



# Paraffin-Olefin Content Analysis and Potential Solutions of Tar from Municipal Solid Waste Gasification Process in Indonesia

Muhammad Ridwan, Prabang Setyono† and Maria Theresia Sri Budiastuti

Environmental Science Study Program, Graduate School, Universitas Sebelas Maret, Surakarta, Indonesia

†Corresponding author: Prabang Setyono; prabangsetyono@gmail.com

Abbreviation: Nat. Env. & Poll. Technol.  
Website: [www.neptjournal.com](http://www.neptjournal.com)

Received: 22-06-2025

Revised: 18-08-2025

Accepted: 19-08-2025

## Key Words:

Tar  
Paraffin-olefin  
Municipal solid waste  
Gasification

## Citation for the Paper:

Ridwan, M., Setyono, P. and Budiastuti, M.T.S., 2026. Paraffin-olefin content analysis and potential solutions of tar from municipal solid waste gasification process in Indonesia. *Nature Environment and Pollution Technology*, 25(2), D1838. <https://doi.org/10.46488/NEPT.2026.v25i02.D1838>

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

## ABSTRACT

The main drawback of gasification technology is the production of tar (byproducts). If not properly managed, tar formation can affect syngas gasification and potentially pollute the environment. The focus of this study was to detect paraffin-olefin content and propose mitigation strategies for tar. Compositional analysis was conducted using GC-MS, FT-IR, and XRF on tar samples extracted using different solvents. The findings indicated that the characterization of tar revealed the presence of aliphatic hydrocarbon compounds belonging to the alkane and alkene groups. GC-MS analysis of solvent extracts showed paraffin-olefin contents of 65.98% (n-heptane), 64.80 wt% (n-hexane), and 22.96% (ethyl acetate), calculated from GC-MS peak area percentages. FT-IR spectra confirmed the C-H stretching of  $-CH_3/-CH_2-$  groups (paraffin indicators) and C=C stretching (olefin indicators). Non-polar solvents were more effective in extracting paraffinic and olefinic fractions. Compared with coal and biomass tar studies, this study uniquely targeted MSW-derived tar and its direct potential as a paraffin-olefin feedstock. Tar exhibits potential as a raw material for paraffin-olefins, which are widely used in the wax, lubricant, asphalt, and fuel industries. The method of converting tar into alternative materials depends on the desired application of tar derivatives and economic feasibility. This research contributes to SDG 7 (affordable clean energy) through the potential of tar and SDG 12 (responsible production) through the clean production of gasification waste.

## INTRODUCTION

The current situation in Indonesia can be described as a waste emergency, because many landfills have negative impacts on the environment and society. Many fires are caused by methane gas emissions from waste dumps, overload cases, and other cases of environmental pollution (Ramadhanti et al. 2021). Many developed countries have addressed waste issues using waste-to-energy (WtE) methods. Accordingly, the Indonesian government is promoting the acceleration of waste management into electricity through Presidential Regulation No. 35 of 2018, concerning the acceleration of the construction of waste management installations into electric energy based on environmentally friendly technology (Article 1). WtE technology, which involves thermal processes such as pyrolysis and gasification, has become a major focus in efforts to utilize the energy contained in waste (Shahabuddin et al. 2020, Abogunrin-Olafisoye et al. 2024, Chang et al. 1962).

Gasification converts solid fuels, such as coal, biomass, or municipal solid waste (MSW), into synthesis gas (syngas) (Chen et al. 2010, Hejazi et al. 2017). Gasification technology is an alternative mechanism for the direct combustion of solid fuels and can be used in multiple applications, including power generation, chemical production, and fuel production (Liu 2019, Styana et al. 2019, Suryawanshi et al. 2023). Gasification technology is considered more environmentally friendly than other thermochemical processes for converting MSW into energy (Qodriyatun 2021, Nurfadhilah et al. 2022, Subekti et al. 2023).



Copyright: © 2026 by the authors

Licensee: Technoscience Publications

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

In Indonesia, MSW is processed at the Putri Cempo landfill using gasification. The type of gasification used is gasification technology with a fixed-bed downflow gasifier. Waste to be converted into energy is first processed into refuse-derived fuel (RDF) and briquettes or pellets (Sukrorini et al. 2014, Sonjaya 2021). The gasification process in raw materials undergoes oxidation with a limited amount of oxygen (partial oxidation), resulting in incomplete combustion. During this conversion, approximately 85% of the chemical energy in the garbage is converted into gaseous forms, known as syngas (Wang et al. 2023). Syngas can be used with natural gas to co-fire a power plant using a gas turbine, which aims to reduce dependence on fossil fuels (Darmawan et al. 2018, Christanti et al. 2022). In addition, the by-products of combustion in the gasification process produce residual solids, such as ash, charcoal, metals, or tar. The by-product, particularly tar, can pollute the environment, disrupt human health, and affect the quality of the syngas produced. Tar is a complex residue that is difficult to burn (Palma 2013, Mishra et al. 2015, Feng et al. 2025).

Tar is a thick, dark brown solid liquid with a distinctive odor, produced by the gasification of biomass or the thermal decomposition of organic materials undergoing condensation (Huang et al. 2015, Škvareková et al. 2016). The formation of tar involves heating of organic matter under oxygen-deprived conditions. Tar from waste/biomass gasification contains numerous complex compounds, including aliphatic and aromatic hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), phenolic compounds, and their derivatives (Rakesh & Dasappa 2018, Tursunov et al. 2020). The chemical composition of tar in gasification technology is influenced by factors such as the reaction temperature, reactor type, and raw materials used in the gasification process (Yu et al. 2014, Huang et al. 2015). The quantity and composition of tar vary according to the type of raw material and operating

conditions. Differences in tar emissions from gasification are affected by variations in temperature, air equivalence ratio (ER), and MSW composition (Feng et al. 2017, Veksha et al. 2019). Several previous studies on the characterization of tar from gasification using MSW as a raw material are listed in Table 1.

Previous research has been limited to the general characterization of all compounds in tar. Therefore, this study analyzed the presence of total aliphatic hydrocarbons and formulated the potential of tar according to its oil/wax-like physical characteristics. Tar from MSW gasification at low standard temperature and pressure (STP) states is a liquid–solid. Aliphatic hydrocarbons, such as alkanes, are common in low-temperature tar (Evans & Milne 1998, Vélez et al. 2015). Based on its physical characteristics and aliphatic hydrocarbon content, tar can be explored as a hydrocarbon source. The hydrocarbons in tar that have the potential to be reused in the oil and fuel industry are aliphatic hydrocarbons in the form of paraffin-olefins, which are a type of alkane-alkene group. (Qin et al. 2010, Kemalov et al. 2016). The paraffin-olefin content has been extensively studied in products that follow thermal processes, such as coal tar and petroleum (Ni et al. 2013, Ivanova & Semenov 2020).

Previous valorization research on coal tar (Ni et al. 2013) and petroleum coker oil (Bartle et al. 1970) has identified high paraffin and olefin fractions suitable for fuel and chemical feedstocks. Biomass tar studies (Huang et al. 2015, Chan et al. 2020) have focused on aromatic hydrocarbons, whereas MSW tar has rarely been analyzed for its paraffin-olefin content. This study differs by quantifying paraffin-olefin fractions from MSW gasification tar and evaluating the solvent-specific extraction performance, with implications for industrial applications. The empirical difference from previous studies is the difference in tar content produced from the composition of waste in European and developed

Table 1: Tar from MSW gasification composition.

Characterization method	Tar composition	Reference
GC-MS (Trace GC, ISQ MS), <sup>13</sup> C-NMR	Miscellaneous hydrocarbons proportion between 69.7-96.3% Other hydrocarbons such as phenol & derivatives, PAHs (naphthalene, phenanthrene, anthracene), benzene, toluene	(Huang et al. 2015)
GC-MS (TSQ 8000 EVO) with Thermo Scientific™ TRACE™	hydrocarbons with chains $\geq C_{17}$ (pyrene and phenanthrene), hydrocarbons with chains $\leq C_{10}$ (naphthalene, indene and toluene)	(Etutu et al. 2016)
GC-MS/MS analyzer, H-NMR	Tar contains 20 major aromatic compounds, such as benzene, methyl isobutyl, toluene, xylene, phenol, cresol, and naphthalene.	(Tursunov et al. 2020)
GC-MS analyzer	Biphenyl, naphthalene, acenaphthylene, 1-methylnaphthalene, indene and others	(Čespiva et al. 2020)
GC-MS (HP7890 GC with 59751 MS, Agilent), FT-IR	Phenol, naphthalene, biphenyl, acetylnaphthalene, phenanthrene, toluene, styrene	(Chan et al. 2020)
GC-MS/MS analyzer, C-NMR	Benzene, toluene, p-xylene, xylene, indene, naphthalene, biphenyl, acenaphthylene, fluorene, phenanthrene, pyrene, and other aliphatic and aromatic hydrocarbon compounds	(Valderrama Rios et al. 2018)

countries. Previous studies have not included the quantitative identification of utilization and have only been general in nature. There has been no research on tar valorization focusing on the paraffin-olefin content of tar from MSW gasification.

This article discusses the identification of the existing characteristics of raw materials in tar MSW gasification. The novelty of this study lies in its focus on analyzing paraffin-olefin compounds in tar samples (by-products). Additionally, this study will formulate potential management strategies for tar, building on previous research by other researchers, so that it can be utilized as a raw material or paraffin material. This research also promotes the realization of a circular economy in Indonesia and Sustainable Development Goal 7 on affordable energy through the utilization of waste as an alternative material, as well as Sustainable Development Goal 12 on responsible consumption and production (clean production in the gasification process).

## MATERIALS AND METHODS

### Materials

Gasification feedstock in the form of pellets or briquettes derived from organic and inorganic MSW at the Putri Cempo landfill. The waste composition includes mixed paper, mixed plastic, wood or ranted, leather, biomass waste, and food waste. Raw material analysis aimed to determine the proximate and ultimate characteristics that influenced the main and side products (tar) produced. Tar samples (by-products) from MSW gasification were obtained from the Putri Cempo landfill in Surakarta, Indonesia. The grab sampling method collected tar in a single container from gasification, including liquid–solid phase samples. These samples, consisting of liquid–solid phases (slurry), were homogenized with various solvents. The samples contained numerous hydrocarbon compounds ranging from polar to non-polar; therefore, solvent extraction with similar properties was employed to

optimize the target compounds. The extraction solvents in this study are semi-polar and non-polar (Niu et al. 2017). The purpose of the extraction was to identify suitable solvents and optimize the extraction of aliphatic hydrocarbon compounds (alkanes and alkenes). The solvents used to extract the tar samples are ethyl acetate, n-hexane, and n-heptane. Since paraffin-olefins are non-polar compounds, the use of these solvents is justified for optimal results (Utami et al. 2023, Yang et al. 2023). Fig. 1 shows the tar from waste gasification at the Putri Cempo landfill in Indonesia. The waste feedstock is in the form of pellets or briquettes derived from municipal solid waste. The waste composition includes mixed paper, mixed plastic, wood or ranted, leather, biomass waste, and food waste. Raw material analysis aims to determine the Proximate and Ultimate characteristics influencing the main and by-product (tar) formation. Tar samples from MSW gasification were obtained from the Putri Cempo landfill in Surakarta, Indonesia. The samples contained numerous hydrocarbon compounds ranging from polar to non-polar; therefore, solvent extraction with similar properties was employed to optimize the target compounds. The samples contain many hydrocarbon compounds ranging from polar to non-polar, so solvent extraction with similar properties is used to optimize the target compounds. The extraction solvents in this study are semi-polar and non-polar (Niu et al. 2017). The goal of the extraction is to identify suitable solvents and optimize the extraction of aliphatic hydrocarbons such as alkanes and alkenes. These were extracted using ethyl acetate, n-hexane, and n-heptane, as paraffin-olefins are non-polar, making these solvents appropriate for optimal extraction (Utami et al. 2023, Yang et al. 2023). This is the tar from waste gasification at the Putri Cempo landfill, Indonesia (Fig 1).

### Experimental Method

#### *Characterization of Feedstock Gasification*

Testing of gasification feedstocks, including Refused



Fig. 1: Tar (byproduct) from MSW gasification in the Putri Cempo landfill, Indonesia.

Table 2: Standardized test methods.

Parameter	Unit	Method
<b>Proximate analysis</b>		
Moisture Content	%, adb	PO/MIN-BT/21
Ash Content	%, adb	PO/MIN-BT/21
Volatile matter	%, adb	PO/MIN-BT/21
Fixed carbon	%, adb	PO/MIN-BT/21
Gross Calorific Value	Kcal.kg <sup>-1</sup> , adb	PO/MIN-BT/04
Gross Calorific Value	Kcal.kg <sup>-1</sup> , ar	
<b>Ultimate analysis</b>		
Carbon (C)	%, adb	ASTM D 5373-16
Hydrogen (H)	%, adb	ASTM D 5373-16
Oksigen (O)	%, adb	ASTM D 5373-16
Nitrogen (N)	%, adb	ASTM D 5373-16

Derived Fuels and pellets from MSW, was conducted using proximate and ultimate analyses with the standard methods PO/MIN-BT/21, PO/MIN-BT/04, and ASTM D 5373-16 (Table 2). The samples were pulverized and sieved to homogenize the mixture and sample size. Subsequently, the sample was pulverized again to 1600  $\mu\text{m}$  using a standard test. The purpose of this analysis was to determine the current condition of the raw materials and gasification process.

### Characterization of Tar

The sample extraction ratio was 1:10 (b/v), or 1 g of the sample was dissolved in 10 mL of a solvent. The tar sample solution was macerated at room temperature for  $1 \times 24$  h and stirred constantly (Wang et al. 2016, Yang et al. 2023). Subsequently, filtration was performed to obtain the filtrate, which was vaporized using a rotary evaporator to obtain the tar extract. The samples analyzed using the instrument were in the form of extracts from various solvents, namely ethyl acetate, hexane, and heptane.

The samples were characterized using gas chromatography–mass spectrometry (GC–MS), Fourier-transform infrared spectroscopy (FT-IR), and X-ray fluorescence (XRF). GC–MS was used to identify volatile compounds, especially aliphatic hydrocarbons, which make up tar. The GC–MS instrument was a Shimadzu GCMS-QP2010 SE with a temperature range of 50–270  $^{\circ}\text{C}$  and a heating rate of 10  $^{\circ}\text{C}$  per min. High-purity helium gas was used as the carrier gas at a flow rate of 1.7 mL per min. Gas chromatography separates compounds based on differences in the speed at which they move through the gas chromatography column. Internal calibration was performed using an n-alkane standard series (with C10–C30 n-paraffins). The results of identifying tar samples using GC–MS revealed the components and concentration/total area of compounds

that could be classified into groups (Niu et al. 2017). FT-IR with Perkin Elmer Spectrum IR 10.6.1 specification using KBr pellet technology detected the functional groups in tar samples. FT-IR analyzed compounds based on their functional groups. IR identification is performed from 400  $\text{cm}^{-1}$  to 4000  $\text{cm}^{-1}$ . The purpose of characterization with infrared was to reinforce the results of chromatography with the presence of the targeted functional groups. Intensity and sharpness of peaks in IR compared to the pure n-paraffin reference spectrum. XRF was used to characterize and determine the chemical elements of minerals or to measure them. Rigaku Supermini200 XRF Instrumentation was used to mass-analyze and analyze metals and other materials (Feng et al. 2024).

### Applications Analysis of Tar

The approach used to analyze tar potential employs a property–function–need framework. The first step involves using experimental methods to determine the main properties of tar. These properties are then associated with potential functions, such as fuel, binder, or carbon material. Next, these functions are aligned with real industrial demands, such as energy, construction, or advanced materials. By matching tar’s capabilities with market needs, this approach produces realistic and highly valuable applications.

## RESULTS AND DISCUSSION

### Gasification Feedstock from MSW

Gasification feedstocks are generally derived from solid waste with a varied composition. The production of pellets from waste materials aims to increase the calorific quality and potential of waste as a fuel. In Surakarta, MSW in 2024 consists of 57.46% organic waste and 42.54% inorganic waste. The Surakarta city waste generation was 419.11 metric tons.day<sup>-1</sup> and 152,974.67 metric tons.year<sup>-1</sup> in 2023 (Rajagukguk 2020). Most of the waste processed into refuse-derived fuel (RDF) and pellets is organic waste. The gasification process begins with the processing of waste into RDF or pellets as fuel. Heterogeneous waste at the landfill is spread out to reduce the moisture content and then undergoes shredding to reduce the particle size and facilitate subsequent processes. After shredding, the material was dried to reduce the moisture content, as a high moisture content can reduce the calorific value of the fuel. The dried waste can then be compressed into pellets (pelletizing) or compressed into RDF blocks (Christanti et al. 2022, Nurfadhilah et al. 2022). The final RDF or pellet products have high calorific values and good storage stability, making them suitable for use as fuel, power generation, or in industrial boilers through gasification. This process not only reduces waste volume but also

Table 3: Result of feedstock proximate and ultimate analysis.

Sample	Pellet from MSW	Organic RDF	Mixed RDF	Unit
Proximate analysis	Content			
Moisture Content	5.90	0.80	20.00	%
Volatile matter	49.64	42.10	56.85	wt%
Fixed carbon	4.88	7.50	9.78	wt%
Ash	39.58	49.60	33.37	wt%
<b>Ultimate analysis</b>	<b>Content</b>			<b>Unit</b>
Carbon	29.89	27.60	39.21	wt%
Hydrogen	4.71	3.65	5.53	wt%
Oksigen	24.87	18.20	20.86	wt%
Nitrogen	0.90	0.92	0.73	wt%
Gross Calorific Value	3410	2580	4776	Kcal.kg <sup>-1</sup>

converts waste into energy in a more sustainable circular economy approach.

The high carbon content in pellets and RDF is due to the organic matter-rich components in MSW. RDF containing a high proportion of plastics and other organic matter tends to have a higher carbon content. The compaction process of RDF aims to increase the energy density, but can also lead to an increase in ash content due to the accumulation of inorganic materials during processing (Longo et al. 2024). An increase in carbon content in RDF is usually followed by an increase in ash content as the burnt organic matter leaves behind inorganic residues in the form of ash (Malik & Mohapatra 2013). The tested samples comprised mixed waste pellets, mixed waste RDF, and organic RDF. Each sample to be tested was first homogenized in size. The results of the proximate and ultimate test analyses of pellets from the MSW at the Putri Cempo landfill are presented in Table 3.

The main product in the gasification of MSW pellet feedstock at the Putri Cempo Landfill with a fixed-bed downdraft gasifier is syngas, which is composed of CO (24.78%), CO<sub>2</sub> (18.65%), H<sub>2</sub> (15.6%), and CH<sub>4</sub> (4.06%) at an air–fuel ratio (AFR) of 0.3 at 600–750°C. The by-product of gasification is tar, a heavy liquid compound formed during the gasification process.

The current management of tar at Putri Cempo landfill is accommodated in large storage ponds. In addition, tar is also found in some ducts, pipes, or other equipment in the system because it tends to solidify at low temperatures or when exposed to cooling, resulting in settling and blockages (Rakesh and Dasappa 2018). This can result in decreased gas flow (affecting syngas quality), decreased operational efficiency, and can even damage equipment (Zheng et al. 2017). Research by Su et al. (2020) revealed that the composition affected the syngas quality and tar yield, whereas pellets with lower plastic compositions increased

gas and H<sub>2</sub> production. A significant decrease in the tar yield of gasification by-products was observed as the ash content in the biomass increased. Ash rich in catalytic minerals increases the efficiency of the tar breakdown reaction into simpler products, thus reducing the tar problem often found in biomass gasification systems (Chan et al. 2020). According to Rakesh and Dasappa (2018), a high water content in the raw material resulted in a lower heating value (LHV) and carbon conversion efficiency (CCE). In his research, the LHV value dropped by 30% when the MSW moisture content increased from 5% to 50%.

## Composition Analysis of Tar

### GC-MS Analysis

The GC-MS instrument used to detect compounds in tar was a Shimadzu GCMS-QP2010 SE. The oven temperature was set between 50 and 270 °C at a heating rate of 10 °C per min. High-purity helium gas was used as the carrier gas at a flow rate of 1.7 mL per min. The samples analyzed by gas chromatography were ethyl acetate tar extracts, n-hexane extracts, and n-heptane extracts. The selection of extraction solvents was based on the degree of polarization between the solvent and the compound to be extracted. This type of solvent was chosen because paraffin-olefin compounds are nonpolar aliphatic alkane hydrocarbons. These compounds are easily extracted with hexane or heptane, which are good solvents. Ethyl acetate, on the other hand, generally extracts aliphatic oxygenated hydrocarbon compounds. Heptane was also used to extract paraffin and olefins from coal tar and petroleum (Zheng et al. 2017, Chan et al. 2020). These results indicate that optimal extraction results were obtained using hexane. Paraffin-olefin extracted with non-polar solvents yielded relatively high results compared to oxidized or conjugated hydrocarbon compounds. (Utami et al. 2023, Yang et al. 2023). The complete composition

of the compounds identified in each sample is shown in Table 4.

The compounds identified in the samples through gas chromatography generally include aliphatic hydrocarbons (alkanes and alkenes), oxygenated hydrocarbons (alcohols and carboxylic acids), ethers, and light aromatic hydrocarbon compounds (benzene, naphthalene, and phenanthrene). Based on the analysis of the characteristics of tar compounds, the majority of the content is dominated by aliphatic hydrocarbons in the form of alkanes and alkenes. There are also alkane derivatives, such as alcohols and carboxylic acids. Alkane/alkenes and their derivatives have been identified as hydrocarbons with carbon atom lengths  $\geq C_{13}$ , including tridecane, tetradecane, pentadecane, hexadecane, heptadecane, nonadecane, octadecane, docosane, triacontane,

and tetratetracontane. This is in accordance with the study by Ni et al. (2013), who showed that tar coal and petroleum products contain aliphatic hydrocarbon compounds, including paraffins and olefins, and can thus be used as fuels or as asphalt.

Previous studies have shown that aliphatic hydrocarbons (such as paraffins and olefins) are widely distributed in tar because they originate from the thermal degradation of lignocellulose or other complex hydrocarbon compounds during pyrolysis or carbonization (Huang et al. 2015).

Under high-temperature conditions, the C–C bonds of long aliphatic chains in organic raw materials such as biomass or coal tend to fragment into more stable saturated and unsaturated aliphatic compounds such as n-hexane and n-heptane. These compounds are non-polar and are

Table 4: Distribution of compounds detected by gas chromatography in different solvents.

Peak	Ethyl acetate tar extract		n-Hexane tar extract		n-Heptane tar extract	
	Name	Area [%]	Name	Area [%]	Name	Area [%]
1	Hexadecane (CAS)	3.61	Isotridecanol-	3.76	1-Tridecanol (CAS)	3.12
2	Tridecanol (CAS)	2.12	1-Tridecanol (CAS)	2.79	1-Heptadecene (CAS)	1.64
3	Tridecanol (CAS)	2.48	1-Tetradecene	3.20	2-Undecanethiol (CAS)	2.72
4	1-Hexadecanol	2.23	Pentadecane (CAS)	3.47	1-Pentadecene (CAS)	3.32
5	Hexadecane (CAS)	3.05	1-Pentadecane (CAS)	5.26	Tridecane	5.09
6	Benz[a]azulene	2.8	Hexadecane (CAS)	6.99	9-Octadecene, (E)	5.60
7	1-Hexadecanol (CAS)	2	1-Hexadecanol	3.59	Pentadecane (CAS)	7.98
8	Hexadecane (CAS)	2.03	1-Hexadecene (CAS)	5.40	1-Hexadecanol	3.70
9	2-Pentadecanone, 6,10,14-trimethyl (CAS)	6.76	Hexadecane (CAS)	6.36	1-Hexadecane (CAS)	5.54
10	Hexadecanoic acid, methyl ester (CAS)	12.53	1-Nonadecane (CAS)	5.34	Pentadecane (CAS)	9.38
11	1-Hexadecanol	2.67	Heptadecane	8.02	1-Heptadecane (CAS)	5.52
12	Heptadecane	3.98	Cyclooctane, 1,2-diethyl-	2.93	Pentadecane (CAS)	8.18
13	9-Octadecenoic acid, methyl ester (CAS)	9.28	Tridecanol (CAS)	8.42	2-Tetradecanol (CAS)	3.73
14	9-Octadecenoic acid, methyl ester (CAS)	9.97	1-Decanol, 2-hexyl-	7.34	Isotridecanol	7.22
15	Octadecanoic acid, methyl ester (CAS)	5.47	1-Heptadecene	4.47	Tridecanol (CAS)	6.86
16	Nonadecane (CAS)	3.38	Tetratetracontane	7.59	1-Hexadecanol	3.82
17	1,2-Benzenedicarboxylic acid, mono ester	4.83	Octadecane	3.34	Tetratetracontane	7.07
18			Hexadecanoic acid (CAS)	3.59	1-Nonadecane	2.83
19			1-Hexadecanesulfonyl chloride	2.80	Octadecane	3.83
20			1-Nonadecene (CAS)	5.36	Tridecanol (CAS)	2.85
<b>Total</b>		100.00	-	100.00	-	100.00

more easily soluble in non-polar solvents (Monir et al. 2020, Wang et al. 2022, Ridwan et al. 2024). Based on the chromatographic results, the detected compounds were classified to determine the total content of each compound group (Fig. 2).

As shown in Fig. 2, aliphatic hydrocarbon compounds (straight chains) are the most abundant compounds detected in tar samples with different solvents. Aliphatic hydrocarbon compounds of the n-alkane type in tar have the highest total content. The abundance order of n-alkanes in the tar extract based on solvent use is n-heptane > n-hexane > ethyl acetate, with total contents of 55.42%, 46.37%, and 22.96%, respectively. The second most abundant group of hydrocarbon compounds is dominated by alcohols. The alcohols detected are aliphatic compounds and are structurally alkanes with a hydroxyl group (-OH) (Spence and Vahrman 1967, Costa et al. 2018). The alcohol content was 31.30% in n-heptane, 25.90% in n-hexane, and 19.29% in ethyl acetate. Aliphatic hydrocarbon compounds, namely alkenes (having double bonds), were detected in non-polar solvents at only 10.56% and 18.43%. The presence of conjugated hydrocarbons of the carboxylic acid type was dominant in the ethyl acetate extract of tar at 42.08%. Aromatic compounds were detected at only 8.92% in EtAc and 2.93% in n-hex.

Detection of dominant aliphatic hydrocarbon compounds resulting from the thermal decomposition of MSW or biomass rich in lignocellulose, such as cellulose, hemicellulose, and lignin. These hydrocarbons are formed during thermal cracking in gasification, which breaks

down long hydrocarbons into simpler compounds (Etutu et al. 2016). Based on the aromatic compounds detected in MSW gasification tar, it is classified as class 4 tar. Class 4 tar is known for its light PAHs (2–3 aromatic rings). These compounds condense at low temperatures at low concentrations. (Li & Suzuki 2010).

Tar extraction with ethyl acetate (a polar solvent) produces many compounds detected by GC, such as conjugated hydrocarbons, such as carboxylic acids, and oxygenated hydrocarbons in the form of alcohols. In contrast, tar extraction using n-hexane and n-heptane (non-polar solvents) optimizes aliphatic hydrocarbons (straight-chain bonds), such as n-alkanes and n-alkenes (Kemalov et al. 2016, Costa et al. 2018, Wang et al. 2022). This is in accordance with the principle of van der Waals bonds (intermolecular interactions), in which compounds dissolve or are attracted based on the similarity of their polarity levels (Cao et al. 2023). Based on the objective of detecting paraffin-olefin compounds (aliphatic hydrocarbons) in tar, the solvents that provide optimal results for the extraction process are n-heptane > n-hexane > ethyl acetate. Analysis of the distribution of compound groups in tar yielded the total paraffin-olefin content, with the optimal order being n-heptane > n-hexane > ethyl acetate at 65.98% > 64.80 wt% > 22.96%.

Based on previous research, coal tar contains 70.90 wt% saturated aliphatic hydrocarbons (paraffin). Tar is utilized as an alternative fuel, namely, a substitute for diesel. The method used is thermal upgrading or pyrolysis (Sholihah, 2018). Other studies on tar derived from petroleum have

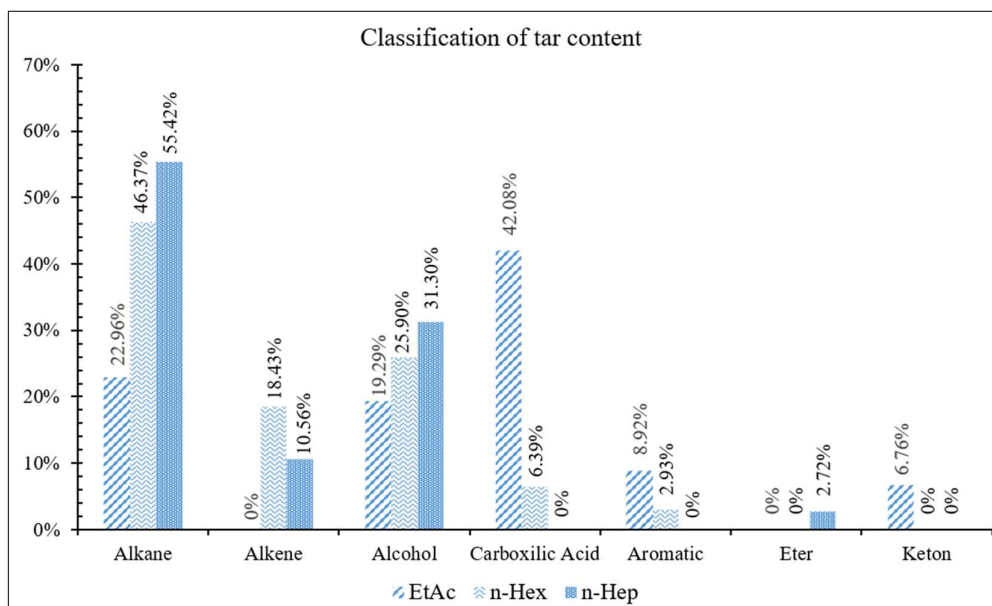


Fig. 2: Distribution of tar content groups using ethyl acetate, n-hexane, and n-heptane solvents.

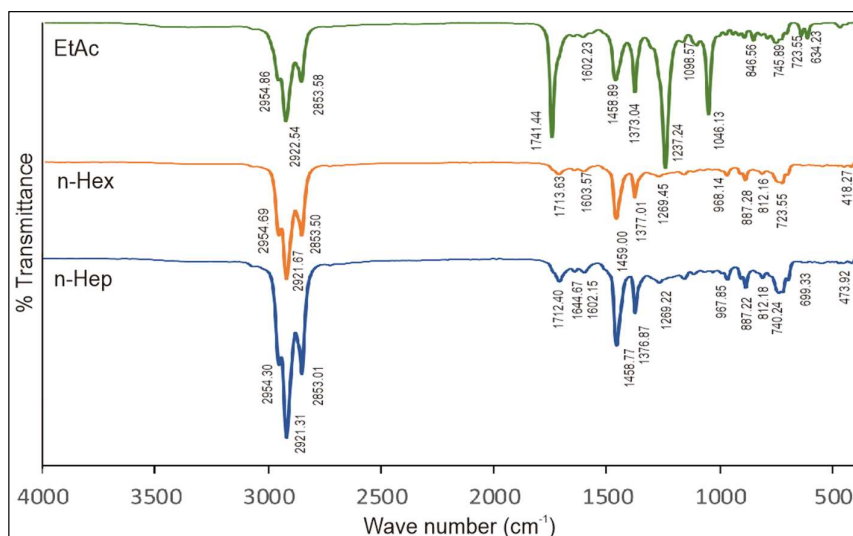


Fig. 3: The results of infrared spectrum analysis of functional group in extract samples.c33

classified the content as paraffin, naphthenic, olefin, and aromatic (National Education Department 2013). Ni et al. (2013) reported the presence of paraffin and olefin compounds in the separation and characterization of coal tar and petroleum coker. Low-temperature coal tar primarily contains di- and tri-nuclear aromatics and acenes, with urea-adjustable paraffins being largely straight-chain C10–C26, similar to higher-temperature coal tars (Bartle et al. 1990).

### FT-IR Analysis

FT-IR testing was used to identify the functional groups and chemical bonds of a compound contained in a tar extract. The instrument used was PerkinElmer Spectrum IR 10.6.1. with a comparison of liquid paraffin/olefin compound searches. The identified functional groups can represent the molecular structure of a compound. Samples were measured based on their infrared absorption spectra at a detection wavelength range of 400–4000  $\text{cm}^{-1}$ . The results of the infrared analysis of the sample are shown in the following spectra (Fig. 3).

As shown in Fig. 3, the three infrared spectra of the samples exhibited differences in the sharpness of the peak wavelength values. Peak sharpness indicates the specificity or focus of the absorption at the frequency of the compound group. The wavelength value results showed that the tar extract contained the C–H group of aliphatic hydrocarbons of the alkane group, detected at absorption wavelengths of 2850–2960  $\text{cm}^{-1}$  and 1359–1470  $\text{cm}^{-1}$ . The wavelength indicated C–H stretching of the  $-\text{CH}_2-$  and  $-\text{CH}-$  groups (paraffinic indicator). The O–H functional group of alcohol compounds was detected at wavelengths 200–3600 with low peak distribution. C–O groups supported the presence of alcohols detected at wavelengths 1080–1300  $\text{cm}^{-1}$  and

simultaneously indicated the presence of carboxylic acid compounds. The C=O group of ester and ketone compounds was present at wavelengths 1690–1760  $\text{cm}^{-1}$ . Alkenes are found at wavelengths of 1640–1680  $\text{cm}^{-1}$  with C=C stretching from olefins (double bond indicator) and at 675–1000  $\text{cm}^{-1}$  C–H stretching in alkenes. Aromatic C=C compounds are shown at wavelengths 1500–1600  $\text{cm}^{-1}$  (Schmid et al. 2012, Yang et al. 2023). Samples have a sharper peak at the absorption of wave numbers 2850–2960  $\text{cm}^{-1}$  and 1359–1470  $\text{cm}^{-1}$ , which indicates the clear frequency of alkane compounds and aligns with the total content it has. Identifying a functional group with FT-IR supports the GC-MS results that show the distribution of aliphatic and halogenated hydrocarbon groups in the tar extract sample.

Table 5 shows the distribution of functional group vibrations detected in tar samples with different solvents. The use of solvents, such as n-heptane, n-hexane, and ethyl acetate, greatly affects the distribution of functional group vibration spectra, especially for identifying paraffinic and olefinic fractions. Non-polar solvents, such as n-heptane and n-hexane, are compatible with non-polar aliphatic compounds, making them more effective at extracting paraffinic and olefinic compounds from tar (Wang et al. 2022). Ethyl acetate, which is more polar, tends to be less soluble in nonpolar compounds, such as paraffins and olefins. The FTIR spectrum of the ethyl acetate fraction tends to show carbonyl groups (C=O ~1740  $\text{cm}^{-1}$ ) and captures more aromatic or polyphenolic compounds if present, with lower intensity for aliphatic groups.

The journal Energy & Fuels noted that n-hexane is more effective in extracting  $\text{CH}_3$  and  $\text{CH}_2$  groups from paraffin

Table 5: Vibrations of the paraffin-olefin functional groups detected in the tar sample.

Vibration Type		Sample [cm <sup>-1</sup> ]		
Paraffin Vibration [cm <sup>-1</sup> ]	Reference	EtAc	n-Hex	n-Hep
C-H (alkane) 2850–2960	(Chatzipanagis et al 2024, Svečnjak et al. 2015)	2954.86	2954.30	2954.69
		2922.54	2921.31	2921.67
		2853.58	2853.01	2853.50
-CH <sub>2</sub> , -CH <sub>3</sub> Deformation 1359–1470	(Yousef et al. 2021) (Utami et al. 2023)	1458.89	1458.77	1459.00
		1373.04	1376.87	1377.01
Olefin Vibration [cm <sup>-1</sup> ]		Reference		
C=C (alkene) 1600–1680 cm <sup>-1</sup>	(Chatzipanagis et al. 2024)	1646.04	1644.67	1603.57
		1602.23	1602.15	
cis/trans alkene 675–1000	(Svečnjak et al. 2015)	912.07	968.14	967.85
		887.19	887.28	908.04
		846.56	812.16	887.22
		812.55	723.55	812.18
		784.37		740.24
		745.89		

than other solvents because of its polarity compatibility and solvation strength with non-polar compounds. Kiran (2020) noted that FTIR of tar fractions with n-heptane solvent showed sharper and more intense spectra for aliphatic C–H vibrations compared to ethyl acetate, which tends to enrich aromatic compounds.

### XRF Analysis

Tar extract samples were identified using a Rigaku XRF instrument, the process of identifying metal or mineral elements in the tar extract was carried out by filtering elements from F to U. The XRF test does not directly identify organic compounds, such as paraffin, in tar, as this technique is specifically for the analysis of inorganic elements (metals and non-metals in the form of free or bound elements). The analytical approach is that if the test results

Table 6: Results of element and oxide analysis.

EtAc tar extract	Element	%Wt	Oxide	%Wt
	Al	0.0239	Al <sub>2</sub> O <sub>3</sub>	0.0452
	Si	0.1900	SiO <sub>2</sub>	0.4060
	S	0.0937	SO <sub>3</sub>	0.2340
	Cl	0.0248	Cl	0.0248
	K	0.0277	K <sub>2</sub> O	0.0334
	H <sub>2</sub> O	99.630	H <sub>2</sub> O	99.256
n-Hep tar extract	Element	%Wt	Oxide	%Wt
	S	0.1140	SO <sub>3</sub>	0.2860
	Cl	0.0377	Cl	0.0377
	K	0.0392	K <sub>2</sub> O	0.0472
	Fe	0.0092	Fe <sub>2</sub> O <sub>3</sub>	0.0131
	Zn	0.0081	ZnO	0.0101
	Br	0.0046	Br	0.0046
	H <sub>2</sub> O	99.787	H <sub>2</sub> O	99.601

show low inorganic content, it can be assumed that the tar has a dominant organic fraction.

XRF analysis detects the amount and type of inorganic elements or minerals/metals present in the sample. The concentrations of these elements are reported as percentages that vary for each sample tested. Based on the analysis results, Table 6 shows that the metal or mineral with the highest concentration is Si or SiO<sub>2</sub> at 0.1900% wt and 0.4060% wt, respectively. The inorganic elements in the tar-hexane extract sample include detected metals, such as Al, Si, and K. The non-metallic inorganic compounds are Cl and S. As shown in Table 6, the element with the highest content is S, both in its elemental form and as an oxide, at 0.1140% wt and 0.2860% wt, respectively. The detected metal elements include K, Fe, and Zn. The inorganic non-metal compounds are S, Cl, and Br. The concentrations of these metal elements or metal oxides are relatively low. The low metal content in the test results indicates a higher organic fraction (including paraffin). If the metal content is high, the carbon and aromatic fractions will be more dominant (Wang et al. 2023).

### Potential Paraffin-Olefin in Tar and Their Applications

The total percentage of paraffin-olefin cannot be identified directly by GC-MS detection; however, the result is an organic volatile chemical compound of an aliphatic hydrocarbon that constitutes the paraffin-olefin. Paraffin, in the form of conditions, remains low in volatility. Paraffin is insoluble in water but exhibits excellent solubility in non-polar organic solvents (Utami et al. 2023, Wang et al. 2022). Paraffin-olefin usually refers to a waxy substance derived from petroleum or crude oil. The main ingredient of paraffin is composed of aliphatic hydrocarbons (straight long chains) and is a saturated hydrocarbon. Paraffin belongs to a group of saturated aliphatic hydrocarbons known as alkanes.

Chemically, paraffin consists of chains of carbon atoms bonded to hydrogen atoms. The general paraffin formula is  $C_nH_{2n+2}$ , where  $n$  denotes the number of carbon atoms in the molecule. The carbon atoms in the paraffin are arranged in a straight or isomeric chain, which causes variations in the physical properties of the paraffin (Chancelice et al. 2020). Olefins, also known as alkenes, are unsaturated aliphatic hydrocarbons that have one or more carbon-carbon double bonds. Physically, olefins are generally unsaturated, meaning they have a carbon-carbon double bond ( $C=C$ ) (Sarikoc 2020).

Characterization of tar samples using GC–MS revealed that aliphatic hydrocarbon compounds, classified as paraffin-olefin compounds, were dominant. The total alkane compounds have the highest content compared to other hydrocarbons (Fig. 2). The total content of paraffin/olefin compounds detected in the sample was 65.98 wt% in n-heptane tar extract, 64.80 wt% in n-hexane, and 22.96 wt% in ethyl acetate. This cumulative total represents significant potential for utilizing tar waste as a renewable material in the paraffin/olefin industry. However, further processing is required to obtain paraffin compounds of higher purity (Ivanova & Semenov 2020). Studies on the content of paraffin-olefins or aliphatic hydrocarbons have previously been conducted in tar from biomass gasification (Palma 2013, Veksha et al. 2019), tar coal, and tar oil (Ni et al. 2013, Chan et al. 2020).

Paraffin olefins can be obtained or purified by distillation or thermal cracking, as in a process known as petroleum distillation. Crude oil undergoes fractional distillation, where crude oil is heated and separated into several fractions based on its boiling point. Paraffin wax is obtained as one of the fractions during this process. Further purification of

paraffin wax involves removing impurities, such as oils, dyes, and odors (Adebiyi 2020, Wang et al. 2023). This refining process improves its quality and purity, making it suitable for various applications. In addition, paraffin wax can also be produced from natural gas through a process called Fischer–Tropsch synthesis (Chernyak et al. 2022). Paraffin is the most popular material for wax production because of its low cost, ease of use, and excellent combustion characteristics. Paraffin wax is used in various industries, such as rubber, textiles, adhesives, lubricants, and asphalt. These candles provide water resistance, increased flexibility, increased adhesive strength, and reduced friction (Chancelice et al. 2020, Sarikoc 2020).

Olefins have great potential as fuels for internal combustion engines, such as gasoline engines. Olefins can serve as fuels because of their higher detonation resistance (ignition resistance), making them suitable for use in high-pressure engines. Properties such as a high octane value and combustion stability also make olefins candidates for alternative fuels, especially when processed from renewable sources or by-products of other chemical processes (Yousef et al. 2021, Chernyak et al. 2022). The main methods for obtaining olefins from tar include thermal cracking reactions, such as the pyrolysis of heavy hydrocarbons, which is often used in the petrochemical industry to produce light olefins, such as ethylene and propylene. This reaction involves heating hydrocarbon feedstocks at high temperatures, breaking down their molecules into simpler olefins (Al-Yasiri & Szabó 2021). Additionally, methanol-to-olefins (MTO) is another method that utilizes the conversion of methanol to olefins using zeolite catalysts. This method provides flexibility in feedstock sources, either from fossil fuels or biomass (Zhong et al. 2021).

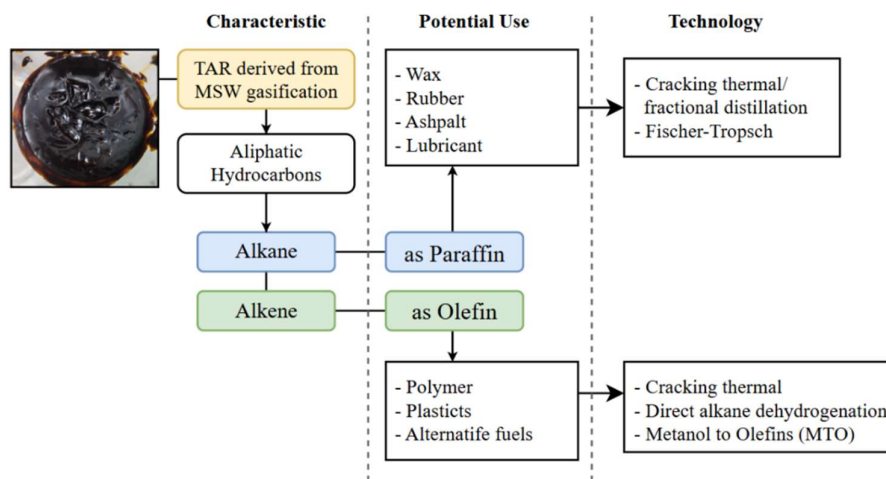


Fig. 4: Potential solutions for tar (by-product) from MSW gasification based on its compound content and processing technology for tar utilization from MSW gasification.

Based on the reported tar yields from fixed-bed MSW gasification (~12–15 kg tar per ton MSW, Huang et al. 2015) and our measured paraffin–olefin content (65.98% for n-heptane extraction), the potential recoverable paraffin–olefin fraction is estimated to be 250–300 g per kg of raw tar under >90% recovery efficiency, aligning with yields from coal tar upgrading studies (Ni et al. 2013). The energy requirements for purification via hydrocracking are estimated to be 1.8–2.5 MJ.kg<sup>-1</sup> feedstock (Chernyak et al. 2022), which could be partially offset by syngas co-firing in the gasification system.

Compounds classified as paraffin-olefins in tar can potentially be used as a mixture of industrial materials. If the paraffin-olefin contained in the tar waste is to be used, it must first be adjusted to the standard quality of the target paraffin product. Such adjustments can be made in various ways, such as purification, further processing, and the addition of certain compounds. The following is a scheme of the potential and application of tar from MSW gasification in the future (Fig. 4).

### Technology of Tar Mitigation Strategy

Regular maintenance and prevention of damage to downstream equipment in gasification are essential, as tar condenses at the thermal gasification temperature of approximately 300–400°C. Several previous studies have investigated tar-related issues using thermal and catalytic cracking methods on tar models containing toluene, benzene, or naphthalene (Min et al. 2011, Guan et al. 2016, Liu et al. 2017). Recent research suggests that catalytic cracking can utilize catalysts, such as biochar, as a tar mitigation strategy (Kastner et al. 2015).

The thermal cracking method for tar aims to break down complex organic compounds. Previous studies have indicated that the effective temperature range for tar cracking is approximately 1100–1300°C. The use of high temperatures is intended to accelerate the cracking process compared to lower temperatures (Han & Kim 2008). In a study by Brandt and Henriksen (2000), tar cracking was conducted at temperatures of 1200, 1250, and 1290°C, demonstrating that tar could be effectively reduced within 0.5 s, particularly at a minimum temperature of 1250°C.

The catalytic cracking method for tar decomposition can operate at lower thermal temperatures. This process involves the use of catalysts to break down complex hydrocarbon molecules in tar into simpler compounds. Various types of catalysts used in this method include metal oxides (NiO, Fe<sub>2</sub>O<sub>3</sub>, CeO<sub>2</sub>, TiO<sub>2</sub>), which play a role in enhancing tar reforming and reducing carbon formation (Niu et al. 2024, Wei et al. 2024). Other studies have suggested that dolomite,

calcium oxide (CaO, MgO), and biochar are often used as cost-effective catalysts with the capability to reduce tar content in gasification (Wang et al. 2025). Previous studies on catalytic tar cracking (Guan et al. 2016, Kastner et al. 2015) achieved up to 80% tar reduction using dolomite or NiO catalysts, which can be adapted to MSW-derived tar. Simulated cracking experiments using model compounds (toluene and naphthalene) could provide quantitative tar conversion data before large-scale trials.

### Future Industry and Environment Outlook

The development of gasification technology in Indonesia remains limited, posing technical, economic, and environmental challenges in managing tar from municipal solid waste (MSW) gasification. Tar consists of a complex composition containing long-chain hydrocarbons and hazardous compounds, such as polycyclic aromatic hydrocarbons (PAHs), requiring advanced purification processes, such as thermal cracking, solvent extraction, and catalytic hydrocracking (Feng et al. 2025). Catalysts, such as CaO and MgO, have been proven effective in enhancing the selectivity toward aliphatic hydrocarbons; however, they often experience deactivation due to coke formation, thereby reducing the conversion efficiency (Luo et al. 2024). Real limitations include solvent extraction's environmental footprint (VOC emissions, solvent losses), which can be mitigated via >95% solvent recovery systems (Niu et al. 2017), and the presence of heavy metals (Fe, Zn, Cl, S) detected via XRF, potentially requiring pretreatment or catalyst poisoning control (Guan et al. 2016).

The implementation of WTE in developing countries, especially in Indonesia, still faces several challenges in terms of technology and regulations. This is because gasification technology (WTE) in Indonesia is limited and is only available in Surakarta. The evaluation of these by-products is important for the evaluation and implementation of WTE technology in Indonesia. According to Achi et al. (2024), WTE technology offers a comprehensive solution for managing large amounts of waste with minimal emissions, however, the technology is expensive. The technology faces challenges in converting waste heterogeneity, thus requiring optimal maintenance. Therefore, it is necessary to emphasize integrated cooperation between the government and stakeholders to realize a shared commitment. Regulatory and policy support are crucial for the implementation and operation of WtE projects. This study highlights the evaluation of gasification by-products to enable further management, thereby supporting the realization of a circular economy.

A detailed techno-economic analysis with reference to the literature provides indicative benchmarks for cost

and performance that can guide future modeling. The purification of paraffin–olefin from MSW tar via fractional distillation and hydrocracking is estimated to require 2.5–3.2 MJ.kg<sup>-1</sup> tar of thermal energy, and operational costs are strongly influenced by solvent recovery efficiency and catalyst lifetime (Adebisi 2020, Chernyak et al. 2022). The capital expenditure for small-scale paraffin recovery units ( $\leq 5$  metric tons.day<sup>-1</sup>) ranges from USD 0.8–1.5 million, depending on process integration and automation level (Guan et al. 2016).

The economic feasibility depends on the market value of the recovered paraffin and olefins. Industrial-grade paraffin sells for USD 0.85–1.10.kg<sup>-1</sup>, whereas light olefins (e.g., propylene) can reach USD 1.2–1.8.kg<sup>-1</sup> (ICIS 2023). Based on an estimated yield of 250–300 g paraffin–olefin per kg tar, the potential gross revenue could reach USD 212–540 per metric ton of tar, assuming current market prices and high recovery efficiency.

Outcome modeling should also incorporate sensitivity analyses for MSW feedstock composition, seasonal variability, and by-product valorization (e.g., aromatic fractions). Further research should integrate life cycle cost assessment with environmental impact analysis to quantify trade-offs between economic returns and sustainability metrics (Niu et al. 2017, Wang et al. 2023). Such integrated models will be essential for guiding investment decisions and scaling strategies in Indonesian waste-to-energy projects.

The utilization of tar as a feedstock for paraffin production remains economically uncompetitive compared with petroleum-based sources because of high purification costs and lower product yields. Ongoing research efforts have focused on improving efficiency by co-processing tar with other hydrocarbon sources and optimizing catalysts to enhance durability and energy efficiency (Wang et al. 2025). Research findings on the potential of paraffin–olefin fractions derived from tar demonstrate significant prospects as an alternative source of energy and chemical feedstock from waste materials, aligning with sustainable development initiatives. Tar, a byproduct of pyrolysis processes from biomass, coal, or plastic waste, contains valuable saturated (paraffinic) and unsaturated (olefinic) hydrocarbons. Paraffinic compounds offer a high calorific value, combustion stability, and chemical inertness, whereas olefinic fractions present high reactivity suitable for petrochemical derivatives, such as waxes, lubricants, and polymer monomers. From the perspective of sustainable development goals (SDGs), the valorization of paraffin–olefin fractions contributes directly to:

- **SDG 7 (Affordable and Clean Energy)** can be achieved by utilizing waste as an alternative and

renewable energy source, thereby reducing dependence on conventional fossil fuels.

- **SDG 12 (Responsible Consumption and Production)** can be advanced by advancing the principles of the circular economy and transforming industrial and organic waste into high-value products. The selective separation and conversion of paraffin–olefin fractions align with sustainable production models and the pursuit of zero-waste industrial systems.

Moreover, this approach supports the national development priorities of Indonesia, particularly within the framework of *Nawa Cita* and the implementation of *Asta Cita*, specifically Goal 5 (accelerating infrastructure development in energy based on local resources) and Goal 7 (achieving economic self-sufficiency through strategic sectors). The use of tar as a paraffin–olefin source serves as a bridge across the energy, environmental, and downstream industrial sectors through waste-based material innovation, mitigating environmental burdens while fostering green economic opportunities at the national and regional levels.

From an environmental perspective, utilizing tar can help reduce industrial waste and dependence on petroleum. However, its purification process generates waste and consumes a significant amount of energy. Circular economy strategies, such as catalyst recycling and the development of biocatalysts, offer solutions to enhance the sustainability of this industry (Zhang et al. 2024). The utilization of tar as a paraffin precursor represents an innovative approach to converting waste into new materials. Despite various challenges, advancements in purification technologies and economic optimization could position tar as a more sustainable and eco-friendly source of paraffin in the future.

## CONCLUSIONS

Tar was a by-product of MSW gasification that contained many hydrocarbon compounds. Tar extracted using an n-hexane solvent contained various volatile organic compounds, including aliphatic hydrocarbons (alkanes and alkenes), oxygenated hydrocarbons (alcohols, ethers, and carboxylic acids), and aromatic hydrocarbons. The total content of paraffin/olefin compounds detected in the sample was 65.98 wt% in n-heptane tar extract, 64.80 wt% in n-hexane, and 22.96 wt% in ethyl acetate. This cumulative total represents significant potential for utilizing tar waste as a renewable material in the paraffin/olefin industry. Purification of paraffin/olefin from optimal tar extracted with n-heptane > n-hexane > ethyl acetate solvents. Tar from waste gasification tended to be stable because of its low content of aromatic compounds. The infrared spectrum shows clear peaks in the C–H stretching group of the –CH<sub>3</sub> and –CH<sub>2</sub>– groups (paraffin indicator),

as well as the C=C stretching group of olefins (double bond indicator). The low metal content in the test results indicates a higher organic fraction (including paraffin).

Paraffin refining is conducted through distillation or thermal cracking, in which samples are separated by boiling points in fractional distillation. Paraffin is widely used in industries such as rubber, textiles, adhesives, lubricants, and asphalt because of its water resistance, flexibility, and adhesion properties. Olefins have significant potential as alternative fuels for internal combustion engines, particularly because of their high resistance to ignition and favorable properties, such as a high octane value and combustion stability. Therefore, paraffin-olefins obtained from tar are utilized for industrial purposes; however, they require further refining and processing to meet the desired quality standards. If properly managed, the utilization of paraffin-olefin compounds from MSW gasification tar could serve as a strategic solution to urban waste challenges while providing positive economic and social impacts. This gasification technology has the potential to shift the paradigm of waste management from mere disposal to the production of high-value products that support a circular economy.

From a technological readiness perspective, the utilization of paraffin-olefin fractions from MSW gasification tar is currently at technology readiness level (TRL) 4–5, with proof-of-concept and laboratory validation completed; however, pilot-scale validation is pending. Future research priorities include (i) optimizing solvent extraction and recovery to reduce operational costs, (ii) conducting physicochemical characterization (viscosity, boiling range, and flash point) of purified fractions, (iii) testing catalytic upgrading pathways, such as hydrocracking and catalytic cracking, at the pilot scale, and (iv) integrating paraffin-olefin recovery with syngas purification to create a closed-loop system. Industrial barriers remain in the form of high purification costs compared with petroleum-derived paraffin, variability in MSW feedstock composition, limited operational experience with large-scale tar upgrading in Indonesia, and the need for stable, long-life catalysts resistant to fouling from impurities. Environmental trade-offs include solvent use and volatile organic compound (VOC) emissions during extraction, energy consumption during thermal upgrading, and secondary waste streams, such as spent catalysts. Mitigation can be achieved through solvent recovery (>95%), catalyst regeneration, and integration of renewable heat sources. Addressing these factors will be essential for moving the technology toward full-scale commercialization while maintaining alignment with SDG 7 and SDG 12 goals for sustainable energy and responsible production.

## ACKNOWLEDGMENTS

The authors would like to express their gratitude to Universitas Sebelas Maret and the Directorate General of Higher Education, Research and Technology for providing funding for this research through the scheme of Pendidikan Magister menuju Doktor Sarjana Unggul (PMDSU) Program for Fiscal Year 2024 with Contract Number: 1076.1/UN27.22/PT.01.03/2024.

## REFERENCES

- Abogunrin-Olafisoye, O.B., Adeyi, O., Adeyi, A.J. and Oke, E.O., 2024. Advanced waste-to-energy technologies: a review on pathway to sustainable energy recovery in a circular economy. *Nature Environment and Pollution Technology*, 23(3), pp.1239–1259. [DOI]
- Achi, C.G., Snyman, J., Ndambuki, J.M. and Kupolati, W.K., 2024. Advanced waste-to-energy technologies: a review on pathway to sustainable energy recovery in a circular economy. *Nature Environment and Pollution Technology*, 23(3), pp.1239–1259. [DOI]
- Adebiyi, F.M., 2020. Paraffin wax precipitation/deposition and mitigating measures in oil and gas industry: a review. *Petroleum Science and Technology*, 38(21), pp.962–971. [DOI]
- Al-Yasiri, Q. and Szabó, M., 2021. Paraffin as a phase change material to improve building performance: an overview of applications and thermal conductivity enhancement techniques. *Renewable Energy and Environmental Sustainability*, 6, p.38. [DOI]
- Bartle, K.D., Jones, D.W., Martin, T.G. and Wise, W.S., 1970. Characterisation of the neutral oil from a low-temperature coal tar. *Journal of Applied Chemistry*, 20(6), pp.197–202. [DOI]
- Bartle, K.D., Jones, D.W., Martin, T.G. and Wise, W.S., 1990. Characterisation of neutral oils from coal tar fractions. *Fuel Chemistry Journal*, 44(3), pp.210–218.
- Brandt, P. and Henriksen, U., 2000. Decomposition of tar in gas from updraft gasifier by thermal cracking. *Biomass Energy Conference Proceedings*, 1(1), pp.1–3. Available at: [http://forskningbasen.deff.dk/Share\\_external?sp=S253829e7-c40b-4230-8f9b-eb9004432101&sp=Sdtu](http://forskningbasen.deff.dk/Share_external?sp=S253829e7-c40b-4230-8f9b-eb9004432101&sp=Sdtu)
- Cao, Y., Mieres-Perez, J., Rowen, J.F., Sanchez-Garcia, E., Sander, W. and Morgenstern, K., 2023. Chirality control of a single carbene molecule by tip-induced van der Waals interactions. *Nature Communications*, 14(1), pp.1–7. [DOI]
- Čespiva, J., Wnukowski, M., Niedzwiecki, L., Skřínský, J., Vereš, J., Ochodek, T., Pawlak-Kruczek, H. and Borovec, K., 2020. Characterization of tars from a novel, pilot scale, biomass gasifier working under low equivalence ratio regime. *Renewable Energy*, 159, pp.775–785. [DOI]
- Chan, W.P., Yusoff, S.A.M.B., Veksha, A., Giannis, A., Lim, T.T. and Lisak, G., 2020. Analytical assessment of tar generated during gasification of municipal solid waste: distribution of GC–MS detectable tar compounds, undetectable tar residues and inorganic impurities. *Fuel*, 268, pp.1–10. [DOI]
- Chancelice, N.C., Philémon, Z.B., Ghislain Arnaud, M.A. and Benoît, N.M., 2020. Aliphatic hydrocarbons extraction from oily sludge using kerosene. *European Journal of Engineering Research and Science*, 5(10), pp.1137–1141. [DOI]
- Chang, T.C., Lo, K. and Karr, C.J., 1962. Gas-liquid chromatographic analysis of C10–C16 n-paraffins, isoparaffins and  $\alpha$ -olefins in a low-temperature coal tar. *Journal of Chromatographic Science*, 5(4), pp.410–418.
- Chatzipanagis, K., Omar, J. and Sanfeliciu, A.B., 2024. Assessment of beeswax adulteration by paraffin and stearic acid using ATR-IR spectroscopy and multivariate statistics—an analytical method to detect fraud. *Foods*, 13(2), pp.1–10. [DOI]

- Chen, C., Jin, Y.Q., Yan, J.H. and Chi, Y., 2010. Simulation of municipal solid waste gasification for syngas production in fixed bed reactors. *Journal of Zhejiang University: Science A*, 11(8), pp.619–628. [DOI]
- Chernyak, S.A., Corda, M., Dath, J.P., Ordonsky, V.V. and Khodakov, A.Y., 2022. Light olefin synthesis from a diversity of renewable and fossil feedstocks: state-of-the-art and outlook. *Chemical Society Reviews*, 51(18), pp.7994–8044. [DOI]
- Christanti, E.Y.I., Kumara, I.N.S. and Partha, C.G.I., 2022. Techno-economic analysis of refuse derived fuel (RDF) as waste to energy (WTE) at Pakusari landfill in Jember, East Java. *Majalah Ilmiah Teknologi Elektro*, 21(2), p.201. [DOI]
- Costa, J.C.S., Mendes, A. and Santos, L.M.N.B.F., 2018. Chain length dependence of the thermodynamic properties of n-alkanes and their monosubstituted derivatives. *Journal of Chemical and Engineering Data*, 63(1), pp.1–20. [DOI]
- Darmawan, A., Ajiwibowo, M.W., Yoshikawa, K., Aziz, M. and Tokimatsu, 2018. Energy-efficient recovery of black liquor through gasification and syngas chemical looping. *Applied Energy*, 219, pp.290–298. [DOI]
- Etutu, T.G., Laohalidanond, K. and Kerdsuwan, S., 2016. Gasification of municipal solid waste in a downdraft gasifier: analysis of tar formation. *Songklanakarin Journal of Science and Technology*, 38(2), pp.221–228.
- Evans, R.J. and Milne, T.A., 1998. Chemistry of tar formation and maturation in the thermochemical conversion of biomass. *Developments in Thermochemical Biomass Conversion*, 1(1), pp.803–816. [DOI]
- Feng, D., Zhao, Y., Zhang, Y. and Sun, S., 2017. Effects of H<sub>2</sub>O and CO<sub>2</sub> on the homogeneous conversion and heterogeneous reforming of biomass tar over biochar. *International Journal of Hydrogen Energy*, 42(18), pp.13070–13084. [DOI]
- Feng, S., Feng, Y.H., Ji, L.J., Zhan, M.X., Wang, J.Q. and Xu, X., 2024. Distribution of gasification products and emission of heavy metals and dioxins from municipal solid waste at the low temperature pyrolysis stage. *Environmental Science and Pollution Research*, 31(10), pp.16388–16400. [DOI]
- Feng, Z., Liu, K., Zhu, T., Li, D. and Zhu, X., 2025. CO<sub>2</sub>-gasification of corncob in a molten salt environment. *Chinese Journal of Chemical Engineering*, 78, pp.58–66. [DOI]
- Feng, Z., Liu, K., Zhu, T., Li, D. and Zhu, X., 2025. CO<sub>2</sub>-gasification of corncob in a molten salt environment. *Chinese Journal of Chemical Engineering*, 78, pp.58–66. [DOI]
- Guan, G., Kaewpanha, M., Hao, X. and Abudula, A., 2016. Catalytic steam reforming of biomass tar: prospects and challenges. *Renewable and Sustainable Energy Reviews*, 58, pp.450–461. [DOI]
- Han, J. and Kim, H., 2008. The reduction and control technology of tar during biomass gasification/pyrolysis: an overview. *Renewable and Sustainable Energy Reviews*, 12(2), pp.397–416. [DOI]
- Hejazi, B., Grace, J.R., Bi, X. and Mahecha-Botero, A., 2017. Kinetic model of steam gasification of biomass in a bubbling fluidized bed reactor. *Energy and Fuels*, 31(2), pp.1702–1711. [DOI]
- Huang, Q., Tang, Y., Lu, S., Wu, X., Chi, Y. and Yan, J., 2015. Characterization of tar derived from principal components of municipal solid waste. *Energy and Fuels*, 29(11), pp.7266–7274. [DOI]
- ICIS, 2023. Global petrochemical and energy market analysis. Retrieved April 2025, from <https://www.icis.com>
- Ivanova, I.K. and Semenov, M.E., 2020. Research on efficiency of solvents of paraffin deposits. *IOP Conference Series: Earth and Environmental Science*, 459(5), pp.1–10. [DOI]
- Kastner, J.R., Mani, S. and Juneja, A., 2015. Catalytic decomposition of tar using iron supported biochar. *Fuel Processing Technology*, 130, pp.31–37. [DOI]
- Kemalov, R.A., Kemalov, A.F. and Maltseva, A.G., 2016. High-melting point asphalt on the basis of high-paraffin oil tar. *Indian Journal of Science and Technology*, 9(43), pp.1–6. [DOI]
- Kiran, A., 2020. Investigation of hydrocarbons in the naphthenic and paraffinic froth treatment tailings. University of Alberta, pp.1–150.
- Li, C. and Suzuki, K., 2010. Tar property, analysis, reforming mechanism and model for biomass gasification—an overview. *Renewable and Sustainable Energy Reviews*, 13(3), pp.594–604. [DOI]
- Liu, S., Mei, D., Wang, L. and Tu, X., 2017. Steam reforming of toluene as biomass tar model compound in a gliding arc discharge reactor. *Chemical Engineering Journal*, 307, pp.793–802. [DOI]
- Liu, Z., 2019. Gasification of municipal solid wastes: a review on the tar yields. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 41(11), pp.1296–1304. [DOI]
- Longo, A., Pacheco, N., Panizio, R., Vilarinho, C., Brito, P. and Gonçalves, M., 2024. Carbonization of refuse-derived fuel pellets with biomass incorporation to solid fuel production. *Journal of Energy Materials*, 45(6), pp.746–761.
- Luo, Z., Tian, Y., Mi, L., Chen, G., Zhou, X. and Bian, A., 2024. Experimental study on wood chips gasification over Ni/dolomite. *Clean Technologies and Environmental Policy*, 26(10), pp.3567–3576. [DOI]
- Malik, A. and Mohapatra, S.K., 2013. Biomass-based gasifiers for internal combustion (IC) engines—a review. *Sadhana - Academy Proceedings in Engineering Sciences*, 38(3), pp.461–476. [DOI]
- Min, Z., Asadullah, M., Yimsiri, P., Zhang, S., Wu, H. and Li, C.Z., 2011. Catalytic reforming of tar during gasification. Part I. Steam reforming of biomass tar using ilmenite as a catalyst. *Fuel*, 90(5), pp.1847–1854. [DOI]
- Mishra, A.K., Singh, R.N. and Mishra, P.P., 2015. Effect of biomass gasification on environment. *Environmental Engineering Review*, 1(4), pp.39–49.
- Monir, M.U., Khatun, F., Ramzilal, U.R. and Aziz, A.A., 2020. Thermal effect on co-product tar produced with syngas through co-gasification of coconut shell and charcoal. *IOP Conference Series: Materials Science and Engineering*, 736(2), pp.1–10. [DOI]
- National Education Department, 2013. Oil and Gas Processing and Petrochemicals. National Education Press, pp.1–250.
- Ni, H., Hsu, C.S., Ma, C., Shi, Q. and Xu, C., 2013. Separation and characterization of olefin/paraffin in coal tar and petroleum coker oil. *Energy and Fuels*, 27(9), pp.5069–5075. [DOI]
- Niu, Y., Wang, X., Shen, J., Sheng, Q., Liu, G., Li, C. and Wang, Y., 2017. Separation of coal gasification tar residue by solvent extracting. *Separation and Purification Technology*, 188, pp.98–104. [DOI]
- Niu, Y.H., Chi, Z.Y., Li, M., Du, J.Z. and Han, F.T., 2024. Advancements in biomass gasification and catalytic tar-cracking technologies. *Materials Reports: Energy*, 4(4), p.100295. [DOI]
- Nurfadhilah, I., Marlina, L., Lutfiah, L. and Zahra, S.F., 2022. Optimization of waste-to-energy power plants based on thermal co-gasification technology with refuse derived fuel as a solution to waste and environmental problems. *COMSERVA Indonesian Journal of Community Services and Development*, 1(10), pp.850–858.
- Palma, C., 2013. Modelling of tar formation and evolution for biomass gasification: a review. *Applied Energy*, 111, pp.129–141. [DOI]
- Qin, Y.H., Feng, J. and Li, W.Y., 2010. Formation of tar and its characterization during air-steam gasification of sawdust in a fluidized bed reactor. *Fuel*, 89(7), pp.1344–1347. [DOI]
- Qodriyatun, S.N., 2021. Waste-to-energy power plants: between environmental issues and accelerating renewable energy development. *Aspirasi: Journal of Social Issues*, 12(1), pp.63–84.
- Rajagukguk, J.R., 2020. Feasibility study of waste-to-energy power plant design as a 200 MW electricity source. *Media Ilmiah Teknik Lingkungan*, 5(1), pp.51–61.
- Rakesh, N. and Dasappa, S., 2018. A critical assessment of tar generated during biomass gasification: formation, evaluation, issues and mitigation strategies. *Renewable and Sustainable Energy Reviews*, 91, pp.1045–1064. [DOI]
- Ramadhanti, N.D., Astuti, W. and Putri, R.A., 2021. The impact of the Putri Cempo landfill on residential areas. *Desa-Kota*, 3(2), pp.103–121. [DOI]

- Ridwan, M., Setyono, P. and Budiastuti, M.S., 2024. Tar derived from municipal solid waste (MSW): composition analysis and potential applications. *Asia Impact Conference Proceedings*, 16(1), pp.149–159.
- Sarikoc, S., 2020. Fuels of the diesel-gasoline engines and their properties. *IntechOpen*, pp.1–25. [DOI]
- Schmid, J.C., Wolfesberger, U., Koppatz, S., Pfeifer, C. and Hofbauer, H., 2012. Variation of feedstock in a dual fluidized bed steam gasifier—Influence on product gas, tar content, and composition. *Environmental Progress & Sustainable Energy*, 31(2), pp.205–215. [DOI]
- Shahabuddin, M. et al., 2020. Advances in the thermo-chemical production of hydrogen from biomass and residual wastes: summary of recent techno-economic analyses. *Bioresource Technology*, 299, p.122557. [DOI]
- Sholihah, A., 2018. Upgrading tar waste (from coal gasification) into synthetic liquid fuel equivalent to diesel oil. *Energy Conversion Studies*, 12(2), pp.1–20.
- Škvareková, E., Wittenberger, G. and Šofranko, M., 2016. Tar related issues in underground coal gasification. *Acta Montanistica Slovaca*, 21(4), pp.298–305.
- Sonjaya, A.N., 2021. Simulation analysis of municipal solid waste gasification using a fixed bed downdraft gasifier. Universitas Indonesia, pp.1–180.
- Spence, J.A. and Vahrman, M., 1967. Aliphatic hydrocarbons in a low-temperature tar. *Journal of Applied Chemistry*, 17(5), pp.143–146. [DOI]
- Styana, U.I.F., Indrawati, R. and Cahyono, M.S., 2019. Characterization of organic waste gasification processes with variations in material types. *Journal of Energy, Manufacturing and Materials*, 3(1), p.29. [DOI]
- Su, H., Liao, W., Wang, J., Hantoko, D., Zhou, Z., Feng, H., Jiang, J. and Yan, M., 2020. Assessment of supercritical water gasification of food waste under the background of waste sorting: influences of plastic waste contents. *International Journal of Hydrogen Energy*, 45(41), pp.21138–21147. [DOI]
- Subekti, S., Sasmito, A. and Rahman, B., 2023. Utilization of waste at the Jatibarang final processing site as a new renewable energy source. *Journal of Environmental Engineering*, 3(1), pp.31–41.
- Sukrorini, T., Budiastuti, S., Ramelan, A.H. and Kafiar, F.P., 2014. Study of the impact of waste accumulation on the environment at the Putri Cempo Surakarta final disposal site. *Jurnal EKOSAINS (Journal of Ecoscience)*, 6(3), pp.56–70.
- Suryawanshi, S.J., Shewale, V.C., Thakare, R.S. and Yarasu, R.B., 2023. Parametric study of different biomass feedstocks used for gasification process of gasifier- A literature review. *Biomass Conversion and Biorefinery*, 13(9), pp.7689–7700. [DOI]
- Svečnjak, L. et al. 2015. An approach for routine analytical detection of beeswax adulteration using FTIR-ATR spectroscopy. *Journal of Apicultural Science*, 59(2), pp.37–49. [DOI]
- Tursunov, O., Suleimenova, B., Kuspangaliyeva, B., Inglezakis, V.J., Anthony, E.J. and Sarbassov, Y., 2020. Characterization of tar generated from the mixture of municipal solid waste and coal pyrolysis at 800 °C. *Energy Reports*, 6, pp.147–152. [DOI]
- Utami, H.H., Yani, S. and Sabara, Z., 2023. The effect of n-hexane solvent extraction process on bitumen extraction from Buton asphalt as a raw material for unconventional petroleum. *Journal of Science, Technology and Environment*, 9(1), pp.35–43. [DOI]
- Valderrama Rios, M.L. et al. 2018. Reduction of tar generated during biomass gasification: a review. *Biomass and Bioenergy*, 108, pp.345–370. [DOI]
- Veksha, A., Giannis, A., Yuan, G., Tng, J., Ping, W., Chang, V.W., Lisak, G. and Lim, T., 2019. Distribution and modeling of tar compounds produced during downdraft gasification of municipal solid waste. *Renewable Energy*, 136, pp.1294–1303. [DOI]
- Vélez, C., Khayet, M. and Ortiz De Zárate, J.M., 2015. Temperature-dependent thermal properties of solid/liquid phase change even-numbered n-alkanes: n-hexadecane, n-octadecane and n-eicosane. *Applied Energy*, 143, pp.383–394. [DOI]
- Wang, B., Gupta, R., Bei, L., Wan, Q. and Sun, L., 2023. A review on gasification of municipal solid waste (MSW): syngas production, tar formation, mineral transformation and industrial challenges. *International Journal of Hydrogen Energy*, 48(69), pp.26676–26706. [DOI]
- Wang, Q., Li, T., Tian, Q., Wang, N., Wang, M., Shen, Y., Yan, L., Kong, J., Chang, L. and Bao, W., 2025. Catalytic upgrading of tar by regulating reactions of coal pyrolysis volatiles over acid-base bifunctional carbon-based composites. *Fuel*, 387, p.134328. [DOI]
- Wang, S., Jiao, T., Zhang, Y., Hao, M., Bai, G., Wang, X. and Liang, P., 2022. Recovery of paraffin from the filter cake used for paraffin decoloration in the Fischer-Tropsch synthetic process. *Fuel*, 324, p.124579. [DOI]
- Wang, X., He, X. and Wang, X., 2023. FTIR analysis of the functional group composition of coal tar residue extracts and extractive residues. *Applied Sciences*, 13(8), pp.1–10. [DOI]
- Wang, X., Shen, J., Niu, Y., Sheng, Q., Liu, G. and Wang, Y., 2016. Solvent extracting coal gasification tar residue and the extracts characterization. *Journal of Cleaner Production*, 133, pp.965–970. [DOI]
- Wei, Z., Li, Y., Zhang, Y., Liu, W., Han, K. and Sun, R., 2024. A DFT study on catalytic cracking mechanism of tar by Ni or Fe doped CaO during biomass steam gasification. *Fuel*, 374, p.132468. [DOI]
- Yang, B., Fan, X., Li, D., Cui, L., Chang, C., Yan, L., Lu, B. and Li, J., 2023. Simulation and experimental study of solid-liquid extraction of coal tar residue based on different extractants. *ACS Omega*, 8(50), pp.47835–47845. [DOI]
- Yousef, S., Eimontas, J., Zakaruskas, K. and Striūgas, N., 2021. Microcrystalline paraffin wax, biogas, carbon particles and aluminum recovery from metallised food packaging plastics using pyrolysis, mechanical and chemical treatments. *Journal of Cleaner Production*, 290, p.125878. [DOI]
- Yu, H., Zhang, Z., Li, Z. and Chen, D., 2014. Characteristics of tar formation during cellulose, hemicellulose and lignin gasification. *Fuel*, 118, pp.250–256. [DOI]
- Zhang, L., Yang, H., Tan, Q., Zhang, J., Dai, J. and Chen, Z., 2024. Base-acid tandem catalytic upgrading of coal pyrolysis volatiles: the effects of alkaline earth oxides and modified HZSM-5 zeolites. *Journal of Analytical and Applied Pyrolysis*, 183, p.106804. [DOI]
- Zheng, X., Chen, C., Ying, Z., Wang, B. and Chi, Y., 2017. Py-GC/MS study on tar formation characteristics of MSW key component pyrolysis. *Waste and Biomass Valorization*, 8(2), pp.313–319. [DOI]
- Zhong, J., Han, J., Wei, Y. and Liu, Z., 2021. Catalysts and shape selective catalysis in the methanol-to-olefin (MTO) reaction. *Journal of Catalysis*, 396, pp.23–31. [DOI]