	Carbon-hydrogen single bond
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	Centistokes
ECHA	European Chemicals Agency
ER	Equivalence ratio
FT-IR	Fourier-transform infrared spectroscopy
g	Grams
GC-MS	Gas chromatography–mass spectrometry
GWP	Global warming potential
HFO	Heavy fuel oil
H_2	Hydrogen
KBr	Kalium Bromida
kg	kilogram
kg/d	Kilogram per day
kg/kg	Kilogram per kilogram
kg/L	Kilogram per liter
kg/m³	Kilogram per cubic meter
KLH	Ministry of Environment (Kementrian Lingkungan Hidup)
L	Liters
LCA	Life cycle analysis
L/d	Liter per day
L/kg	Liter per kilogram
min	Minutes
MJ/kg	Megajoule per kilogram
mL/min	Milliliter per minute
MSW	Municipal solid waste
Mt	Million ton
m_{liquid}	Recovered liquid mass (kg)
M_{msw}	Municipal solid waste feed rate (kg/d)
M_{tar}	Tar formation rate (kg/d)
rpm	Revolutions per minute
SDGs	Sustainable development goals
TEA	Techno-economic analysis
TFO-1	Tar Pyrolysis Oil 1-Sample
TFO-2	Tar Pyrolysis Oil 2-Sample
TFO-3	Tar Pyrolysis Oil 3-Sample
t/d	Ton per day
t/y	Ton per year
VOC	Volatile Organic Compounds
V_{liquid}	Recovered liquid volume (L)
V_{oil}	Daily liquid oil production (L/d)
WtE	Waste to Energy
Y_{liquid}	Tar yield (kg/kg)
Y_{tar}	Liquid recovery yield (wt%)

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