Research Article

Performance Enhancement of Ternary Blending of Biodiesel, Yang-Na (*Dipterocarpus alatus*) Oil, and Plastic Waste Pyrolysis Oil for Agricultural Diesel Engines

Wuttichai Roschat*, Sittichai Watthanalao, Bunterm Maneerat, Phiriyakorn Chaona, Aekkaphon Thammayod, Supakorn Arthan, Tappagorn Leelatam, Noppharat Khotsuno and Sunti Phewphong
Innovation in Chemistry for Community Research Unit, Faculty of Science and Technology, Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand
Biomass Energy Research Laboratory, Center of Excellence on Alternative Energy, Research and Development Institution, Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand

Keyoon Duanguppama
Department of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Kalasin University, Kalasin, Thailand

Somporn Katekaew and Krittiyanee Namwongsa
Department of Biochemistry, Faculty of Science, Khon Kaen University, Khon Kaen, Thailand

Boonyawan Yoosuk and Pathompong Janetaisong
National Energy Technology Center (ENTEC), Thailand Science Park, Pathum Thani, Thailand

Vinich Promarak
Department of Material Science and Engineering, School of Molecular Science & Engineering, Vidyasirimedhi Institute of Science and Technology, Rayong, Thailand

* Corresponding author. E-mail: roschat1@gmail.com DOI: 10.14416/j.asep.2026.03.003
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Abstract
The growing dependence on fossil fuels and the increasing burden of plastic waste underscore the urgency of developing sustainable energy solutions. This study investigates ternary liquid biofuel blends composed of biodiesel derived from waste cooking oil, distilled Yang-Na (*Dipterocarpus alatus*) oil, and plastic waste pyrolysis oil for use in agricultural diesel engines. The fuels were analyzed using Fourier Transform Infrared Spectroscopy (FT-IR), Gas Chromatography (GC), Gas Chromatography–Mass Spectrometry (GC-MS), and physicochemical tests according to ASTM D6751 and EN 14214 standards. Various binary and ternary ratios were prepared and compared with commercial B10 diesel. Engine performance and emissions were evaluated using a single-cylinder Kubota RT100 diesel engine at different speeds, along with field tests on walking tractors in Sakon Nakhon Province, Thailand. Biodiesel contributed oxygenated esters that improved combustion but exhibited high viscosity. Distilled Yang-Na oil showed suitable viscosity and energy content but exceeded density limits, whereas pyrolysis oil provided high calorific value but suffered from poor stability and acidity issues. Optimal blends at 60:20:20 and 70:15:15 (Biodiesel:Yang-Na:Pyrolysis) achieved balanced properties, met international standards, and provided heating values close to commercial diesel. Engine tests demonstrated enhanced torque, reduced fuel consumption, and lower CO and HC emissions. These results demonstrate that ternary blending of local and waste-derived oils can yield efficient, eco-friendly biofuels that support rural energy security and sustainable agriculture.

Keywords: Biodiesel, *Dipterocarpus alatus* oil, Plastic waste pyrolysis oil, Renewable energy

1 Introduction

Energy is vital for economic growth, yet Thailand remains highly dependent on imported petroleum. In 2024, crude oil imports averaged 957,000 barrels per day, while national fuel consumption reached 139.5 million liters per day, including 69.7 million liters of diesel. Rising global demand and declining fossil reserves have intensified the shift toward renewable energy, with biomass offering strong potential for Thailand.

In response, the Ministry of Energy implemented the Alternative Energy Development Plan (AEDP 2015–2036) to promote both large–scale biofuel production and community–based biodiesel systems using local feedstocks. This strategy enhances energy security, strengthens local economies, and supports sustainable rural development [1]–[6]. Biodiesel is a viable alternative fuel for diesel engines and can be used in pure form or blended with petroleum diesel. In Thailand, commercial diesel typically contains 6–7% biodiesel, while higher blends such as B10 and B20 are widely promoted [7]–[9]. However, biodiesel production remains constrained by inconsistent feedstock supply, high production costs, and limited support for small-scale producers [7], [10], [11].

Yang–Na (*Dipterocarpus alatus*) oil is a promising complementary feedstock. The tree is abundant in northeastern Thailand, especially in community forest areas, and can be tapped non–destructively, minimizing harvesting impacts. Its stem oil contains α–Gurjunene and γ–Gurjunene, which exhibit diesel–like chemical and thermal behavior and meet key biodiesel quality indicators. Fast pyrolysis of its resin at 500 °C also yields gasoline–and diesel–like fractions comparable to commercial fuels, further emphasizing its potential as a sustainable local bioresource [7], [12]–[14]. While Yang–Na resin is traditionally used for varnish and local medicines, its availability and low commercial demand reduce competition with existing uses, supporting its feasibility as an energy feedstock. Parallel to bio–based solutions, Thailand is evaluating waste–to–energy pathways to address increasing municipal plastic waste, which resists degradation and poses environmental and health risks [15]–[18]. Conventional disposal methods, including landfilling and incineration, are increasingly inadequate due to limited landfill capacity, illegal dumping, and pollutant emissions such as smog and PM2.5. Low recovery rates and declining recyclability highlight the need for complementary alternatives such as plastic pyrolysis oil to reduce waste burdens while supporting national renewable energy goals [19], [20].

Pyrolysis of plastic waste is a promising thermochemical process that decomposes long–chain polymers at 300–500 °C under oxygen–free conditions, producing combustible gases, carbonaceous char, and hydrocarbon–rich pyrolytic oil [15], [17], [21], [22]. The oil contains gasoline, kerosene, and diesel–range fractions, making it an attractive liquid fuel candidate. However, its direct use in engines is constrained by instability, acidity, and incomplete combustion. Recent studies indicate that co–processing or blending plastic pyrolysis oil with biodiesel can significantly improve fuel stability, combustion behavior, and emission performance, offering a more practical utilization pathway. This approach is consistent with recent findings on biodiesel–plastic oil hybrid fuels and catalytic upgrading strategies [1], [10], [11], [16]. Similar to distilled Yang–Na oil, plastic pyrolysis oil enables the conversion of locally available waste into useful energy, supporting rural energy needs. When incorporated into ternary blends with biodiesel, it contributes to a diversified low-carbon fuel strategy that reduces petroleum dependence and aligns with the Alternative Energy Development Plan (AEDP 2015–2036) [1], [3], [7], [14], [15].

In response to these challenges, this study developed blended biofuels from three renewable sources: plastic waste–derived pyrolysis oil, distilled Yang–Na oil, and biodiesel. The blends, prepared in various ratios, were evaluated according to ASTM D6751 and EN 14214 standards. Physical properties (viscosity, density, cloud point, pour point) and chemical characteristics (acid value, oxidation stability, iodine value, heating value) were measured to assess fuel quality. The blends were further tested in agricultural diesel engines to evaluate performance, combustion efficiency, and compatibility. This approach simultaneously addresses plastic waste reduction and rural sustainable energy, converting local materials into value–added fuel that enhances energy self–reliance and reduces costs for farming communities.

2 Materials and Methods

2.1 *Materials*

For high–grade chemicals and solvents were used to ensure consistency and reproducibility. The reagents included hexane (Fluka), ethanol (99.8%, Fluka),

phenolphthalein (QRëC), isopropanol (QRëC), toluene (QRëC), deuterated chloroform ($CDCl_3$, QRëC), sodium thiosulfate (QRëC), potassium iodide (Ajax), potassium hydroxide (QRëC), methanol (QRëC), distilled water, resublimed iodine (QRëC), and hydrochloric acid (Merck). All chemicals were obtained from reputable suppliers to minimize analytical variability.

Approximately 50 kg of mixed post–consumer plastic waste—mainly PET, HDPE, and LDPE—was subjected to thermal pyrolysis. The process was conducted in a batch reactor under oxygen–free conditions at an operating temperature of 500 ± 20 °C, with a heating rate of 10 °C/min and a residence time of 45–60 min, following the conditions adapted from Moonsin *et al*., [1], [15], [23]. No catalyst was employed, and the reaction proceeded under atmospheric pressure to obtain liquid pyrolysis oil. Crude Yang–Na oil was obtained by trunk drilling of Dipterocarpus alatus trees at Khon Kaen University. The oil was then purified by distillation at ~280 °C at the Yang–Na Biodiesel Refinery, Yang–Na Integrated Learning Center, following established methods [7], [12], [13]. The distilled fraction was stored in airtight amber glass bottles to prevent degradation.

For blending, waste cooking oil (WCO) biodiesel was provided by the Biomass Energy Research Laboratory, Center of Excellence on Alternative Energy, Sakon Nakhon Rajabhat University. The biodiesel was prepared following standard procedures: acid–catalyzed esterification to reduce free fatty acids, followed by alkaline–catalyzed transesterification to convert triglycerides into fatty acid methyl esters (FAME), as described by Roschat *et al*., [7] and Phewphong *et al*., [24]. This process ensures high–quality WCO biodiesel suitable for blending. Commercial diesel B10 (10% of biodiesel blending) from local stations in Sakon Nakhon Province, as specified by the Department of Energy Business Notification on Diesel Fuel Specifications, Ministry of Energy, Thailand [25], was analyzed as a reference. Figure 1(a)–(c) show the WCO biodiesel, distilled Yang–Na oil, and plastic waste pyrolysis oil used in this study.

2.2 *Preparation of ternary fuel blends*

This study investigated various blending ratios to develop liquid biofuels. Here, B denotes WCO biodiesel, Y represents distilled Yang–Na oil, and P corresponds to plastic waste pyrolysis oil. Single–component fuels included Diesel B10, WCO biodiesel, Yang–Na oil, and pyrolysis oil. Binary blends of B + P and B + Y were prepared at 95:5, 90:10, 85:15, and 80:20 ratios, while Y + P blends followed the same proportions. Ternary blends of B + Y + P were formulated at 50:25:25, 60:20:20, 70:15:15, 80:10:10, and 90:5:5 ratios. The prepared blends were evaluated for key physicochemical properties, including viscosity (cSt at 40 °C), density (g/cm^3), heating value (cal/g), and acid value (mg KOH/g). Each blend was prepared and tested immediately, with results compared against the individual fuel components. Experiments were performed in triplicate (n = 3), and although the mean ± SD is not reported due to the volume of measurements, the relative standard deviation (%RSD) was maintained below 3% to ensure reliability and consistency.

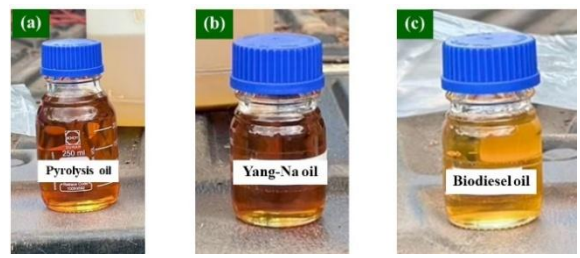

Figure 1: Samples of (a) plastic waste pyrolysis oil, (b) distilled Yang–Na oil, and (c) waste cooking oil biodiesel.

2.3 *Physicochemical characterization of fuel blends*

2.3.1 Chemical functional group analysis using FT–IR

Fourier Transform Infrared Spectroscopy (FT–IR) was employed to characterize the functional groups present in the ternary fuel blends of WCO biodiesel, Yang–Na oil, and plastic pyrolysis oil. Measurements were conducted using a Shimadzu FT–IR–8900 (Japan) over 4000–500 cm^{-1}. For comparison, B10 petroleum diesel—commonly used in agricultural engines—was analyzed under identical conditions. The FT–IR profiles were used to identify key functional groups and assess molecular interactions within the blends relative to conventional diesel, providing insights into their potential as renewable fuels for agricultural applications [1], [15], [23].

2.3.2 Chemical composition analysis using GC and GC–MS

The chemical composition of Yang–Na oil and plastic waste pyrolysis oil was determined using GC–MS (Agilent 7890A GC with 7000B MS, USA). Separation

was achieved on a DB–Wax column (60 m × 0.25 mm, 0.25 μm), with compound identification supported by the NIST MS Search 2.0 library. Each sample (50 μL) was diluted in 950 μL ethanol, filtered through a 0.45 μm membrane, and injected (1 μL, split 20:1) in liquid mode. The MS operated in EI mode (70 eV, 250 °C ion source, 35–550 m/z). GC conditions included a 250 °C injection temperature, helium carrier gas at 1.0 mL/min, and a 250 °C transfer line. The oven program was 70 °C (3 min) to 180 °C at 3 °C/min to 250 °C at 10 °C/min (35 min hold), for a total run time of 81.7 min, following previous methods [1], [15], [26], [27]. WCO biodiesel was analyzed separately using GC–2010 (Shimadzu, Japan) according to EN–14214 to ensure compliance with biodiesel quality standards [1], [2], [6], [7].

2.3.3 Physicochemical Analysis of Fuels and Ternary Blends

The physicochemical properties of used cooking oil biodiesel, Yang-Na oil, plastic waste pyrolysis oil, and their ternary blends were evaluated against commercial B10 diesel following ASTM D6751 and EN 14214 standards. Key parameters measured included density (15 °C), kinematic viscosity (40 °C), acid value, iodine value, oxidation stability, heating value, sulfur and ash contents, pour point, and cloud point. All analyses were performed in triplicate with relative deviations below 3% at the Clean Fuel Technology and Advanced Chemistry Research Laboratory (ENTEC–NSTDA), in collaboration with the Biomass Energy Research Laboratory at Sakon Nakhon Rajabhat University. Methods were adapted from established biodiesel characterization studies to ensure international comparability [2], [7], [8], [22], [28], [29].

2.4 *Engine performance and emission testing*

The Engine performance and emissions of WCO biodiesel, Yang–Na oil, plastic waste pyrolysis oil, and their ternary blends were evaluated using a Kubota RT100 single–cylinder, four–stroke diesel engine at the Mechanical Engineering Laboratory, Kalasin University. The test system consisted of an MT 502HD engine testbed equipped with sensors for fuel flow, air intake, torque, speed, and exhaust temperature. CO, CO_2, HC, and NO_x were measured using an EMS Model 5003 analyzer. To ensure meaningful comparison, all tests were performed at three engine speeds (1000, 1600, and 2400 rpm) under three defined load levels corresponding to 25%, 50%, and 75% of the full-load torque at each speed. Engine speed was controlled within ±20 rpm using a DIGICON DT–0240P tachometer.

The EMS 5003 analyzer was calibrated before each test session using certified span gases (CO, CO_2, HC as propane, and NO_x as NO) following the manufacturer's auto–zero and span–adjustment procedures, ensuring accuracy of the emission measurements. Commercial B10 diesel was used as the reference fuel. Performance indicators (torque and BSFC) were assessed according to ISO 15550–2002. All measurements were performed in triplicate with deviations below 3%. The experimental protocol followed Phewphong *et al*., [6], Roschat *et al*., [7], and Thanikodi *et al*., [30].

3 Results and Discussion

3.1 *Characterization of WCO biodiesel, Yang–Na oil, and plastic waste pyrolysis oil*

3.1.1 Chemical functional group analysis using FT–IR

The FT–IR spectra of WCO biodiesel, Yang–Na oil, and plastic waste pyrolysis oil were compared with commercial B10 diesel to identify key functional groups (Figure 2(a)–(d) and Table 1). WCO biodiesel exhibited a broad O–H band at 3500–3250 cm^{-1}, reflecting alcohols and carboxylic acids typical of transesterified fatty acid esters [1], [2], [6]. This band was absent in B10 and Yang–Na oil, consistent with their lower oxygen content. Plastic pyrolysis oil showed distinct =C–H stretching at 3000–3100 cm^{-1} and overtone bands in the 2000–1650 cm^{-1} aromatic region, confirming the presence of alkenes and aromatic hydrocarbons generated during plastic depolymerization [2], [15], [23]. In contrast, biodiesel and Yang–Na oil displayed only weak aromatic signals, indicating mainly aliphatic structures. A strong ester C=O band at 1750–1740 cm^{-1} appeared in biodiesel and Yang–Na oil, while pyrolysis oil exhibited only a minor peak attributed to trace oxygenates. B10 showed a faint ester band due to its limited biodiesel content. C=C stretching at 1670–1600 cm^{-1} was most prominent in pyrolysis oil and Yang–Na oil, suggesting unsaturation levels relevant to oxidation stability. Additional characteristic peaks included $–CH_2$ and $–CH_3$ bending (1470–1350 cm^{-1}), ester C–O–C linkages in biodiesel (1210–1163 cm^{-1}), alkene out-of-plane bending (995–905 cm^{-1}), and $–CH_2$ rocking (720–780 cm^{-1}) [3]–[6].

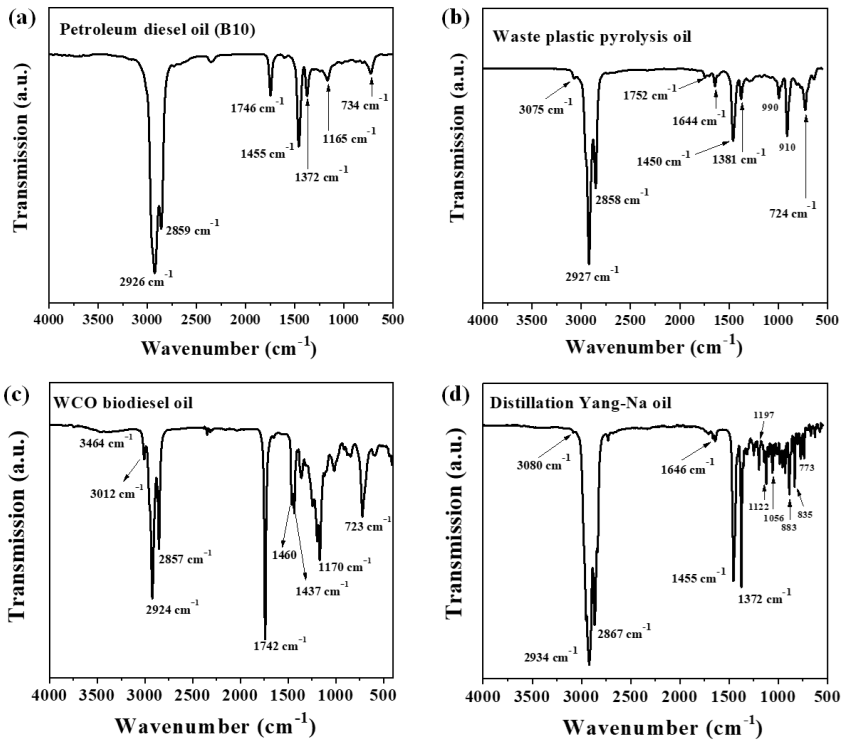

Figure 2: FT–IR spectra of (a) commercial B10 petroleum diesel, (b) plastic waste pyrolysis oil, (c) WCO biodiesel, and (d) Yang–Na oil.

Table 1: Wavenumbers and corresponding functional groups of biodiesel, Yang–Na oil, and compared with commercial B10 petroleum diesel.

Wave number range (cm^{-1})	Functional group	Diesel B10	WCO Biodiesel	Plastic waste pyrolysis oil	Yang-Na oil
3500 – 3250	–OH of alcohol or carboxylic acid (stretching; strong and broad)	–	weak broad	–	–
3000 – 3100	=C–H of alkene (stretching)	–	weak	weak	weak
2950 – 2800	C–H, $–CH_2$ and $–CH_3$ of alkane (stretching; strong, medium, and sharp)	strong	strong	strong	strong
2000 – 1650	C-H of aromatic compound (overtone) (bending; weak)	–	–	weak	–
1750 – 1740	C=O of ester (stretching)	medium	strong	weak	–
1670 – 1600	C=C of alkene (stretching; weak)	–	–	weak	weak
1470 – 1430 and 1375 – 1350	C–H, $–CH_2$ and $–CH_3$ (bending; medium or weak)	medium	medium	medium	strong
1210 – 1163	C–O–C of ester (stretching)	weak	medium	–	–
1050 – 905	=C–H of alkene (bending; medium or weak)	–	–	weak	weak
720 – 780	$–CH_2$ of alkane (rocking; weak)	weak	medium	weak	weak

Therefore, F–TIR analysis reveals clear differences among the oils: biodiesel is rich in ester oxygenates, Yang–Na oil contains unsaturated aliphatic hydrocarbons, and pyrolysis oil comprises mixed alkanes, alkenes, and aromatics. These complementary functional group profiles indicate that ternary blending can balance individual limitations, potentially improving combustion quality, energy density, ignition behavior, and emissions relative to using each fuel alone [1], [6], [7], [15], [23], [31].

3.1.2 Chemical composition analysis using GC and GC–MS

The chemical composition of the biodiesel derived from WCO, as illustrated in Figure 3, consists

predominantly of methyl oleate ($C_{18:1}$), methyl palmitate ($C_{16:0}$), methyl linoleate ($C_{18:2}$), and methyl stearate ($C_{18:0}$), with respective proportions of 43.26%, 33.42%, 15.32%, and 4.48% by weight. These results confirm that the transesterification of WCO effectively converted triglycerides into fatty acid methyl esters (FAME), yielding a high–quality biodiesel product. Minor peaks at lower retention times are attributed to volatile impurities or residual reactants, while the absence of pronounced peaks at higher retention times indicates only trace amounts of unreacted triglycerides or partial glycerides. The dominance of C_{16} – C_{18} FAME in the chromatographic profile is consistent with previous reports of biodiesel derived from vegetable oils and waste cooking oils. This composition highlights the suitability of WCO–derived biodiesel for renewable energy applications, as the high content of methyl oleate and methyl palmitate contributes to favorable fuel properties, including oxidative stability, appropriate viscosity, and good ignition quality [1], [7], [23], [24].

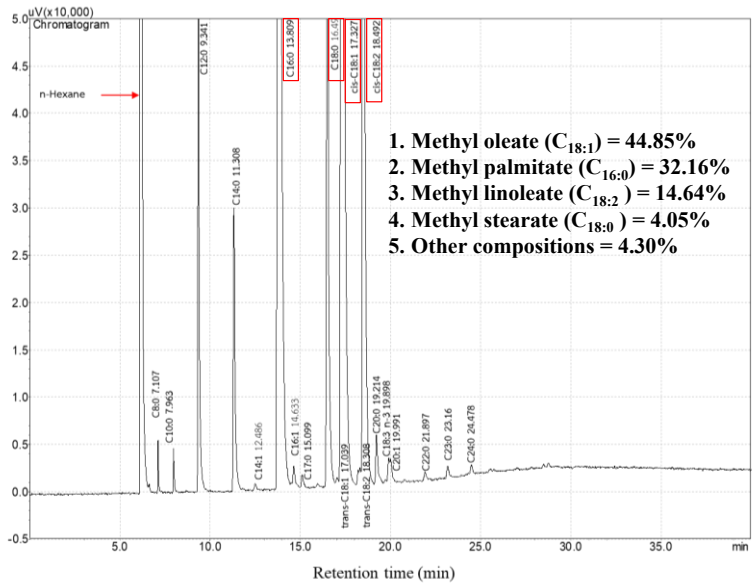

Figure 3: GC chromatogram of WCO biodiesel.

The GC–MS analysis of plastic waste pyrolysis oil (Figure 4 and Table 2) revealed a chemically diverse mixture dominated by straight–chain and branched hydrocarbons in the C_6–C_{22} range. Major constituents were primarily within the C_{10}–C_{14} fraction, including undecane (6.03%), 1-undecene (6.00%), dodecane (6.69%), 1–dodecene (6.14%), and tridecane (6.22%), along with notable contributions from nonane (5.60%), decane (4.17%), and 1–tridecene (5.43%). These compounds confirm the efficient thermal cracking of plastic waste into middle–distillate hydrocarbons comparable to diesel fuels [15], [22], [32]–[34]. The primary molecular structures of these compounds are illustrated in Figure 5. Based on recalculated GC–MS peak areas, the oil consists of 49.80% saturated hydrocarbons (alkanes and cycloalkanes), 45.31% unsaturated hydrocarbons (alkenes and aromatics), and 4.89% oxygenated or heteroatom–containing compounds. This distribution reflects a hydrocarbon–rich composition with a moderate level of olefins, which may reduce oxidative stability during long–term storage [15], [22], [35].

Minor aromatic compounds such as styrene, p–cymene, and methyl–naphthalenes were detected and may contribute to increased soot formation during combustion. Trace oxygenated and heteroatomic species—including dimethyl phthalate (4.00%), cyclohexane–methanol (0.55%), and caprolactam (0.17%)—likely originate from plastic additives or partial oxidation during pyrolysis [15], [22], [35], [36]. Overall, the pyrolysis oil displays a mid-chain hydrocarbon–rich profile with a near balance of saturated and unsaturated components, accompanied by small amounts of aromatics and oxygenates. This composition supports its potential as a liquid hydrocarbon fuel, while indicating the need for

blending, upgrading, or stabilization to address storage and combustion challenges.

Distilled Yang–Na oil exhibits a uniform chemical profile dominated by sesquiterpenes (Figure 6). GC–MS results show α–gurjunene as the major constituent (65.44%), followed by α–caryophyllene (11.12%), γ–elemene (5.23%), and γ–gurjunene (4.28%), consistent with previous studies [7], [12]–[14]. Minor compositional variations are likely influenced by raw material differences and environmental factors. The sesquiterpene–rich nature of Yang–Na oil provides advantages such as enhanced lubricity and improved oxidative stability, while its low levels of oxygenated and aromatic compounds help minimize polymerization and degradation during storage. These properties complement the more reactive and aromatic–containing pyrolysis oil, indicating that blending the two can balance their individual limitations and enhance overall fuel quality. Furthermore, the high proportion of thermally stable sesquiterpenes may support better combustion behavior under engine operating conditions. This makes Yang–Na oil a promising renewable component for developing advanced biofuel blends aimed at cleaner and more efficient diesel alternatives [7], [12]–[14].

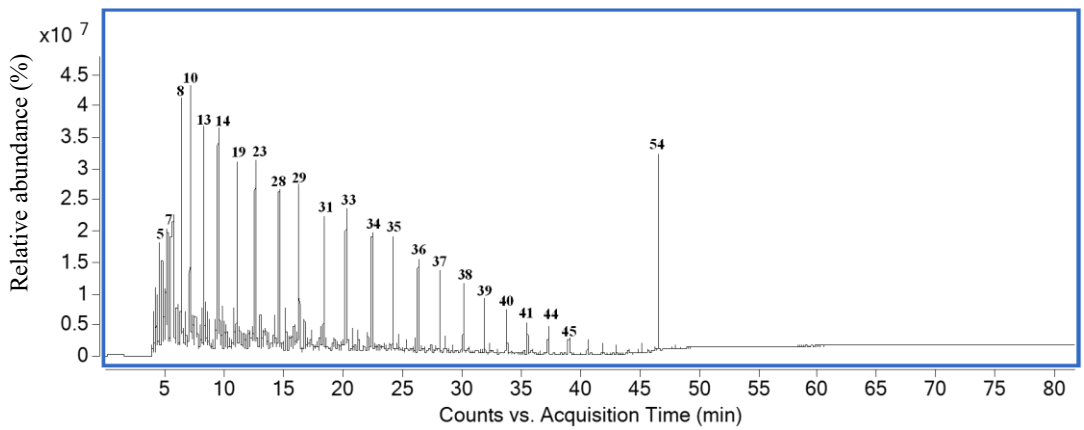

Figure 4: Gas Chromatography–Mass Spectrometry (GC–MS) profile of plastic waste pyrolysis oil. Noted: The numbers shown in the GC–MS chromatogram represents the peak numbers of individual chemical components, which correspond to the data presented in Table 2.

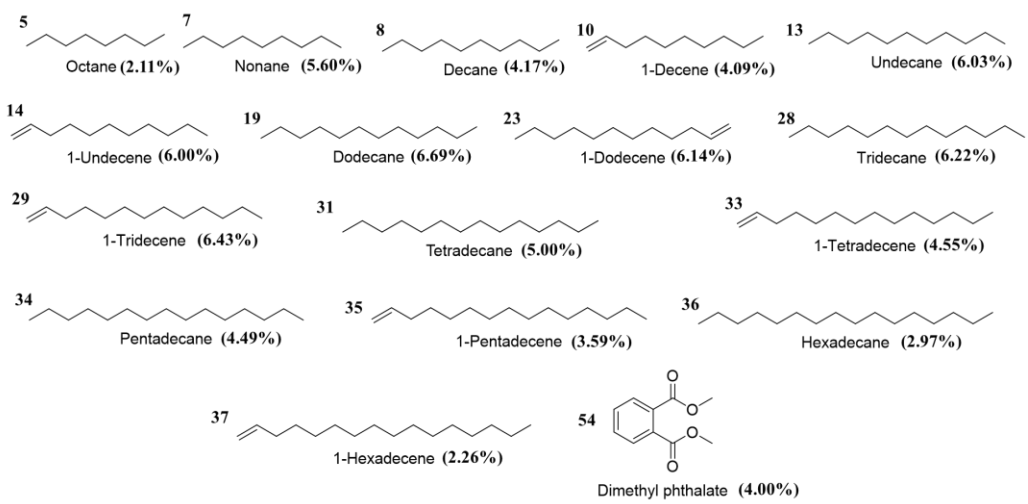

Figure 5: Key molecular structures of principal compounds identified in plastic waste pyrolysis oil.

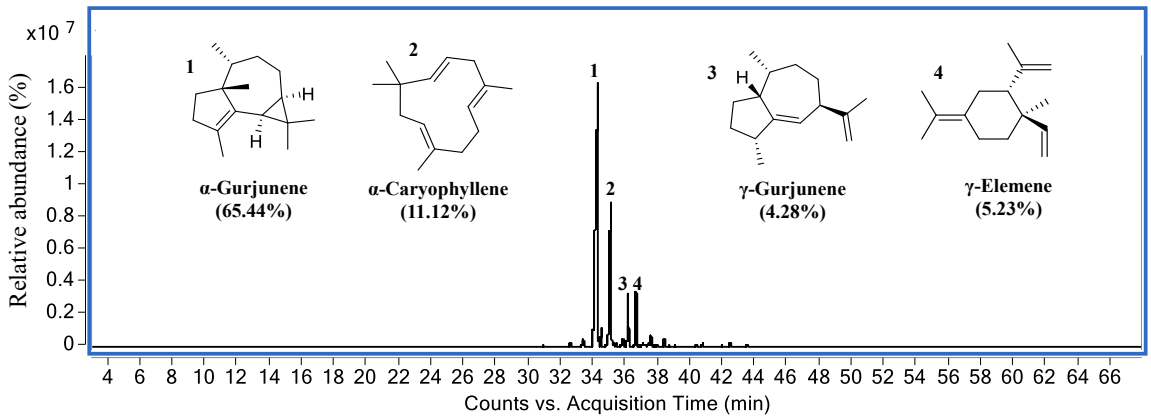

Figure 6: GC–MS chromatographic profile of distilled Yang–Na (*Dipterocarpus alatus*) oil.

Table 2: GC/MS chromatogram compounds list of converting plastic waste by pyrolysis.

Peak number	Retention time (min)	Compound name	Compound formula	Molecular weight	Area percentage (%)
1	4.017	3–methyl–Pentane	C_6H_{14}	86.18	0.33
2	4.083	1–Hexene	C_6H_{12}	84.16	0.59
3	4.190	Heptane	C_7H_{16}	100.2	1.11
4	4.318	1–Heptene	C_7H_{14}	98.19	0.84
5	4.528	Octane	C_8H_{18}	114.23	2.11
6	4.769	1–Octene	C_8H_{16}	112.21	1.75
7	5.219	Nonane	C_9H_{20}	128.25	5.60
8	6.428	Decane	$C_{10}H_{22}$	142.28	4.17
9	6.744	Cyclodecane	$C_{10}H_{20}$	140.27	0.58
10	7.155	1–Decene	$C_{10}H_{20}$	140.27	4.09
11	7.417	5–Decene	$C_{10}H_{20}$	140.27	0.39
12	8.090	Cyclohexane–methanol	$C_7H_{14}O$	114.19	0.60
13	8.341	Undecane	$C_{11}H_{24}$	156.31	6.03
14	9.478	1–Undecene	$C_{11}H_{22}$	154.29	6.00
15	9.616	1,3–dimethyl–Benzene	C_8H_{10}	106.16	0.45
16	9.839	5–Undecene	$C_{11}H_{22}$	154.29	0.83
17	10.794	1,11–Dodecadiene	$C_{12}H_{22}$	166.3	0.75
18	10.891	1,2–dimethyl–Benzene	C_8H_{10}	106.16	0.46
19	11.145	Dodecane	$C_{12}H_{26}$	170.33	6.69
20	11.327	D–Limonene	$C_{10}H_{16}$	136.23	0.40
21	12.104	1–ethyl–3–Methylbenzene	C_9H_{12}	120.19	0.43
22	12.168	1–ethyl–4–Methylbenzene	C_9H_{12}	120.19	0.37
23	12.621	1–Dodecene	$C_{12}H_{24}$	168.32	6.14
24	13.063	(E)–3–Dodecene	$C_{12}H_{24}$	168.32	0.69
25	13.202	Styrene	C_8H_8	104.15	0.35
26	13.723	P–Cymene	$C_{10}H_{14}$	134.22	0.41
27	14.311	Hexyl–Cyclohexane	$C_{12}H_{24}$	168.32	0.21
28	14.634	Tridecane	$C_{13}H_{28}$	184.36	6.22
29	16.326	1–Tridecene	$C_{13}H_{26}$	182.35	5.43
30	16.811	(E)–5–Tridecene	$C_{13}H_{26}$	182.35	0.76
31	18.493	Tetradecane	$C_{14}H_{30}$	198.39	5.00
32	18.636	4–ethenyl–1,2–dimethyl–Benzene	$C_{10}H_{12}$	132.2	0.28
33	20.286	1–Tetradecene	$C_{14}H_{28}$	196.37	4.55
34	22.460	Pentadecane	$C_{15}H_{32}$	212.41	4.49
35	24.274	1–Pentadecene	$C_{15}H_{30}$	210.4	3.59
36	26.378	Hexadecane	$C_{16}H_{34}$	226.44	2.97
37	28.174	1–Hexadecene	$C_{16}H_{32}$	224.42	2.26
38	30.182	Heptadecane	$C_{17}H_{36}$	240.5	1.96
39	31.948	1–Heptadecene	$C_{17}H_{34}$	238.5	1.55
40	33.835	Octadecane	$C_{18}H_{38}$	254.5	1.17
41	35.572	1–Octadecene	$C_{18}H_{36}$	252.5	0.85
42	35.931	2–methyl–Naphthalene	$C_{11}H_{10}$	142.2	0.09

Table 2: (Continued).

Peak number	Retention time (min)	Compound name	Compound formula	Molecular weight	Area percentage (%)
43	37.182	1–methyl–Naphthalene	$C_{11}H_{10}$	142.2	0.08
44	37.347	Nonadecane	$C_{19}H_{40}$	268.5	0.71
45	39.045	1–Nonadecene	$C_{19}H_{38}$	266.5	0.44
46	40.634	Eicosane	$C_{20}H_{42}$	282.5	0.37
47	41.965	(E)–3–Eicosene	$C_{20}H_{40}$	280.5	0.21
48	43.054	Heneicosane	$C_{21}H_{44}$	296.6	0.17
49	44.064	10-Heneicosene	$C_{21}H_{42}$	294.6	0.07
50	44.887	Docosane	$C_{22}H_{46}$	310.6	0.08
51	45.202	Caprolactam	$C_6H_{11}NO$	113.16	0.17
52	45.258	Methyl–Hexadecanoate	$C_{17}H_{34}O_2$	270.5	0.05
53	45.720	1–Docosene	$C_{22}H_{44}$	308.6	0.04
54	46.616	Dimethyl phthalate	$C_{10}H_{10}O_4$	194.18	4.00
55	47.994	4–(2–methylbutan–2yl)–Phenol	$C_{11}H_{16}O$	164.24	0.07
Total					100
Total saturated hydrocarbons (alkanes + cycloalkanes)					49.80
Total unsaturated hydrocarbons (alkenes + aromatics)					45.31
Oxygenates / other (esters, phthalates, alcohols, lactams, phenols)					4.89

Table 3: Physicochemical properties (viscosity, density, heating value, and acid value) of plastic waste pyrolysis oil, biodiesel, distilled Yang-Na oil, and their ternary blends.

Type of oil	Blend ratio (%)	Viscosity (cSt at 40 °C)	Density (g/cm³)	Heating value (cal/g)	Acid value (mg KOH/g)
WCO	–	30.54	0.9190	8768	2.615
Diesel B10	100	3.43	0.8293	11083	0.169
Yang–na	100	3.91	0.9323	10777	0.336
WCO Biodiesel	100	5.44	0.8933	9655	0.420
Pyrolysis	100	1.02	0.7931	10907	0.899
B+P	95 : 5	4.97	0.8952	9708	0.520
B+P	90 : 10	4.44	0.8924	9752	0.600
B+P	85 : 15	4.09	0.8883	9860	0.630
B+P	80 : 20	3.79	0.8860	9948	0.650
B+Y	95 : 5	5.03	0.9012	9718	0.410
B+Y	90 : 10	4.98	0.9003	9767	0.400
B+Y	85 : 15	4.88	0.9060	9804	0.460
B+Y	80 : 20	4.75	0.9060	9929	0.380
Y+P	95 : 5	3.57	0.9233	10785	0.160
Y+P	90 : 10	3.21	0.9162	10892	0.220
Y+P	85 : 15	2.82	0.9084	10955	0.270
Y+P	80 : 20	2.52	0.9019	10989	0.320
B+Y+P	50 : 25 : 25	2.96	0.8866	10255	0.690
B+Y+P	60 : 20 : 20	3.41	0.8863	10101	0.473
B+Y+P	70 : 15 : 15	3.88	0.8875	10004	0.450
B+Y+P	80 : 10 : 10	4.49	0.8961	9862	0.450
B+Y+P	90 : 5 : 5	4.90	0.8978	9736	0.430

Note: WCO refers to waste cooking oil; B denotes biodiesel derived from waste cooking oil; Y represents distilled Yang–Na (*Dipterocarpus alatus*) oil; and P indicates plastic waste pyrolysis oil.

3.2 *Physicochemical properties of individual fuels, binary blends, and ternary blends*

The physicochemical properties of the tested fuels are summarized in Table 3. According to EN 14214 and ASTM D6751, biodiesel should have a viscosity of 3.5–5.0 cSt (40 °C), density of 860–900 g/cm^3 (15 °C), and an acid number below 0.5 mg KOH/g, while heating value is commonly compared with commercial diesel such as B10 [1], [7], [22], [37], [38]. Waste cooking oil (WCO) exhibited very high viscosity (30.54 cSt), elevated density (0.9190 g/cm^3), low heating value (8768 cal/g), and a high acid value (2.615 mg KOH/g), reflecting its triglyceride–rich structure and the accumulation of free fatty acids during repeated frying. These characteristics make raw WCO unsuitable as a direct fuel and highlight the need for transesterification or other upgrading processes [7], [24], [28]. After conversion, WCO biodiesel (B100) showed substantial improvement with reduced viscosity (5.44 cSt), density

of 0.8933 g/cm³, increased heating value (9655 cal/g), and an acid value of 0.420 mg KOH/g—meeting the standard limits. These findings are consistent with earlier studies confirming that properly processed WCO biodiesel is a viable renewable alternative compatible with diesel engine requirements [24].

Distilled Yang-Na oil showed a viscosity of 3.91 cSt—within the EN 14214 range—while its density (0.9323 g/cm^3) slightly exceeded the limit. These characteristics reflect its sesquiterpene–rich composition (α–gurjunene, α-caryophyllene, γ–elemene, γ–gurjunene), where the high molecular weight increases density while the nonpolar hydrocarbon structure maintains moderate viscosity. Its high heating value (10,777 cal/g) and low acid value (0.336 mg KOH/g) indicate energy–rich terpenoid compounds and good storage stability, consistent with previous studies [7], [12]–[14].

Plastic waste pyrolysis oil exhibited very low viscosity (1.02 cSt) and density (0.7931 g/cm³) due to its predominance of light hydrocarbons and short–chain aromatics formed during thermal cracking. Despite its high heating value (10,907 cal/g), the elevated acid value (0.899 mg KOH/g) reflects oxygenated degradation products, making the oil unsuitable for direct use without upgrading [1], [15], [17], [18], [22], [26].

Binary blends displayed intermediate behaviors. In B+P mixtures, viscosity decreased with increasing pyrolysis oil content (4.97–3.79 cSt) and densities remained compliant, but acid values exceeded limits due to pyrolytic oxygenates. B+Y blends meet viscosity and density requirements while achieving higher heating values (9718–9929 cal/g) and acceptable acid values (0.380–0.460 mg KOH/g). Y+P blends presented low viscosities (3.57–2.52 cSt), high heating values (10,785–10,989 cal/g), and low acid values (0.160–0.320 mg KOH/g), though some viscosity values fell below standard thresholds.

Ternary blends (B+Y+P) showed the most balanced properties. Viscosities (2.96–4.90 cSt) and densities (0.886–0.898 g/cm^3) generally met EN 14214 and ASTM D6751 standards, while heating values (9862–10,255 cal/g) approached diesel levels. Most acid values (0.430–0.690 mg KOH/g) were within allowable limits. The 60:20:20 and 70:15:15 formulations exhibited the best overall performance, with optimal viscosity (3.41–3.88 cSt), compliant density (0.886–0.888 g/cm^3), heating values above 10,000 cal/g, and acid values below 0.5 mg KOH/g.

Overall, ternary blending effectively offsets the individual limitations of biodiesel, Yang–Na oil, and pyrolysis oil—reducing viscosity, moderating density, and controlling acidity. The optimized blends combine favorable fuel properties with the advantages of using locally available waste– and bio–based resources, offering practical, sustainable, and engine–compatible alternatives to petroleum diesel [1], [7], [8].

3.3 *Fuel quality assessment of optimized ternary blends against standards*

The fuel properties of biodiesel, distilled Yang–Na oil, plastic waste pyrolysis oil, and their optimized ternary blends (60:20:20 and 70:15:15) were compared with commercial diesel B10 and the EN–14214 and ASTM–D6751 standards, as summarized in Table 4. Biodiesel derived from waste cooking oil contained a high methyl ester content (97.01%), exceeding the EN–14214 minimum requirement of 96.5%. Its kinematic viscosity (5.44 cSt) slightly surpassed the upper limit of the standard range (3.5–5.0 cSt), but density (893 kg/m^3), acid value (0.420 mg KOH/g), oxidation stability (>12 h), and other parameters complied with specifications. These results align with previous reports on WCO biodiesel, confirming its potential as a renewable fuel despite minor viscosity deviations [7], [24], [39], [40].

Distilled Yang–Na oil, rich in sesquiterpene hydrocarbons, showed a viscosity of 3.91 cSt within the standard range, but its density (932 kg/m³) exceeded the 860–900 kg/m³ limit. The high iodine value (193.30 g I_2/100 g oil) reflects a substantial degree of unsaturation, which may reduce long–term oxidative stability, while the acid number (0.336 mg KOH/g) met standard requirements. Although Yang–Na oil alone does not fully meet biodiesel specifications, its high heating value and suitable viscosity make it a valuable blending component. These observations are consistent with findings by Roschat *et al*., [7], Suiuay *et al*., [12], [13], and Sakkampang *et al*., [14], reinforcing its role in improving overall fuel quality when combined with biodiesel and other alternative fuels.

Plastic waste pyrolysis oil displayed significant deviations from biodiesel standards, with low viscosity (1.02 cSt) and density (793 kg/m³), both below the required ranges, and an elevated acid number (0.899 mg KOH/g), indicating chemical instability from oxygenated and acidic compounds. Despite a high heating value (10,907 cal/g), these

properties prevent direct use as a fuel. These findings agree with previous studies by Moonsin *et al*., [15], Mylavarapu *et al*., [16], Pannucharoenwong *et al*., [22], and Faisal *et al*., [35], highlighting the necessity of upgrading or blending strategies to improve plastic pyrolysis oil quality before practical application.

In contrast, ternary blends of biodiesel, Yang-Na oil, and pyrolysis oil at 60:20:20 and 70:15:15 ratios exhibited balanced properties in compliance with EN–14214 and ASTM–D6751 standards. Viscosities of 3.41 and 3.88 cSt, densities of 886 and 888 kg/m³, and acid numbers of 0.473 and 0.450 mg KOH/g all met the recommended criteria. Both blends achieved high oxidation stability (>12 h) and favorable cold–flow properties (cloud point 0 °C; pour point < –5 °C). Iodine values (112.66 and 83.81 g I_2/100 g oil) were reduced compared with Yang–Na oil alone, indicating improved oxidative stability through blending. These results demonstrate that strategic ternary blending compensates for individual feedstock limitations, producing biofuels that are standard–compliant, performance–competitive, and technically feasible for sustainable energy applications.

3.4 *Engine performance of biodiesel, Yang–Na oil, pyrolysis oil, and their ternary blends*

The performance evaluation of various fuels under low–speed diesel engine operation is summarized in Table 5. At 1000 rpm, the ternary blends (B:Y:P at 60:20:20 and 70:15:15) generated higher torque (19.07 Nm and 20.26 Nm, respectively) than commercial diesel B10 (17.23 Nm). This enhancement is primarily attributed to synergistic fuel–property interactions: biodiesel contributes inherent oxygen that accelerates premixed combustion, Yang–Na oil provides sesquiterpenes that improve fuel lubricity and atomization, and pyrolysis oil supplies high–energy hydrocarbons that increase the calorific input per cycle. Together, these effects shorten ignition delay and shift combustion phasing closer to top dead center (TDC), enabling more efficient conversion of chemical energy into mechanical work [6], [7], [41], [42].

At 1600 rpm, all fuels produced similar torque (35–37 Nm), but the ternary blends remained slightly superior to diesel B10. Their balanced viscosity, volatility, and oxygen content likely enhanced fuel–air mixing and combustion stability, consistent with findings reported by Roschat *et al*., [7] and Moonsin *et al*., [1]. At 2400 rpm, diesel B10 produced the highest torque (44.34 Nm), whereas the ternary blends showed slightly lower values (41.49–42.90 Nm), mainly due to the lower volatility and higher density of biodiesel and Yang–Na oil, which can hinder atomization at high injection rates. Even so, the blends outperformed each pure biofuel, indicating that blending can reduce individual feedstock limitations [6], [7], [42], [43].

Table 4: Comparison of physicochemical properties of biodiesel, distilled Yang–Na oil, plastic waste pyrolysis oil, and their optimal blends (60:20:20 and 70:15:15) with commercial diesel B10 and international standards (EN–14214 and ASTM–D6751).

Fuel properties	Standard biodiesel	Diesel B10	Biodiesel oil	Distillation Yang-Na oil	Pyrolysis oil	Blending B:Y:P	
						60:20:20	70:15:15
Methyl ester content by GC (%)	> 96.5	–	97.01	–	–	–	–
Kinematic viscosity at 40 °C (cSt)	3.5–5.0	3.40	5.44	3.91	1.02	3.41	3.88
Acid number (mg KOH/g oil)	< 0.5	0.05	0.420	0.336	0.899	0.473	0.450
Oxidation stability (h)	≥ 6	> 12	> 12	> 12	> 12	> 12	> 12
Iodine value (g I_2/100 g of oil)	< 120	8.81	45.38	193.30	66.48	112.66	83.81
Pour point (°C)	-5 to +10	< -5	< -5	< -5	< -5	< -5	< -5
Cloud point (°C)	-3 to +15	< -5	+4	< -5	< -5	0	0
Density at 15 °C (kg m^{-3})	860-900	829	893	932	793	886	888
Ash (%wt)	< 0.30	0.010	0.020	0.020	0.040	0.030	0.020
Sulphur ash (%wt)	< 0.02	0.000	0.000	0.009	0.019	0.000	0.000

Note: B = Biodiesel from used cooking oil; Y = Distilled Yang-Na oil; P = Plastic waste pyrolysis oil. The specifications are referenced to Thailand biodiesel quality standards for fatty acid methyl ester (FAME), B.E. 2550 (2007), and biodiesel quality standards for agricultural engines (community biodiesel), B.E. 2549 (2006), which require oil distributors to report the cloud point and pour point at low temperatures to the Director–General of the Department of Energy Business.

Table 5: Performance evaluation of different oils and their optimal blends under low-speed diesel engine operation.

Engine speed (rpm)	Diesel B10	Pyrolysis oil	Biodiesel oil	Distillation Yang-Na oil	Blending B:Y:P (60:20:20)	Blending B:Y:P (70:15:15)
Engine Torque (Nm)						
1000	17.23	18.99	15.84	15.14	19.07	20.26
1600	36.92	36.76	35.58	35.50	37.11	37.11
2400	44.34	41.57	39.56	41.72	42.90	41.49
Fuel consumption (kg/s)						
1000	2.52	2.64	3.12	3.19	2.95	2.96
1600	2.66	2.78	3.74	3.81	3.54	3.55
2400	2.75	2.86	3.83	3.89	3.66	3.63

Note: B refers to biodiesel derived from waste cooking oil, Y denotes distilled Yang-Na oil, and P indicates plastic waste pyrolysis oil. Engine performance tests were conducted at 1,000, 1,600, and 2,400 rpm, representing low, medium, and high operating conditions, with engine speed controlled within ±20 rpm. Each measurement was performed in triplicate, and the results are reported as mean values with a deviation of less than 3%, ensuring accuracy and reliability.

Fuel consumption trends further support these observations. Pure biodiesel and Yang–Na oil demonstrated the highest consumption rates due to their higher density and viscosity, while pyrolysis oil exhibited slightly higher consumption than diesel B10 because of its lower cetane number. In contrast, the ternary blends achieved lower fuel consumption than the individual biofuels and approached the performance of diesel B10, reflecting more efficient combustion behavior [6]–[8], [41–43]. Hence, the ternary blends—especially those at 60:20:20 and 70:15:15 ratios—delivered higher torque at low speeds, stable performance at mid-range speeds, and reduced fuel consumption relative to pure biofuels. These results highlight their potential as practical, performance–competitive alternatives to commercial diesel in agricultural applications.

3.5 *Exhaust gas emissions analysis of biodiesel, Yang–Na oil, pyrolysis oil, and their ternary blends*

Figure 7 summarizes the emission characteristics of biodiesel, Yang–Na oil, pyrolysis oil, the ternary blends (60:20:20 and 70:15:15), and diesel B10. CO emissions were highest for Yang–Na oil and pyrolysis oil, particularly at 1000–1600 rpm, due to their oxygen–deficient sesquiterpenes and unstable oxygenates, which limit complete oxidation (Figure 7(a)). Similar observations have been reported for plant-derived oils with bulky terpenoid or pyrolytic structures [1], [7], [35]. Blending with biodiesel significantly reduced CO emissions in both ternary formulations because the oxygenated FAME molecules enhance oxidation and improve combustion completeness [7], [12], [13], [44].

CO_2 emissions reflected the intrinsic carbon content of each fuel (Figure 7(b)). Biodiesel and the ternary blends produced lower CO_2 than Yang–Na oil and pyrolysis oil because their oxygenated structures enhance combustion efficiency while reducing total carbon conversion to CO_2, consistent with trends reported in earlier studies [1], [6], [7], [44]–[47].

For HC emissions, Yang-Na oil and pyrolysis oil exhibited the highest levels across all speeds (Figure 7(c)). This results from incomplete oxidation of bulky sesquiterpenes and aromatics, as well as poorer atomization due to higher viscosity and lower volatility [7], [12], [13]. Biodiesel, in contrast, produced substantially lower HC because its oxygen content promotes efficient fuel–air mixing and oxidation [47], [48]. The ternary blends inherited this advantage; both blends showed markedly reduced HC emissions compared to Yang–Na oil and pyrolysis oil.

NO_x emissions followed a different trend, as shown in Figure 7(c). At 1000 rpm, Yang-Na oil produced the highest NO_x due to elevated combustion temperatures associated with sesquiterpene-rich hydrocarbons [7], while biodiesel produced the lowest NO_x because its oxygen enhances combustion without excessively increasing peak flame temperatures [1], [41]. With increasing engine speeds, NO_x levels decreased for all fuels due to shorter residence times. The ternary blends exhibited intermediate NO_x behavior, generally similar to diesel B10. This pattern is explained by the presence of aromatic and unsaturated hydrocarbons in pyrolysis oil, which promote higher local flame temperatures and sustain thermal NO_x formation [1], [35], [41], [44], [45]. These compounds also contribute to the soot/NO_x trade-off typical of pyrolysis–derived fuels: lower soot

and HC due to improved oxidation, but limited NO_x suppression because aromatic rings elevate heat–release rates and maintain high-temperature zones.

Overall, the ternary blends demonstrated substantially lower HC emissions than Yang–Na oil and pyrolysis oil because the biodiesel fraction provides inherent oxygen that enhances oxidation and reduces unburned hydrocarbons. However, their NOx emissions remained similar to diesel B10. This is attributed to the aromatic and unsaturated hydrocarbons from the pyrolysis oil fraction, which generate localized high–temperature regions that sustain thermal NO_x formation. Consequently, although biodiesel effectively reduces HC emissions, the pyrolytic aromatic content moderate's NO_x reduction, resulting in NO_x levels comparable to conventional diesel. These results show that the ternary blends balance the combustion characteristics of the three feedstocks—achieving lower CO and HC while maintaining NO_x at levels similar to diesel—making them promising candidates for cleaner and more sustainable diesel alternatives.

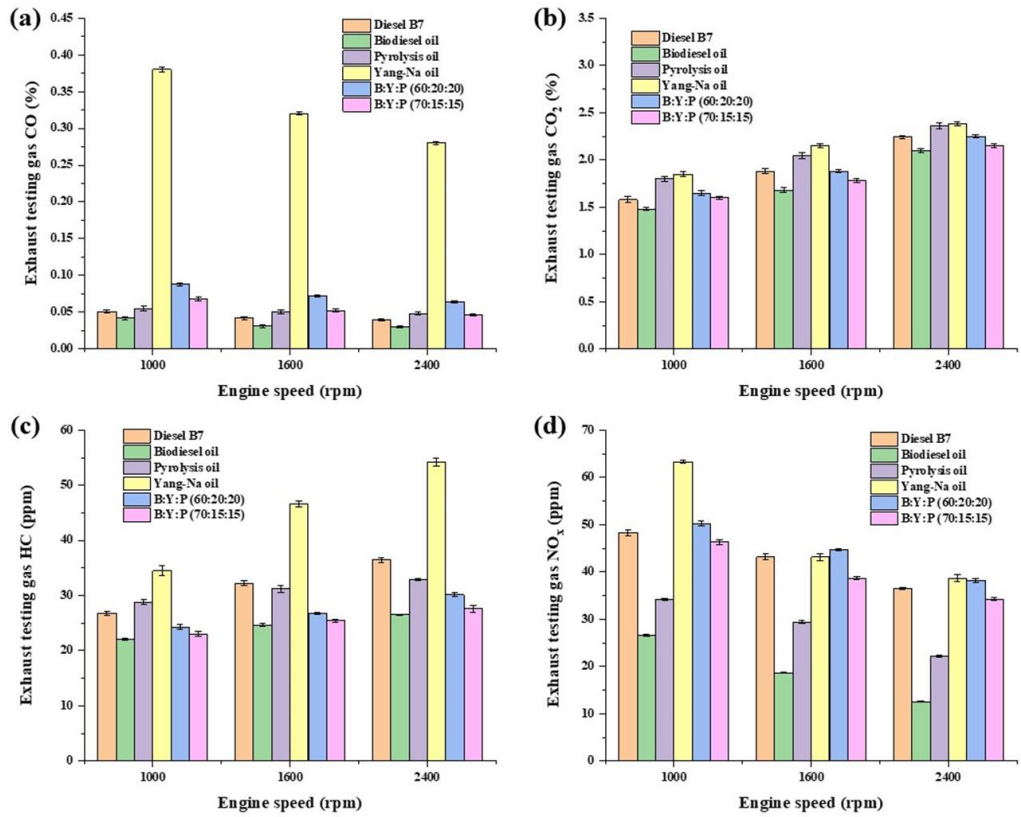

Figure 7: Exhaust emissions of biodiesel, distilled Yang–Na oil, plastic waste pyrolysis oil, their ternary blends (B:Y:P = 60:20:20 and 70:15:15), and commercial diesel B10 at engine speeds of 1000, 1600, and 2400 rpm: (a) CO, (b) CO_2, (c) HC, and (d) NO_x.

3.6 *Field application of liquid biofuel blends in agricultural diesel engines*

The The field application of liquid biofuel blends was conducted using formulations of biodiesel derived from waste cooking oil, distilled Yang-Na oil, and plastic waste pyrolysis oil at ratios of 60:20:20 and 70:15:15. These blends were tested in Ban Khok Sa–At, Um–Chan Subdistrict, Kusuman District, Sakon Nakhon Province, in collaboration with the Homdokhung Rice organic farming community enterprise. As shown in Figure 8, the preliminary trial demonstrated that a small–scale agricultural diesel engine (walking tractor) operated effectively with both blends. Engine power output and fuel consumption were comparable to commercial diesel

B10, confirming the technical feasibility of employing these blends in real agricultural operations.

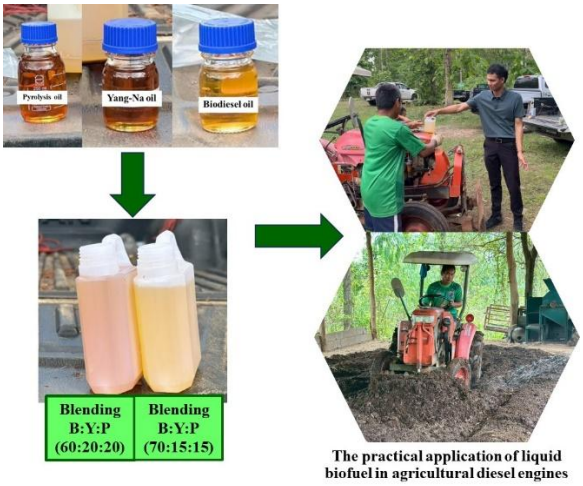

Figure 8: Field test of ternary liquid biofuel blends (B:Y:P at 60:20:20 and 70:15:15) in an agricultural tractor compared with commercial diesel B10 at Homdokhung Rice organic farming community, Ban Khok Sa–At, Um–Chan subdistrict, Kusuman district, Sakon Nakhon province.

Although this study serves as an initial evaluation, participating farmers expressed a clear intention to further adopt these biofuel blends as a substitute for diesel B10. A preliminary sustainability and economic perspective also suggest several benefits. The primary feedstocks—waste cooking oil and community plastic waste—are either low-cost or free materials, and their conversion into liquid biofuels reduces waste management burdens while lowering dependence on commercial petroleum fuels. Distilled Yang–Na oil, sourced from local forest resources where Yang–Na trees are abundant, adds further value by promoting the use of locally conserved biomass. While a full cost analysis and life–cycle assessment were beyond the scope of this work, the observed reduction in purchased fuel demand and the utilization of locally available waste streams indicate strong potential for improving household energy expenditure and strengthening community–level energy resilience.

Moreover, similar field–based evaluations have reported that biofuel blends can be used in agricultural engines without major modifications, supporting the practical feasibility of integrating diversified community feedstocks into rural energy systems. Future studies will therefore incorporate detailed economic assessments, long–term engine performance monitoring, and environmental impact evaluations to more comprehensively quantify the sustainability of these liquid biofuel blends [7], [14], [24], [41], [49]–[52].

4 Conclusions

This study successfully formulated ternary liquid biofuels from WCO biodiesel, distilled Yang-Na oil, and plastic waste pyrolysis oil, integrating three community-derived feedstocks into a single renewable fuel system. Chemical analyses confirmed that pyrolysis oil contains C_6–C_{22} hydrocarbons with high olefin content, Yang-Na oil is dominated by sesquiterpenes, and WCO biodiesel provides oxygenated esters that enhance combustion. These complementary characteristics enable synergistic improvement when blended. Engine testing demonstrated that the 70:15:15 (B:Y:P) blend delivered the most balanced performance, producing higher torque at low speed, reduced CO and HC emissions, and NO_x levels comparable to diesel B10. This behavior results from the combined effects of biodiesel-derived oxygen, Yang-Na oil lubricity, and the high heating value of pyrolysis hydrocarbons, collectively improving combustion phasing and fuel–air oxidation.

Field trials using agricultural walking tractors confirmed that the ternary blends operate reliably under real farming conditions, with fuel consumption and engine power comparable to conventional diesel. Beyond technical feasibility, the approach provides sustainability benefits by converting local plastic waste into fuel, recycling WCO, and utilizing Yang-Na oil from community forests, thereby supporting rural energy self-reliance. However, long-term engine durability, storage stability, and economic or life-cycle assessment were not covered in this study. Future work should address these aspects to support large-scale implementation. Overall, the ternary fuel system—particularly the 70:15:15 blend—offers a practical, efficient, and community-oriented alternative to petroleum diesel.

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Author Contributions

W.R.: Conceptualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Writing – original draft, Writing – review & editing; S.P.: Conceptualization, Methodology, Investigation; S.W.: Methodology, Investigation, Formal analysis; B.M.: Methodology, Investigation, Formal analysis; P.C.: Methodology, Investigation, Formal analysis; A.T.: Methodology, Investigation; T.L.: Methodology, Investigation; N.K.: Methodology, Investigation; S.A.: Methodology, Formal analysis. K.D.; Methodology, Investigation; S.K.; Resources, Investigation; K.N.: Resources, Investigation; B.Y.: Supervision, Conceptualization, Methodology; P.J.: Methodology, Investigation, Formal analysis; V.P.: Supervision, Methodology, Funding acquisition, Conceptualization. All authors have read and agreed to the published version of the manuscript

Conflicts of Interest

The authors confirm that there are no financial, personal, or professional relationships that could have inappropriately influenced the research presented in this study.

Declaration of Generative AI in Scientific Writing

The authors used ChatGPT as a tool for English grammar checking during the preparation of this manuscript. All content was carefully reviewed, revised, and edited by the authors to ensure clarity and accuracy. The authors take full responsibility for the integrity and reliability of the final publication.

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