Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

Original Research

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

ORCID author 1: https://orcid.org/0009-0001-4923-9069
ORCID author 2: https://orcid.org/0000-0001-6440-6083
ORCID author 3: https://orcid.org/0000-0002-4144-4041

Key Words	Tar, Paraffin-olefin, Municipal solid waste, Gasification
DOI	https://doi.org/10.46488/NEPT.2026.v25i02.D1838 (DOI will be active only after the final publication of the paper)
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

ABSTRACT

The main problem of gasification technology is the production of tar (by-product). Tar formation can affect the results of syngas gasification and potentially pollute the environment if not properly managed. The focus of this study is to detect paraffin-olefin content and propose mitigation strategies for tar. A compositional analysis was conducted using GC-MS, FT-IR, and XRF instruments on tar samples extracted using different solvents. The findings indicated that characterization of tar revealed the major 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 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 work uniquely targets MSW-derived tar and its direct potential as a paraffin–olefin feedstock. Tar exhibited potential as a raw material for paraffin-olefin, which was widely used in the wax, lubricant, asphalt, and fuel industries. The method of converting tar into alternative materials depends on the desired application of the tar derivatives and economic feasibility. This research contributes to SDG 7 (affordable clean energy) through potential of tar and SDG 12 (responsible production) through clean production of gasification waste.

INTRODUCTION

The current situation in Indonesia can be described as a waste emergency, as many landfills have negative impacts on the environment and society. There have been many cases of fires 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 through Waste-to-Energy (WtE) methods. Based on this, the Indonesian government is promoting the acceleration of waste management into electricity through Presidential Regulation No. 35 of 2018 concerning the acceleration of 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).

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 in processing MSW into energy (Qodriyatun 2021; Nurfadhilah et al. 2022; Subekti et al. 2023).

MSW processing in Indonesia that uses gasification is at the Putri Cempo landfill. The gasification type used is gasification technology with a fixed-bed downflow gasifier. Waste to be converted into energy is processed first into Refuse Derived Fuel (RDF) and briquettes/pellets (Sukrorini et al. 2014; Sonjaya 2021). The gasification process in raw materials undergoes oxidation with a limited amount of oxygen (partial oxidation), causing incomplete combustion. During this conversion, about 85% of the chemical energy in garbage is converted to gaseous forms, referred to as synthetic or 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, by-products of combustion in the gasification process produce residual solids of ash, charcoal, metal, or tar. The by-product, especially tar, can pollute the environment, disrupt human health, and affect the quality of 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 process of forming tar involves heating organic matter under oxygen-deprived conditions. Tar from waste/biomass gasification contains a large number of complex compounds, including aliphatic, aromatic hydrocarbons, Polycyclic Aromatic Hydrocarbons (PAHs), and phenolic compounds and their derivatives (Rakesh and Dasappa 2018; Tursunov et al. 2020). The chemical composition contained in the tar of the gasification technology process is influenced by factors such as reaction temperature, type of reactor, 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 kind of raw material and operating conditions. The difference in tar emissions emitted by gasification is affected by variations in temperature, equivalence of air ratio (ER), and MSW compositions (Feng et al. 2017; Veksha et al. 2019). Several previous studies on the characterization of tar from gasification using MSW as raw material can be seen in Table 1.

Table 1: Tar from MSW gasification composition

Characterization method	Tar composition	Reference
GC-MS (Trace GC, ISQ MS), ^{13}C-NMR	Miscellanous 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 $\geq_{C17}$ (pyrene and phenathrene), 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, acenapththylene, 1-methylnaphthalene, indene and other	(Čespiva et al. 2020)
GC-MS (HP7890 GC with 5975I 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	(Rios et al. 2018)

Previous research has been limited to the general characterization of all compounds in tar. Therefore, this study focuses on analyzing the presence of total aliphatic hydrocarbons and formulating the potential of tar according to its oil/wax-like physical characteristics. Tar from MSW gasification at low standard temperature and pressure (STP) states are liquid-solid. Aliphatic hydrocarbons such as alkane are common at low-temperature tar (Evans and Milne, 1998; Vélez et al. 2015). Based on its physical characteristics and aliphatic hydrocarbon content, tar can be explored as a source of hydrocarbons. 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 content of paraffin-olefin has been extensively studied previously in products that follow thermal processes, such as coal tar and petroleum (Ni et al. 2013; Ivanova and Semenov 2020).

Previous valorization research on coal tar (Ni et al., 2013) and petroleum coker oil (Bartle et al., 1970) identified high paraffin and olefin fractions suitable for fuel and chemical feedstock. Biomass tar studies (Huang et al., 2015; Chan et al., 2020) have focused on aromatic hydrocarbons, while MSW tar has rarely been analyzed for paraffin–olefin content. This study differs by quantifying paraffin–olefin fractions from MSW gasification tar and evaluating solvent-specific extraction performance, with implications for industrial application. The empirical difference with previous studies is the difference in tar content produced from the composition of waste in European and developed countries. Previous studies have not included quantitative identification of utilization and have only been general in nature. There has been no research on tar valorization that specializes in the paraffin-olefin content in tar from MSW Gasification.

This article will discuss the identification of the existing characteristics of raw materials in tar MSW gasification. The novelty of this research lies in its focus on analyzing paraffin-olefin compounds in tar samples (by-products). Additionally, this study will formulate the potential and 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 Goals (SDGs) 7 on affordable energy through the utilization of waste as an alternative material, as well as SDGs 12 on responsible consumption and production (clean production in the gasification process).

2. MATERIALS AND METHODS

2.1. Materials

Gasification feedstock in the form of pellets/briquettes derived from organic and inorganic municipal solid waste at the Putri Cempo landfill. The composition of the waste is mixed paper, mixed plastic, wood/ranting, leather, biomass waste, and food waste. Raw materials analysis aims to determine the Proximate and Ultimate characteristics that will affect the main and side products (tar) produced. Tar samples (by-products) from MSW gasification were obtained from Putri Cempo landfill Surakarta, Indonesia. The grab sampling method samples tar in a single container of tar from gasification with liquid-solid phase samples. The samples taken consist of liquid-solid phases (slurry) and are homogenized with various solvents. The sample contains many hydrocarbon compounds ranging from polar to non-polar, so extraction using solvents 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 purpose of the extraction is to determine the solvent and optimize the extraction of aliphatic hydrocarbon compounds (alkanes-alkenes). The solvents used to extract the tar sample are ethyl acetate, n-hexane, and n-heptane. Paraffin-olefins have non-polar properties, so the use of these solvents is justified for optimal results. (Utami et al. 2023; Yang et al. 2023). The following is the tar from waste gasification at Putri Cempo landfill, Indonesia (Fig. 1). Gasification feedstock in the form of pellets/briquettes derived from organic and inorganic municipal solid waste at the Putri Cempo landfill. The composition of the waste is mixed paper, mixed plastic, wood/ranting, leather, biomass waste, and food waste. Raw materials analysis aims to determine the Proximate and Ultimate characteristics that will affect the main and side products (tar) produced. Tar samples (by-products) from MSW gasification were obtained from Putri Cempo landfill Surakarta, Indonesia. The grab sampling method samples tar in a single container of tar from gasification with liquid-solid phase samples. The samples taken consist of liquid-solid phases (slurry) and are homogenized with various solvents. The sample contains many hydrocarbon compounds ranging from polar to non-polar, so extraction using solvents 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 purpose of the extraction is to determine the solvent and optimize the extraction of aliphatic hydrocarbon compounds (alkanes-alkenes). The solvents used to extract the tar sample are ethyl acetate, n-hexane, and n-heptane. Paraffin-olefins have non-polar properties, so the use of these solvents is justified for optimal results. (Utami et al. 2023; Yang et al. 2023). The following is the tar from waste gasification at Putri Cempo landfill, Indonesia (Fig. 1).

Fig. 1: Tar (by-product) from MSW gasification in Putri Cempo lanfill, Indonesia.

2.2. Experimental Method

2.2.1. Characterization of feedstock gasification

Testing of gasification feedstock, including Refused Derived Fuels and pellets from MSW using proximate and ultimate analysis with 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. Then, the sample was pulverized again to 1600 µm with the standard test (Tursunov et al. 2020). The purpose of this analysis is to determine the existing conditions of the raw materials and the gasification process.

Table 2: Standardized test methods

Parameter	Unit	Method
Proximate analysis		
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, adb	PO/MIN-BT/04
Gross Calorific Value	Kcal/kg, ar	
Ultimate analysis		
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

2.2.2. Characterization of tar

The sample extraction ratio is 1:10 (b/v), or 1 gram of the sample is dissolved in 10 mL of a solvent. The tar sample solution was macerated at room temperature for 1x24 hours and constantly stirred (Wang et al. 2016;

Yang et al. 2023). After that, filtration is carried out to obtain a filtrate, which is vaporized to get a tar extract using rotary evaporator. The samples analyzed by the instrument were in the form of extracts from various solvents used, namely ethyl acetate, hexane, and heptane.

The samples were then characterized with Gas Chromatography-Mass Spectrometry (GC-MS), Fourier Transform-Infrared Spectroscopy (FT-IR), and X-ray Fluorescence (XRF) instruments. GC-MS was used to identify volatile compounds, especially the aliphatic hydrocarbons that make up tar. The GC-MS instrument is a Shimadzu GCMS-QP2010 SE with a temperature of 50ºC to 270ºC and a heating rate of 10ºC per minute. High purity Helium gas is used as a carrier gas at a flow rate of 1.7 mL per minute. Gas chromatography separates compounds based on differences in the speed at which they move through the gas chromatography column. Internal calibration is performed with an n-alkane standard series (with C10–C30 n-paraffins). The results of identifying tar samples using GC-MS are components and concentration/total area of compounds that their group of compounds can then classify (Niu et al. 2017). FT-IR with Perkin Elmer Spectrum IR 10.6.1 specification using KBr pellet technology detects functional groups in tar samples. FT-IR aims to analyze compounds based on their functional groups. IR identification is performed from 400 cm^{-1} to 4000 cm^{-1}. The purpose of characterization with infrared is to reinforce the results of chromatography with the presence of the targeted functional groups. Intensity and sharpness of peaks in IR compared to pure n-paraffin reference spectrum. The purpose of using XRF is to characterize and determine the chemical elements of minerals or meet them. Rigaku Supermini200 XRF Instrumentation is used to mass-analyze and analyze metals and other materials (Feng et al. 2024).

2.2.3. Applications analysis of tar

The applied approach to analyzing tar potential uses a property-function-need approach. The first step is to use experimental methods to identify the main properties of tar. These properties are then linked to potential functions, such as fuel, binder, or carbon material. Next, these functions are mapped to real industrial needs, such as the energy sector, construction, or advanced materials. By aligning tar's capabilities with market needs, this approach yields realistic and highly valuable applications

3. RESULTS AND DISCUSSIONS

3.1. Gasification Feedstock from MSW

Gasification feedstock is generally derived from solid waste that has a varied composition mixture. Making pellets from waste material aims to increase the calorific quality and potential of waste as fuel. Surakarta's MSW composition in 2024 consists of 57.46% organic waste and 42.54% inorganic waste. Surakarta city waste generation reached 419.11 tons/day and 152,974.67 tons/year in 2023 (Rajagukguk 2020). Most of the waste processed into Refuse-Derive 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 moisture content, then undergoes shredding to reduce particle size and facilitate subsequent processes. After shredding, the material undergoes drying to reduce moisture content, as 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 value and good storage stability, making them suitable for use as fuel, power generation, or industrial boilers through gasification. This process not only reduces waste volume but also converts waste into energy in a more sustainable circular economy approach.

The high carbon content in pellets and RDF comes from 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 and Mohapatra 2013). The samples tested were 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 analysis of pellets from MSW at Putri Cempo landfill are presented in Table 3.

Table 3: Result of feedstock proximate and ultimate analysis

Sample	Pellet from MSW	Organic RDF	Mixed RDF	
Proximate analysis		**Content**		**Unit**
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%
Ultimate analysis		**Content**		**Unit**
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

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 600-750ºC. The by-product of gasification is tar, a heavy liquid compound that can form 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, so it can settle and experience 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 the pellets with lower plastic composition increased the gas and H_2 production. A significant decrease in 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 research by (Rakesh and Dasappa, 2018) the large water content in the raw material resulted in the value of lower heating value (LHV) and carbon conversion efficiency (CCE) decreasing. In his research, the LHV value dropped by 30% when the MSW moisture content increased from 5% to 50%.

3.2. Composition Analysis of Tar

3.2.1. GC-MS analysis

The GC-MS instrument used to detect compounds in tar is a Shimadzu GCMS-QP2010 SE. The oven temperature is set from 50ºC to 270ºC with a heating rate of 10ºC per minute. High-purity helium gas is used as the carrier gas at a flow rate of 1.7 mL per minute. The samples analyzed in gas chromatography were ethyl acetate tar extracts, n-hexane extracts, and n-heptane extracts. The selection of extraction solvents is based on the degree of polarization between the solvent and the compound to be extracted. The reason for choosing this type of solvent is that 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 is also used to extract paraffin and olefin from coal tar and petroleum (Zheng et al. 2017; Chan et al. 2020). These results indicate that optimal extraction results are obtained using hexane. Paraffin-olefin extracted with non-polar solvents yields 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 can be seen in Tables 4.

The compounds identified in the samples through gas chromatography generally include aliphatic hydrocarbons (alkanes, alkenes), oxygenated hydrocarbons (alcohols, carboxylic acids), ethers, and light aromatic hydrocarbon compounds (benzene, naphthalene, 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 aligns with the Research of (Ni et al. 2013), which shows that tar coal and petroleum products contain aliphatic hydrocarbon compounds, including paraffins and olefins, so they can be used as fuel or 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).

Table 5: Distribution of compounds detected by gas chromatography from different solvents.

	Ethyl acetate tar extract		n-Hexane tar extract		n-Heptane tar extract	
Peak	**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
Total		**100.00**	**-**	**100.00**	**-**	**100.00**

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

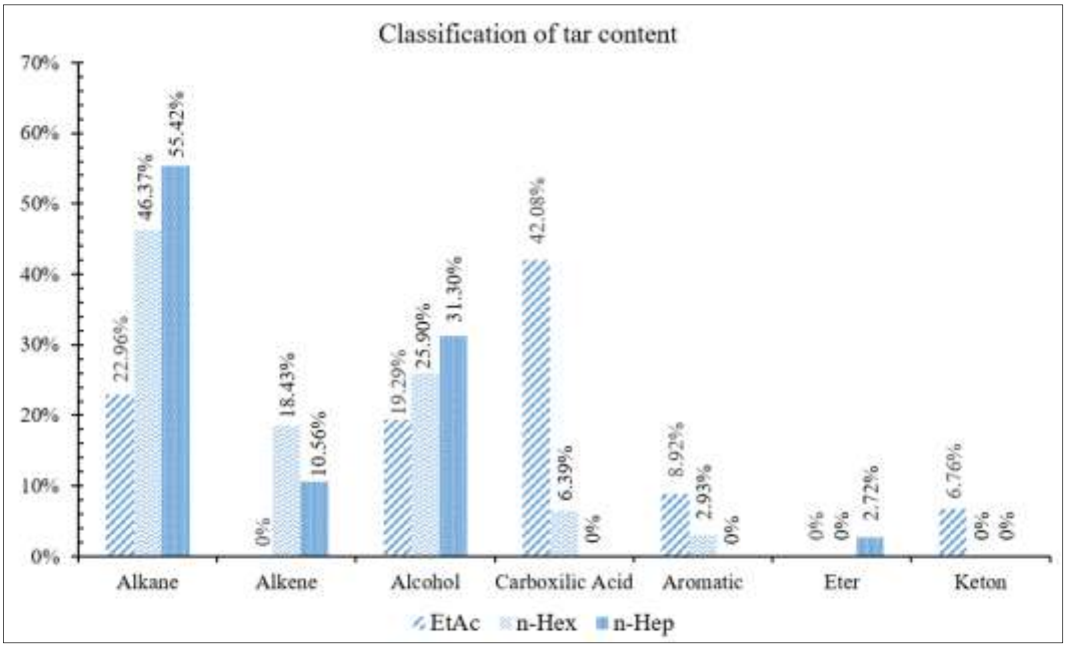

Fig. 2: Distribution of content groups in tar using ethyl acetate, n-hexane, and n-heptane solvents.

Based on Fig. 2, aliphatic hydrocarbon compounds (straight chains) are the most dominant compounds detected from 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%; 22.96%. The second most abundant group of hydrocarbon compounds is dominated by alcohols. The alcohols detected are aliphatic compounds and, structurally, are still derivatives of alkanes with a hydroxyl group (-OH) (Spence and Vahrman 1967; Costa et al. 2018). The alcohol content reached 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 only at 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.

The detection of dominant aliphatic hydrocarbon compounds resulting from the thermal decomposition of MSW or biomass rich in lignocellulose, such as cellulose, hemicellulose, and lignin. The formation of these hydrocarbons occurs 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 PAH compounds (2-3 aromatic rings). These compounds condense at low temperatures at low concentrations. (Li and Suzuki, 2010).

Tar extraction with ethyl acetate solvent (semi-polar) produces many compounds detected by GC in the form of conjugated hydrocarbons such as carboxylic acids and oxygenated hydrocarbons in the form of alcohols. Meanwhile, tar extraction using n-hexane and n-heptane solvents (non-polar) 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 aligns with the principle of van der Waals bonds (intermolecular interactions), where compounds dissolve/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, tar from coal contains a total of 70.90 wt% saturated aliphatic hydrocarbons (paraffin). The 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 mostly have classification content in the form of paraffin, naphthenic, olefin, and aromatic (National Eduation Department 2013). Ni et al. (2013) in their research, stated the presence of paraffin and olefin compounds in the separation and characterization of coal tar and petroleum coker. Low-temperature coal tar contains primarily di- and tri-nuclear aromatics and acenes, with urea-adjustable paraffins being largely straight-chain C_{10}-C_{26}, similar to higher-temperature coal tars (Bartle et al. 1990).

3.2.2. FT-IR analysis

FT-IR testing aims 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. Identified functional groups can represent the molecular structure of a compound. Samples are measured based on infrared absorption spectra at a detection wavelength range of 400-4000 cm^{-1}. The results of the infrared analysis on the sample can be seen in the following spectra (Fig. 3).

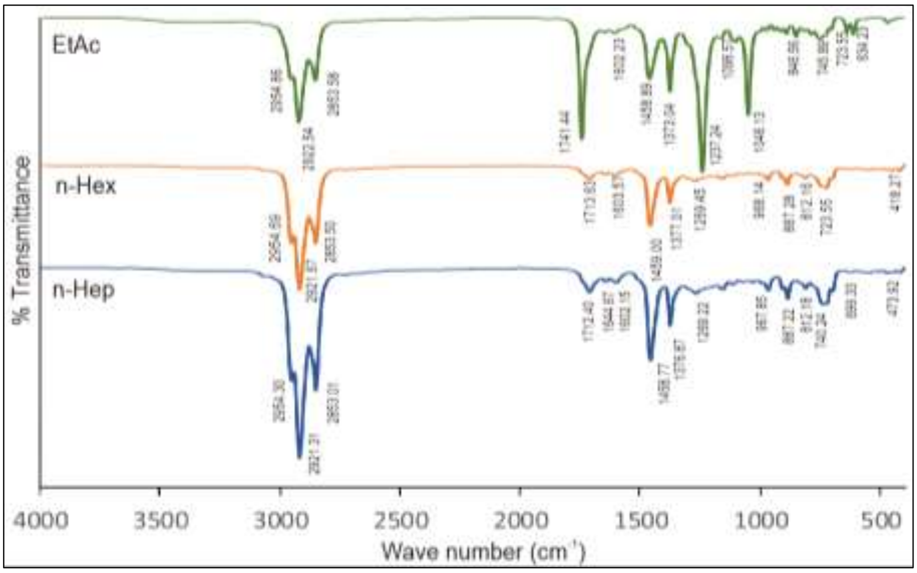

Fig. 3: The results of infrared spectrum analysis of functional group in extract samples

Based on Fig. 3, the three infrared spectra of the samples have differences in the sharpness of the peak wavelength values. Peak sharpness indicates how specific or focused the absorption is at the frequency of the compound group. The wavelength value results show that the tar extract contains the C–H group of aliphatic hydrocarbons of the alkane group detected at absorption wavelengths 2850–2960 cm^{-1} and 1359–1470 cm^{-1}. The wavelength indicates C–H stretching of the $–CH_3$ and $–CH_2–$ groups (paraffinic indicator). The O–H functional group of alcohol compounds is detected at wavelengths

200–3600 with low peak distribution. C–O groups support the presence of alcohols detected at wavelengths 1080–1300 cm^{-1} and simultaneously indicate the presence of carboxylic acid compounds. The C=O group of ester and ketone compounds is present at wavelengths 1690–1760 cm^{-1}. Alkenes are found at wavelengths of 1640–1680 cm^{-1} with C=C stretching from olefins (double bond indicator) and at 675–1000 cm^{-1} C–H stretching in alkenes. Aromatic C=C compounds are shown at wavelengths 1500–1600 cm^{-1} (Schmid et al. 2012; Yang et al. 2023). Samples have a sharper peak at the absorption of wave numbers 2850–2960 cm^{-1} and 1359–1470 cm^{-1}, this indicates the clear frequency of alkane compounds and has alignment 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 6: Vibrations of the paraffin-olefin functional group were detected in the tar sample.

Vibration Type		**Sample (cm^{-1})**		
Parafin Vibration (cm^{-1})	**Reference**	**EtAc**	**n-Hex**	**n-Hep**
C-H (alkane)	(Chatzipanagis et al 2024;	2954.86	2954.30	2954.69
2850–2960	Svečnjak et al. 2015)	2922.54	2921.31	2921.67
		2853.58	2853.01	2853.50
$-CH_2$, $-CH_3$ Deformation	(Yousef et al. 2021)	1458.89	1458.77	1459.00
1359–1470	(Utami et al. 2023)	1373.04	1376.87	1377.01
OlefinVibration (cm^{-1})	**Reference**			
C=C (alkene)	(Chatzipanagis et al. 2024)	1646.04	1644.67	1603.57
1600–1680 cm^{-1}		1602.23	1602.15	
cis/trans alkene	(Svečnjak et al. 2015)	912.07	968.14	967.85
675–1000		887.19	887.28	908.04
		846.56	812.16	887.22
		812.55	723.55	812.18
		784.37		740.24
		745.89		

Table 6 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 like n-heptane and n-hexane have polarity compatibility 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 non-polar compounds such as paraffins and olefins. FTIR of the ethyl acetate fraction tends to show carbonyl groups (C=O ~1740 cm^{-1}) and captures more aromatic or polyphenolic compounds if present, with lower intensity for aliphatic groups.

Research by (Razavian and Fatemi 2020) in the journal Energy & Fuels notes that n-hexane is more effective in extracting CH_3 and CH_2 groups from paraffin than other solvents due to 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.

3.2.3. XRF analysis

Tar extract samples were identified using a Rigaku XRF instrument, with the process of identifying metal or mineral elements in the tar extract 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 show low inorganic content, it can be assumed that the tar has a dominant organic fraction.

Table 7: Results of element and oxide analysis

	Element	%Wt	Oxide	%Wt
EtAc tar extract	Al	0,0239	Al_2O_3	0,0452
	Si	0,1900	SiO_2	0,4060
	S	0,0937	SO_3	0,2340
	Cl	0,0248	Cl	0,0248
	K	0,0277	K_2O	0,0334
	H_2O	99,630	H_2O	99,256
	Element	**%Wt**	**Oxide**	**%Wt**
n-Hep tar extract	S	0,1140	SO_3	0,2860
	Cl	0,0377	Cl	0,0377
	K	0,0392	K_2O	0,0472
	Fe	0,0092	Fe_2O_3	0,0131
	Zn	0,0081	ZnO	0,0101
	Br	0,0046	Br	0,0046
	H_2O	99,787	H_2O	99,601

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 7 shows that the metal or mineral with the highest concentration is Si or SiO_2 at 0.1900% wt and 0.4060% wt. 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. Based on Table 7, the element with the highest content is sulfur, both in its elemental form and as an oxide, at 0.1140% wt and 0.2860% wt. The detected metal elements include K, Fe, and Ze. 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).

3.3. Potential Paraffin-olefin in Tar and Their Applications

The total percentage of paraffin-olefin cannot be identified directly by GC-MS detection, but the result is an organic volatile chemical compound of the aliphatic hydrocarbon that makes paraffin-olefin. Paraffin, in the form of conditions, remains low in volatility. Paraffin is insoluble in water but exhibits excellent solubility in organic nonpolar solvents (Utami et al. 2023; Wang et al. 2022). Paraffin-olefin usually refers to a type of 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 hydro-carbon. 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, otherwise 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).

Based on the characterization of tar samples using GC-MS, aliphatic hydrocarbon compounds classified as paraffin-olefin compounds were dominant. The total alkane compounds have the highest content compared to other hydrocarbons (Figure 2). The total content of paraffin/olefin compounds detected in the sample is 65.98% in n-heptane tar extract, 64.80 wt% in n-hexane, and 22.96% in ethyl acetate. This cumulative total represents significant potential for utilizing tar waste as a renewable material in the paraffin/olefin industry. However, this requires a further processing to obtain paraffin compounds of higher purity (Ivanova and Semenov 2020). Studies on the content of paraffin-olefin or aliphatic hydrocarbons have previously been found 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 uses. In addition, paraffin wax can also be produced from natural gas through a process called the fischer–tropsch synthesis (Chernyak et al. 2022). Paraffin is the most popular material choice for wax production due to 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 in the use of these paraffins (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 due to their higher detonation resistance (ignition resistance), making them suitable for use in high-pressure engines. According to research, properties such as high octane value and combustion stability also make olefins a candidate 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 the hydrocarbon feedstock at high temperatures, breaking down its molecules into simpler olefins (Al-Yasiri and 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).

Using 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 at 250–300 g per kg of raw tar under >90% recovery efficiency, aligning with yields from coal tar upgrading studies (Ni et al., 2013). Energy requirements for purification via hydrocracking are estimated at 1.8–2.5 MJ/kg feedstock (Chernyak et al., 2022), which could be partially offset by syngas co-firing in the gasification system.

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

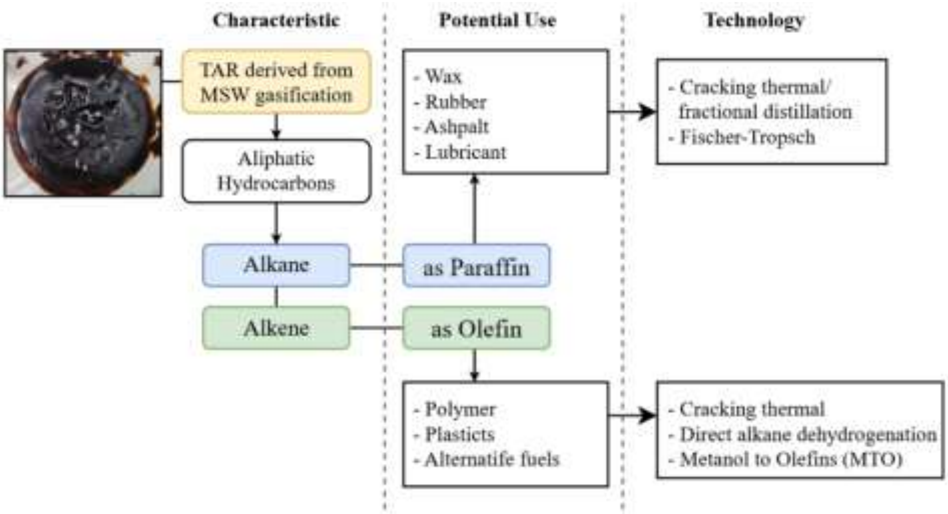

Fig. 4: Potential solutions of tar (by-product) from MSW gasification based on its compound content and processing technology for tar utilization from MSW gasification.

3.4. Technology of Tar Mitigation Strategy

Regular maintenance and prevention of damage to downstream equipment in gasification are essential, as tar can condense at the thermal gasification temperature of approximately 300–400°C. Several previous studies have investigated tar-related issues using thermal cracking 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 and 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 seconds, 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_2O_3, CeO_2, TiO_2), which play a role in enhancing tar reforming and reducing carbon formation (Niu et al. 2024; Wei et al. 2024). Other studies suggest 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, naphthalene) could provide quantitative tar conversion data before full-scale trials.

3.5. Future Industry & 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 complex compositions 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 selectivity toward aliphatic hydrocarbons; however, they often experience deactivation due to coke formation, reducing 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 pre-treatment or catalyst poisoning control (Guan et al., 2016).

The implementation of WTE in developing countries, especially Indonesia, still faces a number of challenges in terms of technology and regulations. This is because gasification technology (WTE) in Indonesia is still limited and only available in the city of Surakarta. Evaluation of these by-products is very 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, but the technology is indeed 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 is 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 literature provides indicative benchmarks for cost and performance that can guide future modeling. Purification of paraffin–olefin from MSW tar via fractional distillation and hydrocracking has been estimated to require 2.5–3.2 MJ/kg tar of thermal energy, with operational costs strongly influenced by solvent recovery efficiency and catalyst lifetime (Adebiyi, 2020; Chernyak et al., 2022). Capital expenditure for small-scale paraffin recovery units (≤5 ton/day) ranges from USD 0.8–1.5 million, depending on process integration and automation level (Guan et al., 2016).

Economic feasibility depends on the market value of recovered paraffin and olefins. Industrial-grade paraffin sells for USD 0.85–1.10/kg, while light olefins (e.g., propylene) can reach USD 1.2–1.8/kg (ICIS, 2023). Based on an estimated yield of 250–300 g paraffin–olefin per kg tar, potential gross revenue could reach USD 212–540 per 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 to petroleum-based sources due to high purification costs and lower product yields. To improve efficiency, ongoing research focuses on co-processing tar with other hydrocarbon sources and optimizing catalysts to enhance durability and energy efficiency (Wang et al. 2025). The 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, in alignment 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 high calorific value, combustion stability, and chemical inertness, while 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)** by utilizing waste as an alternative and renewable energy source, thereby reducing dependence on conventional fossil fuels.
- **SDG 12 (Responsible Consumption and Production)** by advancing the principles of the circular economy, transforming industrial and organic waste into high-value products. The selective separation and conversion of paraffin–olefin fractions aligns 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 national and regional levels.

From an environmental perspective, utilizing tar can help reduce industrial waste and dependence on petroleum. However, its purification process still generates waste and consumes a lot of energy. Circular economy strategies, such as catalyst recycling and the development of bio-catalysts, 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.

4. 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 is 65.98% in n-heptane tar extract, 64.80 wt% in n-hexane, and 22.96% 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 due to its low content of aromatic compounds. The infrared spectrum shows clear peaks in the C–H stretching group of the $–CH_3$ and $–CH_2–$ 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 was conducted through distillation or thermal cracking, where samples were separated by boiling points in fractional distillation. Paraffin was widely used in industries such as rubber, textiles, adhesives, lubricants, and asphalt due to its water resistance, flexibility, and adhesion properties. Olefins had 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-olefin obtained from tar was utilized for industrial purposes, but it required 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 had the potential to shift the paradigm of waste management from mere disposal to the production of high-value products that supported 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, but pilot-scale validation pending. Future research priorities include (i) optimizing solvent extraction and recovery to reduce operational costs, (ii) conducting physicochemical characterization (viscosity, boiling range, flash point) of purified fractions, (iii) testing catalytic upgrading pathways such as hydrocracking and catalytic cracking at 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 to 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 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.

Author Contributions: All authors contributed to the design and execution of the research. M.R.: conceptualization, material preparation, data collection, analysis, writing original draft, and editing. P.S.: conceptualization, analysis discussion, review, project administration, validation, supervision dan as corresponding author. M.S.B.: analysis discussion, review, project administration, validation, supervision. All authors discussed and commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

Funding: This research funding was provided by Directorate General of Higher Education, Research and Technology with Contract Number 1076.1/UN27.22/PT.01.03/2024. through the PMDSU (Pendidikan Magister menuju Doktor untuk Sarjana Unggul) research program scheme.

Acknowledgments: The authors would like to express their gratitude to Universitas Sebelas Maret and 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.

Conflicts 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.

REFERENCES

Achi, C. G., Snyman, J., Ndambuki, J. M., & 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), 1239–1259. https://doi.org/10.46488/NEPT.2024.v23i03.002

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. https://doi.org/10.1080/10916466.2020.1804400.

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. https://doi.org/10.1051/rees/2021040.

Bartle, K. D., Jones, D. W., Martin, T. G., & Wise, W. S. 1970. Characterisation of the neutral oil from a low-temperature coal tar. Journal of Applied Chemistry, 20(6), pp. 197–202. https://doi.org/10.1002/jctb.5010200610.

Brandt, P. and Henriksen, U. 2000. Decomposition of tar in gas from updraft gasifier by thermal cracking. 1st World Conference on Biomass for Energy and Industry, p. 3.http://forskningsbasen.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., & Morgenstern, K. 2023. Chirality control of a single carbene molecule by tip-induced van der Waals interactions. *Nature Communications*, 14(1), pp. 1–7. https://doi.org/10.1038/s41467-023-39870-y.

Čespiva, J., Wnukowski, M., Niedzwiecki, L., Skřínský, J., Vereš, J., Ochodek, T., Pawlak-Kruczek, H., & 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. https://doi.org/10.1016/j.renene.2020.06.042.

Chan, W.P. Yusoff, S. A. M. B., Veksha, A., Giannis, A., Lim, T. T., & 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(December 2019), pp. 1–10. https://doi.org/10.1016/j.fuel.2020.117348.

Chancelice, N.C. Philémon, Z. B., Ghislain Arnaud, M. A., & Benoït, N. M. 2020. Aliphatic Hydrocarbons Extraction from Oily Sludge using Kerosene. *European Journal of Engineering Research and Science*, 5(10), pp. 1137–1141. https://doi.org/10.24018/ejers.2020.5.10.1880.

Chang, T.-C. Lo and Karr, C.J. 1962. Gas-liquid chromatographic analysis of C_{10}-C_{16} n-paraffins, isoparaffins and α-olefins in a low-temperature coal tar. pp. 410–418.

Chatzipanagis, K., Omar, J. and Sanfeliu, 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). https://doi.org/10.3390/foods13020245.

Chen, C. Jin, Y. Q., Yan, J. H., & 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. https://doi.org/10.1631/jzus.A0900792.

Chernyak, S.A. Corda, M., Dath, J. P., Ordomsky, V. V., & 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. https://doi.org/10.1039/d1cs01036k.

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. https://doi.org/10.24843/mite.2022.v21i02.p07.

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. https://doi.org/10.1021/acs.jced.7b00837.

Darmawan, A. Ajiwibowo, M. W., Yoshikawa, K., Aziz, M., & Tokimatsu. 2018. Energy-efficient recovery of black liquor through gasification and syngas chemical looping. *Applied Energy*, 219, pp. 290–298. https://doi.org/10.1016/j.apenergy.2018.03.033.

National Education Department (2013) *Oil and Gas Processing and Petrochemicals.*

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*, pp. 803–816. https://doi.org/10.1007/978-94-009-1559-6_64.

Feng, D. Zhao, Y., Zhang, Y., & Sun, S. 2017 Effects of H_2O and CO_2 on the homogeneous conversion and heterogeneous reforming of biomass tar over biochar. *International Journal of Hydrogen Energy*, 42(18), pp. 13070–13084.

https://doi.org/10.1016/j.ijhydene.2017.04.018.

Feng, S. Feng, Y. H., Ji, L. jie, Zhan, M. X., Wang, J. Q., & 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, pp. 16388–16400. https://doi.org/10.1007/s11356-024-32284-3.

Feng, Z., Liu, K., Zhu, T., Li, D., & Zhu, X. 2025. CO_2-gasification of corncob in a molten salt environment. Chinese Journal of Chemical Engineering, 78, pp. 58–66. https://doi.org/10.1016/j.cjche.2024.07.027.

Guan, G., Kaewpanha, M., Hao, X., & Abudula, A. 2016. Catalytic steam reforming of biomass tar: Prospects and challenges. Renewable and Sustainable Energy Reviews, 58, pp. 450–461. https://doi.org/10.1016/j.rser.2015.12.316.

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. https://doi.org/10.1016/j.rser.2006.07.015.

Hejazi, B. Grace, J. R., Bi, X., & 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. https://doi.org/10.1021/acs.energyfuels.6b03161.

Huang, Q. Tang, Y., Lu, S., Wu, X., Chi, Y., & Yan, J. 2015. Characterization of Tar Derived from Principle Components of Municipal Solid Waste. Energy and Fuels, 29(11), pp. 7266–7274. https://doi.org/10.1021/acs.energyfuels.5b01152.

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). https://doi.org/10.1088/1755-1315/459/5/052014.

Kastner, J.R., Mani, S. and Juneja, A. 2015. Catalytic decomposition of tar using iron supported biochar. Fuel Processing Technology, 130(C), pp. 31–37. https://doi.org/10.1016/j.fuproc.2014.09.038.

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. https://doi.org/10.17485/ijst/2016/v9i43/104977.

Kiran, A. 2020. Investigation of hydrocarbons in the naphthenic and paraffinic froth treatment tailings. University of Alberta.

Li, C. and Suzuki, K. 2010. Tar property, analysis, reforming mechanism and model for biomass gasification — An overview. 13(2009), pp. 594–604. https://doi.org/10.1016/j.rser.2008.01.009.

Liu, S., Mei, D., Wang, L., & 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. https://doi.org/10.1016/j.cej.2016.08.005.

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. https://doi.org/10.1080/15567036.2018.1548508.

Longo, A. Pacheco, N., Panizio, R., Vilarinho, C., Brito, P., & Gonçalves, M. 2024. Carbonization of Refuse-Derived Fuel Pellets with Biomass Incorporation to Solid Fuel Production. pp. 746–761.

Luo, Z., Tian, Y., Mi, L., Chen, G., Zhou, X., & Bian, A. 2024. Experimental study on wood chips gasification over Ni/dolomite. Clean Technologies and Environmental Policy, 26(10), pp. 3567–3576. https://doi.org/10.1007/s10098-024-02926-8.

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. https://doi.org/10.1007/s12046-013-0145-1.

Min, Z., Asadullah, M., Yimsiri, P., Zhang, S., Wu, H., & 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. https://doi.org/10.1016/j.fuel.2010.12.039.

Mishra, A.K., Singh, R.N. and Mishra, P.P. 2015. Effect of Biomass Gasification on Environment. Transplantation, 1(4), pp. 39–49. https://doi.org/10.1097/00007890-200101270-00010.

Monir, M. U., Khatun, F., Ramzilah, U. R., & 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). https://doi.org/10.1088/1757-899X/736/2/022007.

Ni, H. Hsu, C. S., Ma, C., Shi, Q., & Xu, C. 2013. Separation and characterization of olefin/paraffin in coal tar and petroleum coker oil. Energy and Fuels, 27(9), pp. 5069–5075. https://doi.org/10.1021/ef400470v.

Niu, Y. Wang, X., Shen, J., Sheng, Q., Liu, G., Li, C., & Wang, Y. 2017. Separation of coal gasification tar residue by solvent extracting. Separation and Purification Technology, 188, pp. 98–104. https://doi.org/10.1016/j.seppur.2017.07.002.

Niu, Y. H, Chi, Z.Y., Li, M., Du, J.Z., & Han, F.T. 2024. Advancements in biomass gasification and catalytic tar-cracking technologies', Materials Reports: Energy, 4(4), p. 100295. https://doi.org/10.1016/j.matre.2024.100295.

Nurfadhilah, I. Marliana, L., Lutfiah, L., & 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 Jurnal of Community Services and Development, 1(10), pp. 850–858. https://doi.org/10.59141/comserva.v1i10.169.

Palma, C. font 2013. Modelling of tar formation and evolution for biomass gasification: A review. Applied Energy, 111, pp. 129–141. https://doi.org/10.1016/j.apenergy.2013.04.082.

Presidental Regulation Number 35 of 2018. Accelerated Construction of Waste Processing Installations into Electric Energy Based on Environmentally Friendly Technology. The Acceleration of Waste Management Installation Developers into an Environmentally Friendly Technology-Based Energy. 1, 01–18.

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. https://doi.org/10.1016/j.fuel.2009.08.009.

Qodriyatun, S.N. 2021. Waste-to-Energy Power Plants: Between Environmental Issues and Accelerating Renewable Energy Development. Aspirasi: Jurnal Masalah-masalah Sosial, 12(1), pp. 63–84. https://doi.org/10.46807/aspirasi.v12i1.2093.

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. https://doi.org/10.33084/mitl.v5i1.1371.

Rakesh, N. and Dasappa, S. 2018. A critical assessment of tar generated during biomass gasificatio-Formation evaluation, issues and mitigation strategies. Renewable and Sustainable Energy Reviews, 91(August 2016), pp. 1045–1064. https://doi.org/10.1016/j.rser.2018.04.017.

Ramadhanti, N.D., Astuti, W. and Putri, R.A. 2021. The Impact of the Putri Cempo Landfill on Residential Areas. Desa-Kota, 3(2), p. 103. https://doi.org/10.20961/desa-kota.v3i2.48352.103-121.

Razavian, M. and Fatemi, S. (2020) 'Intensified Transformation of Low-Value Residual Fuel Oil to Light Fuels with

TPABr:EG as Deep Eutectic Solvent with Dual Functionality at Moderate Temperatures', Energy and Fuels, 34(5), pp. 5497–5510. Available at: https://doi.org/10.1021/acs.energyfuels.9b04486.

Ridwan, M., Setyono, P. and Budiastuti, Mt.S. 2024. Tar derived from municipal solid waste (MSW): composition analysis and potential applications. in International Of Proceeding: The 16th Asia Impact Conference, pp. 149–159.

Sarikoc, S. 2020. Fuels of the Diesel-Gasoline Engines and Their Properties, Diesel and Gasoline Engines. https://doi.org/10.5772/intechopen.90527.

Schmid, J.C. Wolfesberger, U., Koppatz, S., Pfeifer, C., & 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. https://doi.org/10.1002/ep.

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. https://doi.org/10.1016/j.biortech.2019.122557.

Sholihah, A. 2018. Upgrading Tar Waste (from Coal Gasification) into Synthetic Liquid Fuel Equivalent to Diesel Oil.

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 (Case Study of Putri Cempo Landfill in Surakarta). Universitas Indonesia.

Spence, J.A. and Vahrman, M. 1967. Aliphatic hydrocarbons in a low-temperature tar. Journal of Applied Chemistry, 17(5), pp. 143–146. https://doi.org/10.1002/jctb.5010170506.

Styana, U.I.F., Indrawati, R. and Cahyono, M.S. 2019. Characterization of Organic Waste Gasification Processes with Variations in Material Types. Jurnal Engine: Energi, Manufaktur, dan Material, 3(1), p. 29. https://doi.org/10.30588/jeemm.v3i1.495.

Su, H. Liao, W., Wang, J., Hantoko, D., Zhou, Z., Feng, H., Jiang, J., & 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. https://doi.org/10.1016/j.ijhydene.2020.05.256.

Subekti, S., Sasmito, A. and Rahman, B. 2023. Utilization of Waste at the Jatibarang Final Processing Site as a New Renewable Energy Source. 3(1), pp. 31–41.

Sukrorini, T. Budiastuti, S., Ramelan, A. H., & Kafiar, F. P. 2014. Study of the Impact of Waste Accumulation on the Environment at the Putri Cempo Surakarta Final Disposal Site. Jurnal EKOSAINS, 6(3), pp. 56–70.

Suryawanshi, S.J. Shewale, V. C., Thakare, R. S., & 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. https://doi.org/10.1007/s13399-021-01805-2.

Svečnjak, L. et al. 2015. N approach for routine analytical detection of beeswax adulteration using FTIR-ATR spectroscopy. Journal of Apicultural Science, 59(2), pp. 37–49. https://doi.org/10.1515/JAS-2015-0018.

Tursunov, O. Suleimenova, B., Kuspangaliyeva, B., Inglezakis, V. J., Anthony, E. J., & 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. https://doi.org/10.1016/j.egyr.2019.08.033.

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. Jurnal Sains Teknologi & Lingkungan, 9(1), pp. 35–43. Available at: https://doi.org/10.29303/jstl.v9i1.415.

Valderrama Rios, M.L. et al. 2018. Reduction of tar generated during biomass gasification: A review. Biomass and Bioenergy, 108, pp. 345–370. https://doi.org/10.1016/j.biombioe.2017.12.002.

Veksha, A. Giannis, A., Yuan, G., Tng, J., Ping, W., Chang, V. W., Lisak, G., & Lim, T. 2019. Distribution and modeling of tar compounds produced during downdraft gasification of municipal solid waste. Renewable Energy, 136, pp. 1294–1303. https://doi.org/10.1016/j.renene.2018.09.104.

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. https://doi.org/10.1016/j.apenergy.2015.01.054.

Wang, B. Gupta, R., Bei, L., Wan, Q., & 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. https://doi.org/10.1016/j.ijhydene.2023.03.086.

Wang, Q., Li, T., Tian, Q., Wang, N., Wang, M., Shen, Y., Yan, L., Kong, J., Chang, L., & 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. https://doi.org/10.1016/j.fuel.2025.134328.

Wang, S., Jiao, T., Zhang, Y., Hao, M., Bai, G., Wang, X., & Liang, P. 2022. Recovery of paraffin from the filter cake used for paraffin decoloration in the Fischer-Tropsch synthetic process. Fuel, 324(PB), p. 124579. https://doi.org/10.1016/j.fuel.2022.124579.

Wang, X. lei, Shen, J., Niu, Y. xia, Sheng, Q. tao, Liu, G., & Wang, Y. gao. 2016. Solvent extracting coal gasification tar residue and the extracts characterization. Journal of Cleaner Production, 133, pp. 965–970. https://doi.org/10.1016/j.jclepro.2016.06.060.

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 (Switzerland), 13(8). https://doi.org/10.3390/app13085162.

Wei, Z., Li, Y., Zhang, Y., Liu, W., Han, K., & 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. https://doi.org/10.1016/j.fuel.2024.132468.

Yang, B., Fan, X., Li, D., Cui, L., Chang, C., Yan, L., Lu, B., & 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. https://doi.org/10.1021/acsomega.3c06290.

Yousef, S. Eimontas, J., Zakarauskas, K., & 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. https://doi.org/10.1016/j.jclepro.2021.125878.

Yu, H. Zhang, Z., Li, Z., & Chen, D. 2014. Characteristics of tar formation during cellulose, hemicellulose and lignin gasification. *Fuel*, 118, pp. 250–256. https://doi.org/10.1016/j.fuel.2013.10.080.

Zhang, L., Yang, H., Tan, Q., Zhang, J., Dai, J., & 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(June), p. 106804. https://doi.org/10.1016/j.jaap.2024.106804.

Zheng, X. Chen, C., Ying, Z., Wang, B., & 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. https://doi.org/10.1007/s12649-016-9596-z.

Zhong, J., Han, J., Wei, Y., & Liu, Z. 2021. Catalysts and shape selective catalysis in the methanol-to-olefin (MTO) reaction. Journal of Catalysis, 396, pp. 23–31. https://doi.org/10.1016/j.jcat.2021.01.027.