Vol. 27 No.2 (July 2026) 076-084
e-ISSN 2548-6101 p-ISSN 1411-318X

Jurnal Teknologi Lingkungan

Journal Homepage: ejournal.brin.go.id/JTL

Deep Eutectic Solvents from Palm Empty Fruit Bunch and Waste Cooking Oil: Synthesis, Characterization, and Catalytic Activity

Pelarut Eutektik Dalam dari Tandan Buah Kosong Sawit dan Minyak Goreng Bekas: Sintesis, Karakterisasi, dan Aktivitas Katalitik

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INFORMASI ARTIKEL

Histori artikel:
Diterima 10 Oktober 2024
Disetujui 13 Mei 2026
Diterbitkan 31 Juli 2026

Kata kunci:
Biodiesel
Minyak Jelantah
Pelarut Eutektik Dalam
Poliol
Tandan Kosong Kelapa Sawit

ABSTRAK

Deep Eutectic Solvents (DES) merupakan pelarut alternatif ramah lingkungan yang disintesis dari campuran komponen Akseptor Ikatan Hidrogen (AIH) dan Donor Ikatan Hidrogen (DIH). Pada riset ini, DES disintesis dari AIH yang diekstraksi dari abu limbah tandang kosong kelapa sawit (TKKS) dan DIH yang berasal dari poliol dalam minyak jelantah. Tujuan riset ini adalah untuk menentukan karakterisasi DES dengan variasi mol poliol dan K_2CO_3, dan untuk menguji aktivitas katalitiknya pada proses produksi biodiesel. Poliol diperoleh dari proses hidroksilasi minyak jelantah pada suhu 40°C selama 1,5 jam, sedangkan K_2CO_3 diperoleh dari hasil ekstraksi abu TKKS pada suhu 100°C selama 4 jam. DES dibentuk dari poliol dan K_2CO_3 melalui pengadukan selama 180 menit pada suhu 80°C dengan kecepatan pengadukan 300 rpm dengan variasi rasio mol AIH dan DIH yaitu 1:2, 1:3, 1:5, 1:7, dan 1:9. Pengujian aktivitas katalitik DES dilakukan dengan proses metanolisis Minyak Sawit Mentah (MSM) dengan rasio molar MSM terhadap metanol 1:20 selama 2,5 jam pada suhu 120°C dan dengan DES sebanyak 4% (berbasis MSM). DES berwujud cair tanpa endapan dan tidak berwarna dengan densitas melebihi 1 gr·mL^{-1}, viskositas pada rentang 1,18-1,76 cSt dan pH 1,1-1,45. Analisis FTIR dan NMR menunjukkan adanya ikatan hidrogen antara kalium karbonat dan poliol. DES menunjukkan aktivitas katalitik yang baik dalam produksi biodiesel, dengan menghasilkan rendemen sebesar 96,4% serta memenuhi standar mutu biodiesel (densitas dan viskositas).

ARTICLE INFO

Article history:
Received 10 October 2024
Accepted 13 May 2026
Published 31 July 2026

Keywords:
Biodiesel
Deep Eutectic Solvents
Palm Empty Fruit Bunches
Polyols
Waste Cooking Oil

ABSTRACT

A Deep Eutectic Solvent (DES) is synthesized from a mixture of hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD) components. In this study, DES was synthesized from HBA extracted from PEFB (Palm Empty Fruit Bunches) ash and HBD derived from polyol in waste cooking oil. The purpose of this study was to determine the characterization of DES with variations in the mol ratio of polyol to K_2CO_3, as well as to determine its catalytic activity in the biodiesel production. Polyol was obtained by hydroxylating waste cooking oil at 40°C for 1.5 hours. K_2CO_3 was extracted from PEFB ash. DES was formed from polyol and K_2CO_3 through stirring for 180 minutes at a temperature of 80°C with a agitation speed of 300 rpm with variations in the mol ratio of HBA:HBD, namely 1:2, 1:3, 1:5, 1:7, and 1:9. DES was tested for its catalytic activity on the methanolysis of CPO (Crude Palm Oil) with a molar ratio of CPO to methanol of 1:20 for 2.5 hours at a temperature of 120°C, with DES of 4% (based on weight of CPO). DES is a liquid without sediment and colorless, with a density exceeding 1 g·mL^{-1}, a viscosity in the range of 1.18–1.76 cSt, and a pH of 1.1–1.45. FTIR and NMR analysis indicate the presence of hydrogen bonds between potassium carbonate and polyol. DES shows good catalytic activity in biodiesel production, achieving a yield of 96.4% and meeting the quality standards (density and viscosity) for biodiesel.

1. INTRODUCTION

1.1 Background

Ionic Liquids (ILs), more commonly known as green solvents, are mixtures of organic salts composed of organic cations and anions. ILs possess superior physical and chemical properties compared to conventional solvents, such as being non-flammable, stable at high temperatures, and capable of dissolving a wide range of organic and inorganic compounds. The properties of ILs can be modified by changing the length of the alkyl chain on the cation and the type of anion used. The length of the alkyl chain on the cation affects viscosity, while variations in the anion influence the solubility of the solute. These changes in physical and chemical properties affect intermolecular interactions and the strength of cation-anion interactions. ILs are synthesized through alkylation, metathesis, and protonation reactions (Ratti, 2014). These processes are expensive and quite difficult to carry out, so a new alternative was developed: Deep Eutectic Solvents (DES), which can function as solvents or even catalysts, yielding very satisfactory results (Shaibuna & Sreekumar, 2021).

DES are solvents formed from two components: a quaternary ammonium salt and a hydrogen bond donor (HBD), mixed in a specific ratio to reach the eutectic point. Generally, DES are used as solvents in extraction processes and can also be used to separate biodiesel from free fatty acids (FFAs), unreacted oils, and unsaponifiable matter (Milenia et al., 2021). DES have advantages, including non-flammability, non-volatility, low toxicity, chemical stability, high purity, and biodegradability (Choi et al., 2011; Dai et al., 2013; Chemat et al., 2016; Skulcova et al., 2018). Compared to organic solvents (ethanol, acetone, ethyl acetate, etc.) and ILs, DES are environmentally friendly solvents with low volatility, making them non-flammable and easier to store (Plotka et al., 2020). Nevertheless, most previous research still uses pure chemicals such as choline chloride, ethylene glycol, or technical glycerol, which are relatively expensive and rely on imports. This indicates a research gap in the utilization of more sustainable local resources.

Indonesia, as the world's largest palm oil producer, generates substantial palm empty fruit bunch (PEFB) waste, most of which is burned, causing air pollution (Erivianto et al., 2016). PEFB ash is known to be rich in potassium carbonate (K_2CO_3), which has the potential to serve as a hydrogen-bond acceptor (HBA) (Naser et al., 2013). On the other hand, the consumption of cooking oil in Indonesia generates millions of liters of waste cooking oil per year (Sani, 2017), which, if disposed of improperly, can increase biological oxygen demand and chemical oxygen demand (COD) in waterways (Nindianti, 2014). Waste cooking oil, rich in fatty acids, can be converted into polyols, making it suitable for use as an HBD in the synthesis of DES (Shishov et al., 2017; Nofiyanti & Wardani, 2018).

One application of DES is as a catalyst in the biodiesel transesterification process (Milenia et al., 2021). Biodiesel is an alternative diesel fuel synthesized from a wide variety of vegetable or animal oils. Additionally, biodiesel is an environmentally friendly fuel that contains no hazardous substances, is biodegradable, and produces lower exhaust gas emissions than diesel fuel (Milenia et al., 2021). The transesterification process releases glycerine from the oil, and the free fatty acids are then reacted with alcohol to form methyl esters using a base catalyst (Shanthini et al., 2025). In the transesterification reaction, the carbon chain of vegetable oil is broken down by the catalyst, causing the ester chains of the vegetable oil to be released, resulting in a reaction with alcohol and the formation of biodiesel in the form of methyl esters, as well as the byproduct glycerol (Wang et al., 2023).

Based on these conditions, this research proposes a new approach by using PEFB waste and cooking oil waste as components of DES. The combination of K_2CO_3 from PEFB ash and polyols from waste cooking oil conversion has the potential to produce DES with suitable physicochemical properties and high catalytic activity in biodiesel transesterification reactions. This approach differs from previous research that still relies on pure chemicals, as studied by Naser et al. (2013) and Arita et al. (2026), thus providing added value through the integration of the waste-to-wealth concept with the principles of green chemistry. Thus, this research positions itself at the state of the art of DES-based green catalyst development, while also contributing to reducing environmental pollution and strengthening the independence of the national biodiesel industry.

1.2 Research Objectives

This research aims to synthesize DES from a mixture of polyols (hydroxylated waste cooking oil) with potassium carbonate (PEFB ash extract), characterize the DES, and determine their catalytic activity in biodiesel production.

2. METHOD

2.1 Tools and Materials

The tools used in this research are a hot plate, a three-necked round-bottom flask, a Liebig condenser, beaker glass, a erlenmeyer, a separating funnel, a glass funnel, a measuring flask, a magnetic stirrer, a thermometer, a dropper pipette, an analytical balance, an oven, a pycnometer, a pH paper, a pH meter, a stirring rod, and an Ostwald viscometer. The materials used include waste cooking oil, distilled water, sodium hydroxide, sulfuric acid, formic acid, hydrogen peroxide (H_2O_2), PEFB, crude palm oil (CPO), and methanol.

2.2 Research Procedure

The research was conducted in several stages as follows:

1. Hydroxylation of waste cooking oil

Waste cooking oil was analyzed for the composition of chemical compounds it contains using GC-MS (Gas Chromatography - Mass Spectra). The process of waste oil hydroxylation as described by Nofiyanti and Wardani (2018). A total of 300 mL of waste cooking oil was placed into a three-necked flask equipped with a heater, stirrer, and condenser. After reaching 40°C, 412 mL of 90% formic acid solution and 38 mL of 50% H_2O_2 solution were added. The reaction lasted for 1.5 hours. After the reaction is complete, decantation is performed to separate the polyol (located in the upper layer) from the lower layer, followed by purification of the polyol by washing with distilled water until the pH is neutral.

Subsequently, the polyol solution is analyzed for chemical compound composition using GCMS Shimadzu QP2010 with RTX-5 MS columns (30 × 0.25 mm × 0.25 μm) and an AOC-20i auto-injector, and for functional group analysis using FTIR Perkin Elmer UATR in the frequency range of 4000 to 500 cm^{-1}.

2. Extraction of potassium carbonate from PEFB ash

The process of extracting potassium carbonate from PEFB ash is based on Sanjaya et al. (2017). This process begins by drying 60 grams of PEFB ash in an oven at 105°C for 2 hours, then weighing 50 grams of the dried ash and placing it in a beaker containing 250 mL of distilled water. Next, heating was carried out at 100°C with stirring for 4 hours. The mixture is filtered using filter paper. The extract filtrate was analyzed for potassium content using AAS (Atomic Absorption Spectroscopy).

3. DES synthesis

The synthesis of DES was carried out by mixing potassium carbonate (from PEFB ash) and polyol (from waste cooking oil) at molar ratios of 1:2, 1:3, 1:5, 1:7, and 1:9. The mixture was homogenized for 3 hours at 300 rpm and 80°C. The mixture was decanted to separate the bottom layer (which was a clear and colorless liquid).

4. Determination of the physicochemical properties of DES

The synthesized DES was characterized by performing density, viscosity, and pH tests, functional group analysis with FTIR (Perkin Elmer UATR) in the 4000-500 cm^{-1} range, and molecular structure analysis with NMR (Nuclear Magnetic Resonance) on a JNM-ECZ500R spectrometer using D2O as solvent.

5. Testing the catalytic activity of DES in the production of biodiesel from CPO

The process of biodiesel production from CPO is based on the best reaction conditions reported by Miao et al. (2009). The process begins by mixing methanol and the DES catalyst (4% w/w relative to CPO) in a three-necked flask to 50°C, then adding CPO. The transesterification reaction is carried out at a methanol-to-CPO molar ratio of 20:1, a reaction temperature of 120°C, a reaction time of 2.5 hours, and a stirring speed of 400 rpm. After the reaction is complete, the reaction mixture is separated using a separatory funnel and purified until methyl ester (biodiesel) is obtained. The resulting biodiesel was then tested for density, viscosity, pH, yield, and chemical composition using GC-MS (Shimadzu QP2010) with RTX-5 MS columns (30 × 0.25 mm × 0.25 μm) and an AOC-20i auto-injector.

3. RESULTS AND DISCUSSION

3.1 Hydroxylation of Cooking Oil

The waste cooking oil to be used for the hydroxylation process was analyzed for its chemical compound composition using GC-MS, and the results are shown in Figure 1. The peaks formed represent the composition of each component, allowing for the review of the composition and type of compounds contained (Table 1). Table 1 revealed that waste cooking oil is dominated by fatty acids and contains a contaminant, namely glycidyl palmitate. The saturated fatty acid content is 53.02%, and the unsaturated fatty acid content is 40.32%. This is consistent with the statement by Ramdja et al. (2010) that the saturated fatty acid content in waste cooking oil is higher than the unsaturated fatty acid content. The composition of unsaturated fatty acids in waste cooking oil is 30%, while saturated fatty acids are 70%. This is because some of the double bonds become saturated during the frying process. Long-term use of oil and repeated frying can cause the double bonds to oxidize, forming peroxide groups and cyclic monomers.

Table 1. Waste cooking oil compounds

Peak	Compound	Formula	Composition (%)
1 and 6	Stearic acid	$C_{18}H_{36}O_2$	7.26
2, 3, and 4	Palmitic acid	$C_{16}H_{32}O_2$	45.31
5	Oleic acid	$C_{18}H_{34}O_2$	40.32
7	Arachidic acid	$C_{20}H_{40}O_2$	0.45
8	Glycidyl palmitate	$C_{19}H_{36}O_3$	6.66

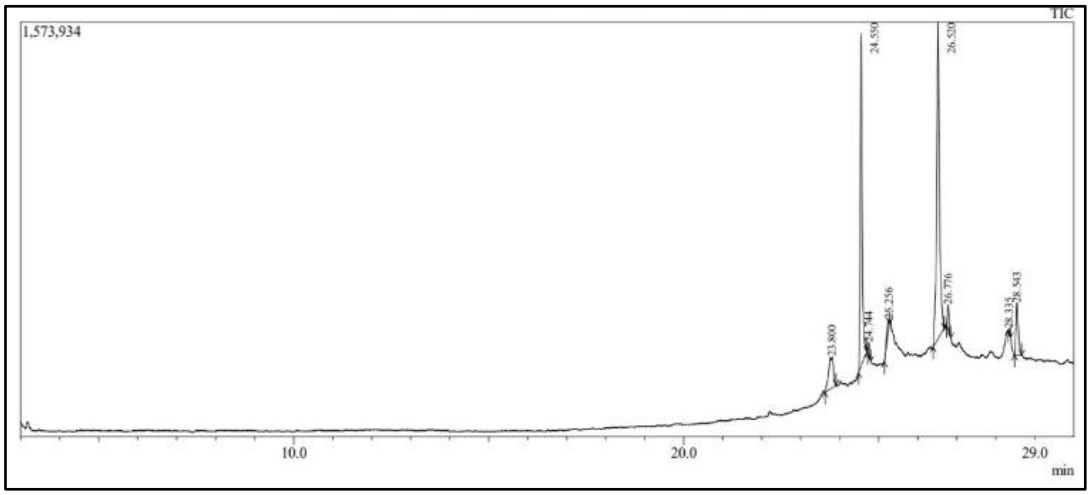

Figure 1. Gas chromatography of waste cooking oil

Polyols are produced from waste oil via a hydroxylation process using formic acid and hydrogen peroxide. The resulting polyol is a liquid, odorless, and yellowish. The infrared spectrum of the polyol produced from waste oil hydroxylation is shown in Figure 2, indicating hydrogen-bond interactions at 3743.38 cm-1. The -OH group will later bond with the anion from HBA to form DES. The chromatogram of the chemical compounds in the polyol obtained from the hydroxylation of used cooking oil by GC-MS is shown in Figure 3, and its composition is shown in Table 2. Peaks 14 and 16 indicate presence of the polyol 2-nitro-1-octanol.

Table 2. Hydroxylation of waste cooking oil compounds

Peak	Compound	Formula	Composition (%)
1	Hexanal	$C_6H_{12}O$	0.59
2	Hexane nitrile	$C_6H_{11}N$	0.13
3	Valeric acid	$C_5H_{10}O_2$	0.08
4	Heptanal	$C_{20}H_{40}O_2$	0.45
5	Heptano nitrile	$C_7H_{13}N$	0.09
6	Caproic acid	$C_6H_{12}O_2$	0.22
7	Octanal	$C_8H_{16}O$	0.1
8	1-nitro hexane	$C_6H_{13}NO_2$	0.52
9	Oxana nitrile	$C_8H_{15}N$	0.44
10	Nonanal	$C_9H_{18}O$	27.08
11	1-nitro heptane	$C_7H_{15}NO_2$	0.18
12	1-isocianat dodecana	$C_{13}H_{25}NO$	0.5
13	Nonana nitrile	$C_9H_{17}N$	1.05
14 and 16	2-nitro-1-octanol	$C_8H_{17}NO_3$	6.07
15	Pelargonic acid	$C_9H_{18}O_2$	1.23
17	9-oksononanoate acid	$C_9H_{16}O_3$	5.07
18	Lauric acid	$C_{12}H_{24}O_2$	0.6
19	6-nitroundec-5-ene	$C_{11}H_{21}NO_2$	0.89
20	Myristic acid	$C_{14}H_{28}O_2$	1.98
21	Palmitic acid	$C_{16}H_{32}O_2$	33.19
22	Oleic acid	$C_{18}H_{34}O_2$	9.63
23	Stearic acid	$C_{18}H_{36}O_2$	7.93
24	Glycidyl palmitate	$C_{19}H_{36}O_3$	0.65
25	Oxirane octanoic acid	$C_{18}H_{34}O_3$	0.73

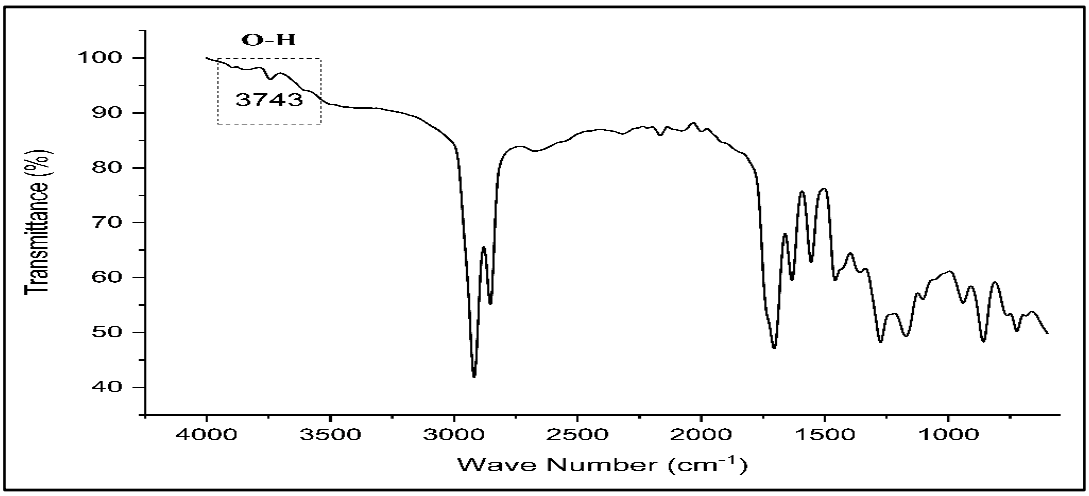

Figure 2. FTIR Spectrum of hydroxylation of waste cooking oil

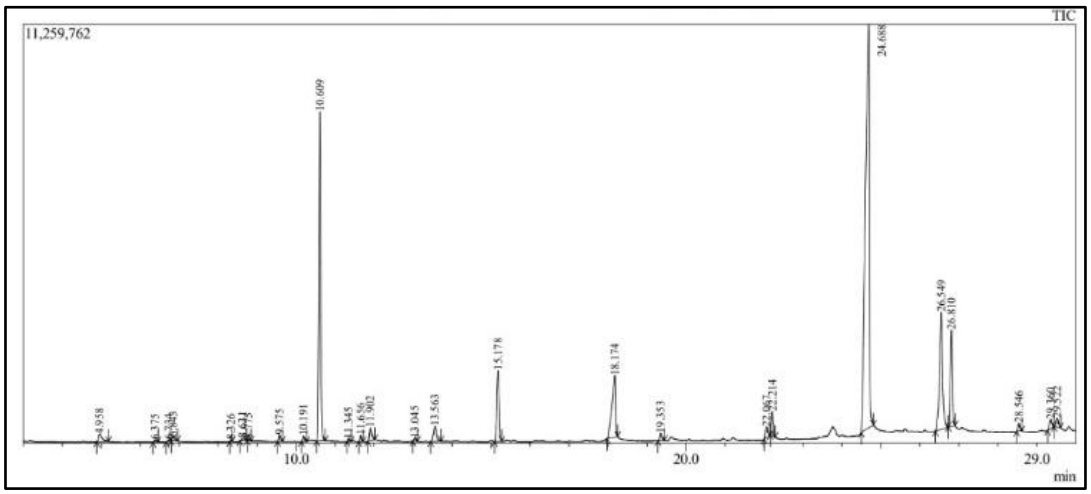

Figure 3. Gas chromatography of hydroxylation of waste cooking oil

3.2 Extraction of Potassium Carbonate from PEFB Ash

Potassium carbonate extracted from PEFB ash is a liquid, colorless compound. Potassium content analysis conducted by atomic absorption spectrophotometry showed a peak at 766.17 nm (Figure 4), indicating the presence of potassium in the extraction solution from palm oil empty fruit bunches ash. Potassium concentration values are shown in Table 3.

Table 3. Potassium concentration by using AAS analysis

Sample	X	Concentration (ppm)	Absorbance	%RSD
Potassium Carbonate	50	7.1966	2.2034	3.24
		5.3395	1.6348	
		7.5340	2.3067	
		7.3652	2.2550	

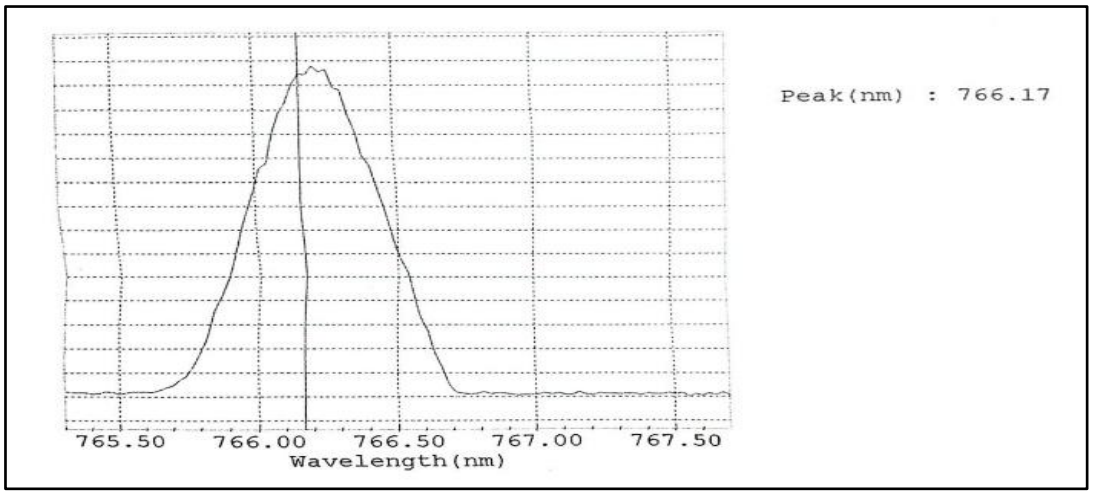

Figure 4. Atomic absorption spectroscopy of potassium carbonate

According to Daulay and Wahyuni (2021), to determine mineral concentration, the sample is first diluted with different dilution factors. The dilution factor for determining potassium content is 50. Based on Table 3, the potassium concentration is 368.26 ppm. This potassium ion will later bind to the -OH group of the HBD to form DES. Potassium carbonate was also pH-determined using a pH meter, yielding a pH of 9.44.

3.3 Deep Eutectic Solvents (DES) Synthesis

The formation of DES occurs when H+ ions from the HBD, which is the polyol, bind with CO32- anions from the HBA, which is potassium carbonate. They bind via hydrogen bonds due to the difference in electronegativity between hydrogen and the carbonate atom. The stable and homogeneous DES was analyzed to determine its physical and chemical properties, including density, viscosity, and pH as shown in Table 4. The density of DES from potassium carbonate (from palm oil empty fruit bunch ash) and polyol (from waste cooking oil) increases with increasing HBD (polyol) content. The density of DES from a mixture of betaine monohydrate and glycerol also increases with increasing HBD (Zahrina et al., 2018a). However, the opposite is true for DES from a mixture of betaine monohydrate and organic acid (Zahrina et al., 2018b).

Table 4. Physico-chemical Properties of DES

DES Molar Ratio	Density (g·mL^{-1})	Viscosity (cSt)	pH
1:2	1.050	1.18	1.45
1:3	1.054	1.25	1.43
1:5	1.078	1.25	1.18
1:7	1.087	1.76	1.10
1:9	1.089	1.71	1.28

DES at a 1:2 molar ratio has the lowest viscosity among the other ratios, at 1.18 cSt. According to Zhang et al. (2012), the viscosity of DES is influenced by the number of hydroxyl groups in the HBD. Additionally, DES with low viscosity is more desirable because it allows molecules to move easily, resulting in greater interaction with reacting substances due to the free volume in the DES molecules.

The pH of the resulting DES is low (pH < 7), so it can be used as an acid catalyst in the biodiesel production process. According to Ching et al. (2007), the high acidity of a catalyst also increases its catalytic activity, thereby accelerating the reaction rate in biodiesel production. According to Arita et al. (2026), a DES product is successful if a clear solution free of sediment is produced, with the density analysis results exceeding the densities of its constituent compounds. The resulting DES is liquid, sediment-free, colorless, stable, and homogeneous, with a density greater than that of the polyol (0.97 g·mL-1).

Functional group analysis by FTIR was also conducted to observe structural changes and hydrogen-bonding interactions between the anions in potassium carbonate and the hydroxyl groups of the polyol. The infrared spectrum in Figure 5 shows the presence of hydrogen bond interactions in the DES. The hydroxyl groups (-OH) in DESs with increasing numbers of HBDs showed a peak shift to lower wavenumbers. This indicates that the DES has stronger intermolecular interactions as the number of HBDs increases. A similar trend also occurred in the DES from a mixture of betaine monohydrate and polyol (Zahrina et al., 2018c).

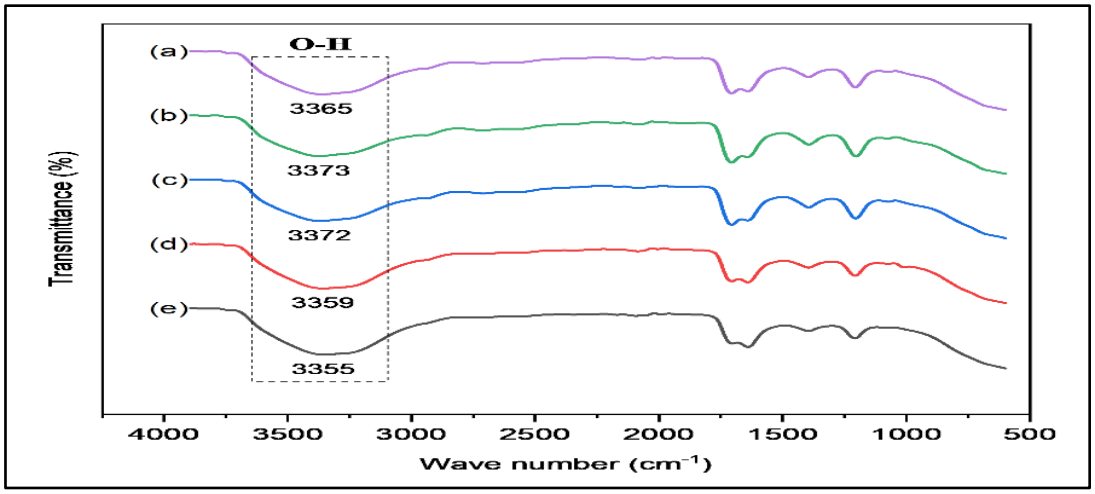

Figure 5. FTIR Spectrum of DES at molar ratio of HBA:HBD (a) 1:2, (b) 1:3, (c) 1:5, (d) 1:7, (e) 1:9

In addition to FTIR, the molecular structure and dynamics were analyzed using Nuclear Magnetic Resonance (NMR) spectroscopy on 1H and NOESY spectra, as shown in Figure 6. The 1H NMR spectrum was used to determine the type, quantity, and molecular structure of DES. Figure 6 shows the chemical shifts (δ) indicating the composition of H atoms in DES. Each of these compositions is shown Table 5. In the 1H spectrum, the chemical shifts (δ ppm) of DES were assigned to 1.239, 1.277, 1.28, 1.38, 3.868, 3.959, and 4.142 ppm as alcohols. Meanwhile, the shift at 1.446 was identified as a carbonyl, indicating that one H atom is bonded to the carbon. NOESY-NMR analysis was performed to obtain data on proton interactions within the DES molecule. In NOESY-NMR, proton relationships within the DES molecule can be observed in two dimensions. In the eutectic composition of potassium carbonate and polyol mixtures, there is an interaction between the protons of the potassium carbonate group and the protons of the polyol group. The interaction between the protons of the methyl group in betaine monohydrate as HBA and the methyl and methylene protons in propionic acid as HBD was also identified in the DES of betaine monohydrate and propionic acid mixtures through NOESY-NMR (Zahrina et al., 2017).

Table 5. ^{1}H NMR and Chemical Shifts Formed in DES

Chemical Shift (δ)	Multiplicity	Number of H	Group
1.239	QUINT	1	RO – H
1.239	QUINT	1	RO – H
1.277	H	1	RO – H
1.277	H	1	RO – H
1.28	TT	1	RO – H
1.28	TT	1	RO – H
1.38	QUINT	1	RO – H
1.38	QUINT	1	RO – H
1.446	TD	1	RC – H
1.446	TD	1	RC – H
3.868	-	1	RO – H
3.868	-	1	RO – H
3.959	TT	1	RO – H
4.142	D	1	RO – H
4.142	D	1	RO – H

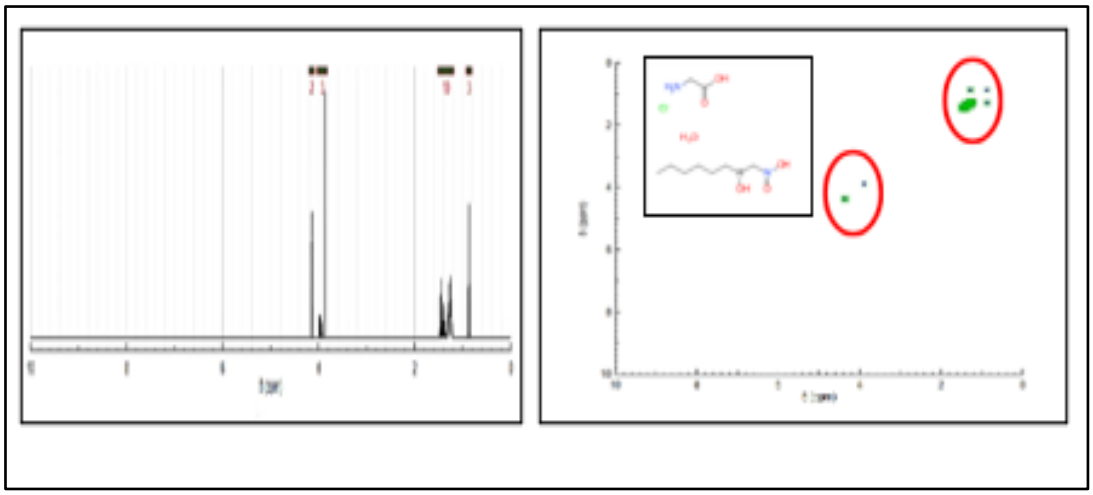

Figure 6. Spectrum of (a) ^{1}H and (b) NOESY NMR of DES

3.4 Application of DES in the Biodiesel Production from CPO

The resulting DES were used to produce biodiesel from CPO. The resulting biodiesel was a yellow liquid. The chemical composition of biodiesel was analyzed by GC-MS, as shown in Figure 7. The biodiesel content in this research is dominated by methyl esters at 94.76% and fatty acids (tetra-decanoic acid and octadecanoic acid) at 5.24%. The methyl ester components are methyl hexa-decanoate (65.92%), methyl stearate (28.03%), and methyl tetra-decanoate (0.81%).

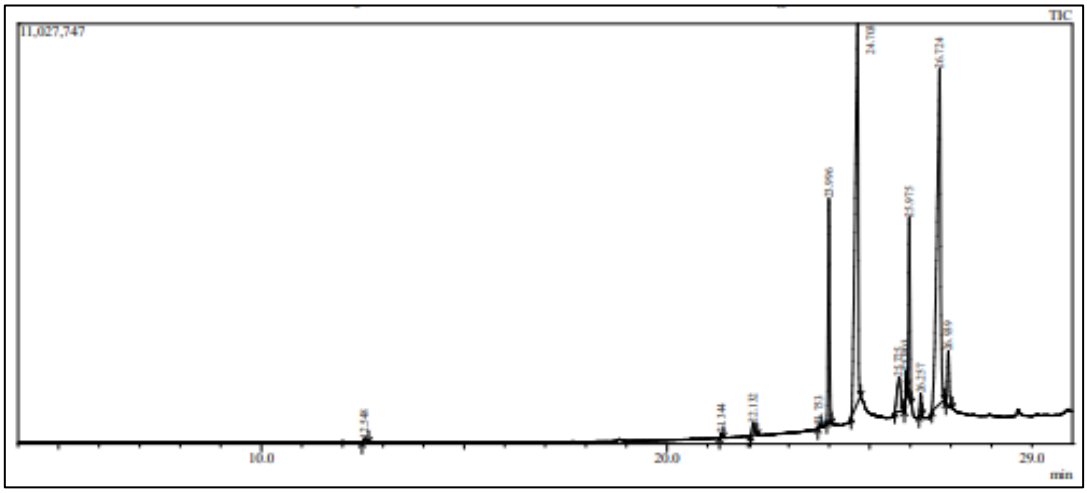

Figure 7. Gas chromatography of biodiesel

In 2020, Liu et al. also applied DES based on p-toluene sulfonic acid as both catalyst and solvent to produce biodiesel from waste cooking oil and used oil. The results of this research produced biodiesel with a yield of 99.2% at 70.5°C, a DES dosage of 24.6% by weight, and a reactant molar ratio of 12.5. This research also shows that DES can be reused as catalysts up to 5 times with a 10% decrease in their catalytic activity. Ranjan et al. (2022) used DES from a mixture of choline chloride and crude glycerol as a solvent in biodiesel production. Additionally, acidic DES are also applied as catalysts in the production of fatty acid emulsifiers (Aisha et al., 2023; Zahrina et al., 2024).

The analysis of the physical and chemical properties of biodiesel is presented in Table 6, which shows the results for all biodiesel products from the research and the physical properties of biodiesel according to SNI 7182:2015, ASTM D6751-09, and EN 14214. According to Budiman (2023), in addition to SNI 7182:2015, quality standards for biodiesel are also set in each country, including the United States with ASTM D6751-09 and Europe with EN 14214. Table 6 shows that the density of the research-produced biodiesel falls within the range specified by biodiesel quality standards. The density of biodiesel is influenced by the molecular weights of its components. According to Setianingsih et al. (2018), the greater the component content, the higher the density. The lower the biodiesel density, the better it is as a fuel because it is lighter.

Table 6. Physico-chemical Properties of Biodiesel

Catalyst	Molar Ratio of Catalyst	Density (g·mL^{-1})	Viscosity (cSt)	Yield (%)	pH
DES	1:2	0.857	5.391	96.40	10.79
DES	1:3	0.881	5.121	92.30	10.74
DES	1:5	0.868	5.049	93.38	9.72
DES	1:7	0.873	5.210	81.36	11.55
DES	1:9	0.865	4.894	94.93	9.44
Sulfuric acid		0.859	4.220	86.94	10.19
SNI 7182:2015		0.85-0.89	2.3-6.0		
ASTM D6751-09		-	1.9-6.0		
EN 14214		0.86-0.9	-		

The viscosity of the biodiesel produced in this research falls within the standard quality range for biodiesel (Table 6). The viscosity value cannot be too high or too low. According to Dzakiroh et al. (2023), if the viscosity value is too high, there will be significant friction losses in vehicle engines, filtration will be difficult, dirt is likely to settle, and it will be difficult to atomize the fuel. This is related to heat transfer, as fouling factors will form. Conversely, if the viscosity is too low, lubrication will be thin, leading to wear if left unchecked.

The biodiesel yield reached over 90%, with the highest yield (96.4%) achieved with DES at a molar ratio of 1:2. This small difference in yield indicates that variations in the molar ratio of DES do not significantly affect biodiesel yield. This shows that DES from palm oil empty fruit bunches and waste cooking oil are capable to producing biodiesel with high yields that meet biodiesel quality standards.

Based on the characterization results, DES catalysts, particularly DES-1 and DES-5, exhibited superior catalytic performance compared to the conventional H_2SO_4 catalyst, as evidenced by significantly higher biodiesel yields (96.40% vs. 86.94%). This advantage stems from the dual catalytic mechanism of DES, which simultaneously activates the triglyceride substrate and the methanol nucleophile, thereby enhancing the selectivity of the transesterification reaction. All biodiesel produced using DES catalysts meets the material quality parameters set by SNI 7182:2015, ASTM D6751-02, and EN 14214, particularly in terms of kinematic viscosity and density.

4. CONCLUSION

DES can be synthesized from a mixture of polyols (from the hydroxylation of waste cooking oil) and potassium carbonate (from PEFB ash extract) in liquid form, without sediment, and is colorless. DES have a density exceeding 1 g · mL^{-1}, a viscosity of 1.18-1.76 cSt, and a pH of 1.1–1.45. Hydrogen bonds were identified between potassium carbonate and polyol. DES at a potassium carbonate to polyol molar ratio of 1:2 exhibited the highest catalytic activity in the biodiesel production, with a yield of 96.4% and meeting biodiesel quality standards. This research develops environmentally friendly catalysts based on palm empty fruit bunches and waste cooking oil for biodiesel production, thereby reducing pollution and enabling catalyst independence.

ACKNOWLEDGEMENT

The author would like to thank the Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi Pendidikan Tinggi for funding this research through the Program Kreativitas Mahasiswa (PKM) 2024. The author would also like to thank the Universitas Riau for contributing to the funding of this research program and the Chemical Reaction Engineering and Catalysis Laboratory for supporting the implementation of the research.

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