Challenges and opportunities of marine propulsion with liquid alternative fuels

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Abstract

The increasingly stringent shipping emissions regulations and global decarbonisation movement have prompted the adoption of alternative fuels in the shipping industry. This review presents the performance results and evaluation of alternative fuel engines under low-medium speed operation that has not been considered by existing reviews. This operating regime is typically used in marine propulsion. Relevant articles published by reputable journals were retrieved from scholarly databases and analysed. The evaluated alternative fuels were waste plastic oil (WPO), tyre pyrolysis oil (TPO), biodiesel, ammonia, vegetable oil (VO), and waste lubricant oil (WLO). Neat WPO and TPO demonstrated poorer emissions performances than diesel; alternatively, retarding the fuel injection timing of the WPO engine and blending the TPO with biodiesel had elevated engine performances substantially. As compared to VO degum and blending VO with diesel, VO preheating was a more promising approach to augment engine performance. Ammonia is an attractive candidate owing to its carbon-free chemical composition, but novel technologies are needed to address its terribly high NO_x emission. Diesel-like fuel (DLF) derived from WLO produced notably better engine performance than fossil diesel. This review provides insight into liquid alternative fuels performances for low-medium speed engine operation, whose combustion physics is considerably different from high-speed operation. Such understandings are vital to address the current issues regarding marine engine systems, promoting the development of combustion technologies and alternative fuels uptake in marine propulsion.

Highlights

1. The low-medium speed alternative fuels engines are reviewed.
2. Retarding fuel injection timing enhances WPO engine performances.
3. Nanoparticle’s addition suppresses biodiesel NO_x formation.
4. Preheating the VO elevates the overall performances of a low-medium speed engine.

5. DLF derived from WLO augments overall diesel engine performances.

Keywords: alternative fuel; marine engine, emissions, waste plastic, tyre pyrolysis, waste lubricant oil

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List of Abbreviations:

2-EHN	-	2-ethylhexyl nitrate
AFO	-	Alternative Fuel Oil
aTDC	-	After Top Dead Centre
BHA	-	2,6-di-terl-4-methylphenol
BHT	-	2(3)-tert-butyl-4-methoxy phenol
BR	-	Butadiene Rubber
BSFC	-	Brake Specific Fuel Consumption
bTDC	-	Before Top Dead Centre
BTE	-	Brake Thermal Efficiency
CA	-	Crank Angle
Cd	-	Cadmium
CeO_2	-	Cerium Oxide
CIB	-	Calophyllum Inophyllum Biodiesel
CIDI	-	Compression Ignited Direct Injection
CI	-	Compression Ignited
CN	-	Cetane Number
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
CR	-	Compression Ratio
Cr	-	Chromium
cSt	-	Centistokes
DEE	-	Diethyl Ether

DLF - Diesel-like fuel
DME - Dimethyl Ether
ECA - Emission Control Areas
EGR - Exhaust Gas Recirculation
FSN - Filter smoke number
GLF - Gasoline-like fuel
g/kW-hr - Gram per kilowatt hour
IDI - indirect injection
HCCI - Homogeneous Charge Compression Ignition
HCO - heated coconut oil
HDPE - High-density Polyethylene
HFO - Heavy fuel oil
HRR - heat release rate
ITE - indicated thermal efficiency
IMO - International Maritime Organization
JME - Jatropha biodiesel
J/°CA - Joule per Crank Angle
kg/kW-hr - Kilogram per kilowatt hour
kg/m^3 - Kilogram per meter cubic
LDPE - Low-density polyethylene
LHV - Lower Heating Value
LNG - Liquified Natural Gas
LSDLF - Desulfurised DLF
MDO - marine diesel oil
MGO - marine gas oil
MJ/kg - Megajoule per kilogram
mm^2/s - Millimeter square per second
NH_3 - Ammonia
Nm - Newton meter
NO_x - Nitrogen Oxide
NR - natural rubber

Pb - Plumbum

PET - Polyethylene Terephthalate

PM - Particulate Matter

PP - Polypropylene

ppm - Parts per million

PS - Polystyrene

PVC - Polyvinyl Chloride

RPM - Revolution per minute

SBR - styrene butadiene rubber

SCR - selective catalytic reduction

SI - spark ignited

SO_2 - Sulphur Dioxide

SO_x - Sulphur Oxide

TPO - tyre pyrolysis oil

UHC - Unburned Hydrocarbon

ULSD - Ultra-Low Sulphur Diesel

VO - vegetable oil

vol% - Volume Percent

WCO - waste cooking oil

WLO - waste lubricant oil

WOS - Web of Science

WPO - waste plastic oil

wt.% - Weight Percent

WVO - waste vegetable oil

η - Efficiency

°C - Degree Celsius

τ - Brake torque

1.0 Introduction

The shipping industry is one of the largest fossil fuels consumers, thus one of the major air pollutant contributors in the world. It is estimated that the shipping industry consumes about 330 million metric tons of fuels annually, mainly due to about 90% of the world's goods are transported by ships [1]. Heavy fuel oil (HFO) is typically used to propel marine cargo vessels. HFO is obtained from residue that is left over from the crude oil distillation. It is a low-grade fuel that contains a high level of sulphur, and contributes directly to the Sulphur Oxide (SO_x) emission following its combustion in the engines to drive the marine cargo vessels [2]. Apart from SO_x, Nitrogen Oxide (NO_x) and Particulate Matter (PM) are two other lethal substances in maritime emissions. It is estimated that the demand for marine fuel will double by year 2030, which will undoubtedly intensify air pollution [1–3].

International Maritime Organization (IMO) has imposed stricter regulations on ship fuel to ameliorate harmful SO_x emission. Fig. 1 shows that IMO requirement for sulphur content in open seas was reduced from 4.5 wt.% to 3.5 wt.% in January 2012. This was further reduced to 0.5 wt.% in January 2020 [4]. This is expected to reduce annual SO_x emission by ~ 8.5 million metric tonnes [4]. For ships that operate in the Emission Control Areas (ECA), the obligatory fuel sulphur content had been restricted to under 2 wt.% since 2005, and later was even reduced to only 0.1 wt.% since January 2015. Despite the use of scrubber can reduce acidic emissions from ships, it undesirably incurs additional cost for maintenance and waste handling. Moreover, additional power is needed to run the scrubber, resulting in poorer engine fuel efficiency. Thus, alternative fuels have been nominated as potential solution to meet the stringent shipping emissions requirements [5].

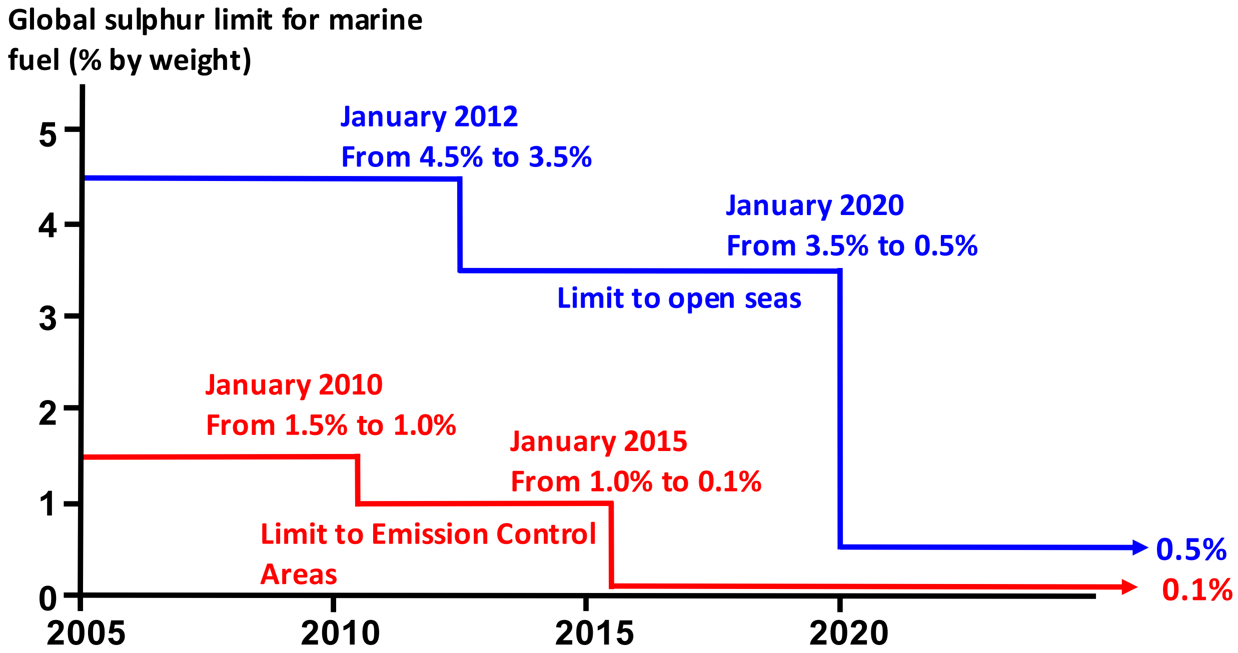


Fig. 1 Global marine fuel sulphur limit from year 2005 to 2020 (adapted from [6])

Majority of marine vessels utilise engines that are principally similar to that in automobiles. In contrast to automobile engines, marine vessels employ heavy-duty, low-speed (~ 70-120 RPM), two-stroke engine or medium speed (~250-1200 RPM) four-stroke engine, coupled with gearbox for the main propulsion system [7]. Fig. 2 depicts the disparities in engine speed regime of ships and vehicles. There have been numerous reviews on alternative fuels vehicles engines, but the understandings of alternative fuel engines for marine propulsions that operate below 1500 RPM are limited. Despite sulphur contents in many alternative fuels being lower than in diesel and HFO, there is no assurance that alternative fuels combustion would be cleaner than that of diesel and/or HFO in terms of lower NO_x, PM, and Carbon Monoxide (CO). Different from the existing reviews, the present study focuses on low-medium speed engine operation (~200-1500 RPM) that is typically used in marine propulsion where engine performances in this specific regime have not been satisfactorily addressed by existing reviews.

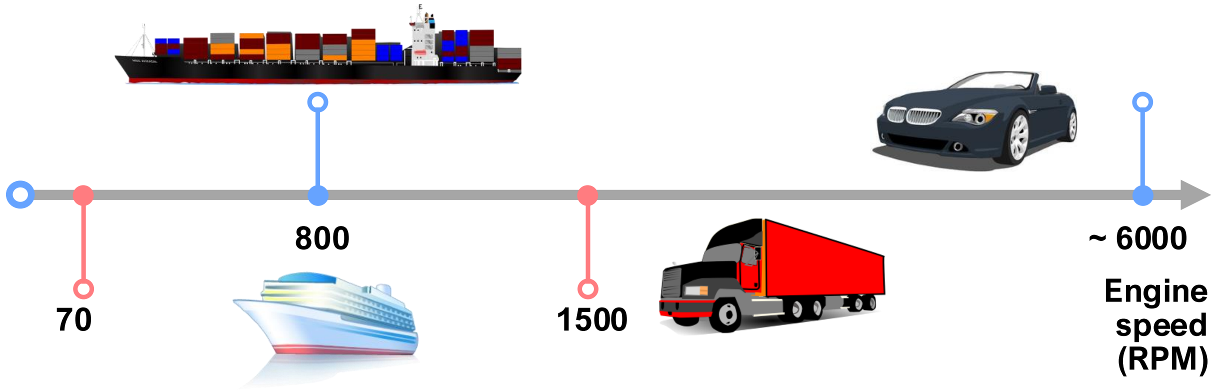


Fig. 2 Comparison of engine operating regimes between ship and vehicle

Low-medium speed engine exhibits distinct combustion characteristics and gas exchange phenomena compared to higher speed engines (>1500 RPM). The reciprocating motion of the piston is slowed down substantially in low-medium speed operation; rendering adequate time for the sprayed fuel to disperse, vaporise, and subsequently burn [8]. Thus, engine is expected to benefit from the low volatile alternative fuel, where prolonged droplets vaporisation time scale is needed to attain complete combustion. Meanwhile, a low-medium speed engine generates lower turbulence fluctuation than high-speed operation [9]. This inhibits turbulence fluctuation penetration through the flame front, and promotes local droplets accumulation [10]. Envelope flames are formed around such large droplets, which consequently thicken the flame front, leading to connected reaction zones that put up a more conducive environment for alternative fuels combustion. Moreover, at high/full load operation, backpressure in the exhaust manifold is expected to increase, owing to the pressure waves set up by the interaction between bulk exhaust gas flow and exhaust manifold. This pressure wave prevents gas exchange processes while increasing exhaust temperature. Although detrimental to engine fuel efficiency, increased backpressure prompts CO oxidation and forms a favourable condition for reducing Unburned Hydrocarbon (UHC) emission [11].

Distinctive differences between low-medium speed and high-speed engines signify those alternative fuels combustion characteristics of high-speed engine operations may not be suitably inferred to the low-medium speed engines. Considering limited understanding on low-medium speed engine performances, this study was conducted to evaluate performances of several alternative fuels in high load, low-medium speed engines that are commonly utilised in marine propulsion. Alternative fuels are desirable from the perspective of fulfilling the emissions goals. In addition to Bio-Liquified Natural Gas (LNG), Bio-Methane, and Bio-Methanol addressed by the previous review [12], present study considers waste plastic oil (WPO), tyre pyrolysis oil (TPO), waste lubricant oil (WLO), ammonia, vegetable oil (VO), and biodiesel. The accessibility of numerous academic databases and search engines, such as Web of Science (WoS), Scopus, Science Direct, and Google Scholar, makes finding and retrieving research articles for this review much easier. WoS is one of the most used academic databases for this purpose considering it has the most indexed publications and conference proceedings, covering approximately 150 scientific disciplines [13]. As shown in Fig. 3, the search string was created to find articles that had a desired combination of terms in their names, abstracts, or keywords. The search yielded different types of papers. In this study, only journal articles, conference proceedings, reviews, and slides from reputable conferences were considered. References of shortlisted publications were also used to search for relevant works. Previous studies related to combustion and emissions performances of these alternative fuels under high load, low-medium speed conditions were evaluated if no new keywords identified. The reviews of WPO, TPO, WLO, ammonia, VO, and biodiesel are presented in Sections 2, 3, 4, 5, 6, and 7, respectively. Section 8 presents the discussions for reviews in the earlier sections while section 9 concludes the major findings from this study.

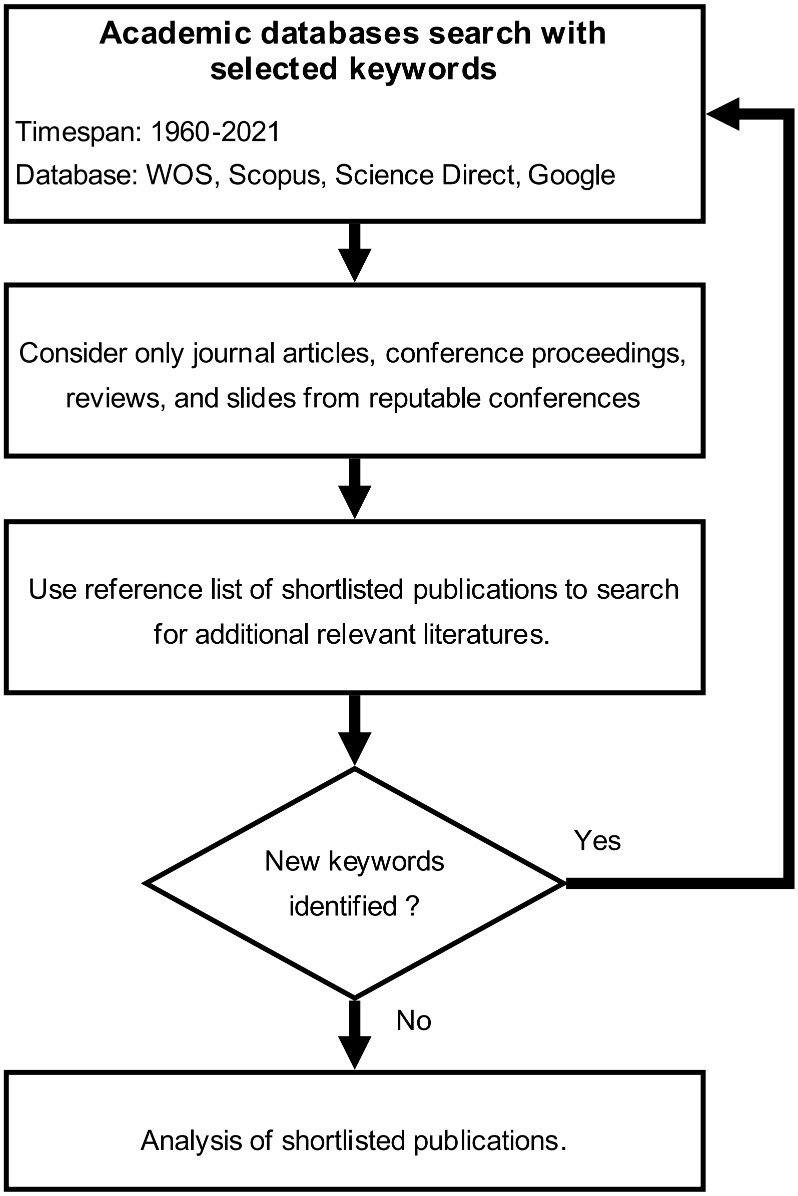


Fig. 3 Search strategy used to retrieve the relevant publications for this review.

2.0 Waste Plastic Oil (WPO) as Alternative Fuel for Marine Propulsions

Disposal and accumulation of waste plastic pose major threat to our living environment, owing to its prolonged decomposition timescale [14,15]. Global plastic production has increased exponentially since the 1950s, climbing from 2 million tons in 1950s to approximately 381 million tons in year 2015, recording an increment of ~ 200-fold[16]. Worse still, 55% of global plastic waste was simply discarded, 25% was incinerated, and only 20% was recycled [16]. Water plastic pollution has triggered global attention. While water purification is one way of handling the water plastic pollution [17], converting waste plastics into alternative fuel for marine vessel propulsion is another potential way to decrease waste plastic pollution and reducing its negative socioeconomic and ecological impacts thereafter. Reducing these negative impacts are essential to ensure sustainable global development [18].

Waste plastic oil (WPO) is produced via thermal degradation (pyrolysis) of plastic under temperature between 300-900°C and in the absence of oxygen. Pyrolysis temperature affects the heating rate and liquid yield of the pyrolysis process [19]. Pyrolysis temperature >600°C typically leads to >75% liquid yield, while pyrolysis temperature ~450 °C produces ~50% liquid yield [20]. Typical plastics encountered in daily life and physicochemical properties of their WPO are shown in Table 1. The calorific values of WPO derived from High-density Polyethylene (HDPE), Polypropylene (PP), and Polystyrene (PS) are very close to that of diesel (40-43 MJ/kg). Substantially low calorific value of Polyethylene Terephthalate (PET) and Polyvinyl Chloride (PVC) can be attributed to low carbon fraction (< 40 wt.%) in these plastics [20]. Although the viscosity of WPO is generally higher than that of diesel, they are very close to that of biodiesel [19], denoting a comparable spray quality between WPO and biodiesel. Overall, Table 1 shows that WPO exhibits noticeably lower viscosity and sulphur contents than HFO. Except for PVC-derived WPO, the sulphur contents in the rest of WPO in Table 1 are safely below the current IMO's limit (0.5 wt.%) [6].

Table 1 Comparison of WPO physical properties derived from different plastics with fossil diesel [20–23]

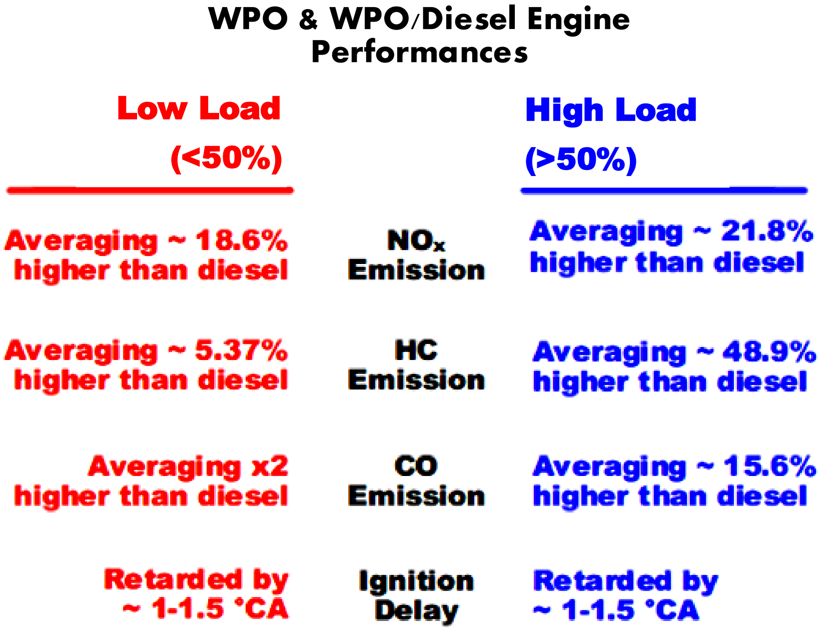
	Calorific Value (MJ/kg)	Viscosity @40°C (mm^2/s)	Density @15°C (kg/m^3)	Cetane Number (-)	Flash Point (°C)	Sulphur (wt.%)
High-density polyethylene (HDPE)	40.5	2.10	890	66	48	0.28
Polyvinyl chloride (PVC)	21.1	4.24	840	63-64	40	0.58
Polyethylene terephthalate (PET)	28.2	-	900	-	-	-
Low-density polyethylene (LDPE)	39.5	2.24	780	-	41	0.28
Polypropylene (PP)	40.8	4.09	860	-	30	0.33
Polystyrene (PS)	43.0	1.4	850	-	26.1	0.19
HFO	40.0	710	982	20	60	2.17
Diesel (Automotive)	42.6	2.6	843	52	72	-

Guntur et al. [24] blended WPO and diesel by 70/30 volumetric ratio (WPO70), and reported that WPO70 improved Brake Specific Fuel Consumption (BSFC) of a 60% loaded engine by roughly 0.1 kg/kW-hr, against neat diesel at 1500 RPM engine speed; denoting higher thermal efficiency of WPO70 engine under high load operation. Nonetheless, CO and UHC emissions of the WPO70 engine were marginally higher than that of a neat diesel engine. WPO/diesel blend was also investigated by Mani et al. [25], where it was found that ignition delay of a 1500 RPM WPO-diesel engine increased by 1 °CA (Crank Angle) under full load operation, as the WPO volumetric ratio was increased from 10% to 100%. By utilising WPO volumetric ratio of 20%, Jeyakumar and Narayanasamy [26] noticed that the fuel efficiency of high load WPO20 engine was 7% lower than that of neat diesel engine. Meanwhile, UHC emission of high load WPO20 engine was higher than that of diesel engine. Ravi and Karthikeyan [27], however, opined that BTE of high load WPO20 engine was only marginally lower than that of a diesel engine. High load WPO20 engine led to higher smoke opacity than that of diesel engines. Ayodhya et al. [28] found that NO_x emission of high load WPO30 engine increased by 500 ppm (~63%) at 80% loading, while CO emission was elevated by nearly 2 times.

Mani et al. [29] showed that Brake Thermal Efficiency (BTE) of full load neat WPO engine was nearly identical to that of a diesel engine, despite the peak cylinder pressure of the former was about 5 bar lower than the latter. This was presumably due to heat release in the neat WPO engine that was not in-phase with the diesel engine. Although the WPO engine produced less smoke emission by 40-50%, NO emission of full load WPO engine was 3 g/kW-hr higher than that of the diesel engine. Kumar et al. [30] also found that neat WPO elevated the BTE of a full load engine operating at 1500 RPM by 2% compared to a diesel engine. UHC and NO_x emissions were less by 25 ppm and 200 ppm, respectively, as compared to diesel. Saravanan et al. [31] reported that the ignition delay of a high load 1500 RPM neat WPO engine was 1 °CA slower than that of the diesel engine.

Neat WPO, although exhibiting very similar physical properties with diesel, yieled ignition delay by about 1-1.5 °CA as compared to diesel, regardless of engine loading [24,25,29,30].

However, this did not cause severe deterioration in engine BTE [25,29]. Emission wise, NO_x emissions from WPO and WPO/diesel blend engines were generally higher than diesel [26,28,29,31], where high load WPO and WPO/diesel blend engines typically resulted in more significant NO_x increase (~ 21.8%) than low load operations (~ 18.6%) [28,29,31]. CO emissions of neat WPO and WPO/diesel blend engines were generally higher than diesel as well[24,25,29,30]. Fig. 4 summarises major findings from the review on low-medium speed WPO and WPO/diesel engines.



WPO & WPO/Diesel Engine Performances

Low Load (<50%)		High Load (>50%)
Averaging ~ 18.6% higher than diesel	NO_x Emission	Averaging ~ 21.8% higher than diesel
Averaging ~ 5.37% higher than diesel	HC Emission	Averaging ~ 48.9% higher than diesel
Averaging x2 higher than diesel	CO Emission	Averaging ~ 15.6% higher than diesel
Retarded by ~ 1-1.5 °CA	Ignition Delay	Retarded by ~ 1-1.5 °CA

Fig. 4 Effects of engine loadings on medium speed WPO and WPO/diesel engine performances (baseline: fossil diesel).

To improve emission performances of WPO and WPO/diesel engines, several strategies had been proposed and examined. The effect of Exhaust Gas Recirculation (EGR) on the WPO engine was investigated by Mani et al. [32], who found that NO_x emission for full load WPO engine with 20% EGR was only 0.5 g/kW-hr lower than 0% EGR WPO engine [32]. CO reduction was more pronounce, where 20% EGR led to reduction of CO emission of full load WPO engine up to 1 g/kW-hr, compared with 0% EGR. Ayodhya et al. [28] reported that NO_x emission of full load WPO30 engine with 20% EGR was reduced by nearly 100 ppm against 0% EGR. Nevertheless, UHC and soot emissions from 20% EGR WPO30 engine increased by 10 ppm and 12%, respectively, as compared to the 0% EGR WPO30 engine. Despite that EGR would lead to lower toxic emissions like NO_x, the use of EGR was found to inherently deteriorate engine BTE, owing to the reduction in oxygen in combustion air [33]. Engine BTE was found reduced by an average of 2-3% when the EGR rate was increased from 0% to 20% [28,32].

Adjusting fuel injection timing is another way to manipulate the heat release rate (HRR) in the combustion chamber, which affects the engine performances. Kalargaris et al. [34] reported that the peak HRR of a 1500 RPM WPO engine was elevated by 125 J/°CA at 75% loading when fuel injection was advanced by 5 °CA. However, UHC and CO emissions increased by a factor of 2 as compared to default injection timing. Damodharan et al. [35] showed that ignition delay, fuel efficiency, and NO_x emission for a high load WPO engine did not improve significantly when fuel injection was advanced by 2 °CA. While advanced fuel injection was found incapable of improving engine performances, Mani et al. [36] found that retarded fuel injection by 9 °CA elevated the efficiency of full load WPO engine by ~ 5%. NO_x and CO improvements due to retarded fuel injection were more significant at low load operation [36]. The present review shows that fuel injection timing of ~ 14 °CA bTDC (before Top Dead Centre) is beneficial for WPO engine operation[36], while fuel injection timing > 20 °CA bTDC leads to declined engine performance [34,36].

Influences of additives like 2-ethylhexyl nitrate (2-EHN) and emulsifiers such as pentanol and hexanol had also been investigated by several groups of researchers. 2-EHN enhanced BTE of 85% loaded WPO engine by 0.5%[34], besides reduction of NO_x emission by 90 ppm [34]. Blending alcoholic fuels with WPO reduced overall emissions substantially, but this was achieved at the expense of lowering the engine BTE up to 20.4% [37]. Instead of blending the WPO with alcoholic fuels, Senthilkumar and Sankaranarayanan [38] blended WPO with biodiesel using 20/80 volumetric ratio, which enhanced the engine BTE by 2%, as compared to neat WPO engine. Although no significant improvement in NO_x emission was reported, CO emission of full load WPO80 engine was nearly 60% lower than the neat WPO engine. Fig. 5 summarises improvement strategies for low-medium speed WPO engine.

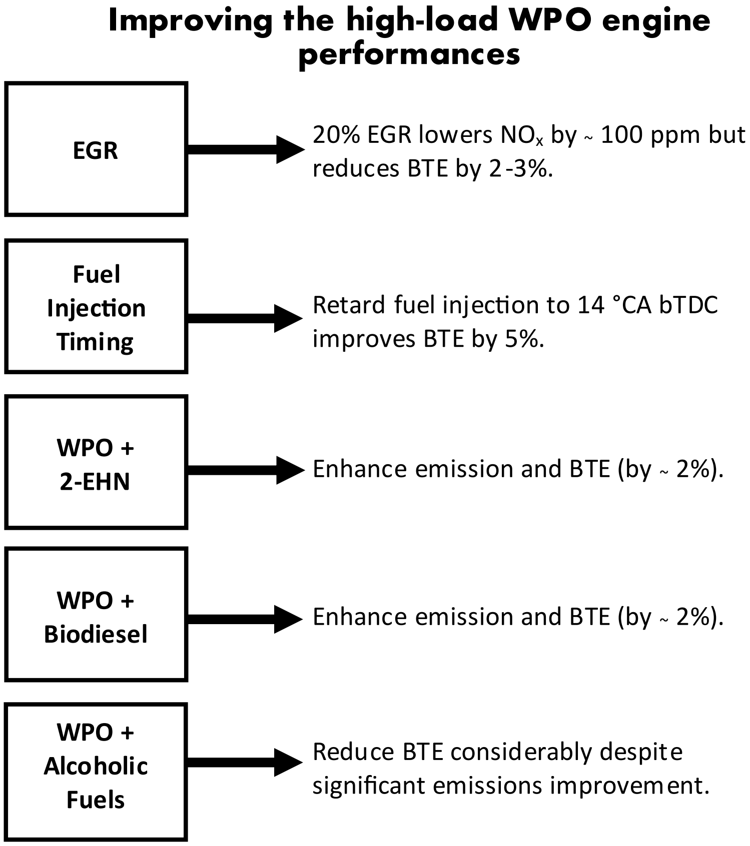


Fig. 5 Improvement strategies for low-medium speed, high load WPO engine.

3.0 Tyre Pyrolysis Oil (TPO) as Alternative Fuel for Marine Propulsions

With increasing number of vehicles worldwide, waste tyre disposal is becoming trickier. One possible way of reusing the waste tyre is to pyrolyse them into Tyre Pyrolysis Oil (TPO). Apart from WPO, TPO is another compelling option for marine propulsion. TPO is a dark brown/black coloured, medium viscosity oil with sulphurous/aromatic odour, containing compounds composed of aliphatic, aromatic, and hetero-atom. Thermal decomposition of the tyre starts at ~250°C and the pyrolysis process is typically performed in temperature range between 450-700°C. Early research showed that thermal decomposition of tyre consisted of two stages: (i) natural rubber (NR) decomposition, and (ii) styrene butadiene rubber (SBR) and butadiene rubber (BR) decomposition [39,40]. Recent research [41] unveiled four stages of tyre pyrolysis: (i) plasticizer decomposition and water vaporisation at temperature < 320°C, (ii) natural rubber decomposition at 320-400 °C, (iii) synthetic rubber breakdown at 400-520 °C, and negligible mass loss at fourth (iv) stage when temperature > 520 °C [42,43]. Tyre pyrolysis is mainly governed by pyrolysis temperature, volatile retention time within the reaction zone, reactor pressure, and type of gaseous in the reactor [44]. A fixed bed reactor is commonly used for tyre pyrolysis, besides the use of fluidised bed, moving bed screw reactors, and rotary kilns that enable continuous process flow (Fig. 6).

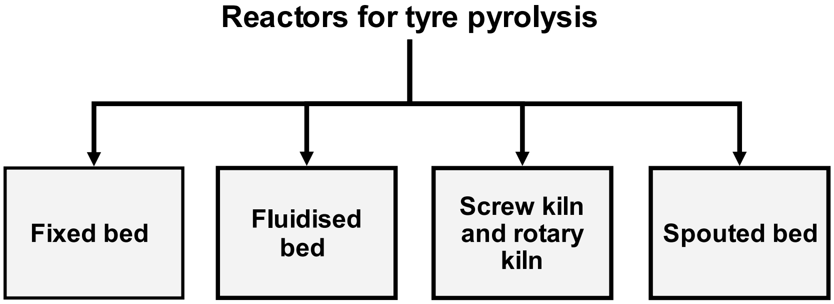


Fig. 6 Typical reactors used for pyrolysing the tyre/waste tyre [44].

TPO produced from the pyrolysis of tyres in a circulating fluidised bed consists of alkanes (26.77 wt.%), aromatics (42.09 wt.%), non-hydrocarbons (26.64 wt.%), and asphalt (4.05 wt.%) [45]. Table 2 presents comparison between typical TPO physical properties with those of HFO and diesel. Although TPO exhibits very similar physical properties with diesel, long-term effects on engine have to be verified [46]. This is mainly due to the contamination of acidic substances, such as sulphur, in TPO which is about a factor of 3 higher than diesel, as shown in Table 2 [46]. The sulphur content in the TPO is clearly higher than the limit set by IMO.

Table 2 Fuel physicochemical properties comparison between TPO, diesel, and HFO.

	TPO [46]	**Diesel** [47]	**HFO** [22]
Density @15°C (kg/m^3)	903	830	982
Calorific value (MJ/kg)	41.9	42.6	40.0
Viscosity @40°C (mm^2/s)	2.9	1.8	710
Flash Point (°C)	58	72	60
CN	NA	52	20
Sulphur (wt.%)	0.97	0.30	2.17

Despite containing higher level of sulphur than diesel, several groups of researchers conducted evaluations to determine neat TPO engine performances. Adam et al. [48] found that the peak cylinder pressure of 1200 RPM neat TPO Compression Ignited Direct Injection (CIDI) engine (Yanmar TF120M) was 10 bar higher than that of diesel engine. NO_x emission of the TPO engine was 300 ppm higher than that of diesel and CO emission from the TPO engine was higher than that of diesel engine by a factor of 6. Vihar et al. [49] reported that the HRR of a 1500 RPM

TPO engine was higher than that of diesel by approximately 30 J/°CA at 50% loading. Żółtowski [50] observed that full load TPO engine resulted in knocking, owing to the combustion instability that happened in the full load operation. Moreover, UHC emission of full load TPO engine was elevated by 2.25 g/kW-hr, compared with by diesel. İlkılıç and Aydın [51] found that the brake power of 1000 RPM TPO engine was nearly identical with that of a diesel engine. Meanwhile, Sulphur Dioxide (SO_2) emission from the TPO engine was 250 ppm higher than a diesel engine. Table 3 summarises the major findings from recent neat TPO engine studies.

Table 3 Combustion and emissions performance TPO marine engine compared with the respective baseline.

Tested Fuel	**Baseline**	**Engine Speed**	**Engine Loading**	**Engine Performances**	**Emissions**	**References**
TPO	Diesel	1200 RPM	-	Peak cylinder pressure ↑ 10 bar Brake torque (τ) ↓ 2 Nm	CO ↑ 600% NO_x ↑ 84.2%	[48]
		2100 RPM	-	Peak cylinder pressure ↑ 20 bar τ ↑ 3 Nm	CO ↑ 266% NO_x ↑ 80%	
TPO	Diesel	1500 RPM	30%	-	$CO_{TPO} \approx CO_{Diesel}$ NO_x ↑14.2% UHC ↑33.3%	[49]
			50%	Peak HRR ↑ 60%	$CO_{TPO} \approx CO_{Diesel}$ NO_x ↑11.1% UHC ↑100%	
TPO	Diesel	1500 RPM	50%	Peak $HRR_{TPO} \approx$ Peak HRR_{Diesel}	CO ↑ 140% NO_x ↑ 21.7% UHC ↑ 63%	[50]
			100%	Peak $HRR_{TPO} \approx$ Peak HRR_{Diesel}	CO ↑ 100% NO_x ↑ 3.84% UHC ↑ 125%	

To promote TPO adoption, the physical properties of TPO need to be improved [52]. Fossil diesel is frequently used for blending with TPO. Pote and Patil [53] reported that BTE of a full load 1500 RPM 90/10 TPO/diesel (TPO90) engine increased by 12%, compared to that of neat diesel. The ignition delay of the full loading TPO90 engine was 3 °CA slower than neat diesel. Murugan et al. [54] showed that NO_x emission for the TPO90 engine was 500 ppm higher than that of diesel engine. Furthermore, peak cylinder pressure for the TPO90 engine was 2.5 bar higher than that of diesel, leading to increased peak HRR of approximately 5 J/°CA. Frigo et al. [46] demonstrated that the performance of the TPO20 engine were comparable with the neat diesel engine. Nonetheless, the engine performance declined significantly when TPO volumetric ratio was raised to 40%. Hürdoğan et al. [55] reported that the BSFC of a 1000 RPM TPO20 engine was higher than the diesel engine by 10 g/kW-hr. Nonetheless, CO emission for the TPO20 engine was 20 ppm higher than that of diesel engine. Table 4 summarises major findings from researches on TPO/diesel blend engine.

Overall, results in Table 4 signify that TPO/diesel blend does not improve engine performances appreciably as compared to diesel. Thus, several other groups of researchers turned their attention to blending TPO with biodiesel. In addition to boosting engine performance, biodiesel has lower sulphur content [56] in the fuel mixture, thus meets the IMO requirement. Krishania et al. [57] blended Jatropha biodiesel with TPO, by 80/20 volumetric proportion (JME80TPO20). The peak cylinder pressure for diesel and JME80TPO20 engines were nearly identical at full loading but BTE for fully loaded JME80TPO20 engine was ~ 3% lower than that of diesel. Sharma and Murugan [58] showed that BTE and CO emissions for both JME50TPO50 and diesel engines were practically identical. The smoke opacity of JME50TPO50 engine was lower than that of diesel engine by 23%, although NO_x emission from JME50TPO50 engine was marginally higher than from diesel engine (~ 0.5 g/kW-hr). By reducing the TPO volumetric proportion to 20% [59], overall engine performance improved, owing to the reduction in TPO volumetric ratio.

In addition to biodiesel, Hariharan et al. [60] blended TPO with Diethyl Ether (DEE) and found that ignition delay of the fully loaded TPO/DEE engine increased by 6 °CA, resulting in slightly higher peak HRR (10 J/°CA) than that of the diesel engine. BTE of the TPO/DEE engine was about 5% higher than the diesel engine. Moreover, TPO/DEE engine produced NO_x lower than diesel engine (2 g/kW-hr), but had elevated CO emission by about 5 g/kW-hr. Smoke emission also increased by 2 BSU when using TPO/DEE. As compared to fossil diesel and DEE, blending the TPO with biodiesel proved to be more promising engine performance improvement, especially in high load-medium speed operations [57,59,60]. BTE of TPO/biodiesel engine was comparable with that of diesel engine, besides exhaust emissions (NO_x and smoke) having reduced satisfactorily [57,59,60].

Table 4 Combustion and emission performance TPO/diesel engine compared with those of fossil diesel.

Tested Fuels	**Baseline**	**Engine Speed**	**Engine Loading**	**Engine Performances**	**Emissions**	**References**
TPO90	Diesel	1500 RPM	35%	BTE ↑ 11% ID ↓ 2°CA	$CO_{TPO} \approx CO_{Diesel}$ NO_x ↑ 16.7% Smoke ↑ 75%	[53]
			100%	BTE ↑ 12% ID ↓ 3°CA	CO ↑ 50% NO_x ↑ 14.3% Smoke ↑ 83%	
TPO75	Diesel	1000 RPM	100%	τ ↓ 1.5 Nm BSFC ↑ 80 g/kW-hr	NO_x ↑ 70 ppm HC ↑ 50 ppm CO ↓ 20%	[61]
		2000 RPM	100%	τ ↓ 2 Nm BSFC ↑ 100 g/kW-hr	$NO_{x,TPO} \approx NO_{x,Diesel}$ UHC ↑ 80 ppm CO ↑ 33%	
TPO90	Diesel	1400 RPM	100%	$BTE_{TPO} \approx BTE_{Diesel}$ $\tau_{TPO} \approx \tau_{Diesel}$	NO_x ↑ 450 ppm UHC ↓ 12 ppm CO ↓ 60%	[62]
		2600 RPM	100%	$BTE_{TPO} \approx BTE_{Diesel}$ $\tau_{TPO} \approx \tau_{Diesel}$	NO_x ↑ 340 ppm $UHC_{TPO} \approx UHC_{Diesel}$ $CO_{TPO} \approx CO_{Diesel}$	
TPO70	Diesel	1500 RPM	50%	BTE ↓ 3% ID ↑ 4 °CA	NO_x ↑ 500 ppm CO ↑ 50% UHC ↑ 20 ppm	[63]
			100%	BTE ↓ 5% ID ↑ 4 °CA	NO_x ↑ 800 ppm CO ↑ 50% UHC ↑ 20 ppm	

4.0 Waste Lubricant Oil (WLO) as Alternative Fuel for Marine Propulsions

Increased numbers of vehicles, ships, and power stations that utilise internal combustion engines for power generation generate undesirable waste lubricant oil (WLO) in bulk. The chemical composition of WLO is principally hydrocarbon, signifying that it can be converted into useable engine fuel [64]. Tajima et al. [65] reported that the ignition delay of a 400 RPM 2-stroke neat WLO engine increased by 2 °CA when compared with HFO at 40% loading. Prolonged HFO ignition delay consequently resulted in higher peak of premixed combustion in compression ignited (CI) engine. Smoke emission from the WLO engine reduced by nearly 0.4 BSU, owing to the less aromatic hydrocarbon in the WLO. Nonetheless, it was found that smoke emission from the WLO engine escalated drastically after 10 hours of continuous operation, mainly due to partially complete combustion products deposited in the combustion chamber of the WLO engine.

WLO deposition in the combustion chamber and dreadful smoke emission signify that WLO is not suitable for direct use in the engine. Moreover, WLO contains harmful heavy metals like Plumbum/lead (Pb), Chromium (Cr), and Cadmium (Cd) that need to be eradicated to enhance fuel quality. Although suffering from inferior physical properties that prohibit its direct application in the CI engine, ~ 24 million metric tonnes of annual WLO production worldwide [66,67] proves that it is an attractive and seemingly irresistible feedstock for alternative fuels production. Thus, subsequent WLO research focuses on converting it into gasoline-like fuel (GLF) or diesel-like fuel (DLF). Fig. 7 illustrates the schematic diagram for typical WLO-DLF conversion plant. As shown, an oil filter is used to remove impurities from the WLO. Catalysts like Aluminium Oxide and Zeolite are added into the reactor to mix with the WLO to accelerate the overall reaction. The mixture inside the reactor is heated up to ~ 600°C, and constantly stirred using a blender to ensure uniform temperature distribution within the mixture [68]. Gases with carbon chain length C10-

C18 are collected by the distiller, and they are subsequently channelled to the condenser to cool them down, transforming into liquid form [68–70].

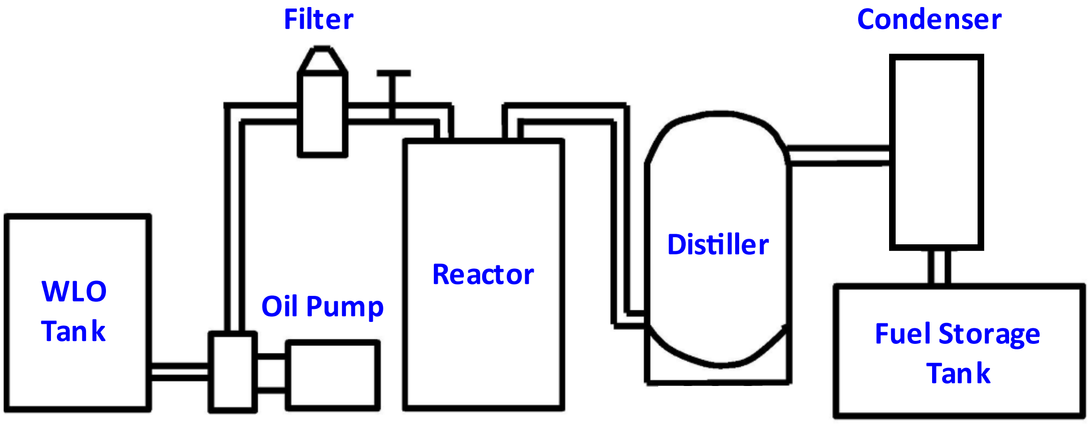


Fig. 7 Schematic of WLO to DLF conversion plant (adapted from [64])

Arpa et al. [71] found that GLF derived from WLO elevated the BTE of a 1500 RPM engine by 5% as compared to that of a gasoline engine. CO emission from the GLF engine was 71% lower than from gasoline engine, while UHC emission from the former was 25 ppm higher than the latter. In another study by Arpa et al. [71], GLF was blended with turpentine by 10%, 20%, and 30% volumetric ratios. Brake torque for a 1500 RPM engine was found increased by 4 Nm when GLF was blended with turpentine by 70/30 volumetric ratio, leading to increased BTE of about 4%. Nevertheless, NO_x and UHC emissions from the GLF/turpentine engine increased by 250 ppm and 50 ppm, respectively. In another effort by Arpa et al. [72], WLO was converted into diesel-like fuel (DLF). The DLF was desulfurised (LSDLF), and its performance was compared with a neat diesel engine. The BTE of 1500 RPM LSDLF engine was about 2.5% higher than that of diesel engine whileSO_2 emission was reduced by ~ 1000 ppm at 2500 RPM engine speed.

Wang and Ni [64] reported that BSFC disparities between DLF and diesel engines were insignificant when engine brake torque was higher than 9 Nm. Furthermore, CO, NO_x, and smoke emissions from both engines were very similar to each other at high load 1500 RPM operation. Gabiña et al. [73] reported that Alternative Fuel Oil (AFO) derived from WLO delayed the peak HRR of CI engine by nearly 10 °CA as compared to diesel engine, reducing the peak cylinder pressure by ~10 bar. CO emission from the AFO engine was elevated by 2609 ppm, but NO_x production was lowered by 24 ppm. Gabiña et al. [67] found that diesel engine generated higher cylinder pressure (~ 5 bar) than the AFO at lower engine speed (~ 1190 RPM). This review proved that the GLF engine would produce higher BTE than by gasoline engine (~ 4-5%) for engine speed ~ 1500 RPM [71,71]. Despite producing lower CO emission (~ 71% reduction) than gasoline engine, the UHC emission for the GLF engine was ~ 25 ppm higher than the gasoline engine [71,71]. DLF, on the other hand, produced comparable engine performance to fossil diesel engine [64,72,74]. Fig. 8 summarises main findings regarding GLF and DLF engine performances.

Positive GLF and DLF engine performances depicted in Fig. 8 can be mainly attributed to their very similar physical properties with gasoline and diesel (Table 5). Meanwhile, published studies proved that GLF and DLF do not cause mechanical failures to the engines [46]. Furthermore, there was no visible carbon deposition inside the combustion chamber and piston after experimental studies. Overall, the present review shows that GLF and DLF are promising alternative fuels for marine propulsion. Nevertheless, more studies are needed to confirm positive DLF engine performances. Desulfurisation of DLF may be needed to reduce sulphur content in the DLF. Meanwhile, sustainability of the fuel delivery system in long term engine operation, as well as DLF performance in low-speed 2-stroke engines, has to be verified as well [46].

		GLF	**DLF**
BTE	**~1500 RPM**	**4-5% higher than gasoline engine**	**~ 2% higher than diesel**
	~3500 RPM	**4-5% higher than gasoline engine**	**~ 1% higher than diesel engine**
CO	**~1500 RPM**	**~ 71% lower than gasoline engine**	**~ 33% lower than diesel engine**
	~3500 RPM	**~ 66% lower than gasoline engine**	**~ 4% lower than diesel engine**
UHC	**~1500 RPM**	**~ 25 ppm higher than gasoline engine**	**~ 14% higher than diesel engine**
	~3500 RPM	**~ 40 ppm lower than gasoline engine**	**~ 3 times higher than diesel engine**

Fig. 8 Comparisons of GLF and DLF engines performances with respective baselines

Table 5 Comparisons of fuel physical properties between GLF, LSDLF, gasoline, and diesel

	GLF [71,71]	**Gasoline** [71,71]		**LSDLF** [72]	**Diesel** [24,25,29]
Density (kg/m^3, at 15 °C)	740	780	**Density (kg/m^3, 15 °C)**	818	840
Calorific value (MJ/kg)	43.0	43.8	**Calorific value (MJ/kg)**	42.5	42.0
Flash Point (°C)	39	-43	**Kinematic Viscosity (cSt, 40 °C)**	3.2	2.57
Distillation range, (°C)			**Flash Point (°C)**	57	50
Initial Boiling Point	38	43.5	**CN**	52.7	52
10 vol%	68	55			
50 vol%	126	102			
90 vol%	223	174			
Final Boiling Point	262	220			

5.0 Ammonia (NH_3) as Alternative Fuel for Marine Propulsions

Carbon-based fuels remain as the primary energy source nowadays to propel our economy and daily life [75,76]. However, these are achieved at the expense of environmental sustainability, where the combustion of carbon-based fuels such as coal, crude oil, and natural gas undesirably elevates Carbon Dioxide (CO_2) concentration in the atmosphere; exacerbating the global warming effects that we are currently suffering with. The CO_2 concentration has been increased linearly by a factor of 1.1 since 2006 [77]. As a consequence, calamitous global warming effects are escalating drastically. 2016 and 2020 are the hottest year since record-keeping began, in which the global surface temperature was 1.02 °C above average temperatures recorded between 1951-1980 [77], as depicted in Fig. 9. This inherently poses direct threats to the coastal cities due to the rise of sea level [78].

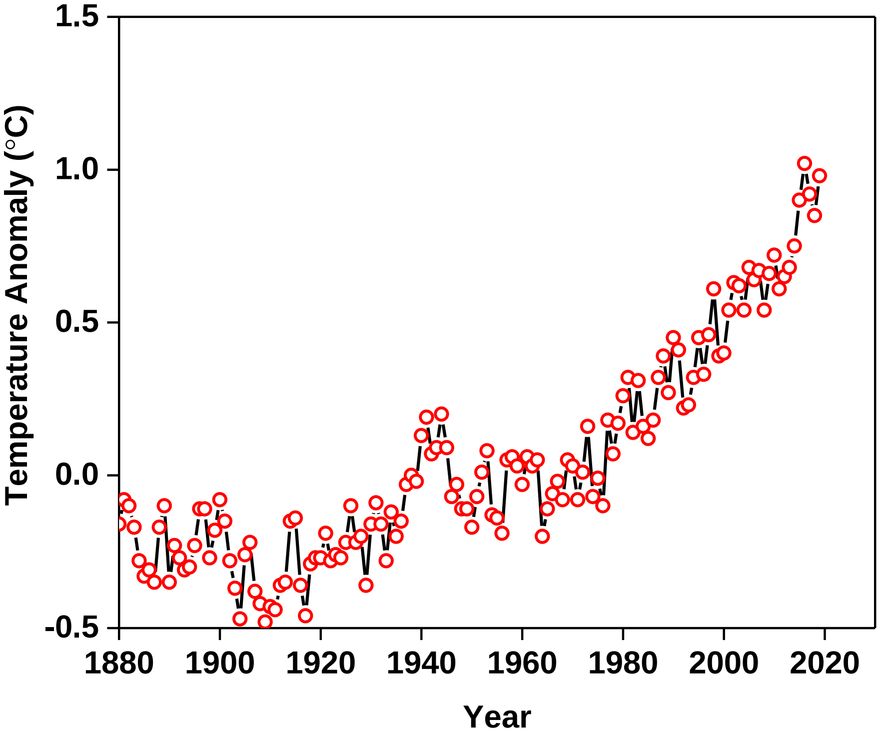


Fig. 9 Global surface temperature as compared to average temperatures recorded between 1951-1980 (data obtained from [77]).

Ammonia (NH_3) is one of commercially available candidates to fulfill the global decarbonisation campaign [79,80]. Thus, although the energy density of liquid ammonia is lower than that of diesel by a factor of ~2.85 (Fig. 10), it is still selected as one of the potential alternative fuels for marine engines in this study. Early research on ammonia combustion reported that significantly high ignition energy was required to ignite ammonia, compared with fossil fuels, owing to the low volatility of ammonia [81,82]. The minimum ignition energy for the ammonia/air mixture at near stoichiometric condition was found higher than the propane/air mixture by a factor of 21.5 [82]. Li et al. [83] showed that laminar flame velocity for fuel-lean NH_3/CH_4 increased by a factor of 4 when NH_3 volume fraction was increased from 40% to 66.7%; denoting poor NH_3 reactivity. Furthermore, flame instability was exaggerated in the fuel-lean regime when NH_3 volume fraction was set > 40%.

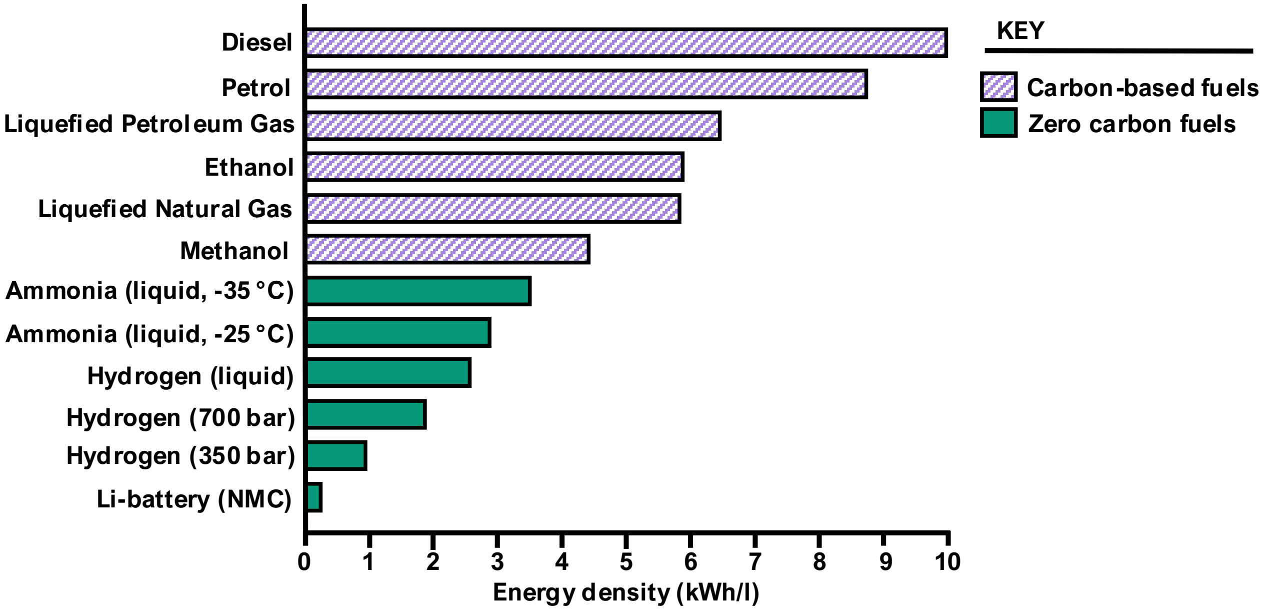


Fig. 10 Energy density of a range of fuel options (adapted from [84])

Early studies on ammonia combustion concluded that mixing ammonia with other fuels is a more sensible way than fueling engines with neat ammonia, due to the relatively low flame speed and reactivity of ammonia [85,86]. Thus, subsequent researches on ammonia engines mostly focused on blending ammonia with other fuels. Grannell et al. [87] demonstrated that the compression ratio (CR) of the gasoline spark ignited (SI) engine can be elevated without causing engine knocking when fueled with ammonia/gasoline blend. It was shown that 70/30 ammonia/gasoline fuel mixture could be used in a full load natural aspirated SI engine. For supercharged engine operation, an ammonia volumetric ratio higher than 70% is needed. Higher engine CR leads to higher engine thermal efficiency, proven by a report that indicated thermal efficiency (ITE) of a full load ammonia/gasoline engine increased by 2% when CR was increased from 8:1 to 10:1. However, the ITE of the engine increased by only 1% when CR was increased from 10:1 to 16:1. Apart from gasoline, performances of ethanol/ammonia and ammonium nitrate/ammonia engines had been examined by several other groups [88–90]. Although engine brake power was raised drastically as compared to neat ammonia, these were achieved at the expense of surprisingly high NO_x emission [88–90].

Haputhanthri [91] reported that no significant engine brake torque improvement was observed when ammonia (~5.65 vol%) was blended with gasoline. When ethanol (10 vol%) was added into the ammonia/gasoline blend, engine brake torque at 2000 RPM was found to increase by ~5 Nm, as compared to that of E10 engine. At higher engine speeds (> 3500 RPM), ethanol/ammonia/gasoline engine resulted in more significant engine brake torque improvement (~ 20 Nm) than that of E10 engine [92]. Apart from blending with the ammonia with ethanol/gasoline, diesel/ammonia combustion had also been examined [93,94]. It was found that for a full load 1400 RPM turbocharged CIDI engine, 50% ammonia input power fraction elevated engine brake torque by 20 ft-lb, as compared to a neat diesel engine. Furthermore, NO_x emission from diesel/ammonia engine was recorded 10 g/kW-hr lower than by a diesel engine, owing to the lower diesel/ammonia combustion temperature. UHC emission from the diesel/ammonia engine was only marginally higher than by the diesel engine (~0.2 g/kW-hr) [93]. By elevating the ammonia input power fraction to 60%, the brake power for 1000 RPM diesel/ammonia engine increased by 20 kW, compared with by diesel engine [94]. Overall, diesel/ammonia combustion resulted in lower NO_x emission than by diesel for ammonia input power fraction < 60% [93,94]. Hogerwaard and Dincer [95] ascertained that diesel/ammonia combustion in the SI engine resulted in CO reduction by nearly 0.2 g/bhp.hr when NH_3 input power fraction was set >0.8. Likewise, NO_x was reduced by about 3 g/bhp-hr when NH_3 input power fraction was set > 0.8. The inclusion of ammonia into Dimethyl Ether (DME) elevated CO, UHC, and NO_x emissions of the engine by a factor of 1-2 as compared to by neat DME engine. In addition to poorer emissions performance, the engine output power was also reduced as the ammonia input power fraction was increased [96]. The exhaust emission from the ammonia/DEE engine did not enhance noticeably after improving fuel injection methods [97], denoting that post-exhaust treatment is essential for the ammonia/DME engine operation.

Apart from liquid ammonia, gaseous ammonia combustion in engine was also studied. It was demonstrated that blending ammonia with ~5 vol% hydrogen could still lead to a good power response [98]. By elevating the hydrogen to ~10 vol%, the engine ITE increased by 0.5% as compared to a neat gasoline engine [99]. Nonetheless, NO_x emission of ~750 ppm was produced when hydrogen content was increased to ~20 vol%, thus suggesting the need for selective catalytic reduction (SCR) of exhaust gases under these conditions. Ammonia/hydrogen engine was also studied by DESTEC in Italy [100]. It was shown that 3000 RPM ammonia/hydrogen engine recorded nearly identical BTE (~28%) to using a gasoline engine. As gasoline engine BTE started to fall below 28% when engine speed was >3000 RPM, BTE of ammonia/hydrogen engine remained at ~28%. Furthermore, NO_x emission from the ammonia/hydrogen engine was at average of 1000 ppm lower than the gasoline engine. In a study by Koike et al. [101], ammonia/hydrogen engine produced engine brake torque at average of 0.2 kNm higher than diesel engine from 1000 RPM to 1700 RPM. Apart from conventional engine, Homogeneous Charge Compression Ignition (HCCI) engine had also been used to determine the combustion and emissions performances of NH_3/H_2 [102]. EGR was incorporated into the engine, and remarkable NO reduction (~1500 ppm) was observed with EGR of 60%. Nevertheless, N_2O showed a mild increasing trend with EGR 60%.

The current review shows that modern engines fueled with NH_3 require a SCR system and/or fuel additive to decompose and mitigate NO_x emission. The concentration of NO_x in engine flue gas was found reduced than the legal requirement when a SCR catalyst was used [103]. The use of secondary exhaust cleaner, however, inherently incurs high-cost catalyst systems. Thus, it was also hypothesised that NO_x emission from ammonia combustion may be enhanced through preheating the ammonia. Waste heat from the exhaust gas can be used to partly decompose ammonia before the combustion and reduce NO_x pollutants [104,105]. Overall, the development of 2-strokes and 4-strokes engine technologies is imminent to enable the use of ammonia in marine propulsion. The challenge to decrease NO_x emission and unburned ammonia further remains as the cornerstone of ammonia internal combustion engine development [106–110].

6.0 Vegetable Oil (VO) as Alternative Fuel for Marine Propulsions

Vegetable oil (VO) are derived from plants such as rapeseed, soybean, jatropha, palm, sunflower, karanja, and jojoba. VO is composed of one molecule of glycerol and three molecules of fatty acids, known as triglycerides. Although the chemical compositions for VO and diesel are significantly different, their calorific values are close to each other (VO = ~38 MJ/kg, diesel = ~43 MJ/kg) [19]. The sulphur content in VO is only ~0.01 wt.% [19]. The major disadvantage of VO is its viscosity, which is an order of magnitude higher than those of diesel and biodiesel. Although marine engines typically use HFO that exhibits even higher viscosity than VO, the high VO viscosity is still undesirable as it could lead to increased carbon deposition [111–114] and inferior combustion efficiency [115]. However, positive VO attributes such as biodegradability, renewability , low sulphur, and aromatic content [116–118] turn it into an appealing candidate for marine propulsion[12].

Performances of VO in low-speed CI engine were investigated by several groups of researchers. Petzold et al. [22] examined the emissions of various VOs (palm, sunflower, soybean) and animal fat using high load 750 RPM CI engine. PM emission of biogenic fuels was reduced to ~15% of HFO. Li et al. [119] reported that BTE of an 800 RPM VO engine was 0.05% higher than by diesel engine. The emissions of NO_x and CO from the VO engine were 50 ppm and 24 ppm lower than by diesel engine, respectively. Canakci et al [120] preheated crude sunflower oil for use in indirect injection (IDI) CI engine. At 1000 RPM, peak cylinder pressure and HRR of the VO engine were very close with that of diesel. Furthermore, UHC emission of the diesel engine was 8 ppm higher than by VO engine. Disparities in CO and UHC emissions between both engines were only marginal.

Hoang et al. [121] examined heated (120 °C) coconut oil (HCO) using a 1500 RPM CI engine. BSFC of the full load HCO engine was 100 g/kW-hr higher than that of diesel, equivalent to 5% of BTE reduction. However, CO and NO_x emissions of the full load HCO engine were about 200 ppm and 300 ppm lower than diesel, respectively. Rakopoulos et al. [122] examined the blends of various VOs with diesel using 10% and 20% volumetric proportion. It was found that the smoke opacity of a high-load 1200 RPM diesel engine was about 2% lower than by 20/80 corn oil/diesel blend. NO_x emission for 20/80 cotton oil/diesel engine was practically the same with that of the diesel engine. CO and UHC emissions for a diesel engine were significantly lower than that of the VO/diesel engine. No major BTE decline was observed when the engine was fueled with VO/diesel blend. In another study, Rakopoulos et al. [123] reported that peak HRR and cylinder pressure for a 60% loaded 1200 RPM 20/80 VO/diesel engine was marginally higher than that of the diesel engine. Despite smoke emission from VO/diesel engine being 2% lower than by diesel engine, the NO_x, CO, and UHC emissions were higher than by diesel engine by ~10 ppm.

Basinger et al. [113] examined waste vegetable oil (WVO) performance using a 650 RPM, 4-stroke, IDI engine. It was found that CO emission from full load WVO engine was 500 ppm higher than by a diesel engine, leading to ~600 ppm lower NO_x emission than the baseline. BSFC of the WVO engine was about 50 g/kW hr higher than that of the diesel engine. Hribernik and Kegl [124] blended WVO with diesel and studied its performance using an IDI engine. Engine brake torque for the WVO75 engine was recorded about 5 Nm higher than diesel engine at 1000 RPM operation. Namliwan and Wongwuttanasatian [125] examined performance of crude palm oil/diesel blend using a CIDI single cylinder 4-stroke engine. The brake torque for 800 RPM VO15 engine was lowered by ~3 Nm, resulting in BSFC 0.1 kg/kW-hr higher than that of neat diesel. Haldar et al. [126] blended diesel with Putranjiva oil by 40/60 volumetric proportion (VO60), and recorded that smoke density for full load 1200 RPM VO60 engine was 20 Hu lower than by diesel engine. NO_x emission was reduced by 35 ppm but UHC production was elevated by 45 ppm.

Despite high viscosity, considerably low toxicity makes VO and WVO attractive alternative fuels for power generation [12]. Various strategies, like preheating, refinement and degum, and blending the VO with fossil diesel, have been employed to lower the viscosity of VO, of which refinement and degum method did not yield satisfactory UHC and CO emissions reduction [122,123]. Preheating the VO is seemingly the most encouraging way of improving low-medium speed VO engine performance by far (Fig. 11), where BTE of the engine was nearly the same with that of diesel engine, and pollutants like PM, UHC, and NO_x having been reduced appreciably [119,120]. Blending VO with diesel without preheating generally resulted in higher NO_x [125], UHC[126], CO, and soot emissions [124] than by diesel engine.

Overall, these strategies have turned VO and WVO into a viable fuel for marine propulsion. Nonetheless, thorough studies are still required as these techniques remain under-researched, resulting in a deficit of a thorough understanding of the overall effect on the marine propulsion system. Although VO and WVO engines can be enhanced via fuel preheating (Fig. 11) and atomisation technologies[19], extensive use of VO may cause adverse environmental and socioeconomic effects [127]. Massive land usage for VO feedstock plantation would elevate the cost of agricultural commodities [128]. The use of second and third-generation VO feedstock would have to be promoted to ensure feedstock sustainability. Utilising WVO for marine propulsion is an economical approach as it is a waste leftover by the kitchen. WVO shares nearly identical physical properties (viscosity, LHV, and CN) with those of VO, except that the density for WVO is slightly lower than that of VO (~10 kg/m^3) [129,130]. Meanwhile, some researchers opined that only physical filtration process is needed to remove food residues from WVO; no complex and expensive treatments are required for WVO before it can be used to power the engine [130].

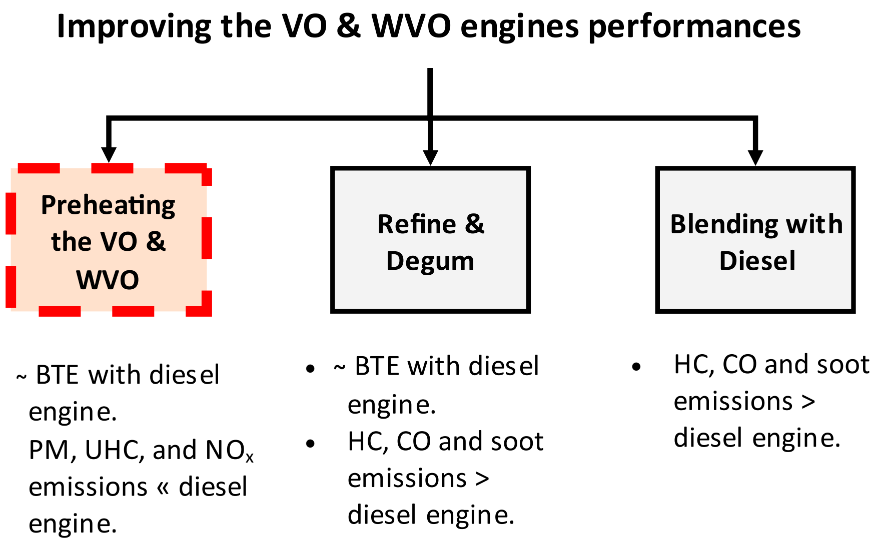


Fig. 11 Methods for improving the low-medium speed, high load VO & WVO engine performances.

7.0 Biodiesel as Alternative Fuel for Marine Propulsions

Biodiesel is mainly derived from plant oil via transesterification process [131,132]. In addition to those depicted in Fig. 11, transesterification is another way of improving fuel quality of VO. Biodiesel exhibits very similar caloric value, viscosity, cetane number, and density with those of fossil diesel. The physicochemical properties of biodiesel are also influenced by the degree of unsaturation of the molecules [133,134]. Sulphur content in biodiesel is ~0.01 wt.% [19]. Biodiesel can be used as fuel directly, or blended with fossil diesel [135,136]. Biodiesel has been tested in compression ignited engine [137–148], microturbo jet engine [149,150], and also lab scale swirl burner [151–154]. Nonetheless, high load biodiesel engines performances in low-medium speed regimes were not adequately accessed in the previous studies. The present review focuses on biodiesel engine performances in low-medium speed regime.

Wei et al. [155] reported that the B50 biodiesel/marine gas oil (MGO) engine reduced peak HRR by nearly 20 J/°CA, as compared to neat MGO at 75% loading 1050 RPM operation. NO_x emission for the B50 engine was roughly 50 ppm lower than by neat MGO. Zhang et al. [156] investigated performances of cottonseed, sunflower, rapeseed, and soybean biodiesels at 1000 RPM engine speed. The peak HRR of full load cottonseed biodiesel engine was about 100 J/°CA lower than that of diesel engine. UHC emission from the full load cottonseed biodiesel engine was reduced by 50 ppm compared to by diesel. Nishio et al. [157] examined 257 kW marine biodiesel engine performances at 420 RPM engine speed. The NO_x between marine diesel oil (MDO) and palm biodiesel was not significant for engine loading >75%. Smoke production from the biodiesel engine was lowered by 0.5 FSN as compared to that of neat MDO engine. Mohd Noor et al. [158] found that BSFC for B15 palm biodiesel/diesel engine was higher than for neat diesel by 80 g/kW-hr at 800 RPM engine speed, corresponding to roughly 6% of engine BTE reduction.

Geng et al. [159] found that the peak HRR of a waste cooking oil (WCO) biodiesel engine was 14.3% lower than by Ultra Low Sulphur Diesel (ULSD) engine at 1050 RPM. Ignition delay in the WCO engine was shortened by 2 °CA for both 25% and 75% loadings. Monirul et al. [160] reported that NO_x emission of a full load B10 Calophyllum inophyllum biodiesel (CIB)/diesel engine was about 50 ppm higher than that of the diesel engine. Rasheda et al. [161] reported that BSFC of a full load 1000 RPM B20 palm biodiesel/diesel engine was 25 g/kW-hr higher than that of diesel, corresponding to a 3% reduction in engine BTE. CO reduction by the B20 engine was only marginal. Major findings from low-medium speed biodiesel engine studies are summarised in Table 6. It can be generalised that biodiesel engines can yield less UHC emission, by nearly 30% as compared to diesel engine at ~1000 RPM operation [160–164]. UHC emission for low-medium speed biodiesel engine was ~25.7% lower than by diesel engine but the reduction was only ~18.1% during high-speed operation [160,161], denoting that biodiesel is a cleaner solution for low-speed marine engine operation. The CO emission of biodiesel engines was lower than by diesel engine at average of 40% at ~1000 RPM operation [156,160–163,165,166]. CO emission for high-speed biodiesel engine was roughly 41% lower than by diesel engine, whereas the reduction was only about 26.2% in low-medium speed operation [166,167].

NO_x emission has been the major concern of biodiesel combustion by far [168–171]. Low-medium speed biodiesel engines frequently lead to a more drastic NO_x escalation than high-speed operation [155,158,159]. NO_x emission from low-medium speed biodiesel engine was recorded ~45% higher than by diesel engine, while the increment was only ~ 25.9% for high-speed operation [166,167]. This could be because low-medium speed operation renders prolonged droplets residence time scale, therefore increasing local fuel-rich pockets that might consequently give rise to the prompt NO_x formation. In addition to the higher biodiesel NO_x emission, peak HRR of biodiesel engines was lower than that of diesel engine at average of 15%, resulting in poorer engine BTE and brake torque [155,156,158,159,172]. Reduction in biodiesel BTE and brake torque was principally due to its lower calorific value than that of fossil diesel.

Nanoparticles have been proposed as one of the potential solutions to improve BTE and reduce NO_x emissions for low-medium speed biodiesel engines. Jiaqiang et al. [173] examined the effects of Cerium Oxide (CeO_2) nanoparticles on biodiesel marine engine performances. At 628 RPM engine speed, biodiesel/water/diesel/CeO_2 blends elevated engine BTE by 3%, against diesel. Furthermore, NO_x, CO, and UHC emissions for 628 RPM biodiesel/water/diesel/CeO_2 engine were lower than those of neat diesel by factors of 0.86, 0.67, and 0.84, respectively. Nanoparticles principally promoted heat transfer in the reaction zone; hindering local higher temperature regions formation and hastening the oxidation of CO and UHC species. Apart from the findings by Jiaqiang et al. [173], Karthikeyan and Prathima [174] reported that Carbon Nano Wires addition can reduce UHC, CO, and NO_x emissions considerably at high load operation.

Apart from nanoparticles, Rizwanul Fattah et al. [163] examined the effects of antioxidants on biodiesel engine performance. Antioxidants 2,6-di-terl-4-methylphenol (BHA) and 2(3)-tert-butyl-4-methoxy phenol (BHT) were considered. However, no noticeable engine BTE nor NO_x emission improvement was observed. The present review indicates that nanoparticle and Carbon Nano Wires are promising approaches to improve BTE, fuel efficiency, and NO_x emission of low-medium speed biodiesel engines. However, substantial efforts are still needed to verify findings reported by published studies. The current study also unveils that performance of high load-2 strokes biodiesel engines below 500 RPM has not been determined. The efficacy of EGR [33] and dual-fuel operation [175,176] in reducing NO_x emission from low-medium speed biodiesel engine remains unknown as well, signifying that considerable efforts are very much in need to augment biodiesel engine performances in the low-medium speed regime.

Table 6 Combustion and emissions performance biodiesel marine engine compared with respective baseline.

Tested Fuels	Baseline	Engine Speed	Engine Loading	Engine Performances	Emissions	References
50/50 waste cooking oil biodiesel/MGO blend	MGO	1050 RPM	75%	Peak HRR ↓ 12.5%	NO_x ↓ 11.1%	[155]
			25%	Peak HRR ↓ 11.1%	$NO_{x,B50} \approx NO_{x,MGO}$	
Rapeseed, Sunflower, Soybean, and Cottonseed biodiesels (B100)	Diesel	1000 RPM	10%	BSFC ↑ 11.1%	UHC ↑ 80 ppm NO_x ↓ 200 ppm $CO_{Biodiesel} \approx CO_{Diesel}$	[156]
			100%	BSFC ↑ 12.5%	UHC ↓ 100 ppm NO_x ↑ 200 ppm CO ↓ 800 ppm	
Palm biodiesel (B100)	Diesel	265 RPM	25%	$\eta_{Biodiesel} \approx \eta_{MDO}$	NO_x ↑ 350 ppm Smoke ↓ 0.5 FSN	[157]
		420 RPM	100%	$\eta_{Biodiesel} \approx \eta_{MDO}$	$NO_{x,Biodiesel} \approx NO_{x,Diesel}$ Smoke ↓ 0.5 FSN	
Palm biodiesel/diesel blend (B15)	Diesel	800 RPM		η ↓ 6%	NO_x ↓ 6.1%	[158]
		1400 RPM		η ↓ 4%	NO_x ↓ 7.8%	
Waste Cooking Oil Biodiesel (B100)	Diesel (Ultra low Sulphur)	1050 RPM	25%	Peak HRR ↓ 14.3%	NO_x ↓ 20%	[159]
			75%	Peak HRR ↓ 21.3%	NO_x ↓ 26.3%	

10/90 Calophyllum inophyllum biodiesel/diesel blend (B10)	Diesel	1400 RPM	100%	$\eta_{Biodiesel} \approx \eta_{Diesel}$	UHC ↓ 18.1% NO_x ↑ 22.2%	[160]
		2400 RPM	100%	$\eta_{Biodiesel} \approx \eta_{Diesel}$	$UHC_{B10} \approx UHC_{Diesel}$ $NO_{x,B10} \approx NO_{x,Diesel}$	
20/80 Palm biodiesel/diesel blend (B20)	Diesel	1000 RPM	100%	BSFC ↑ 6.67%	UHC ↓ 33.3% NO ↑ 33.3%	[161]
		2500 RPM	100%	BSFC ↑ 6.67%	UHC ↓ 36.3% NO ↑ 10%	
50/50 Jatropha biodiesel/diesel blend (B50)	Diesel	1000 RPM	100%	τ ↓ 10% BSFC ↑ 12.5%	CO ↓ 33.3% NO ↑ 125%	[167]
		2000 RPM	100%	τ ↓ 8.1% BSFC ↑ 14.9%	CO ↓ 64.4% NO ↑ 69.2%	
Soybean biodiesel (B100)	Marine fuel	1000 RPM	100%	τ ↓ 5% BSFC ↑ 14.2%	CO ↓ 19% NO_x ↑ 29.1%	. [166]
		2000 RPM	100%	τ ↓ 5% BSFC ↑ 15%	CO ↓ 33.3% NO_x ↑ 21.7%	
Biodiesel (B100)	Diesel	1250 RPM	10%	BSFC ↑ 41.7%	CO → 0 ppm $NO_{x,B100} \approx NO_{x,Diesel}$	[164]
		1250 RPM	100%	$BSFC_{Biodiesel} \approx BSFC_{Diesel}$	CO ↑ 90% $NO_{x,B100} \approx NO_{x,Diesel}$	

8.0 Considerations of alternative fuels for marine propulsion

Despite WPO engine performances could be enhanced via strategies delineated in Fig. 5, Kalargaris et al. [177] stressed that engine components have to be redesigned to prolong WPO engine endurance in operations, mainly because the engine piston for WPO75 engine was found cracked after 36 hours of continuous operation [177]. Further analysis unveiled that the failure was primarily due to the excessive wear in the WPO/diesel engine [177], implying the necessity to upgrade/redesign existing engine components and/or lubricants to accommodate longer term of WPO operation. Of many strategies depicted in Fig. 5, it is shown that EGR rate 20% reduced BTE by~2-3%, denoting that it is not possible to increase EGR rate furthermore to reduce NO_x emission. This is due to the excessive exhaust gas flow will inherently deteriorate combustion efficiency of the engine. Likewise for advancing fuel injection timing, advanced fuel injection timing beyond ~ 14 °CA could reduce NO_x emission but it is also expected to lower engine BTE due to substantial heat loss as combustion takes place at the very beginning stage of compression stroke. Biodiesel that exhibits slightly lower calorific value than WPO is expected to lower soot emission from WPO engine. However, higher biodiesel volume fraction in the blend would also lead to lower engine BTE. Endeavour studies are still needed to figure out optimum biodiesel volume fraction and fuel injection timing for WPO engine operation.

Table 3 implies that neat TPO does not enhance engine emissions performances significantly. Furthermore, it was highlighted by Frigo et al. [46] that long-term TPO effects on vehicle engine, especially fuel injection system and combustion chamber, are questionable. This is mainly due to contamination of acidic substances in the engine (TPO has considerably higher sulphur content than diesel [24,46]). Some studies even argued that TPO volumetric ratio > 40% is not suitable for engine operation [46]. In addition to deteriorating overall engine performances, lubrication oil was also found contaminated with TPO/diesel mixture, owing to the leakage of fuel residue that was not completely evaporated into the oil sump. Although sulphur level in the HFO is substantially higher than in TPO, thorough investigations are still needed to verify TPO's long-term effects on marine propulsion system. As compared to fossil diesel and DEE, blending the TPO with biodiesel proved to be more promising engine emissions improvement, especially in high load-medium speed operations [57,59,60]. BTE of TPO/biodiesel engine was comparable with that of diesel engine, besides exhaust emissions (NO_x and smoke) having reduced satisfactorily [57,59,60]. Such improvement is presumably due to the presence of oxygen in biodiesel that promotes fuel and soot oxidation. Nonetheless, comprehensive flame analysis is still needed to ascertain the interactions between TPO and biodiesel under low-medium speed engine operation.

To enhance the NH_3 combustion in CI engines, delaying fuel injection timing to aTDC is not the best solution. While this method significantly decreased NO pollution, it also resulted in a significant rise in unburned NH_3. Aqueous ammonia happens to be a better way to boost efficiency and reduce pollution. However, because of the accelerated heat release during the pre-mixing burning period, this approach would almost certainly raise the engine's noise level. In general, multiple injections with optimised mass fraction and timing for pilot and main injection can potentially lead to simultaneous reduction of N_2-based emission and increased engine HRR. The GLF and DLF show promising engine performance (Fig. 8) mainly because their physicochemical properties resemble that of gasoline and diesel, respectively, denoting that these are the most suitable alternative fuels for marine propulsion. However, sulphur contents in these fuels were not quantified yet, and systematic comparison between GLF and DLF with WPO, TPO, ammonia, WVO and biodiesel are needed to draw a form conclusion.

By referring to Fig. 11, inferior VO/diesel blend emissions are primarily due to the presence of aromatic in diesel that promote soot formation. Aromatics is a precursor to soot formation that does not present in the VO and WVO. Hence, soot emission was not reduced after blending with diesel. As shown in the same figure, viscosity of VO and WVO are reduced to equivalent level with that of diesel via preheating, leading to a more appreciable emissions reduction. Preheating is desirable as it does not introduce aromatics into the VO and WVO. To reduce the viscosity of the VO, a twin-fluid atomiser may be used [178–180], other atomisation methods such as flow-blurring atomisation [181] and superheated steam atomisation [182] may be integrated into the fuel preheating method. Nonetheless, further research is required because these methods are still understudied, resulting in a lack of awareness of their overall impact on engine operation [19].

Because of its similar properties to traditional fuels, biodiesel has proven to be a viable biofuel in the power generation and transportation industries [19]. The very similar physicochemical properties between biodiesel and diesel allows the use of the former in engines with only minimal change to the existing system. Extensive use of edible VO as feedstock to produce biodiesel may cause adverse environmental and socioeconomic effects, owing to the excessive land usage for plantation activities [127]. Moreover, direct competition between food and biodiesel feedstock is also another concern, and this would possibly give rise to the agricultural commodity price [128]. Hence, the use of second and third generations feedstock is imminent for marine propulsion. The growing popularity of third-generation biofuels necessitates more studies into the combustion properties of biodiesel made from third-generation feedstocks like algae.

9.0 Conclusion

The combustion performances of five liquid alternative fuels under high-load, low-medium speed engine operation have been reviewed. Such specific engine operating regime is typically encountered in marine propulsion and have not been evaluated by existing reviews that mainly focused on automotive applications. Findings in this study show that emission performances of neat WPO and TPO are visibly poorer than that of fossil diesel. Retarding the fuel injection timing of WPO engine to ~14 °CA yields promising improvement to the high-load, low-medium speed WPO engines. Blending the TPO with diesel does not improve the engine performances noticeably. Nonetheless, blending the TPO with oxygenated fuel such as biodiesel results in enhanced engine performances. This can be mainly attributed to the fuel-bound oxygen that promotes reactant oxidation. Still, extensive works are required to determine WPO and TPO sustainability for long-term marine engine operation. Although producing lower UHC emission than by diesel engine, NO_x emission from high-load, low-medium speed biodiesel engine is generally higher than that of diesel engine. Nanoparticle (CeO_2) and Carbon Nano Wires are effective solutions for reducing NO_x emission from biodiesel engines, primarily because they promote heat transfer in the reaction zone that lower the flame temperature. WVO is a more desirable option for marine propulsion than VO, considering the adverse environmental and socioeconomic effects of bulk VO consumption. Preheating the WVO is another ideal option to improve VO engine performances because it decreases WVO viscosity and subsequently enhances atomisation quality. Despite ammonia being attractive from the perspective of the global decarbonisation campaign, the extremely high NO_x and unburned ammonia emission hinder its usage at the present stage. Technological developments such as optimisation of multiple fuel injections to reduce substantial NO_x and unburned ammonia emissions are imperative to promote the use of ammonia in marine propulsion. DLF derived from

WLO has been found capable to produce better engine performances than fossil diesel engine in terms of BTE, CO, and UHC emissions, thus establishing itself as a competitive marine alternative fuel. In short, this review unveils inclusive studies using heavy-duty, low-speed (~ 70-120 RPM), two-stroke alternative fuels engine are needed for a more thorough evaluation. Furthermore, advancement in combustion technologies is also crucial to foster the adoption of alternative fuels with inferior physical properties (such as TPO, ammonia, VO, and WVO) in marine propulsion.

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