NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Supported by:

Singapore Maritime Institute

BIOFUEL COMPATIBILITY STUDY

FOR SINGAPORE HARBOUR CRAFT

Maritime Energy & Sustainable Development (MESD) Centre of Excellence (CoE)

BIOFUEL COMPATIBILITY STUDY FOR SINGAPORE HARBOUR CRAFT

This study is conducted by the Maritime Energy & Sustainable Development (MESD) Centre of Excellence (CoE) and has received research funding from the Singapore Maritime Institute (SMI).

Launched in October 2017, MESD CoE is jointly funded by SMI and Nanyang Technological University (NTU). As the first maritime research centre supported by SMI, MESD is set up to deepen Singapore's maritime R&D capability and Maritime Singapore's position as a global maritime knowledge and innovation hub to support Singapore's strategic maritime needs. With the focus on future port and shipping applications, MESD CoE aims to develop innovative and sustainable solutions by working closely with all the key stakeholders within the maritime cluster.

Published in July 2023

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With inputs from Maritime and Port Authority of Singapore

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EXECUTIVE SUMMARY

The harbour craft industry is identified as one of the potential marine transport sectors that can contribute to the greenhouse gas (GHG) emissions target set by Singapore's enhanced Nationally Determined Contribution and Long-Term Low-Emissions Development Strategy.

Why biofuel? Sustainable biofuels are potential alternative fuels as the nature of their feedstocks is renewable, carbon-neutral and evenly distributed over the Earth's surface when compared with fossil fuel deposits. From the perspective of a life-cycle assessment, they provide a near-term solution as drop-in fuels to reduce GHG emissions for Singapore harbour craft.

The two-year project "Biofuel Compatibility Study for Singapore Harbour Craft" is the first systematic approach in Singapore to evaluate sustainable biofuel for the harbour craft industry. Led by the Maritime Energy and Sustainable Development Centre of Excellence at Nanyang Technological University, various stakeholders from the maritime industry actively collaborated to develop a viable strategy for the transition to sustainable biofuels. The objective is to address the gaps in the literature and gain hands-on experience using palm oil methyl ester (PME), used cooking oil methyl ester (UCOME) and hydrotreated vegetable oil (HVO) on an operational harbour craft. The feasibility of using biofuel as a marine fuel is assessed through technical, environmental, operational and economic considerations. Data sources are drawn from literature, surveys, experiments and sea trials.

Biofuel blends, PME, UCOME and HVO blended with marine gas oil (MGO) are evaluated in the study. PME and UCOME have similar properties to marine distillate fuels and are used as drop-in fuels for marine diesel engines if the blending ratio is kept low. HVO, on the other hand, is considered identical to marine distillates due to its paraffinic nature. In this study, PME comes from sustainable palm oil, while UCOME is made from locally sourced used cooking oil. HVO, also known as renewable diesel, is made primarily from waste and residue fat fractions.

The availability of a regional biofuel supply chain is crucial. The production of PME from the three major regional producers (Indonesia, Malaysia and Thailand) has been increasing for the past decade, except for 2020, when the Covid-19 pandemic broke out. However, the exports from these producers do not follow the increase in production due to strong domestic demand in compliance with the national mandates. Increasing biofuel production and expanding 2nd or 3rd generation feedstocks are needed to support the total demand from the maritime industry.

Biofuel bunkering can operate in the existing bunkering infrastructure due to its similar properties as an ambient liquid. The current and widely referenced standard from International Organization for Standardization (ISO), ISO 8217, is being revised to allow a higher percentage of fatty acid methyl ester (FAME) to be blended into distillate and residual fuel, setting benchmarks for both bunker sellers and buyers and shall address all practical and compatibility considerations arising from fuel combustion, injection, fuel delivery system and storage stability. Besides ISO 8217, European standards (EN) provide comprehensive coverage that includes additional parameters affecting cold flow and filter blockage for FAME-based biofuel[1].

The storage stability of biodiesel is a concern due to the hygroscopic property of biodiesel. Five parameters that indicate fuel quality have been chosen: viscosity, water content, acid value, oxidation stability by sediment, and oxidation stability by induction time (Rancimat test). HVO-based blends stayed within specifications during the four-month-long experiment. PME and UCOME blends gave mixed results. While the acid value and viscosity of all biofuel blends stayed within specifications, the ingress of moisture was hard to avoid and the water content of PME and UCOME samples of B20 and B30 went out of specification after two months of storage referencing more stringent EN standards. The oxidation stability shows mixed findings too, of which the lower blends are more susceptible than neat B100 for both PME and UCOME. There is a need to set new benchmarks for marine biofuel.

The study provides a comprehensive summary of three common methodologies to determine the carbon footprint: Life Cycle Assessment (LCA), Intergovernmental Panel on Climate Change (IPCC) guidelines, and International Sustainability & Carbon Certification (ISCC) system. GHG emissions estimated from the ISCC and IPCC approaches provide practical and comparable insights for industry and regulators. ISCC-certified biofuels UCOME, HVO and PME offer GHG emission savings of 84%, 83% and 52.5%, respectively. The GHG emission savings based on IPCC guidelines for biofuel blends (20 % v/v to 100 % v/v) range from around 18% to 99%. The calculation supports the use of biofuel blends B20 (PME), B20 (UCOME) or R20 (HVO) to meet the 2030 decarbonisation target for domestic harbour craft.

[1] The storage stability in this report was assessed against published EN and ISO standards. WA 2:2022 and the ISO 8217:2024 draft for international standard have been published since project completion. Parameters such as water content and oxidation stability would meet recently promulgated specifications, or at least exhibit a small deviation from being out of specification. For example, the oxidation stability (Rancimat test) limit for WA 2 and ISO 8217:2024 draft international standard is 6 and 8 h respectively, which are significantly shorter than 20 h required by EN 16709. MESD will work with MPA to assess if adjustments to the standards are required.

Before switching over to biofuel for the sea trial, guidelines and precautions from the engine manufacturer were followed. A cargo launch with a high-speed marine diesel engine ran smoothly with all three biofuels for all blending ratios (20 % v/v to 100 % v/v) without retrofitting. After the trials, the engine's fuel injectors were sent for testing, where they did not show a significant change from those of MGO. The cellulose-based fuel oil filter and lube oil filter worked normally and the fuel oil pumps appeared normal during maintenance inspection. Nitrile-butadiene rubber (NBR) seals and gaskets found on the fuel oil filter and lube oil filter maintained integrity except for a minor hardening. Based on lube oil tests, engine wear and tear were monitored and were indifferent from the MGO baseline. Overall, the sea trial demonstrated good engine compatibility[2] of a marine diesel engine with B30 PME-based biofuel, based on operations for more than 300 engine hours as recommended by the engine manufacturer.

Energy and Emissions Performance

An important observation is a change in specific fuel oil consumption (SFOC) from onboard measurements conducted during the sea trials. In the presence of operational variables in a sea trial, the study relied on data collected over several non-consecutive weeks and regression analysis to provide the following insights[3]. The volumetric lower heating values (LHV) of B100 PME and UCOME-based biofuels are around 13.3% lower than that of MGO from laboratory test results. The difference in LHV is the main contributor to an increase in SFOC. Besides having lower LHV, engine maintenance, engine speed, and engine room temperature are significant factors of the change in SFOC of biodiesel blends. The engine room temperature is also a significant variable as CO emission increases with temperature. However, nitrogen oxides (NOx) emissions decrease with the same variable. Proper engine maintenance reduces NOx emissions but does not significantly impact CO emissions. Higher biodiesel blends emit a slightly higher amount of NOx, with a slight reduction in CO emission. On the other hand, higher blending ratios of HVO/MGO do not affect NOx emission but may impact CO emission.

Economic Assessment

The cost factors of biofuels for Singapore harbour craft were analysed using the average market prices in 2021 (Argus Media, 2021) and factoring in other operational costs. The prices of MGO form the baseline and are taken from the Ship and Bunker database over the same period. The average fuel cost for biofuel blends increases by 18% for B20 (PME), 30% for B20 (UCOME) and 47% increase for R20 (HVO). Thus, the industry may initially consider sustainable PME over other biofuels due to its higher availability and lower cost. Investment in energy efficiency and technologies to reduce overall fuel consumption may buffer the increase in fuel costs.

Biofuel Compatibility Survey and Mapping of Harbour Craft

Eleven participating engine manufacturers advised on the biofuel compatibility of their engines. Engine manufacturers express caution and additional maintenance steps in switching to biodiesel, although up to 7% (v/v) biodiesel is accepted by the current marine fuel standard ISO8217. Engine mapping of Singapore harbour craft covers nearly 83% of the 2,561 engines from the 2021 database. The results demonstrate that 68% of the engines from participating engine manufacturers are at least B20 biofuel-compatible. All the participating engine manufacturers support at least B20 biodiesel blends and all HVO blends. Thus, it is recommended that shipowners seek assistance from the engine manufacturers.

[2] These findings on engine compatibility are specific to the test engine and end users should consult their engine manufacturer on the performance and compatibility of their engines.

[3] These findings on energy and emissions performance are specific to the test engine and end users should consult their engine manufacturer on the performance of their engines.

TABLE OF CONTENTS

Executive Summary 3

List of Figures 7

List of Tables 7

List of Abbreviations 9

Chapter 1 Introduction 11

1.1 Biofuel Feedstocks and Production Processes 11

1.2 Objectives 13

1.3 Methodology 13

Chapter 2 Regional Biofuel Production and Supply Chain 14

2.1 Production and Exports in Southeast Asia 14

2.2 Overview of Biofuel Supply Chain in Singapore 15

2.2.1 Supply chain in Singapore 15

2.2.2 Ground sentiments 16

Chapter 3 Biofuel Bunkering Considerations 17

Chapter 4 Biofuel Quality and Storage Stability 19

4.1 Biodiesel Blends and its Standards as Marine Fuels 19

4.1.1 Marine Gas Oil 19

4.1.2 Biodiesel 19

4.1.3 Hydrotreated Vegetable Oil 20

4.2 Biodiesel Standards for Singapore Harbour Craft 20

4.3 Biodiesel Parameters and Its Importance to Engine Performance 21

4.4 Storage Stability Experiments with Biofuel Blends 21

4.4.1 Fuels and materials 23

4.4.2 Methodology 23

4.5 Results and Discussion 24

4.5.1 Viscosity 24

4.5.2 Water content 25

4.5.3 Acid value 25

4.5.4 Oxidation stability by Rancimat method 25

4.5.5 Oxidation stability by the measurement of total insolubles 26

4.5.6 Impact of storage stability results of biodiesel as marine fuels 26

Chapter 5 GHG Emissions and Environmental Impact **32**
5.1 Overview of LCA, ISCC and IPCC **32**
5.1.1 Life Cycle Assessment (LCA) 32
5.1.2 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories 35
5.1.3 International Sustainability & Carbon Certification (ISCC) system 36
5.2 GHG Emissions of Biofuel Blends **37**
5.2.1 GHG emissions by ISCC methodology 37
5.2.2 IPCC GHG emissions 38
5.3 Environmental Impact of Biofuel Blends **39**

Chapter 6 Sea Trial Case Study **40**
6.1 Introduction **40**
6.1.1 Main engines 40
6.1.2 Vessel and engine preparation 41
6.1.3 Instrument preparation 41
6.2 Maintenance and Observations **42**
6.3 Data Analysis **50**
6.3.1 Engine performance analysis – fuel consumption 50
6.3.2 Emission analysis 54
6.4 Assessment of Economic Factors of Biofuels **58**
6.4.1 Potential economic factors of biofuels for Singapore harbour craft 58
6.4.2 Evaluation of cost factors for MGO, biofuels and blends 60
6.4.3 Economic assessment and discussion 62

Chapter 7 Biofuel Compatibility Survey **63**
7.1 Highlights from the Survey and Interviews **63**
7.2 Biofuel-compatible Engine Mapping with Singapore Harbour Craft Registry **65**
7.2.1 Engine mapping results (by engine brands) 65
7.2.2 Engine mapping results (by harbour craft prefix) 67

Chapter 8 Conclusion **68**

References **70**

LIST OF FIGURES

Figure 1.1	Methodology for data collection and analysis	13
Figure 2.1	Supply chain of biofuel in Singapore	16
Figure 3.1	Bunkering standards adopted in Singapore for marine fuel oils	17
Figure 5.1	RED 2018/2001/EC requirement on GHG emission savings from biofuels and biogas consumed in the transport sector	36
Figure 6.1	Schematic drawing of the vessel	40
Figure 6.2	Test route for the sea trial of biofuels in a cargo launch	41
Figure 6.3	LO sampling procedures	43
Figure 6.4	Condition of the fuel injectors	45
Figure 6.5	Condition of the piston top from starboard engine	45
Figure 6.6	Condition of the needle valves taken at the manufacturer factory	46
Figure 6.7	Condition of the fuel injectors during the 2nd maintenance after the high FAME blends of biofuels (B50-B100)	46
Figure 6.8	Fabrication integrity tests for coarse filters - first bubbles identified from the filter caps	47
Figure 6.9	Fabrication integrity tests for the FO fine filters – no bypass identified, and bubbles are mainly from the filter layers	47
Figure 6.10	Condition of the fuel pump plungers and barrels	48
Figure 6.11	Condition of the fuel supply pump	48
Figure 6.12	Analysis of the LO samples	50
Figure 6.13	SFOC comparison for different fuels	52
Figure 6.14	Engine Max RPM trend	53
Figure 6.15	Fuel cost (USD/mt) against biofuel blends for three types of biofuels	61
Figure 6.16	Energy cost (USD/mt) of MGO and three types of biofuels, PME, UCOME and HVO	62
Figure 6.17	Fuel consumption cost (USD/kWh) of MGO and biofuel blends for three types of biofuels	62
Figure 6.18	Average fuel cost increase (%) with biofuel blend from B20 to B100	63
Figure 7.1	Overview from the engine mapping of the biofuel-compatibility of harbour craft	67
Figure 7.2	Distribution of biodiesel compatible engines for all prefixes of Singapore harbour craft	69

LIST OF TABLES

Table 3.1	Considerations on biofuel bunkering	18
Table 4.1	Comparison of parameters regulated in international standards for FAME and HVO	21
Table 4.2	Effect of different parameters in the standard on the fuel properties	22
Table 4.3	Viscosity of biofuels with different blending ratios over four months of storage	27
Table 4.4	Water content of biofuels with different blending ratios over four months of storage	28
Table 4.5	Acid values of biofuels with different blending ratios over four months of storage	29
Table 4.6	Oxidation stability by Method 1 of biofuels with different blending ratios over four months of storage	30
Table 4.7	Oxidation stability by Method 2 of biofuels with different blending ratios over four months of storage	31
Table 5.1	Summary of LCA, ISCC, IPCC GHG guidelines	33
Table 5.2	Total GHG emissions based on ISCC guidelines	37
Table 5.3	Contribution to Singapore IPCC GHG inventory by domestic marine transport	38
Table 6.1	Spare parts list for the sea trial	41
Table 6.2	Lists of the instrument deployed onboard	42
Table 6.3	Materials of the engine components	43
Table 6.4	LO analysis parameter	43
Table 6.5	NCV for B100, MGO, UCOME and HVO by mass	51
Table 6.6	NCV for fuels at different blends	51
Table 6.7	Operating status for vessel in this study	52
Table 6.8	Recorded parameters for regression study during high-speed cruising	53
Table 6.9	Description of variables for the multiple linear regression models of engine performance	53
Table 6.10	Regression analysis for engine performance	54
Table 6.11	Description of variables for the multiple linear regression models of emissions on operating conditions	55
Table 6.12	Results of regression of CO_2 emission on operating conditions	56
Table 6.13	Results of regression of NOx emission on operating conditions	56
Table 6.14	Results of regression of CO emission on operating conditions	56
Table 6.15	Summary of CO_2, CO, and NOx emissions during high-speed cruising	57
Table 6.16	Fuel composition by mass (%)	57
Table 7.1	Consensus, risks and impact on engine system and general mitigation measures by engine manufacturers	64
Table 7.2	Breakdown numbers of biofuel-compatibility by engine brands	67

LIST OF ABBREVIATIONS

°C	Degrees Celsius	FFAs	Free Fatty Acids
A	Ampere	FO	Fuel Oil
AFOLU	Agriculture, Forestry and Other Land Use	g	gram
ASTM	American Society for Testing Materials	GHG	Greenhouse Gas
BFO	Bio-Fuel Oil	GJ	Gigajoule
BTL	Biomass-to-Liquid	GTL	Gas-to-Liquid
BXX	Blend Ratio of Fatty Acid Methyl Ester and Marine Gas Oil	GWP	Global Warming Potential
CFPP	Cold Filter Plugging Point	HVO	Hydrotreated Vegetable Oil
CH_4	Methane	IEA	International Energy Agency
CO	Carbon Monoxide	ILCD	International Reference Life Cycle Data System
CO_2	Carbon Dioxide	IMO	International Maritime Organization
CO_2eq/MJ	Carbon Dioxide Equivalent for Greenhouse Gases per Megajoule of Energy	IPCC	Intergovernmental Panel on Climate Change
COQ	Certificate of Quality	IPPU	Industrial Processes and Product Use
CP	Cloud Point	ISCC	International Sustainability and Carbon Certification
cST	centistokes	ISO	International Organization for Standardization
CTL	Coal-to-Liquid	kg	Kilogram
DAFAS	Department of Agriculture Foreign Agriculture Service	KOH	Potassium Hydroxide
DF	Distillate FAME	LCA	Life Cycle Assessment
EN	European Standards	LCI	Life Cycle Inventory
ETFE	Ethylene Tetrafluoroethylene	LCIA	Life Cycle Impact assessment
EU	European Union	LHV	Lower Heating Value
FAME	Fatty Acid Methyl Ester	LO	Lube Oil

m/m	Mass/mass	PM	Particulate Matter
MARPOL	International Convention for the Prevention of Pollution from Ships	PME	Palm Oil Methyl Ester
MESD	Maritime Energy and Sustainable Development	PO	Palm Oil
METB	Maritime Energy Test Bed	ppm	Parts per Million
MGO	Marine Gas Oil	PP	Pour Point
MJ	Megajoule	PT	Port
mm	Millimetre	RED	Renewable Energy Directive
MPA	Maritime and Port Authority of Singapore	RPM	Rotations Per Minute
Mt/tonne	Metric Tonne	RXX	Blend Ratio of HVO and Marine Gas Oil
N·m	Newton-metre	SFOC	Specific Fuel Oil Consumption
N_2O	Nitrous Oxide	SNI	The Indonesian National Standard
NBR	Nitrile-Butadiene Rubber	SO_2	Sulfur Dioxide
NCV	Net Calorific Value	STBD	Starboard
NDC	Nationally Determined Contribution	ton	Displacement Ton
NEA	National Environment Agency	UCO	Used Cooking Oil
NM	Nautical Mile	UCOME	Used Cooking Oil Methyl Ester
NO	Nitric Oxide	V	Voltage
NO_2	Nitrogen Dioxide	v/v	Volume/volume
NOx	Oxides of Nitrogen	WTP	Well-to-Propeller
NTU	Nanyang Technological University	WTT	Well-to-Tank
O_2	Oxygen		

CHAPTER 1
INTRODUCTION

Singapore is committed to achieving net zero emissions by 2050 and has recently revised the 2030 Nationally Determined Contribution (NDC) to reduce carbon emissions to around 60 million tonnes of carbon dioxide equivalent ($MtCO_2e$) in 2030 after peaking emissions between 2025 and 2028 (NCCS, 2022). Singapore's harbour craft industry is identified as one of the potential sectors that can contribute to Singapore's decarbonisation target. In the near term, biofuel has gained attention from the maritime industry as a mature and viable alternative solution to conventional marine fuels.

Biofuel combats climate change by significantly reducing emissions over the entire life cycle (Hsieh & Felby, 2017). Two types of biofuels: biodiesel and renewable diesel, are identified as feasible drop-in alternative fuels for the harbour craft industry to reduce carbon emissions (Liu et al., 2020). Biodiesel can be blended with marine distillate and used in existing ships and bunkering infrastructure with minor or no modifications.

The two-year Biofuel Compatibility Study for Singapore Harbour Craft focuses on biodiesels from used cooking oil or palm oil and renewable diesel. The MESD research team have worked closely with various stakeholders, including the government regulator, biofuel suppliers, bunker supplier, fuel test laboratory, shipowner, engine manufacturers and an engine expert consultant, to investigate the use of sustainable biofuels for the harbour craft industry.

1.1 Biofuel Feedstocks and Production Processes

Types of biodiesels (also known as Fatty Acid Methyl Esters/FAME) can be classified by their feedstock, for example, Palm Oil Methyl Ester (PME) and Used Cooking Oil Methyl Ester (UCOME). Used cooking oil is collected from eateries or food processing industries and palm oil is harvested from the fruit of oil palm trees. Biodiesel blends are usually labelled with their blending ratio ("BXX"). For example, B20 is made by blending 20% (v/v) of biodiesel content and 80% (v/v) of conventional marine fuels. Renewable diesel (also known as Hydrotreated Vegetable Oil/HVO) is distinct from biodiesel as the feedstock undergoes a hydrotreating process and is differentiated by using the label "RXX". It is chemically similar to conventional paraffinic diesel, except it is derived from recently living biological sources that are chemically not esters (Hilbers et al., 2015). HVO blends are similarly defined by the blending ratio; for example, R20 contains 20% (v/v) of HVO and 80% (v/v) of conventional marine fuels. HVO is usually made of different feedstocks such as vegetable oils, waste and residues in a single batch, but the resultant product has to meet the same stringent standard for HVO.

Global biofuel production has increased around tenfold from 2000 to 2021 (Statista, 2022a). Biofuels, including bioethanol, biodiesel and HVO, etc., have provided about 3.5% of transport energy in 2020 (REN21, 2022). The United States was the leading producing country for biofuel production in 2021, followed by Brazil, Indonesia, China, Germany, France, Thailand, etc. (Statista, 2022b). While ethanol dominates the market in terms of production volume, the proportion of biodiesel and HVO in the biofuel mix has grown in recent years due to rising production in Asia and Europe. Indonesia is the current leader in biodiesel production, accounting for 18% of the total global production, followed by Brazil (IEA, 2021).

The production of HVO has also risen by 36% in 2021, with a forecast of an estimated 30 million tonnes by 2025 (REN21, 2022; Neste, 2022a). Finland, Netherlands and Singapore are a few of the major producers of HVO. Recently, the production of HVO has increased in the United States, driven by several domestic standards and financial incentives (REN21, 2022).

Currently, 90% of biodiesel is produced from vegetable oil (BCC Research, 2020). The most common vegetable oil is rapeseed oil for Europe, soybean oil for America, and palm oil for Asia-Pacific. Used cooking oil is one of the strongest growing sub-segments due to its easy availability, low price and sustainability. Furthermore, animal fat-based feedstock is expected to see strong growth across geographies due to high availability and low price. Biodiesel made from animal fat, is also expected to have high cloud point, high cetane number, and a smaller increase in NOx emission which are important fuel quality and performance indicators.

Generally, there are four major types of biodiesel technologies. Transesterification is a cost-effective method which gives a high conversion efficiency (Ramli et al., 2017). This production process involves the chemical reaction of triglycerides (oils/fats) with alcohols to form esters and glycerol (Gerpen, 2005). However, transesterification generates unpurified by-products and a large amount of contaminated wastewater (Sankumgon et al., 2018). As an alternative method, Micro-emulsion process can be used to produce biofuel with suitable properties, avoiding the problems of waste disposal (Sankumgon et al., 2018). The method produces a finished product of two liquid phases which are not mutually dissolving; instead, one liquid phase is dispersed in another. Biodiesel pyrolysis is another production method. Heating vegetable oil or animal fat in the absence of oxygen produces less waste and pollution compared to other processes (Noor et al., 2018). Furthermore, the dilution process can be applied in biofuel production by mixing biodiesel with diesel fuel and ethanol solvent. The dilution process aims to reduce the viscosity of biodiesel. However, it results in density reduction too (Noor et al., 2018).

The HVO production process typically involves hydrogenation of triglycerides using existing refinery infrastructure and it is chemically equivalent to petroleum diesel. The major feedstocks include rapeseed, soybean, corn oil, industrial waste and used cooking oil. The HVO production volume accounts for only 6% of total biofuel production in 2020 (Renewables, 2021). However, when considering the expansion of existing facilities and new production sites, the additional capacity is expected to exceed biodiesel (Renewables, 2021).

In the long term, the production volume will be influenced by several factors: the availability and conversion efficiency of new renewable feedstocks, higher production costs due to an increase in feedstock cost and the development of robust catalysts and cost-effective production methods. Feedstock cost accounts for the largest component of biodiesel production cost, which takes up 70%-95% of the total biodiesel production cost (BCC Research, 2020; Fadhil et al., 2012; Karmee, 2016; Meira et al., 2015) and the increased demand for feedstocks keeps prices high. Thus, it is important to widen the pool of new renewable feedstocks and improve production processes. An example is the use of heterogeneous catalysts, which have been recognised as the best choice for biofuel production because heterogeneous catalysts can be recycled and recovered easily and have environmentally friendly behaviour (Ramli et al., 2017).

1.2 Objectives

This study aims to investigate the compatibility of biofuels as a near-term measure to reduce the GHG emissions for Singapore harbour craft. The objectives include:

- Establish the technical and operational viability of biofuels as a potential pathway.
- Assess the availability of biofuels from existing suppliers to bunkering and onboard usage.
- Assess the technical, environmental, operational and economic factors of the candidate biofuels as compared to conventional Marine Gas Oil (MGO) used by the Singapore harbour craft community.

1.3 Methodology

The study assesses the feasibility of biofuels as marine fuels for Singapore harbour craft using technical, environmental, operational and economic considerations (Figure 1.1). These factors are evaluated based on information from a literature review, engine manufacturers, fuel suppliers, experiments and sea trials conducted by the research team. Storage stability of biofuel blends is tested by storing biofuel blends, PME/UCOME/HVO with MGO, under the ambient environment over four months and then analysed by an accredited laboratory. A Singapore cargo launch was selected for the sea trials with different biofuel blends from 20% (v/v) to 100% biofuels. The sea trials were supported by MESD's propriety method for onboard measurements and data analysis to determine engine performance and emissions.

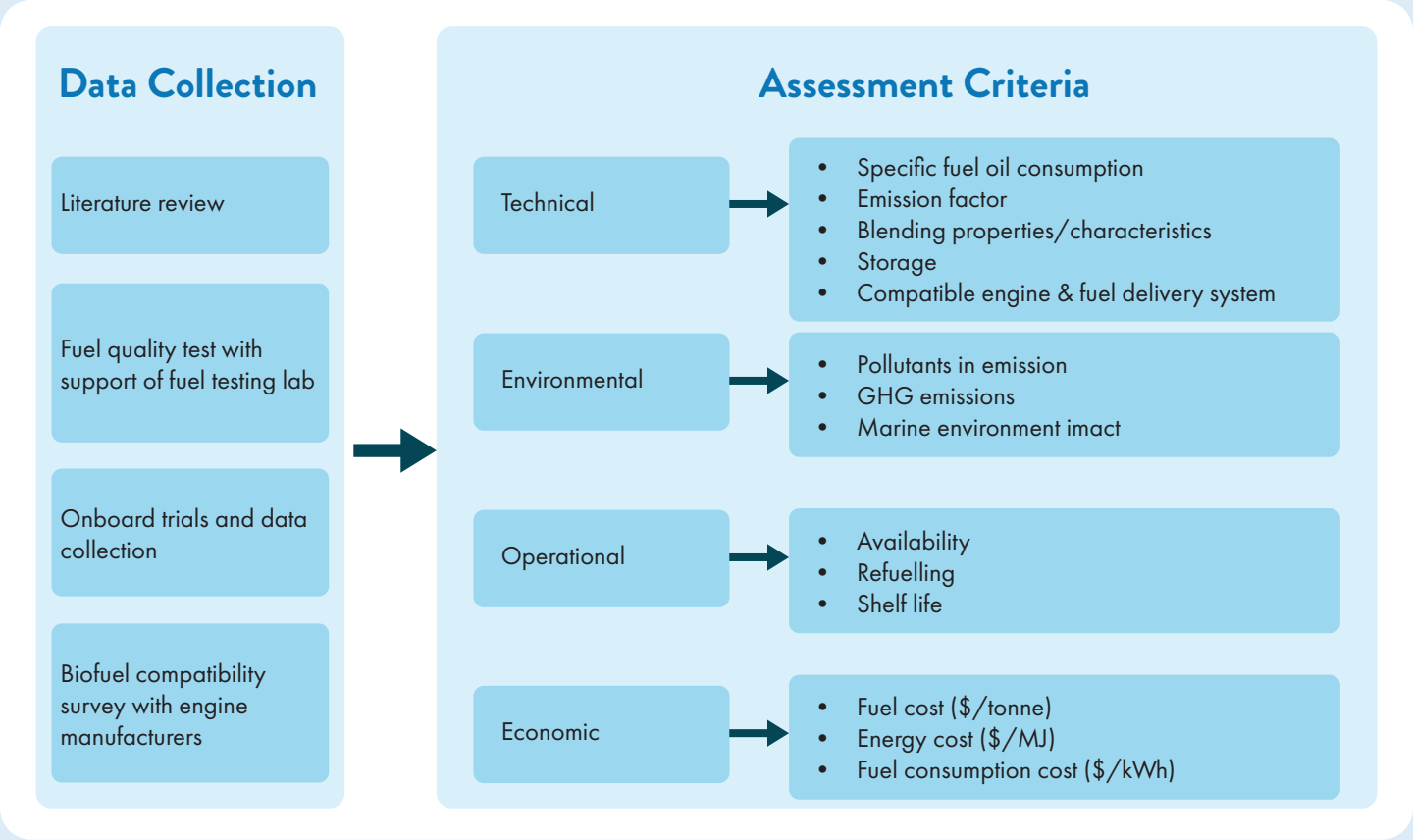


Figure 1.1 Methodology for data collection and analysis

CHAPTER 2
REGIONAL BIOFUEL PRODUCTION AND SUPPLY CHAIN

2.1 Production and Exports in Southeast Asia

Southeast Asia is growing in importance in the biodiesel market, with Indonesia, Thailand and Malaysia accounting for a large share of biodiesel production. These countries are now among the top 10 major biofuel-producing countries in 2021 (Statista, 2022b). However, the capacity use of biofuel refineries in Indonesia, Malaysia and Thailand only achieved 61.8%, 64.3% and 43%, respectively in 2021 (US DAFAS, 2021; US DAFAS, 2022a; US DAFAS, 2022b). With strong domestic mandates in Southeast Asia, Singapore may need to cast a wider net to import biodiesel from Asia. In addition, the latest EU Renewable Energy Directive (EU RED II) has limited the use of crop-based feedstocks, shining the spotlight on waste and residue feedstocks. Given the limited supply of these feedstocks, manpower and facilities, biofuel production and blending ratio must increase gradually over time.

Indonesia

Biodiesel production and consumption have grown significantly since 2011 as the government of Indonesia has financially supported and mandated a biodiesel blending programme since 2015 (US DAFAS, 2020a; US DAFAS, 2022a). The blending mandate is a nationwide directive to blend PME with diesel to reduce reliance on fuel imports, generate domestic demand for palm oil and reduce GHG emissions. The blending ratio has increased from 5% to 30% by 2022 (US DAFAS, 2022a), and is expected to rise to B40 after 2023 (Reuters, 2022; US DAFAS, 2022a). Data shows Indonesia can produce sufficient biodiesel to meet its domestic consumption in 2022 (10.1 billion litres) and biodiesel production is expected to reach 16.6 billion litres (US DAFAS, 2022a). However, exports have dipped from a peak of 2000 million litres to a negligible quantity for the past decade (US DAFAS, 2022a). Export quantities are affected by domestic consumption and a sharp drop in diesel prices, eliminating demand from China.

Thailand

Thailand's biofuel supply and demand have increased from 2011 to 2020 (US DAFAS, 2020c; US DAFAS, 2022b). A slight decline of 10% in biodiesel production to 1,658 million litres in 2021 corresponds to reduced biodiesel fuel consumption (1,675 million litres) caused by the COVID-19 pandemic (US DAFAS, 2022b). Biodiesel imports have been negligible because the government restricts the import of biodiesel to protect domestic palm growers (US DAFAS, 2022b). The government of Thailand keeps the mandatory blending rate as low as B5 (US DAFAS, 2020c; US DAFAS, 2022b) and reduces excise tax until June 2022 to mitigate the impact of high energy prices on transportation and production costs for consumer goods.

Malaysia

Malaysia has produced sufficient biodiesel for its consumption since 2011 (US DAFAS, 2020b; US DAFAS, 2021), while its biodiesel production, consumption and exports have generally increased from 2011 to 2019. The biodiesel production and export quantities in 2020 were 1,249 million litres and 412 million litres, respectively (US DAFAS, 2021). The European Union is currently the largest importer of Malaysian biodiesel, accounting for about 70% of total biodiesel exports in Malaysia (US DAFAS, 2021). The government of Malaysia has revised the mandatory biodiesel blend from B10 to B20 in 2022. It is worth noting that while the number of biodiesel refineries increased from 11 in 2011 to 19 in 2021, the capacity use of these plants fell from 73.3% to 43% (US DAFAS, 2021).

2.2 Overview of Biofuel Supply Chain in Singapore

2.2.1 Supply chain in Singapore

Singapore is heavily dependent on trade and imports, especially with its neighbouring countries. Singapore may import PME from Malaysia and Indonesia as they are the top producers of palm oil. HVO is produced from a mix of feedstocks, including animal fat from food industry waste, UCO and other waste and residues. Waste cooking oil to produce UCOME is collected locally. In order to meet the demand in the future, UCOME may also be imported from other Asian countries with excess UCO.

Three potential biofuel supply chains for Singapore are shown in Figure 2.1. The supply chains are also used for calculating the GHG emission savings and fuel costs in Chapter 5 and 6, respectively. The supply chains are differentiated by the location of feedstocks. In the first supply chain, biodiesel is produced with domestic feedstock; this scenario provides the least emissions from transportation. The second supply chain illustrates the use of imported feedstock for the production HVO. The third supply chain assumes a case where biodiesel is produced overseas and imported into Singapore.

The potential supply capacities of three biofuel producers are presented after discussions with the study's collaborators. Singapore's local biofuel supplier Alpha Biofuels collects used cooking oil from the local F&B industry and can produce 300 tonnes of biodiesel a month. It has a blending capacity of 1,000 tonnes a month, requiring one week to complete a full blend with MGO. Alpha Biofuels plans to further increase its production capacity by 1,000 tonnes a month and even explore the option of setting up regional production facilities. Facilities near the feedstock source would mean lower GHG emissions from the transportation of biodiesel. Neste imports its feedstock of waste, residues and vegetable oils from worldwide to produce its renewable diesel in Singapore before distributing it to global markets. Neste currently produces 1.3 million tonnes and is expanding Singapore's production capacity by another 1.3 million tonnes per annum by 2023 (Neste, 2022b). Wilmar International may export up to 5 million tonnes and 1 million tonnes of PME from Indonesia and Malaysia, respectively due to their vast plantations of oil palm, providing a reliable supply of imported biodiesel for blending in Singapore.

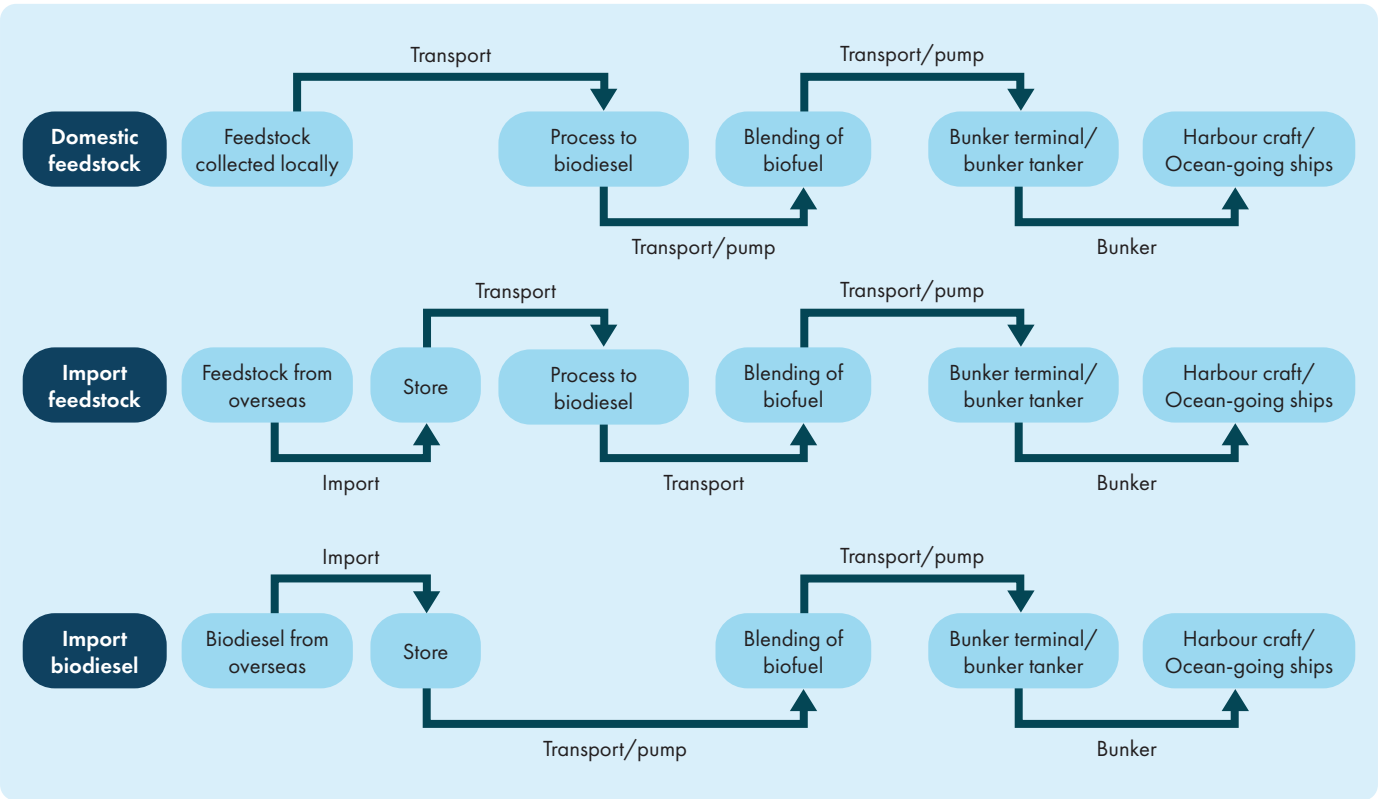


Figure 2.1 Supply chain of biofuel in Singapore

** The above supply chain information is based on our industry partners from this project.*
** Above flow is based on current to near-future processes.*

There is a limited number of blender and blending facilities in Singapore. However, current fuel storage and processing facilities in Singapore may be converted to store and blend biofuels. A reference can be taken from Europe, where a Eurotank project converted 75,000 m^3 of gasoil tanks at its terminal in the Port of Amsterdam to store biofuels, blended biofuels, and HVO) (Tank Storage Magazine, 2021).

2.2.2 Ground sentiments

Sustainable PME from neighbouring countries may become the main supply, driven by its high production capacity and low price. The uptake of biofuels is expected to further encourage the local collection of used cooking oil. As a key bunkering hub, Singapore needs to meet the demand from international shipping. Given the global demand for waste and residues as feedstocks, the increase in biofuel blend has to be weighed carefully against the availability of feedstocks. Although the availability at a commercial scale and compatibility of new feedstocks may require further R&D efforts, there is now a clear interest for biofuel producers to widen the selection of feedstocks.

Singapore has to establish and strengthen its infrastructure in producing and blending biofuel blends. Existing infrastructure and facilities can be converted into blending facilities. Currently, bunker suppliers have to manage biofuel blends separately from MGO but in the future when biofuel blends are widely adopted by the industry, operation cost is expected to be gradually lowered.

CHAPTER 3
BIOFUEL BUNKERING CONSIDERATIONS

Singapore is a major bunkering hub, with around 50 million tonnes of total bunker sales in 2021 (MPA, 2022). Several bunkering standards are mandatory, such as SS 600: 2014, SS 648: 2019, SS 660: 2020, which cover documentation, equipment, procedures, quality of bunker fuel supplied, etc., as shown in Figure 3.1. The current bunker system with bunkering standards improves the bunkering efficiency, accuracy and transparency of bunkering in Singapore.

There are three main bunkering modes for marine fuels, namely ship-to-ship bunkering, truck-to-ship bunkering and shore/terminal pipeline-to-ship bunkering. Ship-to-ship bunkering is the most common method of delivering large quantities of bunker fuel to ships. Truck-to-ship bunkering is the most common way to deliver small quantities of bunker fuel, such as distillates, to harbour craft. The trucks are equipped with hoses carried on racks at the side and pumps on board driven by the engine. For truck-to-ship bunkering, bunker quantity is measured by gauging tank contents using a gauging stick, flow meter or by weighing bridge. For shore/terminal pipeline-to-ship bunkering, the terminal pipeline and pumping system are designed to allow internal fuel transfers for batch blending and delivery to receiving vessels.

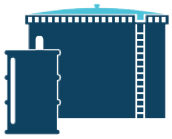
Oil Terminal	Bunker Tanker	Receiving Vessel
		
	ISO 8127: 2017	
	SS 524: 2014	
	TR 80: 2020	
SS 660: 2020		SS 660: 2014
		SS 648: 2019
		ISO 13739: 2020
		ISO 21562: 2020
		ISO 22192: 2019

Figure 2.1 Supply chain of biofuel in Singapore

There are regular biofuel bunkering operations and sea trials in some ports. For example, the Port of Rotterdam has integrated biofuel production, storage, trade and transhipment. Several vessels, such as the M/V Trudy, Nord Highlander, and Stena Immortal vessel, have used Bio-Fuel Oil (BFO) as a marine fuel (Manifold Times, 2018). As biodiesel is recognised as a drop-in ambient liquid fuel for marine engines, biofuel bunkering has largely followed conventional fuel bunkering modes and procedures.

Table 3.1 summarises a list of considerations recommended for developing future biofuel bunkering standards to meet Singapore's strict bunker quality and quantity requirements. Storage stability, indicated by parameters such as viscosity, water content, acid value, and oxidation stability (mass and conductivity), is at risk of deteriorating over time and impacts fuel quality. Material compatibility needs to be considered, as copper, bronze, zinc, tin and brass are not compatible materials for biofuel storage (Fazal et al., 2010). The preferred materials are steel, aluminium, fibreglass, Teflon, fluorinated polyethylene, fluorinated polypropylene and rubber compound (Van Gerpen, 2012). Additives may be used to enhance certain properties of biodiesel, for example, the oxidation stability (Noor et al., 2018) and the engine compatibility of additives needs to be assured.

Table 3.1 Considerations on biofuel bunkering

Considerations	**Remarks**
Storage stability	Viscosity Water content Acid value Oxidation stability Material compatibility
Corrosivity	Selection of storage materials Frequency of sample testing
Additives	Adjusted based on fuel property and geography
Blending	Less than B25 as Marpol Annex I bulk cargo
Mass flow meter	Fuel type, pressure and fuel temperature
Bunkering standards	No specific international standard for biofuel bunkering
Oil spill	Similar dispersion behaviour as conventional marine fuels

The corrosivity of biodiesel and the corrosion rate depends on the feedstock type, water contamination and microbial growth. Deterioration of non-compatible materials impacts the fuel system, including gaskets, hoses, fuel filters and fuel injectors. All components in the fuel system have to be verified for their compatibility with the intended biofuel blend (ABS, 2021). The use of the B100 biodiesel can soften and deteriorate the rubber compounds of marine hoses and gaskets, while B20 and lower blends do not significantly harm (Nayyar, 2010). Furthermore, bacterial and fungal growth can occur when water is present. It is recommended to conduct regular fuel sample testing or add a high-quality fuel filter system to remove water from fuel tanks (ABS, 2021).

Fuel additives can improve fuel flow properties and combustion. However, additives are not a must for biofuel and sometimes negatively affect cold flow properties. It is worth noting that the additives shall be adjusted based on geography and season.

Blending biodiesel and conventional marine fuels onboard may incur operational risks and hazards for ship owners and operators (ABS, 2021, UK P&I, 2021) and is not allowed in Singapore waters. Based on the MARPOL Annex I carriage requirement, bunker tankers carrying conventional marine fuels are permitted to hold up to B24 biofuel blend in their cargo tanks.

The lack of maritime standards for marine biofuel is also a constraint for its implementation. No specific international biofuel standard is used in maritime applications (also see Chapter 4 on biofuel standards). The latest version of ISO 8217, which is a work in progress, will take into consideration of biofuel properties at higher blending ratio.

For biofuel trials in Singapore, several documents shall be approved by MPA, such as inspection and maintenance activity, risk assessment, and contingency plan. Hazards associated with bunkering activity include fire, fuel spillage, fumes, exposure to chemicals, and slip and fall.

CHAPTER 4
BIOFUEL QUALITY AND STORAGE STABILITY

4.1 Biodiesel Blends and its Standards as Marine Fuels

Biodiesel has different storage stability and combustion performance from MGO due to its characteristics. As a result, the applicability of existing marine fuel standards to biofuel and biofuel blends with MGO is reviewed.

4.1.1 Marine Gas Oil

MGO is a conventional marine fuel for harbour craft and is produced as a product from the fractional distillation of petroleum in a refinery. ISO 8217 is the international standard that specifies the requirements for fuel use in marine diesel engines and boilers (IMO, 2020). In 2017, ISO 8217 introduced DF (Distillate FAME) grades DFA, DFZ, and DFB, which allow FAME up to 7% (v/v) in the marine fuel (ISO, 2017). Diesel fuel with FAME content up to 7% (v/v) can generally be stored and handled in the same storage and machinery as conventional marine diesel fuels (CIMAC, 2013). Diesel fuel with FAME content of up to 7% (v/v) has been widely used in land transportation for many years (Infineum International Limited, 2022) and are also specified in EN 590 (British Standards Institution, 2013). With respect to HVO, ISO 8217 states that the marine fuel composition shall consist predominantly of hydrocarbons primarily derived from petroleum sources while it may also contain hydrocarbons from the following: synthetic or renewable sources such as Hydrotreated Vegetable Oil (HVO), Gas to Liquid (GTL) or Biomass to Liquid (BTL), which does not set a particular blending ratio of HVO.

4.1.2 Biodiesel

4.1.2.1 Pure biodiesel (B100)

There are two widely adopted standards for B100, EN 14214 and ASTM D6751. EN 14214 is a restrictive standard that only applies to pure biodiesel made from triglycerides and methanol. The minimum ester content inside B100 must be at least 96.5% (British Standards Institution, 2012). Adding components other than fatty acid methyl esters is not allowed (except for additives). ASTM D6751 defines biodiesel as a long-chain fatty acid without specifying the type of alcohol used during the production. Therefore, it is less restrictive and applies to biodiesel made with triglycerides and any type of alcohol (e.g., methanol, ethanol) (ASTM, 2020). Contrary to ASTM D6751, EN 14214 allowed B100 to be used unblended in a diesel engine or blended with diesel fuel, in accordance with other applicable standards for specific blends (e.g., B7, B20, B30). The most common biodiesel blends are B7 and B20 (US Department of Energy, 2022).

4.1.2.2 Biodiesel blends up to B7

In addition to ISO 8217, ASTM D975 and EN590 standards are relevant for low-level biodiesel blends containing up to 7% (v/v) of FAME. Both standards regulate distillate fuel for use in diesel engines, which limits FAME content up to 5% (v/v) (ASTM D975) and 7% (v/v) (EN 590), respectively. Generally, EN 590 specifies more parameters relevant to biodiesel, such as water content, total contamination, and oxidation stability. The Eighth Schedule: Environmental Protection and Management (Vehicular Emissions) Regulations (Singapore Statutes Online, 2019) applies to Singapore's land transportation. While it is a local standard, there are seven parameters for diesel fuel that are almost identical to those specified by EN 590. It also requires that the FAME, as blending stock (B100), meets the EN 14214 standard.

4.1.2.3 Biodiesel blends up to B20

B20 is a popular blend of biodiesel for automotive diesel engines because it has good cold-weather performance and materials compatibility (US Department of Energy, 2022). Some studies have found that B20 achieved better fuel quality with higher cetane, higher lubricity, and lower particulates (National Biodiesel Board, 2020). Almost 80% of the engine manufacturers in the USA support using B20 in their vehicles and equipment (Clean Fuels Alliance America, 2022). There are two existing standards for low-level biodiesel blends: ASTM D7467 and EN 16709, depending on the location of their markets.

4.1.2.4 Biodiesel blends above B20

Higher biodiesel blends containing FAME above 20% (v/v) are less common due to a lack of regulatory incentives and higher prices (US Department of Energy, 2022). EN 16709 is the only international standard for biodiesel up to 30% FAME. Contrary to other standards, EN 16709 specifies the criteria of biodiesel to be used in captive fleets, which are vehicles with predictable routes and refuelling patterns. It is worth noting that the oxidation stability under EN 16709 requires a minimum of 20h, which is significantly higher than the 6h specified under ASTM D7467.

Another biodiesel standard, SNI 7812, was implemented in 2008 by Indonesia, and the latest version includes biodiesel up to 30 % (v/v) (Wibowo, 2022). Compared to EN 16709, the standard requires biodiesel (B100) to meet the SNI 7812 standard before blending with diesel oil. Therefore, SNI 7812 is more similar to EN 14214 in this aspect. Similarities between the standards are the acid number, FAME content, water content, density, viscosity, and monoglyceride content. However, SNI does not consider saturated methyl esters, diglyceride, and triglyceride. Parameters such as carbon residue, colour, water and sediment are found in SNI 7812 but are not considered in EN 14214. At present, there is no international standard on blends higher than B30 and Indonesia is undertaking a study to consider B40 fuels (Wibowo, 2022).

4.1.3 Hydrotreated Vegetable Oil

HVO is considered to have a similar performance to conventional diesel, with some parameters outperforming it (e.g., higher cetane rating, very low sulfur content) (ETIP Bioenergy, 2020). The standards of HVO are described below.

4.1.3.1 Pure HVO (R100)

EN 15940 specifies quality standards for paraffinic fuel, synthetic Fischer-Tropsch GTL, BTL, and Coal-to-Liquid (CTL) (British Standards Institution, 2016). It applies to fuels for diesel engines and vehicles compatible with paraffinic fuel. Under EN15940, HVO can be categorised into Class A and Class B due to different acceptable ranges of densities and cetane numbers. The grades, A to F, are differentiated by different cold filter plugging points from 5 oC to -20 oC. EN590 defines parameters that are largely similar to EN15940, except for higher total aromatics content of 8 mass%, cetane index of 46 and a higher range of densities from 820 to 845 kg/m3.

4.1.3.2 HVO blends (R99 and below)

When HVO is blended with diesel fuel, it does not have to meet EN 15940 requirements. Instead, diesel blends are guided by EN 590, which requires certain technical requirements to be met regardless of the feedstock used. This means GTL diesel fuels, BTL fuels, and HVO can be used as blending components. Compared to the standards for biodiesel, which limits the FAME content, there is no limit for HVO-based blends. EN 590 applies to all HVO/MGO blends (British Standards Institution, 2013).

4.2 Biodiesel Standards for Singapore Harbour Craft

Singapore applies the EN 14214 standard for its biodiesel blend stock and ISO 8217 for its marine fuel (Singapore Statutes Online, 2019) to all ships sailing in Port limits. ISO 8217 allows the blending of FAME with MGO up to 7% (v/v). To accelerate the decarbonisation target, Singapore is gearing up to develop standards for alternative fuels for shipping, including biodiesel (Seatrade Maritime News, 2021). However, there are different standards for biodiesel (i.e., ASTM, EN, ISO) and blending ratios from B7 to B100. The parameters are recommended based on factors such as the local climate, type of feedstock, and safety considerations. Thus, the Cold Filter Plugging Point (CFPP) is not applicable to harbour craft but is defined in the standard because of its usage in the winter months of North America and the European Union (EU).

Table 4.1 shows the existing international standards for biodiesel blends. In the study, ISO and EN standards are selected as a basis for comparing parameters. ISO 8217 is the current marine fuel standard for Singapore harbour craft, while EN 16709 covers biofuel blends up to B30. EN 14214 is applicable for PME B100 and UCOME B100. For HVO, EN 15940 applies to HVO R100 and HVO-based blends with diesel fuels are regulated by EN 590.

Table 4.1 Comparison of parameters regulated in international standards for FAME and HVO

Blending Ratio[a]	Available Standards						
	Biodiesel			HVO	Singapore Biodiesel		Singapore HVO
	EN	ASTM	ISO	EN	Land-based	Marine	
B100 / R100	EN 14214	D6751	NA	EN 15940	EN 14214		NA
B31 - B99/ R31 - R99	NA	NA		EN 590	NA	NA	
B30 / R30	EN 16709						
B24 / R24							
B20 - R24/ R20 - R24	NA						
B20 / R20	EN 16709	D7467					
B14 / R14							
B10 - B14/ R10 - R14	NA						
B10 / R10	EN 16734						
B7 / R7	EN 590		ISO 8217		Singapore Statute Eighth Schedule		
B6 / R6							
B5/ R5		D975					
MGO (B0 / R0)						ISO 8217	

[a]*BXX is biodiesel blend; RXX is HVO blend*

4.3 Biodiesel Parameters and Its Importance to Engine Performance

Degradation of biodiesel impacts the fuel quality and the storage duration of biodiesel blends. Biodiesel, as a strong solvent, may corrode some engine components and affect engine maintenance and performance. A review of important parameters specified in biodiesel standards has been summarised in Table 4.2 to highlight the areas of impact to fuel injection system and engine performance.

4.4 Storage Stability Experiments with Biofuel Blends

As biodiesel oxidises easily after moisture absorption from the air due to prolonged storage duration, microbial growth in the fuel, fuel quality degradation and alteration of fuel properties are likely to occur. This inevitably leads to reduced engine combustion performance, filter clogging, and corrosion in engine components. Experiments on the storage stability of biofuel blends are important to determine the biofuels' oxidation stability in Singapore's hot and humid conditions.

Table 4.2 Effect of different parameters in the standard on the fuel properties

S/N	Parameter	Importance of the Parameter as a Fuel
1	Cetane Number	Measure fuel ignition quality.
2	Cetane Index	Measure fuel ignition quality.
3	Calorific value	Energy obtained from burning fuel.
4	Elemental composition	Affect fuel quality and performance (calorific value, emission, lubricity).
5	Sulfur	Affect emission quality, lubricity, and corrosion.
6	Phosphorus	May cause catalyst poisoning and deposit formation.
7	Manganese	Affect PM emissions and deposit formation.
8	Alkali content (Na,K, Ca, Mg)	May improve lubrication and cause deposit formation.
11	Kinematic Viscosity	Affect fuel efficiency and handling.
12	Density at 15°C	Affect fuel efficiency and handling.
13	Cloud Point (CP)	Determine fuel operability in cold weather.
14	Cold Filter Plugging Point (CFPP)	Determine fuel operability in cold weather.
15	Pour Point (PP)	Determine fuel operability in cold weather.
16	Flash point	Determine fuel safety and handling.
17	Water content	Affect fuel degration and corrosion.
18	Oxidation stability	Determine fuel ability to resist degradation.
19	Acid value	Measure the presence of acid that can cause fuel degradation and corrosion.
20	Copper strip corrosion	A measure of the fuel corrosiveness.
21	Iodine number	Measure the degree of unsaturation and susceptibility to oxidation and polymerisation.
22	Carbon residue	Measure the amount of carbonaceous materials that can cause deposit formation.
23	Ash content	Measure the amount of inorganic materials that can cause deposit formation.
24	Total contamination	Measures the amount of foreign materials in fuel which may cause damage to engine.
25	Ester content	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
26	Linolenic acid methyl ester	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
27	FAME content	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
28	Methanol content	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
29	Monoglycerides	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
30	Diglycerides	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
31	Triglycerides	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
32	Free glycerol	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.
33	Total glycerol	Determine the purity and quality of a FAME-based biofuel that affect the fuel quality, stability, efficiency, and deposit formation.

Five identified parameters can be used to quantify the stability of biodiesel: Iodine value, Peroxide value, Acid Value, Viscosity, and Oxidizability (Rajesh et al., 2016). Rashed compared biodiesel's stability using parameters such as biodiesel content, induction period, acid value, iodine value, density, and viscosity (Rashed et al., 2015). They tested over 20 types of biodiesel feedstock (e.g., Rapeseed Methyl Ester of RME, Palm oil Methyl Ester or PME, etc.). Rashed's findings show a correlation between the storage duration of biodiesel with its properties, where longer storage duration leads to a worse biodiesel quality. From the industry perspective, engine manufacturer, Weichai, recommends storage stability tests should include oxidation, acid number, viscosity, and sediments (Weichai, 2019). Generally, B20 has a recommended shelf life of up to 6 months.

These five parameters are eventually selected for the storage stability experiments: viscosity, water content, acid value, and two variations of oxidation stability (based on mass and induction period).

i. Regardless of fuel type, the viscosity of the fuel affects injection timing and pressure prior to engine combustion. For biodiesel, viscosity is an indication of degradation when oxidation takes place. The formation of gums and sediments will increase the viscosity of the fuel.

ii. Higher water content is apparent when higher blends are used. High water content leads to microbial growth in the biodiesel, which degrades the biodiesel into acids and produces sludges or slimes that may clog fuel filters and damage the fuel injection systems. Water content also decreases the calorific value of biodiesel.

iii. Studies show that one of the by-products of biodiesel oxidation is free fatty acids (FFAs) (DeMello et al., 2007). Acid value in biodiesel measures the quantity of FFAs in the biodiesel. FFAs is formed when water in the biodiesel causes hydrolysis of the FAME to form alcohol and acids. High acid value can lead to sedimentation and clogging in the fuel system and corrosion of engine parts such as the gasket (Aworanti et al., 2019).

iv. During storage, biodiesel is susceptible to oxidation due to the presence of unsaturated fatty acid in the ester. Oxidation reduces the fuel quality and produces insoluble that may clog the engine fuel system. Moreover, one study indicates that when the oxidised biodiesel is blended with diesel fuel such as MGO, the antagonistic effect driven by the low solvency of the diesel may increase the amount of insoluble produced (Andrew Waynick, 2005). Two test methods of oxidation stability are investigated: (a) oxidation stability based on Rancimat method is measured in hours (Method 1), and (b) oxidation stability by the measurement of the quantity of total insoluble in biodiesel is measured in g/m^3 (Method 2).

4.4.1 Fuels and materials

The experiments are conducted for PME, UCOME and HVO and five blends with MGO (B7/R7, B20/R20, B30/R30, B50/R50, and B100/R100). PME is supplied by Wilmar International, UCOME is supplied by Alpha Biofuels, and HVO is supplied by Neste. A single type of biofuel is blended with MGO produced in Singapore. The suppliers provide a Certificate of Quality (COQ) for the fuels before blending.

4.4.2 Methodology

4.4.2.1 Blending and storage

The desired blending ratio of biofuels was obtained by measuring the appropriate volume of each fuel using a graduated cylinder and poured into a borosilicate glass container with a Teflon-lined screw and ETFE ring to prevent material corrosion from the biodiesel (Hodam, 2008). A uniform mixture was achieved by repeatedly shaking the bottles. The samples were placed under sheltered ambient conditions at the Maritime Energy Test Bed (METB) at NTU.

4.4.2.2 Sampling and testing methods of parameters

The fuel samples are sent to Viswa Limited, an accredited marine fuel analysis laboratory in Singapore. Before blending, PME, UCOME, HVO, and MGO samples are tested according to their respective standards to establish their baseline parameters. PME and UCOME B100 samples are tested according to EN 14214, R100 is tested according to EN 15940, and MGO is tested based on ISO 8217. The first set of experiments (T1) was conducted over four months, and the experiments were repeated in a second set (T2) with a lower sampling frequency after the interim results from T1 showed a minimal decay rate of the parameters. The methods used for measuring the five key parameters are described on the following page.

a. Viscosity (Unit: mm^2/s or centistoke, cSt)

Following the standard ISO 3104, the time required for a liquid to flow into the viscometer is measured. The kinematic viscosity is the result of the measured flow time and constant of the viscometer (ISO, 2020).

b. Water content (Unit: %m/m or mg/kg)

The measurement of water content follows ISO 12937. Biodiesel appearance is inspected before analysis. If the sample is not clear and bright, sodium dioctylsulfosuccinate is added to the solution. Otherwise, the sample is put directly into the titration vessel of coulometric Karl Fischer with iodine as the titrator. One mole of iodine reacts with one mole of water, and the quantity of water is proportional to the total integrated current (ISO, 2000).

c. Acid value (Unit: milligrams of potassium hydroxide per gram of fuel, mg KOH/g)

The measurement of acid value follows EN 14104. The acid value is obtained by measuring the amount of potassium hydroxide (KOH) required to neutralise free fatty acids in biodiesel through titration, with phenolphthalein as an indicator (British Standards Institution, 2021).

d. Oxidation stability by Rancimat method (Method 1) (Unit: hours)

The first method for oxidation stability follows EN 14112 or EN 15751. The principle of the Rancimat method is an accelerated aging test using hot air (110°C) to oxidise biodiesel into carboxylic acids. The conductivity of the sample is measured during the dissociation of carboxylic acid in demineralised water (British Standards Institution, 2014).

e. Oxidation stability by measurement of total insoluble (Method 2) (Unit: g/m^3)

The second method for oxidation stability follows ISO 12205. The sample is aged at 95°C for 16 hours while oxygen is bubbled through the sample. The sample is then cooled and filtered. Both weights of adherent insolubles (obtained from oxidation cell) and filterable insolubles are measured and combined together (ISO, 1995).

4.5 Results and Discussion

4.5.1 Viscosity

Table 4.3 shows the viscosity measurement results for biofuel blends over time. It is observed that B7 samples have the lowest viscosities, which gradually increases with the blending ratio. The biodiesel's viscosity is typically higher than MGO due to the compound structure of biodiesel. The high polarity of biodiesel leads to dipole-dipole interactions. Biodiesel molecules, which are typically longer than MGO, lead to dispersion forces between hydrocarbon chains. As a result of these differences, the molecules are pulled closer to one another, resulting in higher viscosity. If viscosity is lower than the specific range, it may lead to uncontrolled volatilisation and oil consumption, while higher than desired viscosity will cause poor fuel injection, excessive heat generation and wear and tear of fuel injection pump. Throughout the experiments, the viscosities of all biodiesel samples are within the range of their respective standards, ranging between 2.5 cSt and 4.5 cSt at 40°C. The viscosities of biodiesel blends are also relatively constant over time, with a slightly higher viscosity of PME observed in the 2nd Month, but still within the specified range. HVO has a similar property to diesel oil when it comes to energy content, density, flash point, and viscosity (Dimitriadis et al., 2018). The viscosity of HVO is relatively constant regardless of the blending ratio, ranging between 2.5 cSt and 3 cSt.

[4] *The B100 samples received in small quantity have a higher tendency to be affected by the ambient moisture. B100 delivered in bulk with nitrogen blanketing has lesser chance to go off specification.*

4.5.2 Water content

Table 4.4 shows the results of water content for different biodiesel blends over time. Before blending, the water content of the received B100 PME and B100 UCOME are 890 mg/kg and 620 mg/kg, respectively[4]. The amount of water content from PME B100 and UCOME B100 exceeds the allowable amount of water content in EN 14214, which states a maximum of 500 mg/kg. The hygroscopic methyl esters may have continued to absorb moisture from the air during the time gap between delivery and blending, leading to higher water content than that specified in the COQ. After blending with MGO, the water content decreases because of the effect of dilution from MGO with a lower water content of 110 mg/kg. At the beginning of the test, the water content of B7 PME and B7 UCOME are the lowest at 90 mg/kg and 110 mg/kg, respectively, and gradually increases when the blending ratio is higher, contributed by water from B100. The water content of B20 PME and B20 UCOME are 170 mg/kg and 190 mg/kg, respectively, the water content of B30 PME and B30 UCOME are 210 mg/kg and 230 mg/kg, respectively, and the water content of B50 PME and B50 UCOME are 340 mg/kg and 380 mg/kg respectively. These results meet the EN 16709 standards for B20 and B30 at a maximum of 260 mg/kg and 290 mg/kg, respectively. There is no applicable standard for B7 and B50 for distillate fuel on the water content. Throughout the experiments, the water content of biodiesel blends gradually increases. PME B20 and B30 can only meet EN 16709 standards between 3 and 4 months of storage duration, and UCOME B20 and B30 can meet EN 16709 standards between 2 and 3 months of storage duration. These results show that the methyl esters enhance moisture absorption, as the water content increases by 80 to 150 mg/kg at various blends after four months of storage. The increase in water content of the biodiesel blend is significantly higher than that of MGO, which increases by 40 mg/kg after a similar storage duration.

HVO does not contain methyl esters and HVO (R100) has very low water content of 30 mg/kg before blending. After blending with MGO, the water content of HVO slightly increases because of the higher water content in the MGO. At Month 0, the water content of R7 is the highest at 60 mg/kg and gradually decreases at a higher blend because of the effect of dilution from R100 with the lower water content of 30 mg/kg. Similar to MGO, the water content of HVO blends increases gradually throughout the test. However, the water content is significantly lower than biodiesel. After 4 months, all HVO blends meet EN 590 standard of a maximum of 200 mg/kg standard.

4.5.3 Acid value

Table 4.5 shows the results of acid value of biofuel blends over time. Before blending, the acid value of B100 PME and B100 UCOME are 0.31 mg/kg and 0.37 mg/kg, respectively, which meets EN 14214 standards. After blending with MGO, the acid value of B7 PME and B7 UCOME are the lowest at 0.04 mg KOH/g and 0.04 mg KOH/g, respectively, and gradually increases when the blending ratio is higher, contributed by acid content from B100. These results meet the ISO 8217 standard of a maximum of 0.5 mg KOH/g for B7. While EN standards do not specify the acid values for B20 to B50, the acid value of B20 PME and B20 UCOME are 0.1 mg KOH/g and 0.09 mg KOH/g, respectively, which meet ASTM D7467 standards. Throughout the tests, the acid value of all biodiesel blends increases gradually, indicating that oxidation has taken place and FFAs are produced as by-products. After four months, biodiesel blends are able to meet specified acid values under ISO 8217 and ASTM D7467.

4.5.4 Oxidation stability by Rancimat method

Table 4.6 shows the results of oxidation stability by Rancimat method (Method 1) for different biofuel blends over time. Prior to blending, PME and UCOME B100 samples achieve 19.4 hours and 6.3 hours, respectively. Only the B100 PME fuel samples achieve a minimum of 8 hours. There is a significant difference in oxidation stability between PME and UCOME, which may be contributed by the uncertainty of the feedstock quality of UCOME. The quality of used cooking oil varies between batches due to the chemical processes such as oxidation, hydrolysis, and polymerisation which deteriorates the cooking oil. Throughout the experiments, the oxidation stability biofuel blends decrease gradually regardless of the blending ratio. If the specification of the more stringent EN 16709 is referenced, none of the B20 and B30 samples meet the required minimum 20 hours. However, recent WA2:2022 and ISO 8217:2024 draft are proposing 6 h and 8 h, respectively, as the promulgated number for marine biofuel. Under such circumstances, one may expect at least one month of storage for all lower UCOME blends (B7 to B50) and two months for UCOME B100. Being more consistent in quality, the PME are considered staying within specifications for at least two months for lower blends (B7 to B50), and up to four months for B100.

Due to the lack of fatty acids, the results for oxidation stability by Method 1 for HVO show that no endpoint was achieved from the conductivity curve, indicating that HVO is very stable and has a much lower oxidation potential than biodiesel (Table 4.7).

4.5.5 Oxidation stability by the measurement of total insolubles

Table 4.7 shows the test results by Method 2 for biofuel blends over time. Before blending, B100 PME and B100 UCOME are 4 g/m^3 and 11 g/m^3, respectively. After blending with MGO, B7 PME and B7 UCOME samples are 8 g/m^3 and 5 g/m^3, respectively, and meet the ISO 8217 standard. However, the source of the total insoluble cannot be ascertain as the baseline oxidation stability of MGO before blending has a similar value of 9 g/m^3. Most test results by Method 2 for biofuel blends also fluctuates without clear trends as the blending ratio increases, starting from B20 and above. These findings differ significantly from the test results by Method 1, which show a clear trend that oxidation stability decreases at a higher blend ratio and longer storage duration.

Oxidation stability by Method 2 for pure HVO or R100 is constant at 2 g/m^3 throughout the storage duration. However, HVO-based blends have values which fluctuates at higher blends. One possible explanation is that the relevance of oxidation stability by Method 2 gradually diminished for higher biodiesel blends because the parameter is not suitable for biodiesel. This parameter may not apply to fuels containing residual or other components from a non-petroleum source (Pachemtech, 2022).

4.5.6 Impact of storage stability results of biodiesel as marine fuels

Over the duration of four months, there is no significant change in viscosity, acid value, and oxidation stability by Method 2, while water content and oxidation stability by Method 1 fail the standard between 0 and 4 months of storage, depending on the type of feedstock and blends. Thus, the potential issues of using biofuel are the higher water content and lower oxidation stability.

While microbial bacteria growth is not investigated in this study, inappropriate storage conditions or high humidity in Singapore may contribute to the accumulation of water in biodiesel, leading to microbial bacteria growth where methyl esters may be oxidised into acid and metallic parts in engines and piping systems are at a risk of corrosion.

Storage stability experiments indicate that the quality of biodiesel varies depending on the storage environment, type of feedstock, and the blending ratio. The shelf life of biodiesel blends reduces for higher blends and implies a risk of failing standards in less than six months. Increased testing by bunker suppliers to ensure biodiesel quality at the time of delivery may be necessary. From the customer's perspective, they may need to consider the storage location and shelf life of the fuels before use.

Table 4.3 Viscosity of biofuels with different blending ratios over four months of storage

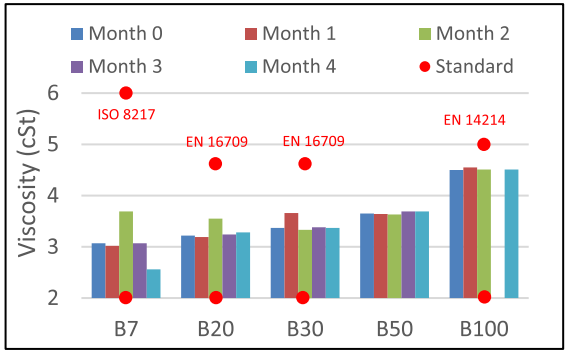
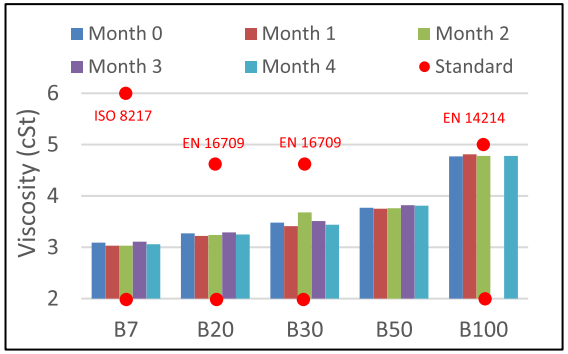
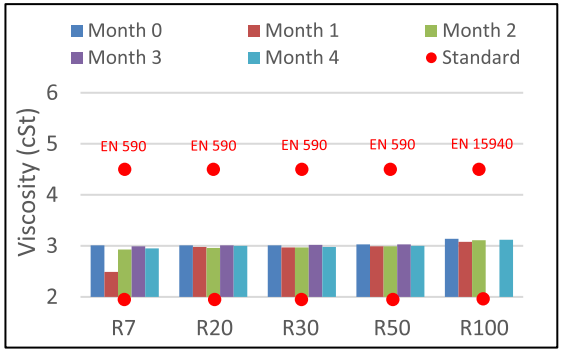
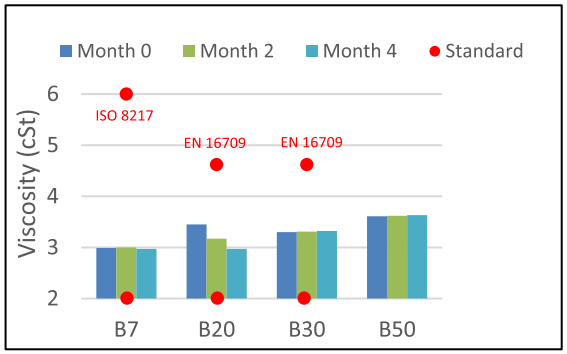
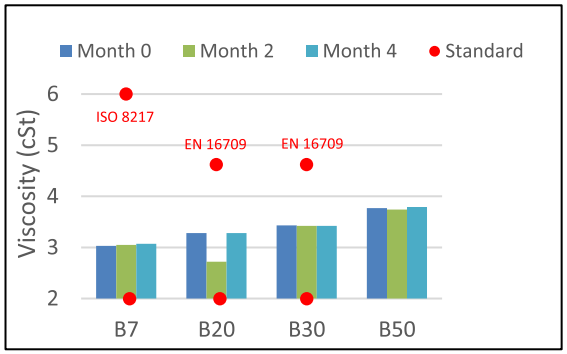
	PME	UCOME	HVO
T1			
T2			

Table 4.4 Water content of biofuels with different blending ratios over four months of storage

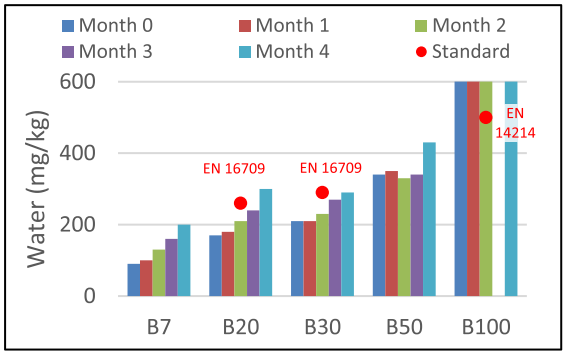
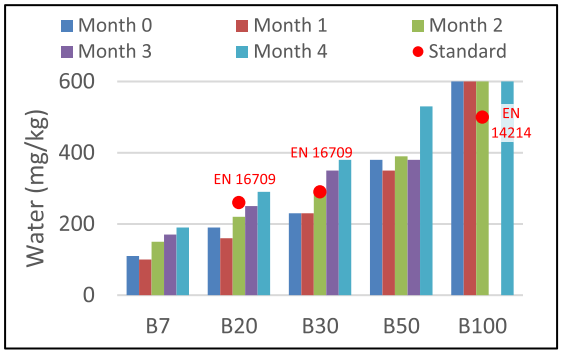
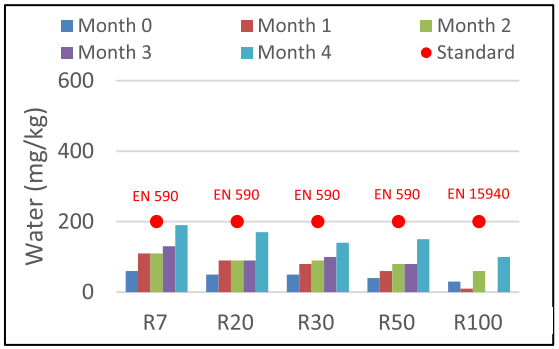
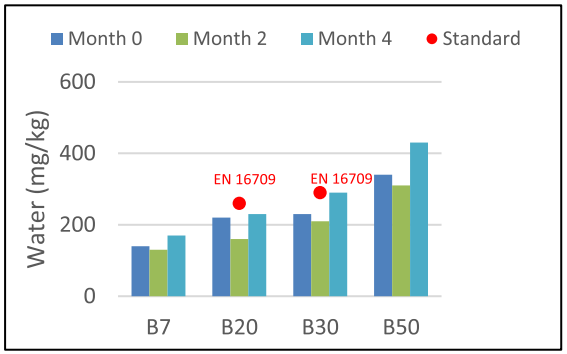
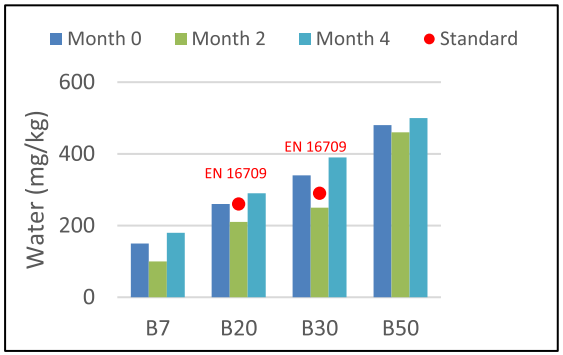
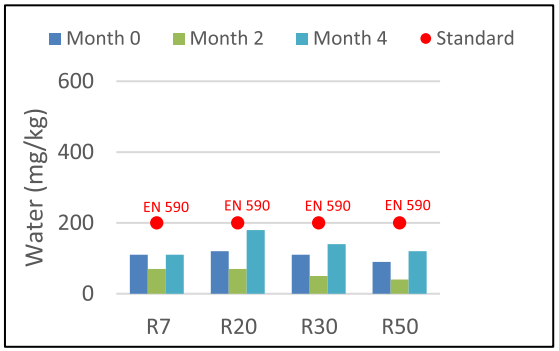
	PME	UCOME	HVO
T1			
T2			

Table 4.5 Acid values of biofuels with different blending ratios over four months of storage

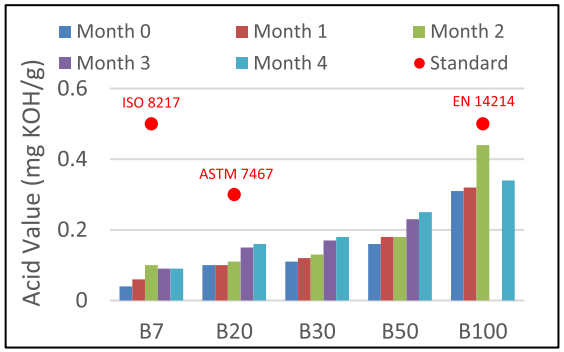
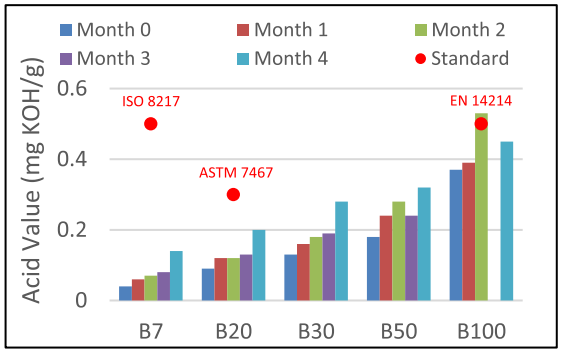
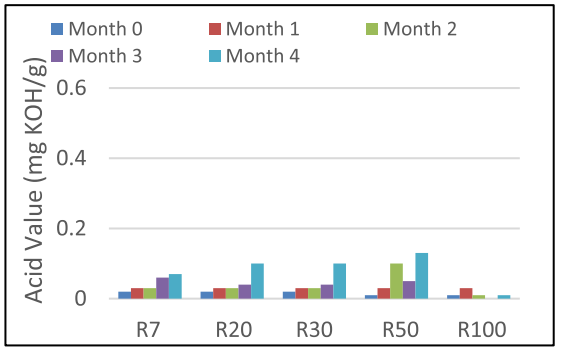
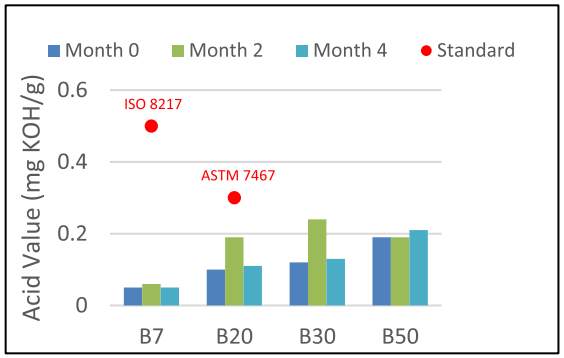
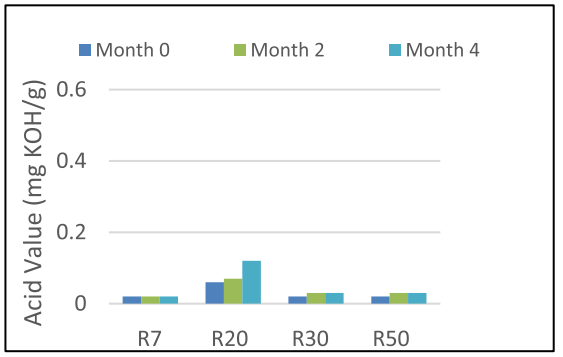
	PME	UCOME	HVO
T1			
T2			

Table 4.6 Oxidation stability by Method 1 of biofuels with different blending ratios over four months of storage

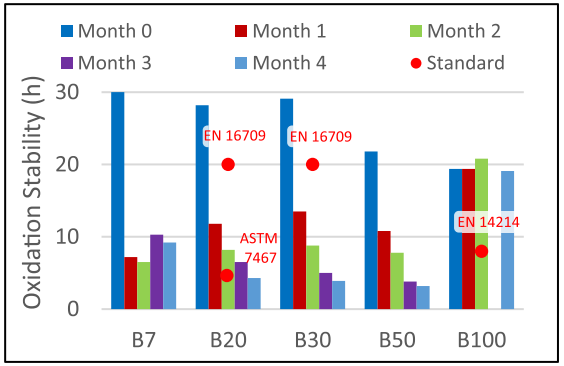
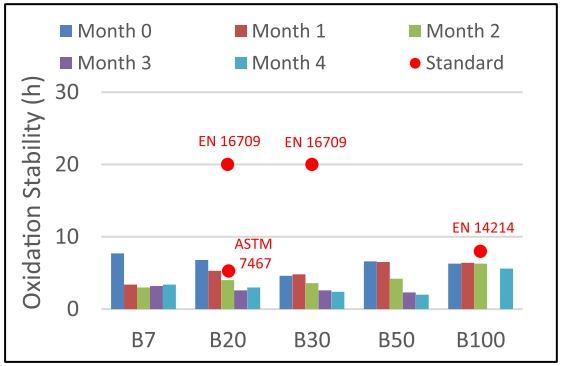
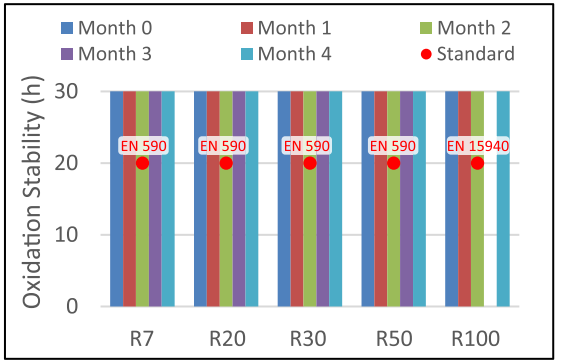
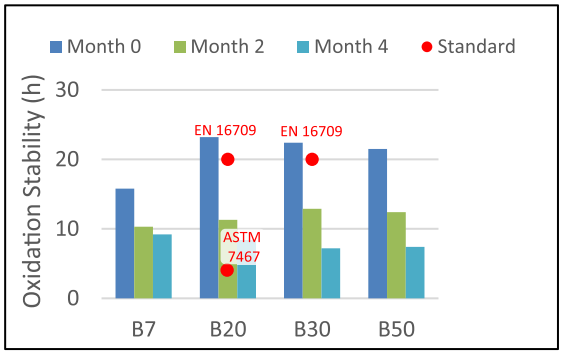
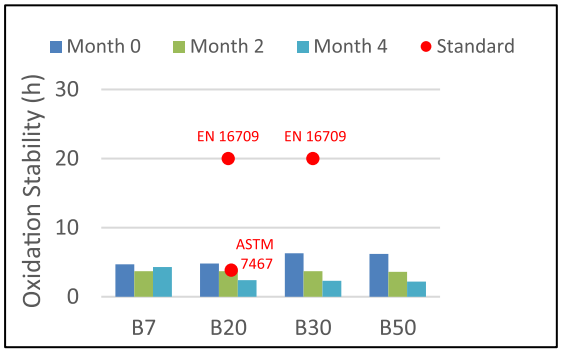
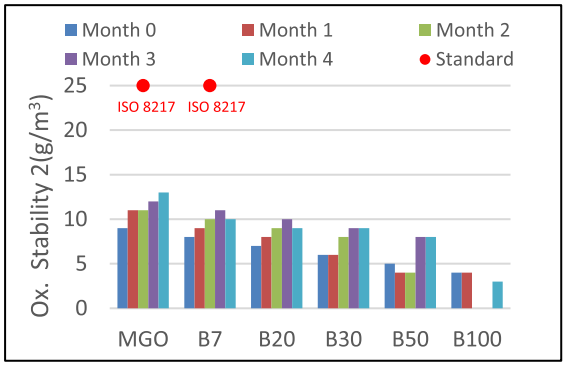
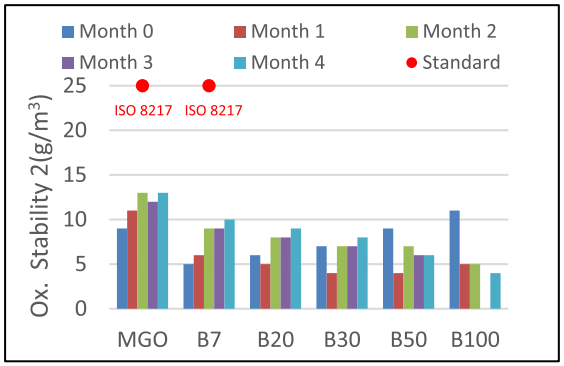
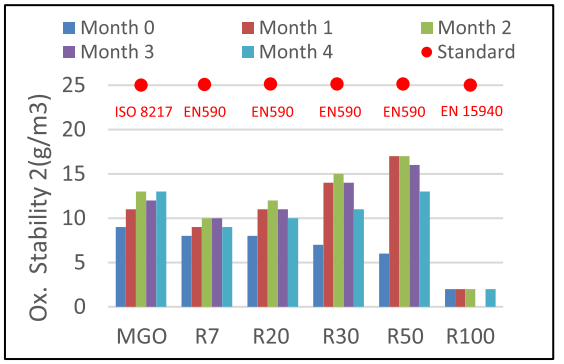
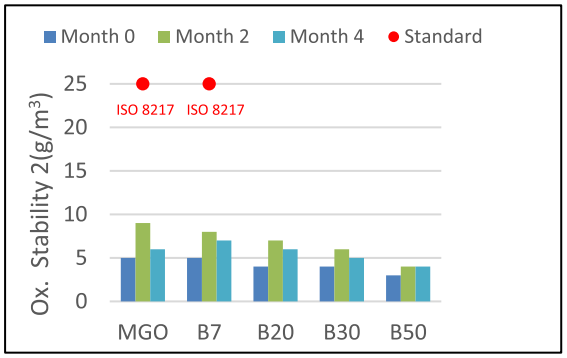
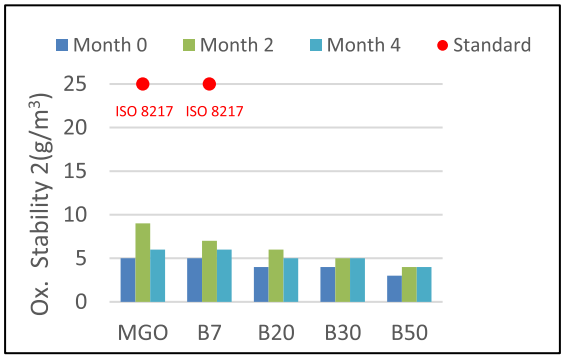
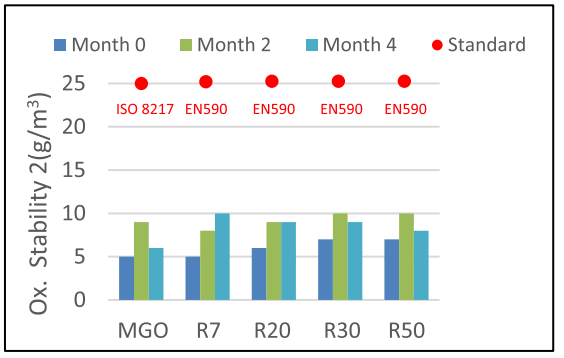
	PME	UCOME	HVO
T1			
T2			

Table 4.7 Oxidation stability by Method 2 of biofuels with different blending ratios over four months of storage

	PME	UCOME	HVO
T1			
T2			

CHAPTER 5
GHG EMISSIONS AND ENVIRONMENTAL IMPACT

5.1 Overview of LCA, ISCC and IPCC

Multiple methodologies can be used to calculate GHG emissions at the product, project or national level. The methodologies reviewed are Life Cycle Assessment (LCA), Intergovernmental Panel on Climate Change (IPCC) guidelines, and International Sustainability & Carbon Certification (ISCC) system. Depending on the specific purpose of GHG emissions calculation, these methodologies are of interest to different maritime industry stakeholders. An overview of LCA, ISCC, and IPCC methodologies is provided in Table 5.1.

5.1.1 Life Cycle Assessment (LCA)

LCA is a comprehensive and internationally recognised method that quantifies the environmental impact of a product, service or system, covering its complete life cycle from extraction of raw material to its production, use, recycling and final disposal of remaining waste (EC, JRC and IES, 2010). LCA provides a fair and holistic assessment and avoids the unwanted "shifting of burdens" where the environmental impact is reduced at one stage but increased at another stage in the life cycle. For marine fuels, this is commonly known as "well-to-propeller" (WTP), when defining fuel combustion in marine engines as the endpoint, and "well-to-tank" (WTT) when excluding fuel combustion.

Multiple standards and guidelines exist for LCA, such as ISO 14040/44, ISO 14067, ISO 14025, International Reference Life Cycle Data System (ILCD) handbook, GHG protocol, and PAS 2050. Many of them are developed based on the ISO 14040/44 standard. With no detailed methodology in ISO 14040/44, practitioners are left with the flexibility of wide choices that can affect the consistency of the results. To overcome this, European Commission, Joint Research Centre and Institute for Environment and Sustainability jointly published the ILCD handbook, which provides detailed guidelines in line with ISO 14040/44. The use of IPCC GWP_{100} factors to evaluate the impact of climate change is recommended. At the time of writing, International Maritime Organization (IMO) is also developing LCA guidelines to assess the overall climate impact of alternative marine fuels (IMO, 2021.)

According to ISO 14040/44, an LCA study consists of four phases. In the first phase, the goal and scope of a LCA study are clearly defined based on the intended application. This is an essential step that sets the frame for the remaining steps. Under certain circumstances, the goal and scope may be revised later due to unexpected limitations or additional information.

In the second phase, a life cycle inventory (LCI) of the studied system is established by collecting input/output data, including energy requirement, raw materials, consumables, other resources, waste and emissions to water, air, or soil throughout the entire life cycle of the product or service. Based on these data, elementary flows of the studied system can be established, representing extractions and emissions from and to the environment (e.g., emissions of 1 kg CO_2 and 1 g CFC142b).

In the third phase, two mandatory steps are required in the ISO standards – classification and characterisation. Classification means that the LCI results are assigned to the impact categories that they can contribute to. For example, CO_2 contributes to only one impact category of climate change, while CFC142b contributes to two categories of climate change and ozone layer depletion. One substance may contribute to multiple impact categories. Different substances may contribute to the same impact category differently.

Table 4.7 Oxidation stability by Method 2 of biofuels with different blending ratios over four months of storage

Aspects	LCA	ISCC	IPCC
Documents	ISO 14040/44, ILCD handbook	ISCC EU/PLUS Documents	2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2013 Wetlands supplement, 2019 Refinement
Goals	To be defined by LCA practitioners	To calculate the GHG emission savings from the use of biofuels, bioliquids and biomass fuels	To estimate the national GHG inventories
Scope	• Applicable to any product/service/system • No spatial boundary • Lifetime of the product/service/system	• Only applicable to biofuels, biomass, or bioenergy production • No spatial boundary • Lifetime of the products	• Applicable to individual countries • Limited to national boundary • One-year period
Users	LCA practitioners (academic and industry)	Companies and Certification Boards (affiliated with ISCC)	Each country's designated GHG inventory team
Focused impacts	Various categories (e.g., Climate change, acidification, ozone depletion, etc.)	Climate change only	Climate change only
Data required	Life cycle inventory data	Default values from RED II, Activity data, Emission factors	Activity data, Emission factors, or Energy supply data
Capital goods#	Generally included*	Excluded	Included in Machinery sector (1A2), not in manufacture of marine fuels (1A1cii)
Biofuels combustion	• CO_2 emissions can be included or excluded depending on the methods or assumptions§ • CH_4 and N_2O emissions are included	GHG emissions are taken to be zero	• CO_2 emissions are not included but reported separately as an information item • CH_4 and N_2O emissions are included
Emissions	Considers both GHG and non-GHG emissions to air, to water, to soil and to waste treatment (e.g., heavy metals, PM2.5, etc.)	Only considers GHG emissions	Only considers GHG emissions
Emission factors	Use actual values (site-specific)	Must use default EF, which is at global level	Can use default or country-specific EF
Results	Quantified environmental impact in different categories or areas of protection (e.g., Climate change, Toxicity, Land-use)	Result of compliance with REDII GHG saving requirements	Annual GHG inventory for a country
Beneficiaries	Organisations and eco-conscious customers	Companies and eco-conscious customers	Governments and the public
Comparability of results	Not always comparable due to different system boundary and methods used	Compared with other ISCC-certified products or processes	Comparable between countries as the framework is consistent.
Validity	No expiry date, but may be updated	Valid for one year	Valid for a calendar year

Note:

 # Capital goods: Manufacturing or construction of goods that are fixed assets for an entity, examples are buildings, trucks and machines.

** Based on ILCD handbook (2021). Justification must be provided if they are excluded.*

§ The industry usually excludes the CO_2 emissions from biofuel combustion in the LCA analysis due to the assumption that the carbon emitted from biofuel combustion equals to the carbon captured during the cultivation process.

In order to capture the difference, characterisation is needed using a common indicator. Through characterisation each LCI result is multiplied with a characterisation factor before they can be added. For example, greenhouse gas emissions can be characterised using global warming potential (GWP) across 100-year time horizon in kg CO_2eq. This can be illustrated using the following equation:

$$E_{k,LCA} = \sum_j e_{k,j} \times B_j, \quad (5.1)$$

where

$E_{k,LCA}$ represents the total environmental impact in category k using LCA analysis,

$e_{k,j}$ represents the characterisation factor describing the contribution of substance j to category k,

B_j represents the total quantities of substance j in the studied system.

In LCIA, there are two levels of assessment – midpoint and endpoint. The LCI results are characterised to different impact categories at the midpoint level. The characterised impact under different categories can be further aggregated to the areas of protection at the endpoint level. Depending on the goal and scope of an LCA study, one or more impact categories can be selected for analysis based on the relevance to the goal and scope.

In the fourth phase, the LCIA results enable the identification of major impacts and corresponding contributing processes. The information is useful to identify the "hot spots" for system improvement or innovation. The practitioner may undertake sensitivity analysis and consistency checks to ensure the completeness and reliability of the results. Finally, conclusions and recommendations are reported in a complete, transparent, and unbiased way.

LCA has its limitations and is by no means the most appropriate way to measure the global warming impact in all circumstances. For instance, companies may perform the LCA studies of the same type of fuel using different boundaries due to different goals with results that are sometimes incomparable with one another. Furthermore, inventory data of subprocesses and subproducts may be difficult to obtain or time consuming and costly to gather.

Common Impact Categories in the Midpoint Assessment:	**Areas of Protection in the Endpoint Assessment:**
• Climate change	• Human health
• Ozone depletion	• Natural environment
• Acidification	• Resources
• Human toxicity	
• Respiratory inorganics	
• Eutrophication	
• Ecotoxicity	

5.1.2 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories

IPCC was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization to provide policymakers with regular comprehensive assessments and recommendations on climate change. Guidelines are created to estimate national anthropogenic emissions of greenhouse gases. It focuses on GHG emissions and removals within national territory and offshore areas over which the country has jurisdiction. The 2006 IPCC Guidelines for National GHG Inventories summarise the basic approach and provide guidance for national GHG inventory development. The 2013 Wetlands Supplement and 2019 refinement update are the latest supplements of the guidelines. The established guidelines help to reach a consensus on the best way to estimate national inventories and bolster any international agreements to limit climate change.

Two approaches are available in IPCC – sectoral and reference approach. The sectoral approach is a bottom-up method using fuel consumption to calculate GHG emissions in five sectors: 1) Energy, 2) Industrial processes and product use (IPPU), 3) Agriculture, Forestry and other land use (AFOLU), 4) Waste, and 5) Others. The reference approach is a top-down method using a country's energy supply data to calculate the GHG emissions. IPCC requires countries to submit results using both approaches. Depending on the level of analytical complexity and data requirements, GHG emissions may be estimated across three tiers. Tier 1, the basic one, uses default emission factors (EFs) provided by IPCC. Tier 2, the intermediate one, uses country-specific EFs. Tier 3, the most demanding one, requires detailed emission measurement and activity data at an individual plant level.

Singapore adopts the sectoral approach to estimate its national GHG inventory due to volatility in Singapore's energy trading data as a global trading hub (NEA, 2020). The Tier 1 method is applied to estimate the emissions under the Energy 1A sector, while the Tier 3 method is used to estimate the emissions under IPPU 2B sector (Chemical industry) (NEA, 2020). Both the Energy 1A and IPPU 2B sectors are relevant to analyse the emissions from the supply chain of marine fuels in Singapore. While Energy 1A sector includes emissions from fuels combusted in biofuel manufacturing industries and transport, IPPU 2B sector includes emissions from industrial processing of chemical products such as ammonia and methanol.

The Tier 1 method to estimate emissions from fuel combustion activities can be simplified using the following equation:

$$E_{IPCC} = EF * AD, \tag{5.2}$$

where

E_{IPCC} represents emissions following IPCC guidelines,

EF represents emission factor (e.g., tonne CO_2 per tonne fuel consumed),

AD represents activity data (e.g., the amount of fuel consumed).

The Tier 3 method to estimate plant-specific emissions of chemical production like ammonia and methanol follows this equation:

$$E_{IPCC} = E_{combustion} + E_{process,\ vent} + E_{flare} \tag{5.2}$$

where

$E_{combustion}$ represents emissions from combusting fuel/process by-products to provide thermal energy to the production process of the petrochemical,

$E_{process,\ vent}$ represents emissions from the process vent during the production of the petrochemical,

E_{flare} represents emissions from flared waste gases during the production of the petrochemical.

This study observes IPCC guidelines. Emissions from fuel combustion in international sea transport are not included in national totals, but emissions from fuel combustion in domestic transport are included in national totals. CO_2 emissions from biofuels combustion in domestic transport are not included in the national totals, but other GHG gases like CH_4 and N_2O are included. The CO_2 emission from biofuels is reported separately as an information item.

5.1.3 International Sustainability & Carbon Certification (ISCC) system

The ISCC certification system demonstrates the product's compliance with the EU RED II requirements for sustainable biofuels, biomass fuels, and bioenergy production. A product is certificated along the entire supply chain from the origin to the end user. Two similar certification schemes are available: ISCC EU certifies the compliance of sustainability requirements specified in the RED II, while ISCC PLUS is applicable for all markets and sectors not regulated by the RED II, such as food, feed, or energy markets, for diverse industrial applications, and for biofuels, biomass, and bioenergy production outside of the European Union. ISCC PLUS covers all types of agricultural and forestry raw materials, waste and residues, non-bio renewables, and recycled carbon materials.

ISCC requires a minimum level of GHG emission savings of final biofuels, biomass fuels and bioliquids, wxqhen compared with the fossil reference, following RED requirements (see Figure 5.1).

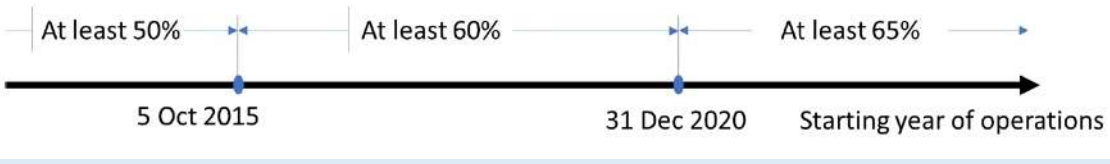


Figure 5.1 RED 2018/2001/EC requirement on GHG emission savings from biofuels and biogas consumed in the transport sector

The methodology to calculate the GHG emissions is documented in ISCC EU 205. The GHG emissions are summed up as follows:

$$E_{ISCC} = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} + e_{sca} + e_{ccs} + e_{ccr} \quad (5.4)$$

where

E_{ISCC} total emissions from the use of the fuel following ISCC guidelines,

e_{ec} emissions from the extraction or cultivation of raw materials,

e_{l} annualised emissions from carbon stock changes caused by land-use change,

e_{p} emissions from processing,

e_{td} emissions from transport and distribution,

e_{u} emissions from the fuel in use,

e_{sca} emission savings from soil carbon accumulation via improved agricultural management,

e_{ccs} emission savings from CO_2 capture and geological storage,

e_{ccr} emission savings from CO_2 capture and replacement

Based on the ISCC requirement, three data sources are stated clearly in the sustainability declarations. They are (i) total default values (TDVs), (ii) disaggregated default values (DDVs), and a combination of default values and actual values are allowed, and (iii) individually calculated actual values. The TDVs and DDVs are provided in RED II Annex V and VI. They reflect conservative estimates of standardised biofuels, bioliquids, and biomass fuels supply chains and processes. DDVs are available for emissions from cultivation, processing, and transport and distribution.

5.2 GHG Emissions of Biofuel Blends

Although LCA is a comprehensive method, there is not yet a harmonised LCA approach for marine fuels. The study will present the GHG emission savings using the ISCC and IPCC methods to enable the maritime industry and government agencies to shape their future strategy in alternative fuels.

5.2.1 GHG emissions by ISCC methodology

The following considerations and values are undertaken in the study.

- Emissions from the manufacturing of machinery and equipment are not included.
- Zero GHG emissions for extraction or cultivation of the raw materials if wastes or residues are used as raw materials in the process. The GHG calculation starts from the point of origin of the waste or residue.
- GHG emissions from biofuel combustion for transport are set to zero. Note that ISCC includes CH_4 and N_2O emissions for bioliquids and biomass fuels[5] only.
- Detailed breakdown of all elements of GHG emissions are reported when DDVs or actual values of GHG emissions are used.
- GHG emissions of final fuels are presented in CO_2eq/MJ fuel.
- Fossil fuel comparator for transport is set as 94g CO_2eq/MJ fossil fuel.

For biofuel UCOME B100, default EF values are used and the respective suppliers for PME B100 and HVO B100, provide actual EF values. Actual values will vary with production batch as the values depend on the feedstocks. The ISCC GHG emissions of those biofuels are summarised in Table 5.2. UCOME B100 and HVO R100 can reduce GHG emissions by 84% and 91.6%, respectively. With a combination of default and actual values, the PME can reduce GHG emissions from 52.5 to 73.6%.

Table 5.2 Total GHG emissions based on ISCC guidelines

	UCOME[2] B100 (Alpha)	**HV0[3] R100 (Neste) - Lowest Saving Case[4]**	**PME[5] B100 (Wilmar) - Lowest Saving Case**
Total emissions (gCO_2eq/MJ fuel)	14.9	7.93	44.63
GHG emission savings[1]	84%	91.6%	52.5%

Note:

[1] compared to fossil fuel comparator for transport: 94 gCO_2eq/MJ.
[2] based on default values set by RED II.
[3] The result is based on feedstocks from waste and residues which accounted for 92% of renewable raw materials inputs globally in 2021 (Neste 2022). Emissions from cultivation are considered zero, while the emissions for processing and transportation and distribution are from actual values.
[4] Even for the lowest saving case, the biofuels can still meet the ISCC minimum requirement on GHG emission savings (Refer to Figure 5.1).
[5] Emissions for cultivation and processing are from actual calculations; emissions for transportation and distribution are from default values.
[5] In RED II and ISCC, bioliquid is defined as liquid fuel for energy purposes other than for transport, such as electricity, heating and cooling. Biomass fuel is defined as gaseous and solid fuel produced from biomass. Biofuel is defined as liquid fuel for transport produced from biomass.

5.2.2 IPCC GHG emissions

The contributions to Singapore's domestic GHG inventory and NDC by biofuels and biofuel blends by IPCC method are shown in Table 5.3. The first set of results under Table 5.3 (1), are the contributions by domestic marine transport and are applicable to Singapore harbour craft. Under Table 5.3 (2), the results exclude the combustion by domestic marine transport and are applicable to the supply chain of ocean-going ships. These results only include emissions from transportation, production and blending of biofuels within Singapore's national boundary. Although the inclusion of the emissions from the production of UCOME and HVO in Singapore results in slightly lower GHG emission savings when compared with PME, the difference is negligible.

Table 5.3 Contribution to Singapore IPCC GHG inventory by domestic marine transport

Scenarios	(1) IPCC Contribution (g CO_2eq/MJ fuel)	GHG Emission Savings over MGO for (1)	(2) IPCC Contribution, excl. Combustion (g CO_2eq/MJ fuel)	GHG Emission Savings over MGO for (2), excl. Combustion
MGO[1]	80.46	NA	4.92	NA
B20 (UCOME[2])	65.90	-18.1%	4.37	-11.2%
R20 (HVO[3])	65.79	-18.2%	4.73	-3.9%
B20 (PME[4])	65.57	-18.5%	4.03	-18.0%
B30 (UCOME)	58.44	-27.4%	4.08	-17.0%
R30 (HVO)	58.36	-27.5%	4.63	-5.8%
B30 (PME)	57.93	-28.0%	3.58	-27.2%
R50 (HVO)	43.29	-46.2%	4.44	-9.8%
B50 (UCOME)	43.14	-46.4%	3.50	-28.8%
B50 (PME)	42.28	-47.5%	2.65	-46.2%
R100 (HVO)	4.38	-94.6%	3.93	-20.1%
B100 (UCOME)	2.50	-96.9%	1.96	-60.1%
B100 (PME)	0.71	-99.1%	0.18	-96.4%

Note:

[1] MGO blended with biofuel is produced in Singapore.
[3] HVO is produced in Singapore with feedstocks imported from overseas.
[2] UCOME is sourced and produced in Singapore with used cooking oil.
[4] PME is imported overseas.

Low-level biofuel blends around 20% (v/v) could help Singapore's domestic maritime transportation achieve around 18% GHG emission savings. While sustainable PME could play an important role due to its high availability in neighbouring countries, the use of waste and residues leads to much higher GHG emission savings based on ISCC guidelines. A strategic selection of biofuels for local production and target market (domestic or international) is essential, because the local production of biofuels will contribute to the national GHG inventory. Apart from global warming potential, there are other environmental factors such as eutrophication potential and particular matter formation potential. Future studies could involve more environmental impact categories to assess the sustainability of alternative marine fuels.

5.3 Environmental Impact of Biofuel Blends

According to the study (Zhang et al., 1998), biodiesel has higher biodegradability than diesel. There have been a number of straight vegetable oil spills where microbes in the sea are able to break them down (Bucas and Saliot, 2002). However, if the reactions were initiated at the double bonds of the fatty acids in these fatty acid glyceride-based oils, the polymeric framework make it less available to bacteria even when stimulated with nutrients. Mudge (1997) also hypothesised that some spilt straight vegetable oil residues may be more recalcitrant than mineral oils.

Once the straight vegetable oil is converted into mono-chained FAME, it biodegrades at a similar rate as the n-alkanes, and certainly more quickly than other fossil diesel components (DeMello et al., 2007). Always, in case of a leak or spill of fuel, the FAME component will be consumed by bacteria. Samples from a contaminated area may be indistinguishable from a conventional fossil diesel spill after only a short period of time. FAME will not affect the rate of evaporation of petroleum hydrocarbons. Moreover, FAME will likely biodegrade before evaporating from spilt biodiesel.

Given the physical properties of FAME, the environmental behaviour of petroleum hydrocarbons may be altered. Based on dispersion experiments, FAME stabilises biodiesel oil droplets in the water column, which may influence the transport, weathering rate, and ecological impact of spilt biodiesel. FAME might also enhance the dissolution rates of conventional hydrocarbons by stabilising small oil droplets in the water column (DeMello et al., 2007).

An optimum volumetric mixture will need to be identified to meet the requirements of the fuel standards. Producing and using the correct blends have both environmental and economic benefits. Nguyen and Otsuka's (2016) provided a proper approach and tool to assess and determine the diesel oil and FAME concentration in the aqueous phase under the oil slick, which has direct and long-term impacts on the marine microorganisms. It showed that the cumulative water-accommodated fractions concentration of biodiesel spills was about seven to twenty-time less than diesel oil, which confirms that the environmental friendliness of biodiesel far exceeds that of fossil diesel when an oil spill occurs. In the study, the results present an approximately twice the biodegradation rate of vegetable oil-based biodiesel fuel than that of diesel oil. In 28 days, the biodegradability of biodiesel fuel and diesel oil varied around 90% and 40%, respectively. In addition, more than 60% of biodiesel fuel is degraded within the first seven days. From the literature findings, it is believed that the biofuel blends show lesser impact on the marine environment as they could be more easily broken down than diesel. This is assuring as the sea trial in the study does observe that potential leaks and spills are part of the operational issues.

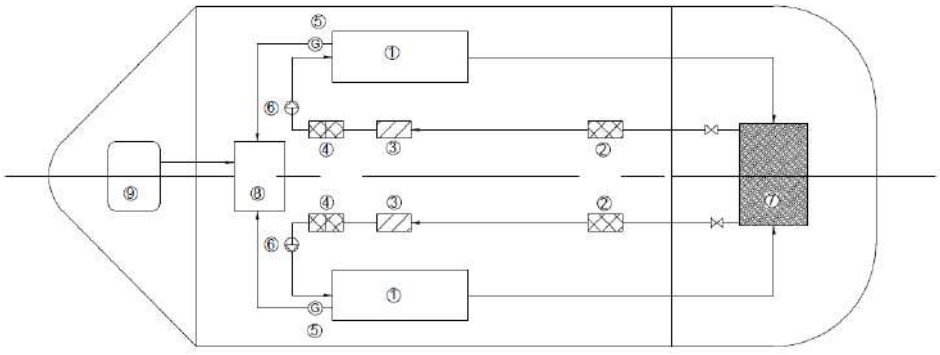
CHAPTER 6
SEA TRIAL CASE STUDY

6.1 Introduction

PME, UCOME, and HVO and their blends are selected for sea trials within Singapore port limits. The sea trials started with a 300 h endurance run with PME B30, while the rest of the blends are tested for a shorter duration. Low blends are gradually increased to B100. The biofuel blends are blended and sealed in IBC tanks by Alpha Biofuel in batches, which are consumed within a month. The tanks are stored under shelter to avoid direct exposure to sunlight, and dedicated fuel pumps and fuel hoses are used.

The selected harbour craft has an existing fibreglass mono hull retrofitted with new diesel engines and twin-screw propeller shafts. The vessel's design speed is 22 knots, but normally operates at 18 knots or around 75% of its maximum engine load. Solar photovoltaic panels and a lithium energy storage system replace an original diesel generator. A dynamo, attached to each of the diesel engines, provide additional power for the air conditioner and navigation equipment. A central fuel oil service tank with a capacity of 1050 L was located at the aft of the vessel to supply to the port and starboard diesel engines. Fuel surplus from the diesel engines returns to the same service tank at the ambient temperature. Two valves are installed at the outlet of the tanks to isolate the fuel oil supply for maintenance. A primary filter with a water separator is installed in the individual fuel supply line to minimise impurities and water residues. The harbour craft's general arrangement is illustrated in Figure 6.1.

The fixed test route is chosen from Banyan Shipyard to Sudong anchorage, as shown in Figure 6.2. The harbour craft was operating along the same test route under similar load conditions and controlled operation modes during onboard measurements. The engine performance and emissions were recorded continuously throughout the sea trials.



S/N	Description	Remarks
1	Main Engines	
2	Primary Filters	By Shipyard
3	Rough Filters	By Engine OEM
4	Fine Filters	By Engine OEM
5	Dynamos	Engine Driven
6	Fuel Pumps	Engine Driven
7	Fuel Oil Tank	1,050 L, Fibreglass
8	Batteries	
9	Solar Panels	

Figure 6.1 Schematic drawing of the vessel

Figure 6.2 Test route for the sea trial of biofuels in a cargo launch

6.1.1 Main engines

The diesel engines are compression-ignited high-speed Weichai engines, which have been certified under IMO Tier II. Each engine delivers a maximum output of 240 kW at the flywheel revolution of 2100 rpm. There are reduction gearboxes with the gear ratio at 1: 1.97 installed between the diesel engine and the propeller shaft. It helps reduce the engine's input revolution to the propeller and increases the torque output to generate sufficient thrust for the vessel movement.

The engine is equipped with a mechanical in-line injection pump that produces high fuel pressure in a pumping element for each engine cylinder, transferring the fuel pressure pulse through a high-pressure injection line and then spraying this fuel into the cylinder via the nozzles of injectors (AVL, 2022). The injection quantity per engine cycle relies on the engine speed and rack position in the injection line from the pump to the spring-loaded fuel injectors, which is regulated by the engine controls. The engines are initially recommended for use with biofuel blends B20 and below. Due diligence is carried out with the engine manufacturer and consultant to ensure preventive measures and relevant considerations are put in place for the vessel's safe operation with higher biofuel blends.

6.1.2 Vessel and engine preparation

The fuel oil (FO) pipes were initially made of incompatible copper material but were replaced with stainless steel pipes during the retrofit. The bunkering was also conducted with a volumetric flow meter at the bunkering station, so the total fuel consumption is recorded.

With the increment of the biodiesel blending ratio, there may be impacts on the fuel systems, including the fuel pumps, injectors, and sealing gaskets. Hence, two key steps are undertaken. The first step is to continuously monitor the engine parameters. An engine control panel with additional sensors are installed to detect the temperature of the turbocharger's outlet and the air pressure at the intake manifold to monitor the engines' indicators. In addition, safety alarms with control measures are embedded into the engine control panel. The second step is to have critical spare parts for the fuel injection system. The engine parts, listed in Table 6.1, are observed from time to time and changed when deemed necessary.

Biofuel has different net calorific value and oxygen content from MGO and may influence the combustion behaviour and power output of the engine under the same volumetric fuel flow. Filter clogging might happen during the interchanging refuelling with different biofuels and MGO (AVL, 2022). A good practice is to minimise the quantity of remaining fuels inside the service tank before bunkering with a new batch of biofuel, and to flush the fuel oil system with the new batch of biofuel when applicable. Another concern is the residues of biofuels from the combustion chamber may penetrate into the lube oil (LO) sump and dilute the LO. Thus, regular testing of LO samples is recommended.

Table 6.1 Spare parts list for the sea trial

S/N	Name of the Spare Parts
1	Injector Bush
2	Seal Washer
3	Injector Assembly
4	Seal Washer
5	Injection Pump
6	High-Pressure Pipe Assembly
7	FO Return Pipe Assembly
8	Fuel Filter
9	Fuel Filter – Water Separator
10	Lube Oil Filter

6.1.3 Instrument preparation

Portable instruments were deployed during the fixed test route with the list of measured parameters as shown in Table 6.2.

Table 6.1 Spare parts list for the sea trial

S/N	Instrument	Parameters	Units	No of the Units Deployed
1	FO Flow Meter	Volumetric Flow Rate FO Temperature	m^3/h °C	2
2	Shaft Power Meter	Shaft Speed Shaft Torque	RPM Nm	2
3	Electrical Power Analyser	Current Voltage Power	A V kW	3
4	Gas Analyser	Nitric Oxide (NO) Nitrogen Dioxide (NO_2) Sulphur Dioxide (SO_2) Carbon Monoxide (CO) Carbon Dioxide (CO_2) Oxygen (O_2) Exhaust Temperature	ppm ppm ppm ppm % % °C	2
5	Temperature & Relative Humidity Meter	Temperature Relative Humidity	°C %	2
6	Global Positioning System	Time Distance	mm.hh Km	1

6.2 Maintenance and Observations

As the study aims to investigate the impacts of different fuel characteristics on existing engines, the factory settings for the fuel injection system are retained. In addition, four engine maintenance are scheduled during the sea trial. Before the first use of biofuels, the first maintenance is scheduled where the FO tank is emptied before refuelling with PME B30 and both the FO and LO filters are replaced. During the second and third engine maintenance, filters are replaced, and fuel injectors are pressure-tested to study the influence of the biofuels on the components of fuel injection system. At the end of the sea trials, the fuel pump system is removed and returned to the manufacturer for detailed investigation.

The quality of the LO samples is monitored by drawing LO samples at regular intervals for testing at an accredited laboratory (illustrated in Figure 6.3). For consistency, the engine LO is replaced during each maintenance. The LO samples are analysed against a quality standard, GB/T 7607 and compared with the parameters selected based on the materials used for the engine components that are in direct contact with the biofuels. The list of materials of the engine components is shown in Table 6.3.

Sample to glassware *Transfer to sample bottle* *Cap and seal before testing*

Figure 6.3 LO sampling procedures

Table 6.3 Materials of the engine components

S/N	Description	Material
1	Engine Block	Cast Iron
2	Cylinder Liner	Alloy
3	Piston	Alloy
4	Piston Rings	Cast Iron
5	FO HP Pipes	Stainless Steel
6	FO LP Pipes	Stainless Steel
7	Flexible Horse	PTFE
8	Seals, O-Rings & Gaskets	NBR

When GB/T 7607 is used as a reference, there are 13 parameters to be monitored during the prolonged sea trial with biofuels. These parameters are listed in Table 6.4.

Table 6.4 LO analysis parameter

S/N	Parameter	Units	Test Method
1	Kinematic Viscosity @ 100°C	mm^2/s	ASTM D 445
2	Acid Number	mg KOH/g	ASTM D 664
3	Base Number	mg KOH/g	ASTM D 2896
4	Water Content	mass %	ASTM D 6304
5	Flash Point	°C	ASTM D 3828
6	Oxidation - B	Abs/cm	ASTM E 2412
7	Aluminium	mg/kg	ASTM D 5185
8	Copper	mg/kg	ASTM D 5185
9	Iron	mg/kg	ASTM D 5185
10	Zinc	mg/kg	ASTM D 5185
11	Sodium	mg/kg	ASTM D 5185
12	Calcium	mg/kg	ASTM D 5185
13	Magnesium	mg/kg	ASTM D 5185

Fuel Oil (FO) Injectors

Pressure tests for the FO injectors were arranged in two stages to check the impacts of the biofuels on the fuel injectors. The first stage was conducted at the end of B30 endurance trials after approximately 350 engine running hours. The second stage was conducted after sea trials with higher biodiesel blends (B50 and B100) to identify the impacts at high blends. Before the pressure tests, a visual inspection of the FO injectors at the workshop observed potential impacts from biofuels on the injectors, such as excessive soot adherent on the nozzles. Figure 6.4 shows a layer of soot deposited on the FO injectors. At the same time, the endoscope was adopted to check the internal condition of the combustion chamber, cylinder liners, and the top of the piston crown. While hints of rust on the exhaust valve and scratches are observed on the cylinder liners, these outcomes may not be attributed to the use of biofuels but may be due to normal wear and tear. There was no indication of the excessive burning or dripping of the fuels from the FO injectors. In addition, the top of the piston crown remained in good condition (Figure 6.5),

The first pressure tests with MGO and UCOME B100 were conducted locally with Weichai at a third-party workshop using a manually operated test bench. During the test with MGO, four FO injectors were found in relatively poor atomisation conditions, and injection pressure was reduced by approximately 10 to 20 bar from the factory setting. Thus, one of the "malfunctioning" injectors was dismantled and compared to another healthy unit. It was observed the sealing surface of the needle valve seemed to be scratched, affecting its sealing characteristics with the injector nozzle, eventually reducing the valve opening pressure for atomisation. On the other hand, another pressure test was conducted using biofuel UCOME B100, and it was observed that there was no significant change in the injection pressures. In addition, there was an enhancement of the atomisation of the "malfunctioning" units. That could be a cause of the fuel properties of the UCOME B100, which is more viscous and denser, favouring large biofuel droplets to travel longer (Alleman et al., 2016). The suspected "malfunctioning" injectors were replaced with the spares and installed back in the engines to continue the sea trials. At the same time, three FO injectors were returned to the engine manufacturer for further investigation.

Figure 6.4 Condition of the fuel injectors

Figure 6.5 Condition of the piston top from starboard engine

The three FO injectors were subjected to further testing on a program-controlled test bench to simulate the injection performance during engine operations, where the fuel pump would be throttled to a specific speed over time to detect its feedback signal. The conditions of the FO injectors were evaluated against their performance curves. The tests strictly follow a Chinese standard JB/T8818 "Technical requirement of nozzle and holder assemblies of diesel engines". The manufacturer's test report indicated a minor defect on the surface of the needle valve in Figure 6.6 (b), but this would not affect the performance of the injectors. Besides this, there was no further abnormality detected from the tests.

Twelve pieces of the FO injectors removed from the engines after 150 h of operation with higher biofuel blends were sent for the second test conducted at Weichai's factory (Figure 6.7). Carbon was found deposited on the nozzle tips, but no corrosion marks were observed on the O-rings and copper washers. Although the tests showed no defects and normal injection pressures for all the FO injectors, the results may not fully represent their impacts on the fuel injection system and a longer testing duration is recommended.

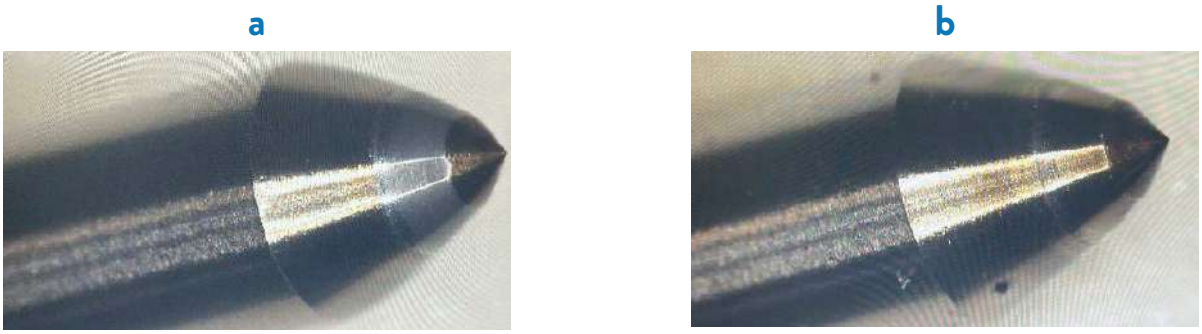


Figure 6.6 Condition of the needle valves taken at the manufacturer factory

a): minor wear of the needle valve, (b): excessive wear on the sealing surface of the needle valve from defect unit

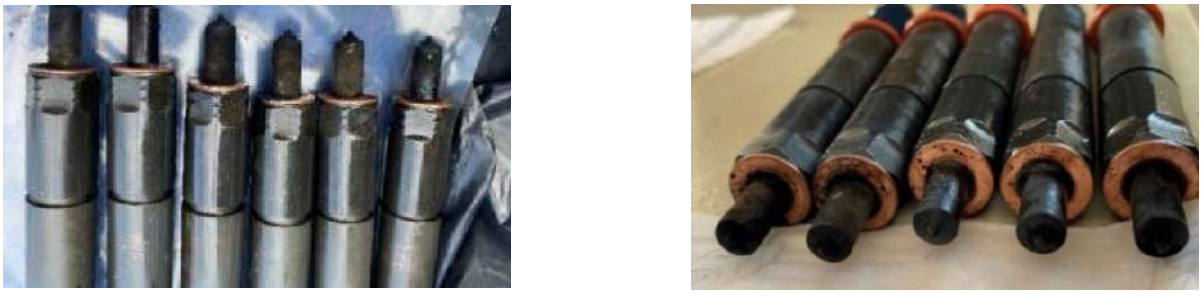


Figure 6.7 Condition of the fuel injectors during the 2nd maintenance after the high FAME blends of biofuels (B50~B100)

Engine Filters

There are two types of disposable oil filters attached to the engine, namely the FO filters and LO filters. Along the fuel oil line, coarse and fine FO filters remove impurities and prevent foreign particles from the fuel from flowing into the engine system. The coarse filter (particle size of 30 μm) is the primary filter and deployed before the delivery oil pump. It also features a water removal function to minimise the condensate water in the fuel pumps. In contrast, the fine filters (particle size of 15 μm) are of the duplex type, consisting of two separate filters connected in parallel. This arrangement allows the replacement of filters without interrupting the fuel supply during engine operation. An additional coarse fuel filter is installed after the fuel tank outlet as a protective measure and to maximise the filters' life span.

During the sea trial, instead of following the recommended replacement interval of 250 h, the filters were replaced at the end of the B30 test trial after approximately 350 h and replaced again at the end of the higher biofuel blends. This step allowed the observation of the full life span of the oil filters.

The fuel oil filter elements were inspected in the Weichai's factory under the two national standards, ISO 4020 and ISO 2942. The first inspection was conducted on the test bench to study the flow resistance across the filter elements. During the test, MGO was continuously pumped into the filters to measure the differential pressure across the filter at the rated flow, which helped to identify the instantaneous filtration efficiency of the filter, serving as the critical factor in evaluating the filter condition. Next, the integrity of the filters is according to ISO 2942:2004(E) standard. Using a typical test apparatus, the filter element is connected to the air supply and fully immersed in the MGO basin before the test. Subsequently, an air valve is throttled, and the air pressure (supplied by compressed air) is gradually increased to the specified values. A measuring instrument monitors the stability of the test medium throughout the operation, and it stops as soon as a continuous stream of bubbles is observed, which represents the first bubble point at that location at the test pressure and temperature.

Based on the test report, the differential pressures across the FO filters and LO filters are still within the design tolerance but with a reduction in the filtration efficiency due to the clogging of the filter elements. Impurities from the biofuel mixtures of different feedstocks during the sea trial may be the cause of the clogging. This happened despite efforts to minimise the residual biofuel before bunkering a new batch of the biofuel. Filter integrity tests observed failures on the FO coarse filters, representing the defect in the functionality of the filter elements.

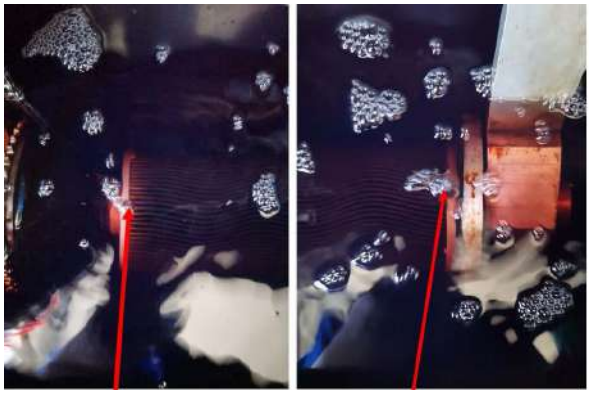


Figure 6.8 Fabrication integrity tests for coarse filters - first bubbles identified from the filter caps

Figure 6.9 Fabrication integrity tests for the FO fine filters – no bypass identified, and bubbles are mainly from the filter layers

Filter Seals & Gaskets

Filter seals and gaskets are made from nitrile butadiene rubber (NBR) and placed on the filter cartridge as a seal to prevent oil leakage from the filter and prevent air from entering the fuel system. There are initial concerns of a deterioration of the NBR material due to the corrosive property of the biofuels. However, upon physical observation after use, only minor hardening was felt by touch and no integrity loss was observed.

The materials' hardness and elasticity properties were tested at Weichai's factory, in accordance with ASTM D395 (test method B). The results show a reduction in the hardness of the FO filter gaskets but no reduction for the gaskets used in LO filters. This may be associated with the properties of the biofuels, which have been reported to shorten the service life of NBR seals used in the system.

FO Pump Assembly

At the end of sea trials, one of the fuel pump assemblies was sent to the manufacturer for detailed investigation. The analysis covers characteristic verification, sealing test and virtual inspection. During the analysis, the pump assembly was throttled to the rated and idling engine speeds to measure each cylinder's fuel oil supply rate under specific pressure and temperature. Subsequently, the flow rates in millilitres per stroke and its corresponding fuel rack position are recorded to compare with the design requirement. The test report shows that the measured values are close to the manufacturer's specifications. Afterwards, the fuel supply pump and high-pressure pump assembly were soaked into a basin of lube oil to investigate their sealing characteristics. There was no leakage, and air bubbles were observed from the sealing surface, indicating no significant corrosion on the sealing gaskets and O-rings. Lastly, the pump assembly was dismantled to check the condition of the movable components and housing directly in contact with the biofuels. The fuel pump plungers and barrels were measured against the designed specifications to verify potential wear and corrosion. No abnormalities were observed, and the measured dimensions are still within the tolerance (Figures 6.10 and 6.11).

Figure 6.10 Condition of the fuel pump plungers and barrels

Figure 6.11 Condition of the fuel supply pump

LO Samples

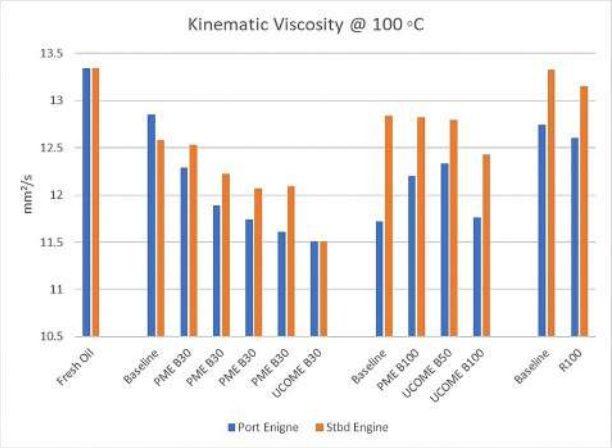
The quality of the LO is a critical factor in assessing engine performance and maintenance duration. There is a risk where the unburnt biofuels from combustion tend to stick on the surface of the cylinder liners (Lube-Tech, 2009; Infineum Insight, 2014) and scrubbed into the crankcase by the piston rings, affecting the properties of the engine LO. As a result, there could be unexpected abrasive wear patterns on the engine moving components. There are 14 LO batches drawn from the sump tanks of each engine to evaluate the potential impacts on the engine. The analysis focused on the samples from the B30 endurance sea trial. The results were compared to the analysis of fresh lube oil samples, which were drawn during the lube oil change at maintenance.

Based on the test results, the kinematic viscosity of the LO gradually reduced due to the use of PME B30. Further dilution was observed under prolonged operation. This may be from the impact of unburnt biodiesel, which slowly accumulates in the engine sump tank and dilute the lube oil. Changes in LO temperatures may be another factor contributing to the oil viscosity reduction. Unlike the B30 test results, the kinematic viscosity of the Port Side engine under the higher content of FAME from B50 to B100 increased during the operation. The test results indicate the lube oil became viscous after being replaced and put into service for a period, but it eventually dropped. It is hard to trace the cause, but an explanation could be that this is caused by the mixture of the clean oil and the residuals from the engine sump tank.

A drop of the total base number indicated the alkalinity of the lubricant was reduced from the neutralising of the acidic products formed from the combustion. As a result, the values of acid number from the sampled LO slowly build up. As one of the critical additives, Zinc is primarily added as the anti-wear and antioxidant agent to enhance the ability of the LO (Shanta et al., 2011). There are two batches of LO samples collected during the HVO operations. HVO is fully hydrotreated and free from oxygen), therefore influences the lube oil's oxidation differently. However, it is inconclusive to confirm the observed changes from the short trial duration using HVO.

The water content of the LO samples remains relatively constant during the sea trial. However, there was a surge in the water content on the Starboard side engine when the engine switched into B50 and above. Previously, it was identified that there was a backflow of seawater into the exhaust system during engine maintenance, which could be the potential source of the water.

Due to lower kinematic viscosity, the LO's anti-friction characteristic changed during the sea trial. This caused wear on the engine's moving components. As the engine liner is made from alloy, and the piston rings are made of cast iron, the metal content increases due to wearing of the engine's components. Compared with the port side engine, the metal content inside the starboard side engine is higher due to increased rust formation. The kinematic viscosity, total base number and acid number of LO samples are affected by the use of biofuels. It is observed that the change of kinematic viscosity was faster than if the LO was used with conventional marine fuels. In contrast, other parameters of the LO had reached their lower limits of the product specification at the end of the trials.



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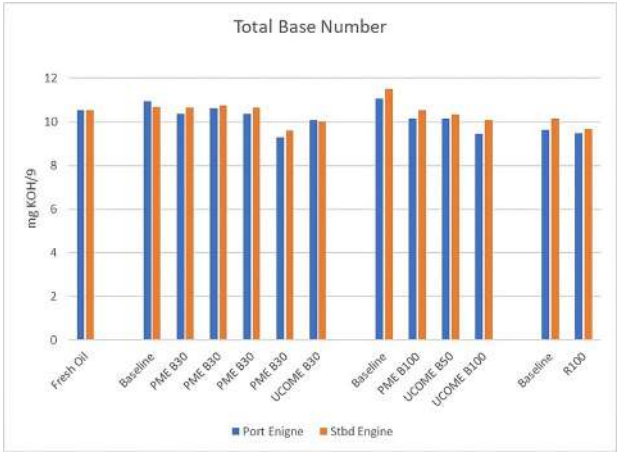

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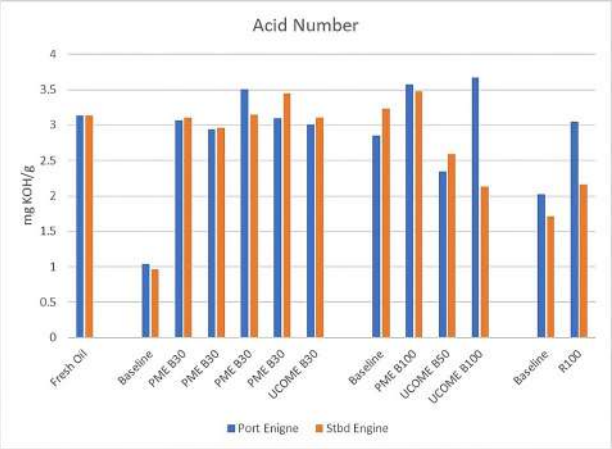

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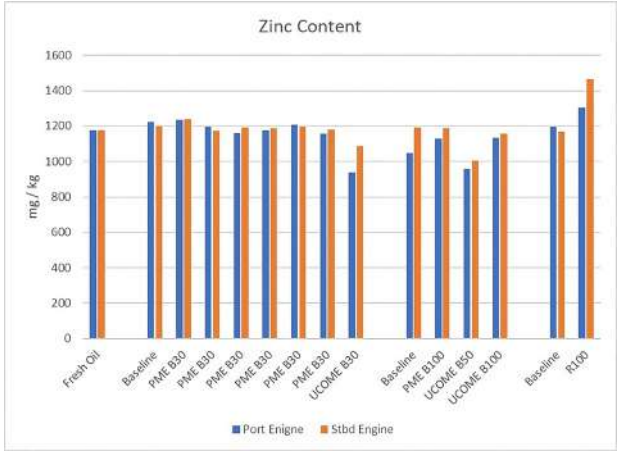

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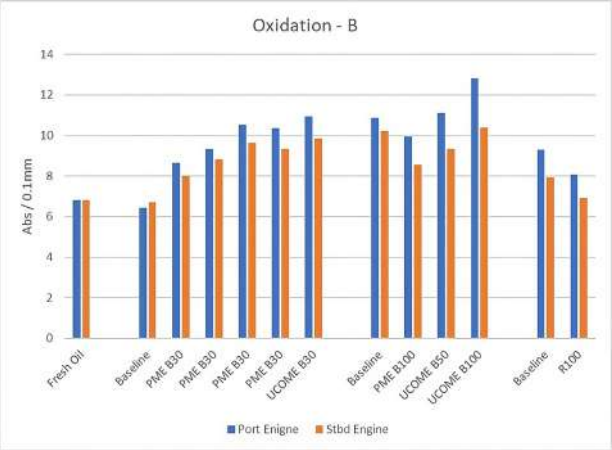

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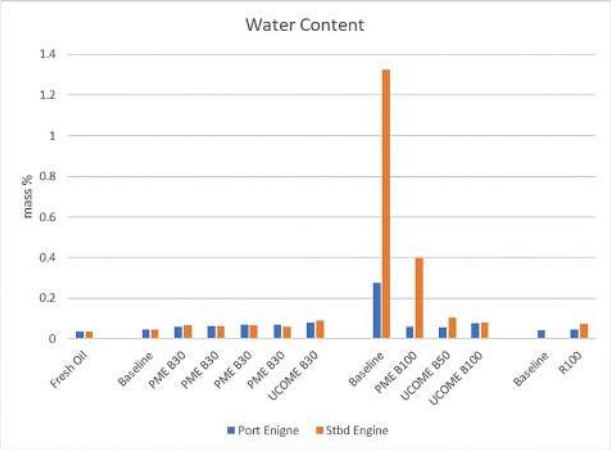

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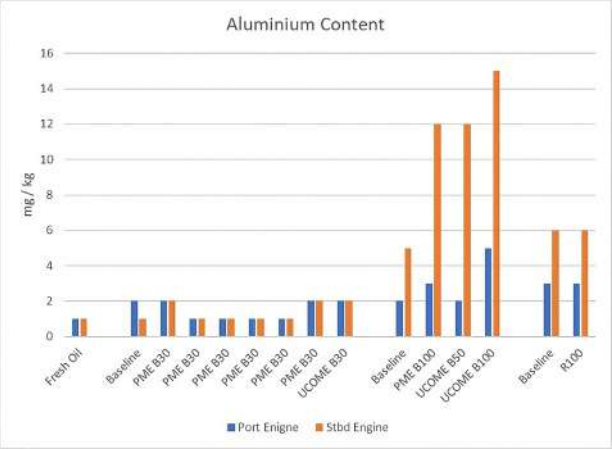

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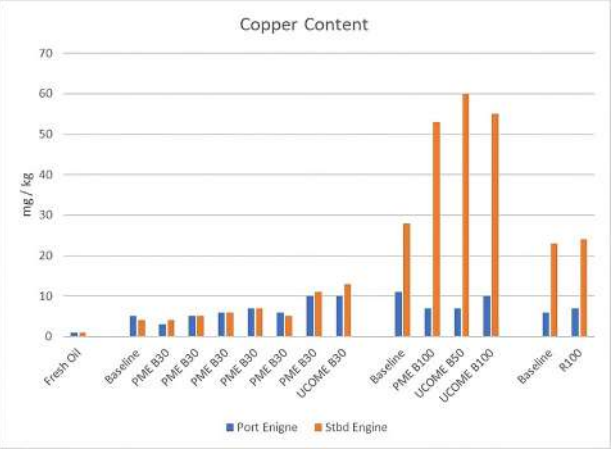

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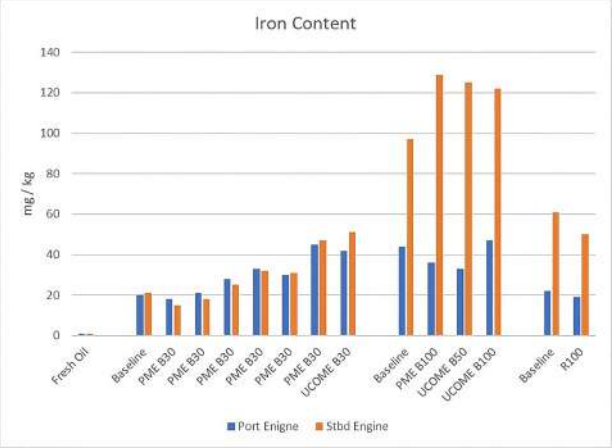

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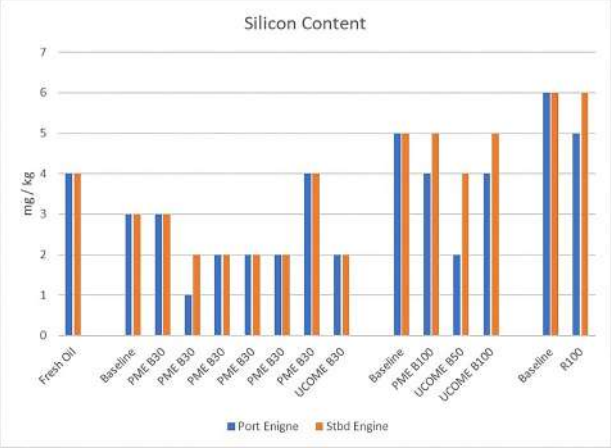

(j)

Figure 6.12 Analysis of the LO samples

(a) Kinematic Viscosity, (b) Total Base Number, (c) Acid Number, (d) Zinc Content, (e) Oxidation, (f) Water Content, (g) Aluminum Content, (h) Copper Content, (i) Iron Content, (j) Silicon Content

6.3 Data Analysis

6.3.1 Engine performance analysis – fuel consumption

The specific fuel oil consumption (SFOC, unit: g/kWh) is an important engine performance parameter and is calculated as the measured fuel consumption (g) per unit of shaft power generated (kWh). The measured shaft power is normally used to determine engine load, which is a key factor that affects fuel consumption. However, during the sea trial, there is fluctuation in the shaft power data. After comparing the engine speeds and shaft power and finding a good agreement between the datasets, the project team decided to use engine speed (RPM) for data analysis. Figure 6.13 illustrates the SFOC of MGO and biofuel blends at different engine speeds. As determined by the engine manufacturer, the engine specification is illustrated by the red line. Data from a sea trial with MGO (yellow line) shows that the measured SFOC is higher than engine specification due to the variables of a sea trial. The highest SFOC values are recorded during the endurance sea trial with B30 PME (illustrated with a black line). B100 sea trials show similar SFOC (light green line). B50 has a slightly lower SFOC than B100, and there is an insignificant difference between PME and UCOME. HVO and HVO biofuel blends demonstrate improved SFOC over MGO. As an insignificant difference is observed between different biofuel blends, the data is aggregated together, as shown by a single blue line.

Several factors influence specific fuel oil consumption. As the fuel injection volume is fixed at each engine cycle, the different densities of the biofuels change the mass of the injected fuel. The types of biofuels used also have different chemical compositions (see Table 6.16). Another factor is the different energy content (or Net Calorific Value, NCV) of the biofuels, leading to different shaft power generated per mass of fuel (see Table 6.5 for the NCVs of fuels).

The NCVs of the biofuel blends are adjusted to the type of fuels, the temperature assumed during blending (30°C), and onboard temperature measurement (35°C) during the sea trials. The NCVs are first calculated according to volumetric energy content (MJ/litre), as the blending is done according to the fuel volume. Next, the NCVs of biofuel blends are adjusted by factoring in the density of fuels at 35°C. Table 6.6 shows the NCV of biofuel blends at different temperatures and the loss of NCV when compared with MGO. The NCVs of biofuel blends are considered when assessing the total fuel oil consumption of biofuel blends.

The maximum engine speed (max. engine RPM) is closely monitored as it influences the specific fuel consumption. The maximum RPM is found to be inconsistent because of normal engine degradation over time. Figure 6.14 illustrates the port and starboard engines' maximum engine RPM measured over 12 months. The data points in the orange circle represent the maximum engine RPM using MGO, while blue data points are for PME and UCOME, and yellow data points are assigned for HVO. The maximum engine RPM normally decreases over time and improves after each maintenance period. In the first maintenance, the FO injector of the starboard side engine was changed, but no component was changed for the port side engine. During the following months of operations, the port side FO injector was blocked and affected the engine performance. This is reflected by a sharp decrease in port-side engine RPM. All FO injectors were replaced during the second maintenance, resulting in a higher maximum engine RPM. Operational and weather conditions are other minor factors that may lead to higher SFOC. The engine is optimised for operation at around 80% MCR, and a lower-than-optimal load will increase SFOC. Higher ambient temperature can reduce the mass of intake air for combustion and reduce engine performance.

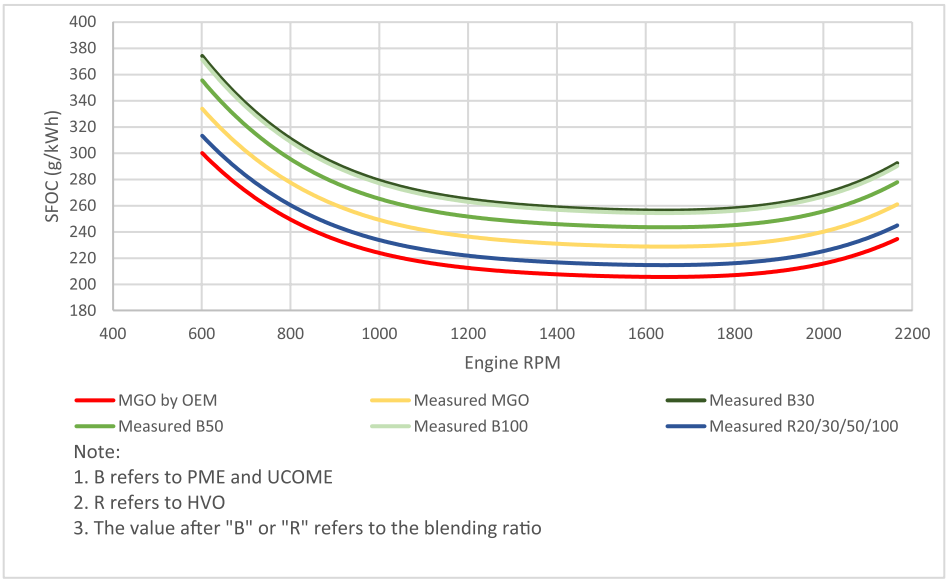

Figure 6.13 SFOC comparison for different fuels

Table 6.5 NCV for B100, MGO, UCOME and HVO by mass

B100 NCV (PME kJ/kg)	MGO NCV (kJ/kg)	UCOME NCV (kJ/kg)	HVO NCV (kJ/kg)
36.98	42.648	36.862	43.704

Table 6.6 NCV for fuels at different blends

Fuel type	Blending ratio at 30°C (%)	NCV at 35 °C (MJ/L)	Density at 35°C (kg/L)	NCV at 35°C (MJ/kg)	Change in NCV (Baseline MGO)
UCOME	0	35.17	0.825	42.65	
UCOME	20	34.48	0.832	41.45	-3%
UCOME	30	34.13	0.835	40.86	-4%
UCOME	50	33.44	0.842	39.69	-7%
UCOME	100	31.71	0.860	36.86	-14%
PME	0	35.17	0.825	42.65	
PME	20	34.54	0.833	41.47	-3%
PME	30	34.22	0.837	40.89	-4%
PME	50	33.58	0.845	39.75	-7%
PME	100	32.00	0.865	36.98	-13%
HVO	0	35.17	0.825	42.65	
HVO	20	34.88	0.814	42.85	0%
HVO	30	34.74	0.809	42.95	+1%
HVO	50	34.44	0.798	43.16	+1%
HVO	100	33.72	0.772	43.70	+2%

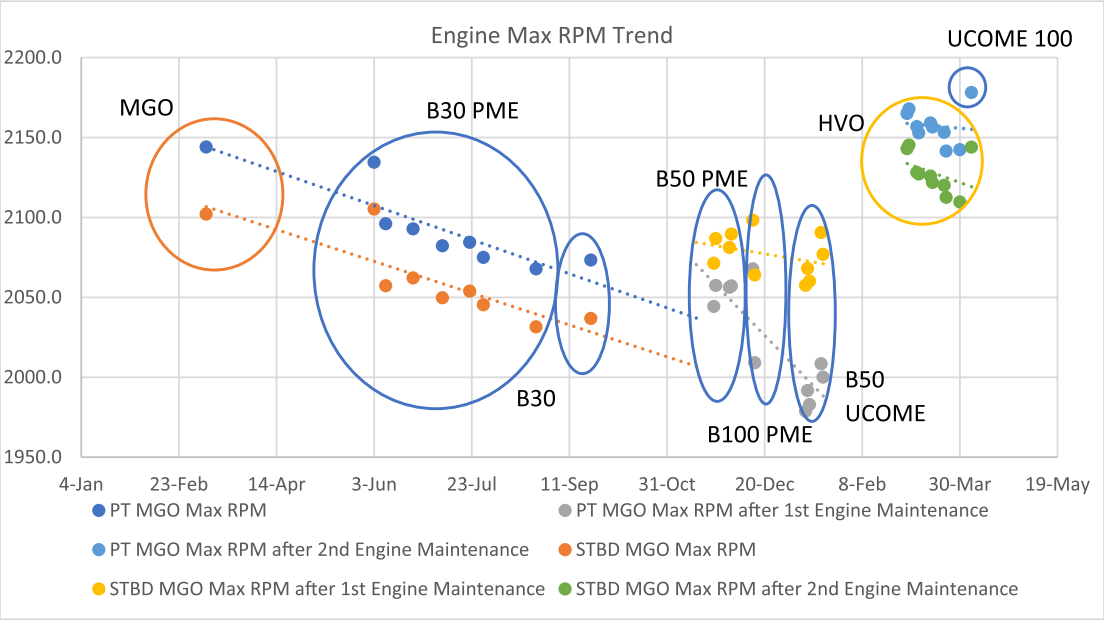

Figure 6.14 Engine Max RPM trend

The ship's operation modes are idling, manoeuvring, slow-speed cruising, medium-speed cruising, and high-speed cruising. The range of engine RPM for each operation mode is provided in Table 6.7. The table also summarises the respective measured data under different operation modes.

Table 6.7 Operating status for vessel in this study

Operation Mode	Engine RPM	Average Engine RPM Port Side	Average Engine RPM Starboard Side	Average Power Load Port Side	Average Power Load Starboard Side	Average Vessel Speed (knot)	Operation Time (h)
Idling	<645	582.4	577.2	2.2%	2.6%	0.7	351
Manoeuvring	645-1100	807.9	803.8	7.2%	7.3%	6.5	286
Slow-speed Cruising	1100-1450	1,271.4	1,270.5	23.8%	23.9%	10.8	492
Medium-speed Cruising	1450-1850	1,694.5	1,708.3	53.4%	54.7%	15.3	595
High-speed Cruising	>1850	2,006.1	2,015.1	87.5%	88.6%	19.0	3,004

The data during high-speed cruising for different fuels is chosen for regression analysis as the recorded speed of the ship engine is greater than 1850 rpm most of the time, as shown in Table 6.8. Six factors influencing the SFOC were selected for a regression analysis to verify their impact. The factors are 1) maintenance effect, 2) biodiesel blend ratio, 3) time to previous maintenance, 4) HVO blending ratio, 5) average engine RPM, and 6) engine room temperature (Table 6.9).

The result is shown in Table 6.10. All factors are significant except for the biodiesel blending ratio. There is insufficient evidence to prove that the different biofuel blends affect fuel consumption significantly. Therefore, the slightly higher SFOC value of B30, compared to other blending ratios, is more likely due to factors such as engine maintenance, engine RPM, and engine room temperature. For example, higher engine room temperatures of 50.0°C were recorded for B30 PME and 48.5°C for B30 UCOME. Maintenance is shown to reduce the engine's fuel consumption, and the engine's normal degradation over time will increase SFOC. Besides, higher engine RPM at a higher power load leads to higher SFOC, and higher engine room temperature will also affect SFOC. The results for high HVO biofuel blends show that a higher blending ratio leads to slightly higher SFOC with a standard coefficient of 0.0519, indicating that blending ratios of HVO have a limited impact on SFOC.

Table 6.8 Recorded parameters for regression study during high-speed cruising

Fuel Type	Cumulative Engine Running Time (hour)	PT RPM	STBD RPM	PT Load	STBD Load	Trial Time (min)	Speed (knot)	Distance Travelled (NM)	Highest Recorded ER Temp (°C)	Estimated PT Fuel (kg/min)	Estimated STBD Fuel (kg/min)
MGO	377.1	1,991.8	1,998.5	85.5%	86.4%	433	18.4	132.9	51.8	0.83	0.84
B30 PME	432.0	1,985.3	1,991.8	84.7%	85.5%	566	18.3	172.3	50.0	0.90	0.91
B30 UCOME	509.1	1,993.6	1,970.2	85.7%	82.7%	182	17.8	53.8	48.5	0.91	0.88
B50 PME	575.5	1,989.2	2,020.3	85.1%	89.2%	248	19.6	81.0	43.9	0.87	0.93
B100 PME	612.7	1,965.0	1,998.0	82.1%	86.2%	308	19.2	98.5	44.8	0.80	0.85
B50 UCOME	667.2	1,939.6	2,011.6	78.8%	88.0%	155	19.2	49.5	46.5	0.78	0.90
R20	779.1	2,065.2	2,053.5	95.5%	93.9%	199	19.8	65.5	45.9	0.89	0.87
R30	795.2	2,080.8	2,066.4	97.7%	95.6%	200	19.8	66.1	46.1	0.82	0.80
R50	815.9	2,081.5	2,061.1	97.7%	94.9%	201	19.9	66.6	47.4	0.91	0.97
R100	842.7	2,043.2	2,035.0	92.3%	91.2%	204	19.5	66.3	49.2	0.85	0.83
B100 UOCME	855.1	1,999.7	2,021.1	86.8%	89.3%	308	19.3	99.0	47.1	0.93	0.96

Table 6.9 Description of variables for the multiple linear regression models of engine performance

Variables	Description
Dependent Variables	
SFOC	Recorded Specific Fuel Oil Consumption
Independent Variables	
Maintenance effect	Operationalised as value 0.5 for samples after 15-Nov-2021 (1st Maintenance), value 1 for samples after 02-March-2022 (2nd Maintenance), value 0 otherwise.
Biodiesel blending ratio	Operationalised as a continuous variable with a value range of 0 to 1, value 1 for 100% PME or UCOME, value 0 for 0% PME or UCOME
Time to previous maintenance	Operationalised as the number of days between the sample time and the most recent end date of an engine maintenance
HVO blending ratio	Operationalised as a continuous variable with a value range of 0 to 1, value 1 for 100% HVO, value 0 for 0% HVO
Average engine RPM	Operationalised as the cubic value of the average value between PT and STBD engine RPM
Engine room temperature	Operationalised the recorded engine room temperature (°C) during the sample time

Table 6.10 Regression analysis for engine performance

Dependent Variable Specific Fuel Oil Consumption	Coefficients	Standard Error	T-Stat	P-value
Intercept	-0.0577	0.0134	-4.2901	<0.001
Maintenance effect	-0.0880	0.0057	-15.4280	<0.001
Biodiesel blend ratio	-0.0050	0.0037	-1.3593	0.1741
Time to previous maintenance	0.0005	0.0000	15.7017	<0.001
HVO blend ratio	0.0519	0.0076	6.8236	<0.001
Average engine RPM	0.0000	0.0000	531.9985	<0.001
Engine room temperature	0.0017	0.0003	5.7408	<0.001
F-value		52120.6181		
Significance F		<0.001		
R-square		0.9851		
Adjusted R-square		0.9851		
Number of samples		4728		

6.3.2 Emission analysis

Table 6.15 summarises the CO_2, CO, and NO_x emissions for the port and starboard main engines for different fuel types during high-speed cruising. Little variations are observed after comparing the CO_2 emissions from the port and starboard, which is in line with the fuel oil consumption data. The port-side engine presents a slightly lower CO emission and a higher NO_x emission, and the potential factors may be the differences in injection parameters, engine calibration, and engine load (Hoekman & Robbins, 2012). The differences affected the adiabatic flame temperature and a higher adiabatic flame temperature generally imply higher NO_x and lower CO formation. However, the average exhaust temperature measured at the port main engine is slightly lower than that at the starboard engine. The cause for the discrepancy is currently unknown. A possible explanation may be the proximity of the exhaust temperature sensors to the location of the engine exhaust discharge.

Across different fuel types, the differences in CO_2, CO and NO_x emissions between biodiesel (i.e., PME and UCOME) and MGO are not apparent. But HVO appears to be associated with a slightly lower CO_2 emission, slightly higher CO emission, and slightly lower NO_x emission than MGO. It is worth noting that the fuel compositions of the three types of biofuels are different (Table 6.16). A fuel with more carbon is expected to generate more CO_2 after combustion than another fuel with lower carbon content if the fuel consumptions of both fuels are the same. The presence of molecular bond oxygen may also have an impact on CO and NO_x emissions. It is suggested that the oxygen in the fuel may favour higher combustion efficiency, thus a lower CO emission, higher adiabatic flame temperature, and a higher NO_x emission (Varatharajan & Cheralathan, 2012).

Due to the complexity of factors that may affect emission data, multiple regression models have been constructed to investigate the use of biodiesel and HVO on emissions. The independent variables are the same as the regression model for fuel consumption (see Table 6.9). Table 6.11 describes the dependent variables for the multiple linear regression models of emissions on operating conditions.

Table 6.11 Description of variables for the multiple linear regression models of emissions on operating conditions

Variables	Description
Dependent Variables	
CO_2 Emissions	Operationalised as the sum of PT and STBD CO_2 emissions in kg/min
NO_x Emissions	Operationalised as the sum of PT and STBD NO_x emissions in g/min
CO Emissions	Operationalised as the sum of PT and STBD CO emissions in g/min

The results of the regression models are shown in Tables 6.12-6.14. Among the independent variables, average engine RPM is found to be positively significant in all regression models, highlighting the significance of power load in all types of emissions. Engine room temperature is another significant variable that positively impacts CO_2 and CO emissions and negatively impacts NO_x emissions. A likely explanation is that an engine is less efficient when operating in a hotter engine room. The amount of oxygen from hotter air is lower than that from cooler air, reducing the oxygen-to-fuel ratio and leading to less efficient combustion and higher fuel consumption and CO_2 emission for the same output power. Less efficient combustion could also result in higher CO emissions. As the engine burns less efficiently, the adiabatic flame temperature reduces, causing less NO_x emission.

Variables related to engine maintenance render mixed impacts on exhaust emissions. For example, the maintenance effect positively impacts CO_2 and NO_x emissions but does not affect CO emissions. This finding suggests that comprehensive engine maintenance could help reduce CO_2 and NO_x emissions. However, the maintenance steps taken during the sea trial may not have significantly reduced CO emissions. The time to the previous maintenance is found to impact CO_2 emission positively but negatively impact CO emission. This is in line with expectation as it implies the continuous usage of the engine without any maintenance could reduce the engine's energy efficiency and thus increase the CO_2 emission at the same engine output.

A higher HVO blending ratio is found to be insignificant in regression models of both CO_2 and NO_x emissions but is significantly associated with higher CO emissions. The expected increase in CO emission by using 100% HVO is 1.12g/min, or 27% of the average actual CO emissions. A higher biodiesel blend is also found to be associated with slightly higher CO_2 emissions, slightly higher NO_x emissions and slightly lower CO emissions. Based on B100, the change in the emissions is expected to be (a) increased CO_2 emissions of 0.14kg/min, or 3.5% of the actual average CO_2 emissions; (b) increased NO_x emissions of 2.55g/min, or 7.5% of the actual average NO_x emission and (c) decreased CO emission of 0.156g/min or 3.8% of the actual CO emission. While the increase in NO_x and decrease in CO emission align with the existing literature (Varatharajan & Cheralathan, 2012), the increase in CO_2 emission could be largely explained by the differences in fuel composition. Assuming the same combustion efficiency between biodiesel and MGO and given the differences in the carbon content of the fuels, the expected increase in CO_2 emission is about 3% for UCOME B100 and 2% for PME B100.

Table 6.12 Results of regression of CO_2 emission on operating conditions

Dependent Variable: CO_2 Emissions	**Coefficients**	**Standard Error**	**T-Stat**	**P-value**
Intercept	-0.351	0.051	-6.877	<0.001
Maintenance effect	-0.377	0.021	-17.584	<0.001
Biodiesel blend ratio	0.140	0.014	10.254	<0.001
Time to last maintenance	0.00154	0.00011	13.470	<0.001
HVO blend ratio	0.0325	0.0289	1.127	0.260
Average engine RPM	6.44E-10	1.45E-12	444.387	<0.001
Engine room temperature	0.00834	0.00114	7.336	<0.001
F-value		36522.90		
Significance F		<0.001		
R-square		0.98309		
Adjusted R-square		0.98306		
Number of samples		3777		

Table 6.13 Results of regression of NO_x emission on operating conditions

Dependent Variable: NO_x Emissions	**Coefficients**	**Standard Error**	**T-Stat**	**P-value**
Intercept	18.583	1.163	15.977	<0.001
Maintenance effect	-9.671	0.488	-19.818	<0.001
Biodiesel blend ratio	2.549	0.311	8.209	<0.001
Time to last maintenance	0.00314	0.00260	1.210	0.226
HVO blend ratio	-0.2242	0.6579	-0.341	0.733
Average engine RPM	4.09E-09	3.302E-11	123.947	<0.001
Engine room temperature	-0.16740	0.02590	-6.464	<0.001
F-value		2681.50		
Significance F		<0.001		
R-square		0.81016		
Adjusted R-square		0.80986		
Number of samples		3777		

Table 6.14 Results of regression of CO emission on operating conditions

Dependent Variable: CO Emissions	**Coefficients**	**Standard Error**	**T-Stat**	**P-value**
Intercept	-0.507	0.162	-3.121	0.002
Maintenance effect	0.054	0.068	0.795	0.427
Biodiesel blend ratio	-0.156	0.043	-3.594	<0.001
Time to last maintenance	-0.00089	0.00036	-2.452	0.014
HVO blend ratio	1.1192	0.0919	12.180	<0.001
Average engine RPM	3.81E-10	4.613E-12	82.592	<0.001
Engine room temperature	0.02541	0.00362	7.024	<0.001
F-value		1641.14		
Significance F		<0.001		
R-square		0.72314		
Adjusted R-square		0.72270		
Number of samples		3777		

Table 6.15 Summary of CO_2, CO, and NOx emissions during high-speed cruising

Fuel Types	Sampling Time (min)	PT Power (kW)	STBD Power (kW)	PT CO_2 (kg/kWh)	STBD CO_2 (kg/kWh)	PT CO (g/kWh)	STBD CO (g/kWh)	PT NO_x (g/kWh)	STBD NO_x (g/kWh)	PT Average Exhaust Temperature (°C)	STBD Average Exhaust Temperature (°C)
MGO	433	204.8	206.9	0.77	0.77	0.51	0.53	7.0	5.1	479.0	507.7
B30 PME	566	202.8	204.8	0.81	0.81	0.47	0.51	7.8	5.9	473.6	501.8
B30 UCOME	182	205.3	198.2	0.81	0.81	0.49	0.54	7.4	5.9	488.7	514.0
B50 PME	248	204.0	213.7	0.76	0.77	0.60	0.64	6.4	5.1	452.1	496.1
B50 UCOME	155	189.1	210.9	0.74	0.76	0.60	0.59	6.5	5.5	460.7	495.9
B100 PME	308	196.6	206.7	0.68	0.69	0.42	0.43	6.0	5.0	444.9	485.4
B100 UCOME	308	207.2	214.0	0.76	0.76	0.43	0.48	6.7	5.5	467.5	493.4
R20	199	228.3	224.4	0.64	0.65	0.40	0.46	5.6	4.7	481.4	505.3
R30	200	233.5	228.7	0.66	0.65	0.47	0.58	5.2	4.3	489.5	511.8
R50	201	233.7	226.9	0.72	0.72	0.57	0.72	5.5	4.5	493.9	514.4
R100	204	221.0	218.4	0.71	0.71	0.62	0.77	5.2	4.1	488.5	512.4

Table 6.16 Fuel composition by mass (%)

Element	MGO	PME B100	UCOME B100	HVO R100	PME B30	PME B50	UCOME B30	UCOME B50	HVO R20	HVO R30	HVO R50
Carbon (%)	86.9	76.7	77.3	84.9	83.7	81.7	83.9	82.0	86.5	86.3	85.9
Hydrogen (%)	13.0	12.7	12.6	15.3	12.9	12.9	12.9	12.8	13.5	13.7	14.1
Oxygen (%)	0.0	10.6	10.0	0.0	3.3	5.4	3.1	5.1	0.0	0.0	0.0
NCV (MJ/kg)	42.65	36.98	36.86	43.70	40.89	39.75	40.86	39.69	42.85	42.95	43.16

6.4 Assessment of Economic Factors of Biofuels

The assessment of economic factors focuses on the regional supply chains for Singapore and commercially produced biofuels (also see Section 2.2). The market prices, obtained from Argus Media, reflect the base prices of FAME or HVO from global markets (Europe, China, Malaysia and Indonesia). MGO prices are available from Ship and Bunker (Ship & Bunker, 2022). All prices are in US dollars for the period from 1 January 2021 to 31 December 2021. 2021 is selected as the year of assessment as several outlier events in 2020 and early 2022 (major supply chain disruptions due to Covid-19 and the Russian invasion of Ukraine) are avoided. All other cost factors are estimated after a discussion with bunker suppliers and project collaborators.

The following key cost factors are investigated:

1. The fuel cost (USD/metric tonne) includes the commodity prices of PME (Indonesia and Malaysia), UCOME (China) and HVO (China and Singapore). The costs of transportation, blending, and service fees are estimated and included after considering current practices.
2. The energy cost (USD/GJ) is based on fuel cost and the energy content of biofuels.
3. The fuel consumption cost (USD per kWh) is based on the difference in net calorific values among the types of fuel and the engine's SFOC of MGO during the sea trial.

Regional and local shipping and land transport costs from biodiesel plant to bunker suppliers (in bulk quantities) have been assumed to remain the same throughout 2021. Blending and storage of biofuel blends are done on land before bunkering. Local transportation cost for trucking MGO to the blending site is negligible. Biofuel bunker suppliers may convert existing bunker infrastructure (storage tanks, fuel pumps and barges) to support biofuel. Service fees in bulk quantities (transportation, blending, bunker) remain similar for all biofuel types and blends and are marginally higher than for MGO.

6.4.1 Potential economic factors of biofuels for Singapore harbour craft

The study evaluates the potential economic factors along the value chain and divides the section into two areas: (i) upstream factors which impacts fuel costs and (ii) downstream factors which affects operational and fuel consumption costs.

Upstream factors: Availability of feedstocks, production capacity, distribution and mandates

i. Production capacity of biofuels produced commercially within Asia

   Among the three types of biofuels, PME from sustainable palm oil has the best availability as Indonesia and Malaysia are major producers of palm oil and regional producers of biodiesel. However, UCOME offers a balance of between affordability and high GHG emission savings using ISCC or LCA guidelines. UCOME may be sourced locally or imported from regional suppliers. Production plants for PME and UCOME are widely located around Asia (Go et al., 2022), thus the production of biodiesel may be carried out where there are economies of scale. While Singapore has the largest renewable diesel production plant within Southeast Asia (Neste, 2022), its production capacity (3.9 tonnes by 2025) dwarfs in comparison with Europe (11.3 million tonnes by 2025) and America (12.6 million tonnes by 2025) (Greenea Analysis, 2020).

   Despite the uncertainty surrounding the growth in production capacity (Elder & Hayashi, 2018), increased demand continues across all transportation sectors, driven by environmental mandates and energy insecurity issues. The gap in supply and demand of biofuels is expected to remain high in the near term. The availability of new streams of feedstock and the biomass conversion efficiency will determine the growth in production capacity.

ii. Cost of production

   Production of HVO has a higher CAPEX than biodiesel; resulting in the dominance of a few major suppliers with high-capacity production plants. The ease of setting up biodiesel production plants and lower start-up costs means biodiesel is produced widely in many countries. Imports of feedstocks or biodiesel may also be feasible for Singapore as Singapore is a key shipping hub.

   Currently, biofuels are blended with conventional marine fuels to be commercially viable. Using nitrogen blanketing and additives for biodiesel are two ways to store biodiesel for a duration of 3 to 6 months before blending, which will provide a level of flexibility for fuel suppliers.

iii. Distribution and blending of biofuel blends

Transportation costs from the regional shipping of biofuels are part of the total fuel costs. As the costs of transport, handling and bunkers are usually not broken down by fuel suppliers, estimates of the additional costs are assumed to be around 8 to 14% of the market prices of MGO. Blending procedure is relatively uncomplicated for the industry, so the cost is unlikely to differ for different blends. Additional costs for biofuel blends have been estimated to be around 4 to 12% of the market prices of biofuels. As there is no economic incentive to use a higher blend beyond a mandate at the current high biofuel prices, the industry will adopt the least expensive type and blend from B20 to B30 to meet regulatory requirements on emissions reduction.

The shorter shelf life of biofuels is assessed to have a minimal impact on logistics and bunkering practices as fuel suppliers typically store fuels for less than three months. Thus, higher water content in biofuels may not pose an immediate concern to bunkering. However, bunker suppliers have to perform frequent fuel quality tests as microbial growth in biofuels will pose a risk to engines.

iv. Mandates and economic incentives for the use of biofuel blends

The Indonesian government mandated that marine gas oil be blended with locally produced PME in early 2019 (Manifold Times, 2019) and eventually raised the blending ratio from B20 to B30 in January 2020 to reduce reliance on imported diesel fuel and boost domestic production of palm oil. Malaysia's biofuel mandate has also increased to 20%, from 10%. But as palm oil prices is set to increase, this might lead to reduced overall demand and falling prices (S&P Global, 2020). On the other side of the world, EU has a similar mandate and fuel subsidies in its transport sector to use biofuel under its Renewable Energy Directive (RED) and Fuel Quality Directive. The mandate has supported local farmers of rapeseed oil (contributing to 36% of biodiesel production) but has also been heavily reliant on imported palm oil (30%) and Used Cooking Oil (1.9 Mt) (Rangaraju, 2021). The concerns for unsustainable biofuel feedstocks led to a revised RED II in December 2018 to restrict the use of biofuels produced from food-based crops. A realistic target for renewables and support of alternative fuels will be useful to dampen soaring prices of biofuels due to mandates.

There have been several fuel subsidies for using biofuels, especially by early adopters in the US, EU and Indonesia (FitchRatings, 2020; Reuters, 2020; EPA, 2022). Fuel subsidies come under debate as it is not sustainable in the long-term and may have encouraged unsustainable feedstocks. Thus, the supply chain of biofuels is moving towards transparency and sustainable pathways with a reduction of crop biomass and providing subsidies only to advanced biofuels. The alternative is market-based measures to encourage an overall reduction in CO_2 emissions, such as using carbon credits for low-carbon fuels or investing in more fuel-efficient ships and technologies.

Downstream factors: Handling, storage and application in marine diesel engines

The switch from MGO to biofuels requires a diligent check on the material compatibility of the fuel injection system, fuel-water separators and other engine components which may be in contact with biofuels and fuel pipes. Shorter maintenance intervals, especially in the initial months of use, are recommended. Degradation of lube oil and high water content may pose risks if left unmonitored. While there is no requirement for retrofit for B30 and below, cautions are expressed by engine manufacturers over higher blends. For the harbour craft used in the sea trial, the overall operational and maintenance costs are estimated to be 30 to 40% higher after factoring in increased vessel downtime, additional lube oil testing and engine parts. These costs may be minimised if fuel standards for biofuels are established to establish high-quality biofuel blends.

6.4.2 Evaluation of cost factors for MGO, biofuels and blends

Figure 6.15 presents the fuel costs for MGO (B0), biofuel blends (B20, B30, B50 and B100) for three types of biofuels. MGO is the baseline price for all calculations, and the fuel cost of MGO ranges from USD503 to 786.50 per mt (average of USD644.75 and standard deviation of USD200.46). For neat biofuels, HVO is the most expensive biofuel and has the largest price deviation. Compared with UCOME at the lowest price range, the lower price range of HVO is around 15% more than UCOME. At the peak prices, HVO costs USD3014.10 per mt, which is 63% higher than the peak price of UCOME (USD 1840). In the short term, the industry may begin with low blends of either B20 or B30, of which PME was the cheapest bio-component among the three options studied. UCOME and HVO will gain importance under future mandates to use only waste and residues.

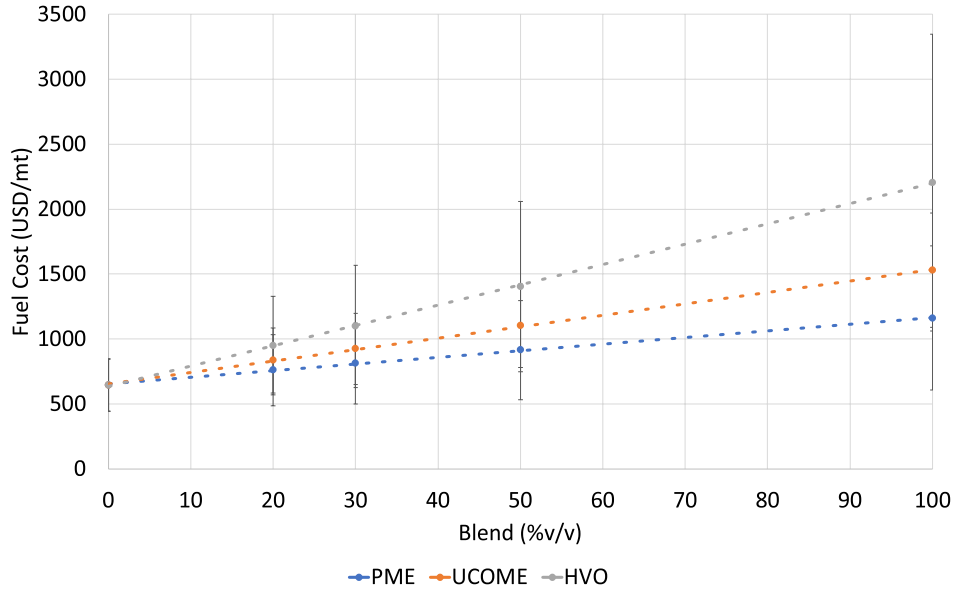

Figure 6.15 Fuel cost (USD/mt) against biofuel blends for three types of biofuels

Figure 6.16 illustrates the comparison of energy costs of MGO with the three types of biofuels. The average energy costs of biofuels are USD29.53 and 48.87 per GJ. In comparison with a recent energy cost estimates of green hydrogen of around USD25 to USD54.6 per GJ (calculated based on 120 MJ/kg energy density of hydrogen), B100 biodiesel, HVO or high biofuel blends might be highly uncompetitive (European Commission, 2020).

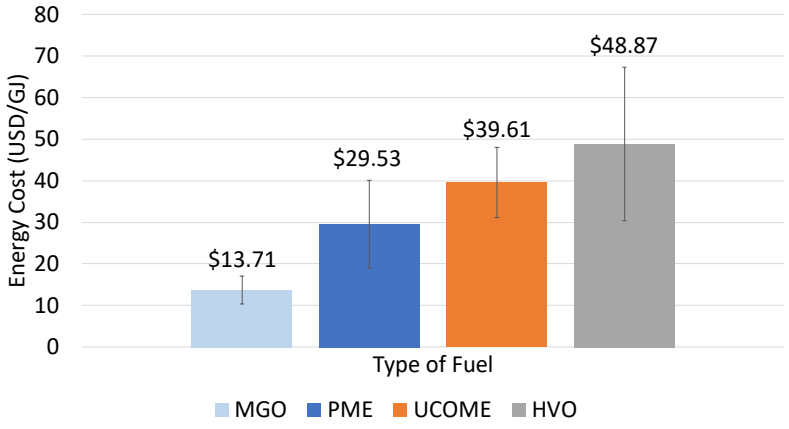

Figure 6.16 Energy cost (USD/mt) of MGO and three types of biofuels, PME, UCOME and HVO

Figure 6.17 presents the fuel consumption costs in USD per kWh for MGO and biofuel blends. These results are for the marine diesel engine operating at an optimal SFOC. The fuel consumption cost has factored in the expected increase in SFOC due to lower net calorific values of biodiesel as no thermodynamic efficiency loss is observed for the diesel engine. The average fuel cost increase (%) with biofuel blends from B20 to B100 is shown in Figure 6.18. The marine industry has to brace an 18 to 30% cost increase for FAME B20 and 47% cost increase for HVO R20, respectively.

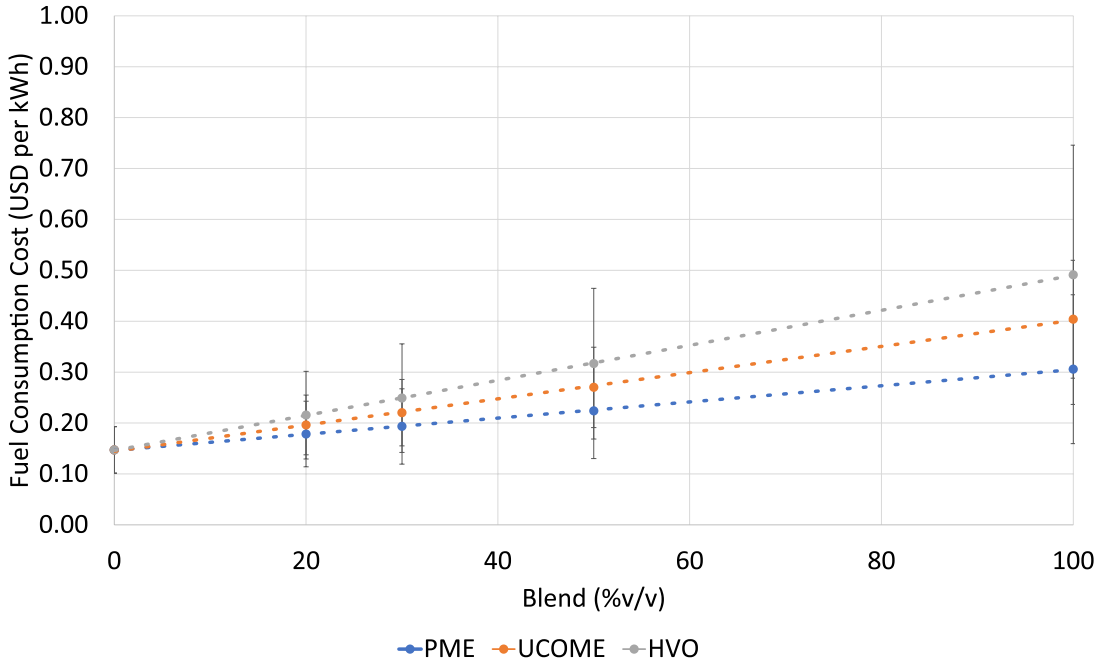

Figure 6.17 Fuel consumption cost (USD/kWh) of MGO and biofuel blends for three types of biofuels

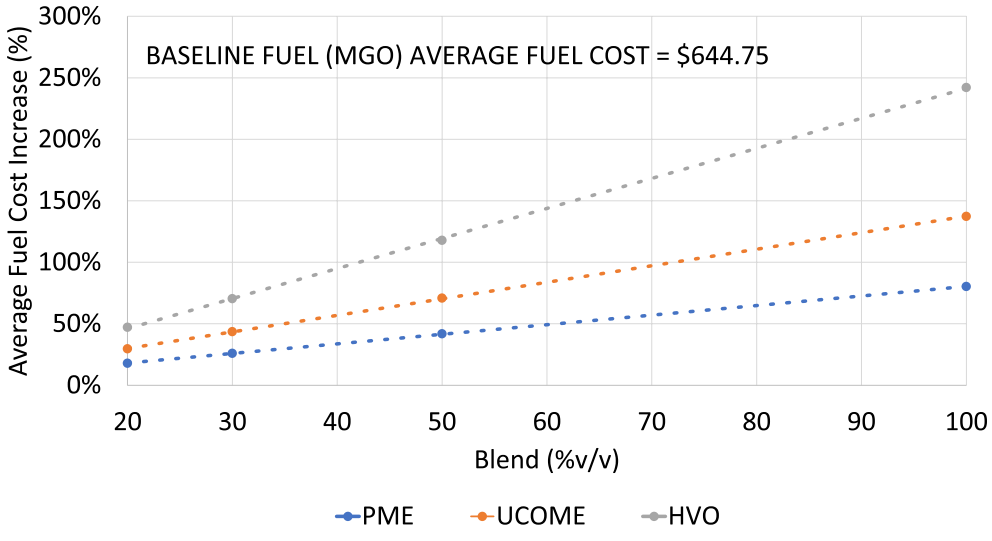

Figure 6.18 Average fuel cost increase (%) with biofuel blend from B20 to B100

6.4.3 Economic assessment and discussion

The costs of all biofuels have been steadily increasing in 2021. This price increase is due to an increased global demand and the implementation of increasing biofuel blends by mandates, according to the International Energy Agency (IEA, 2021). Generally, by comparing the biofuel's average prices, the cheapest biofuel is PME, followed by UCOME and HVO. When compared with MGO, the price of PME B20 is 11% to 20% higher, UCOME B20 is 31% higher and HVO R20 is 45% to 60% higher. In the short term, B20 and B30 blends are likely able to meet the short-term GHG emissions reduction target.

The key recommendations from the economic assessment have been summarised in this section.

- Given that the fuel costs are a main cost component for the harbour craft, the industry needs a clear and realistic mandate to use biofuels to account for the increase in fuel costs between MGO and biofuels. A push for a higher biofuel blend may not be viable without any economic incentives.
- The recommended blend must balance the cost increase and the GHG emission reduction offered by the type of biofuel.
- Investment in energy efficiency and technologies to reduce the overall fuel consumption may buffer the increase in fuel costs.
- The industry may initially use sustainable PME due to its high availability and lower cost. Still, a more sustainable pathway forward will be to increase the production of 2nd generation biofuels, such as UCOME or advanced biofuels.
- HVO is recommended as a premium fuel due to its similar performance with diesel and is considered a 100% drop-in alternative. However, R20 is at least 45% higher in fuel cost than MGO and the demand for HVO is not expected to reduce in the short-term.

CHAPTER 7
BIOFUEL COMPATIBILITY SURVEY

A survey with the top engine manufacturers used by Singapore harbour craft is an alternative to extensive testing requirements of diesel engines on biofuel compatibility. The survey has gathered recommendations to plug the knowledge gaps on biofuel compatibility engines among harbour craft. A total of 11 engine manufacturers participated in an engine mapping of the Singapore harbour craft to determine the biofuel compatibility of existing engines. The survey was conducted according to NTU-Institutional Review Board guidelines to maintain research ethics and integrity.

7.1 Highlights from the Survey and Interviews

Engine manufacturers express caution and additional maintenance steps in switching to biodiesel, while acknowledging that up to 7% (v/v) FAME is accepted by current marine fuel standards ISO 8217, with no additional requirements. The cautions do not apply to the use of synthetic fuels according to EN15940, which covers sustainable fuels, e.g. HVO, BTL and e-diesel. The guidelines vary slightly among the manufacturers, likely based on the different test results and experiences of the engine manufacturers. Table 7.1 presents the general consensus among engine manufacturers, the risks and impact on engine systems and general mitigation measures as of November 2021. The recommendations and insights are categorised under four areas: (i) fuel quality and standards; (ii) biofuel blends; (iii) engine components and maintenance and (iv) fuel consumption and emissions.

Caution for the use of biodiesel is mainly due to the differences in the intrinsic fuel properties between biodiesel and fossil fuels, which are the causes of fuel quality concerns. For instance, biodiesel has a stronger solvency effect than paraffinic diesel. Thus, contact with paint shall be avoided and all seals shall use compatible materials. A gradual increase in biofuel blend over several months is also highly recommended.

Palm and rapeseed oils, common in Asia and Europe, respectively have higher oxidation stability than the soy oil used by the Americas due to the lower amount of unsaturated double bonds in the oil fraction. On the other hand, soy oil has better cold flow behaviour due to higher content of polyunsaturated double bonds. While the cold flow behaviour is not a concern for biodiesel used in tropical countries, it is an important consideration for bunkering biofuel blends to ocean-going ships.

There may be the presence of higher metal content in biofuels, due to certain materials that were naturally occurring or due to processing (e.g., phosphorus, sodium, calcium, potassium and magnesium). The maximum levels of these metals shall be controlled by the appropriate specifications.

There are more restrictions on the use of materials in the fuel delivery system. Natural rubber, butyl rubber and some types of nitrile rubber may be susceptible to degradation. Copper, bronze, brass, tin, lead and zinc may cause deposit formations. Thus, these materials shall be avoided for fuel tanks and fuel lines.

Although the energy content of biofuels is lower when compared to conventional diesel fuels, the engine rating will normally not be changed to compensate for potential power loss, as the engine may face complications engine problems when it is converted back to conventional fuels.

It is clear that not all engine manufacturers have extensive experience and could present detailed reports with data on the short-term and long-term use of biofuels. However, it is noteworthy that none of the engine manufacturers has reported serious issues with engines that have used biofuels for the past decade.

Table 7.1 Consensus, risks and impact on engine system and general mitigation measures by engine manufacturers

	Consensus	Risks and Impact	Mitigation Measures
Fuel quality and standard	HVO accepted as drop-in fuel up to R100 ISO 8217 is widely accepted by all engine manufacturers ASTM D6751-19 or EN 14214:2012 (E) typically used for specifying biodiesel quality Biodiesel manufacturers recommend varying storage durations of biofuel blends, from maximum one month to three months. Higher metal content occurs naturally or due to processing.	Biodiesel is susceptible to elements and bacteria growth and microbial contamination causes plugged fuel filters and engine failure. Gaps in fuel standards for biofuel blends from B7 to B99. Varying storage durations dependent on manufacturers' recommendation.	Fuel quality shall adhere to Certificate of Analysis. Maximum levels of metals are controlled by appropriate specifications. Provide standards for intermediate blends (from B7 to B99). Some manufacturers provide internal guidelines to manage the use of biodiesel. Use of approved antioxidant additives. Frequent and repeated testing of biofuels if stored beyond half of its recommended duration.
Biofuel blends	Technical guidelines support up to • B5 (Mitsubishi) • B20 (Cummins, MTU, Weichai, Yanmar) • B30 (Shanghai Diesel, MAN, Volvo) • B20 to B100 (Caterpillar). Upper blend limit not specified in documents (Daihatsu, Wartsila) – B7 is accepted or Biofuel compatibility is assessed separately by survey.	Blend above B20 is generally not recommended as "drop-in" fuel due to impact on fuel consumption, NOx emissions and engine maintenance, even if the blend has been pre-approved. Warranty may be voided if non pre-approved marine fuels are used. Limited sea trial data to support long-term use of high blends. Specific engine models approved for varying blend limits.	Sea trials with gradual increase of blending are encouraged for higher blends. Check with manufacturers for a full list of supported engine models and latest technical guidelines. Further study required for blend above B50. Fuel COQ is an initial assessment required for fuel quality and biofuel compatibility.
Engine components and maintenance	Good solvency properties. Biodegradable nature and hygroscopic properties increase microbial growth in biodiesel. Higher water content may result in hydrolysis of FAME and formation of acid and alcohol. Poor oxidation and storage stability in blends with higher FAME content.	Negative effects on engine system, including deposit formation, filter clogging and chemical fuel-properties such as fuel-acidity and increased risk of corrosion. Restriction in material compatibility Oxidised biodiesel, if enters the engine's lubricant oil, can affect the ageing resistance of lubricant oil and formation of oil sludge. Higher boiling point means FAME does not evaporate but remains in the lube oil. Engine damage is possible under certain conditions that initiate chemical reactions between FAME and lube oil. Corrosion in fuel injection nozzle. Cold flow behaviour may gel and plug filters, hoses and transfer lines.	Fuel filter and lube oil change carried out after initial switch to FAME (25 to 50 operation hours for higher blends or at half the usual maintenance interval for intermediate blends B7 to B20.) Use recommended high quality filter material and lube oil. Monitor quality of lubricant oil and reduce oil change interval. Observe tank maintenance (low storage temperature, little water and oxygen). Fuel tank cleaning when shifting from diesel fuel to high FAME diesel fuel. Use recommended materials compatible with biofuels. e.g., nitrile hoses are not compatible. Avoid metals due to its catalytic effect on oxidation and avoid NBR sealing materials. Avoid contact with paint. Replace fuel hoses and sealings. Avoid long down-time (1-4 weeks) or flush fuel system and replace with B0. Ensure biodiesel pour point is appropriate for the climate of the application.
Fuel consumption and emission	Insignificant impact to fuel consumption for B5 to B7 Reduction in smoke, particulate matter Fuel temperatures is important and it depends on both biofuel quality and degree of processing.	Minor increase in fuel consumption for B20 and below. Noticeable increase in fuel consumption from B30 and above. Unsafe operation of engine and fuel system if fuel temperature if not maintained before fuel injection pump. Shortened lifetime of fuel injection equipment and fuel filter clogging.	Engine power correction are not permissible. Emission measurement for NO_x to ascertain NO_x levels Check and confirm fuel temperature requirement for fuel injection system before use

7.2 Biofuel-compatible Engine Mapping with Singapore Harbour Craft Registry

Using the information from MPA 2021 harbour craft database, an independent survey by MPA and recommendations from engine manufacturers, engine mapping of the biofuel compatibility of the harbour craft has covered nearly 83% of the total number of engines used by existing harbour craft. Figure 7.1 provides an insightful summary of the biofuel-compatibility of vessels and engines.

A key takeaway from the survey is that shipowners ought to approach their engine manufacturers to confirm the biofuel compatibility of their current engines and consider implementing all additional cautions for a new engine, as there are significant differences among engine manufacturers in their recommendations for high biofuel blends.

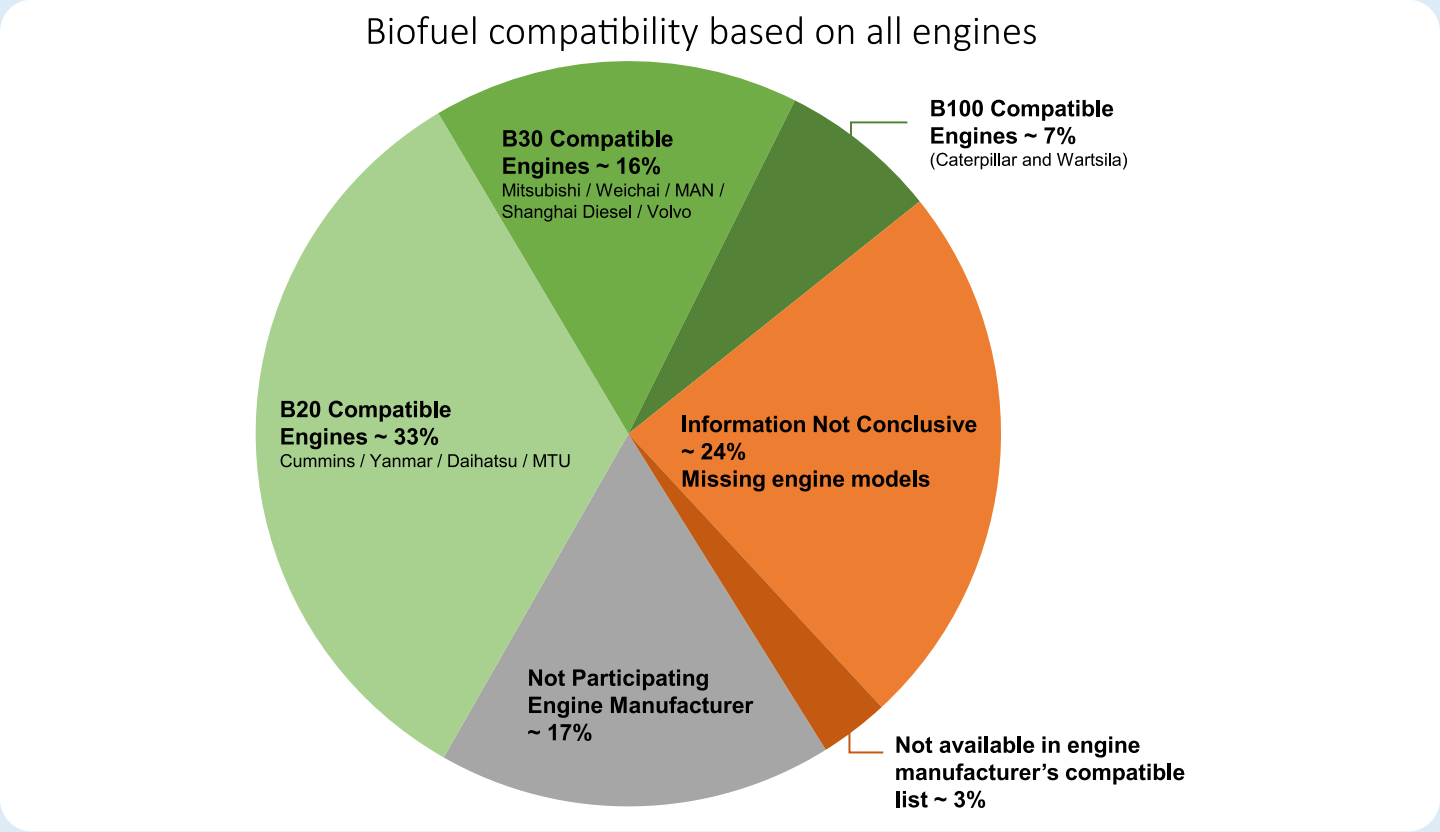

Figure 7.1 Overview from the engine mapping of the biofuel-compatibility for Singapore harbour craft

7.2.1 Engine mapping results (by engine brands)

The engine mapping covers 2,122 engines, which represents nearly 83% of the total number of engines in the 2021 database (2,561 engines). Based on identifiable engine models, it is possible to conclude that around 56% of the total number of engines are at least B20 biofuel-compatible. The remaining 44% of the engines are inconclusive, primarily due to missing engine models and non-participating engine manufacturers. The majority of the engines by participating engine manufacturers (68%) have been identified as biofuel compatible. The remaining gap (total of 687 engines) is termed as "inconclusive engines". The breakdown of the compatibility by engine brands is shown in Table 7.2. Caterpillar and Wartsila are two engine brands that support up to B100. It is noted that Wartsila has included a condition that the biofuel's fuel quality should meet Wartsila biofuel specifications. None of the engine manufacturers have concerns about the use of neat HVO in their engines if their fuel quality specifications are met.

Table 7.2 Breakdown numbers of biofuel-compatibility by engine brands

For Prefix (SB) (SC) (SP) (ST) (SR)

Engine Brand	Number of Surveyed Engines	Number of Compatible Engines	Percentage of Compatible Engines	Remarks	Percentage of the Compatible Engines out of 2,561 Engines
Cummins	584	503	86%	Up to B20	
Mitsubishi	353	35	10%	Up to B30	
Yanmar	327	258	79%	Up to B20*	
Weichai	273	251	92%	Up to B30	
Caterpillar	233	160	69%	Up to B100	
MAN	136	44	32%	Up to B30	
Daihatsu	92	84	91%	Up to B20**	
Shanghai Diesel	61	61	100%	Up to B30	
Volvo	25	16	64%	Up to B30	
MTU	21	6	29%	Up to B20	
Wartsila	17	17	100%	Up to B100***	
Total	**2,122**	**1,435**	**68%**		**56%**

* *B50 blend ratio is being tested on model 6N21A-EW*
** *For B20 to B30, consult the engine manufacturer. Note that for 6DLM Series, modification is required.*
*** *When BXX meets Wartsila biofuel B100 specification.*

7.2.2 Engine mapping results (by harbour craft prefix)

Figure 7.2 illustrates the number of compatible engines (for biodiesel blends ≤ B20) for five harbour craft prefixes and the total number of engines under each type of harbour craft and the engine brands. The engine mapping concludes that SB's engines have high biofuel-compatibility of 92% in the existing fleet, with 100% of the engines by Cummins, Weichai, Daihatsu and Wartsila biofuel-compatible. Only 35 engines are inconclusive. For ST harbour craft, 313 out of a total of 400 engines (survey numbers) are biofuel-compatible, achieving 78% compatibility. The remaining gap (total of 687 engines) is grouped as "inconclusive engines" due to the missing engine model numbers (89% of the inconclusive engines) or outdated engine models (11% of the inconclusive engines).

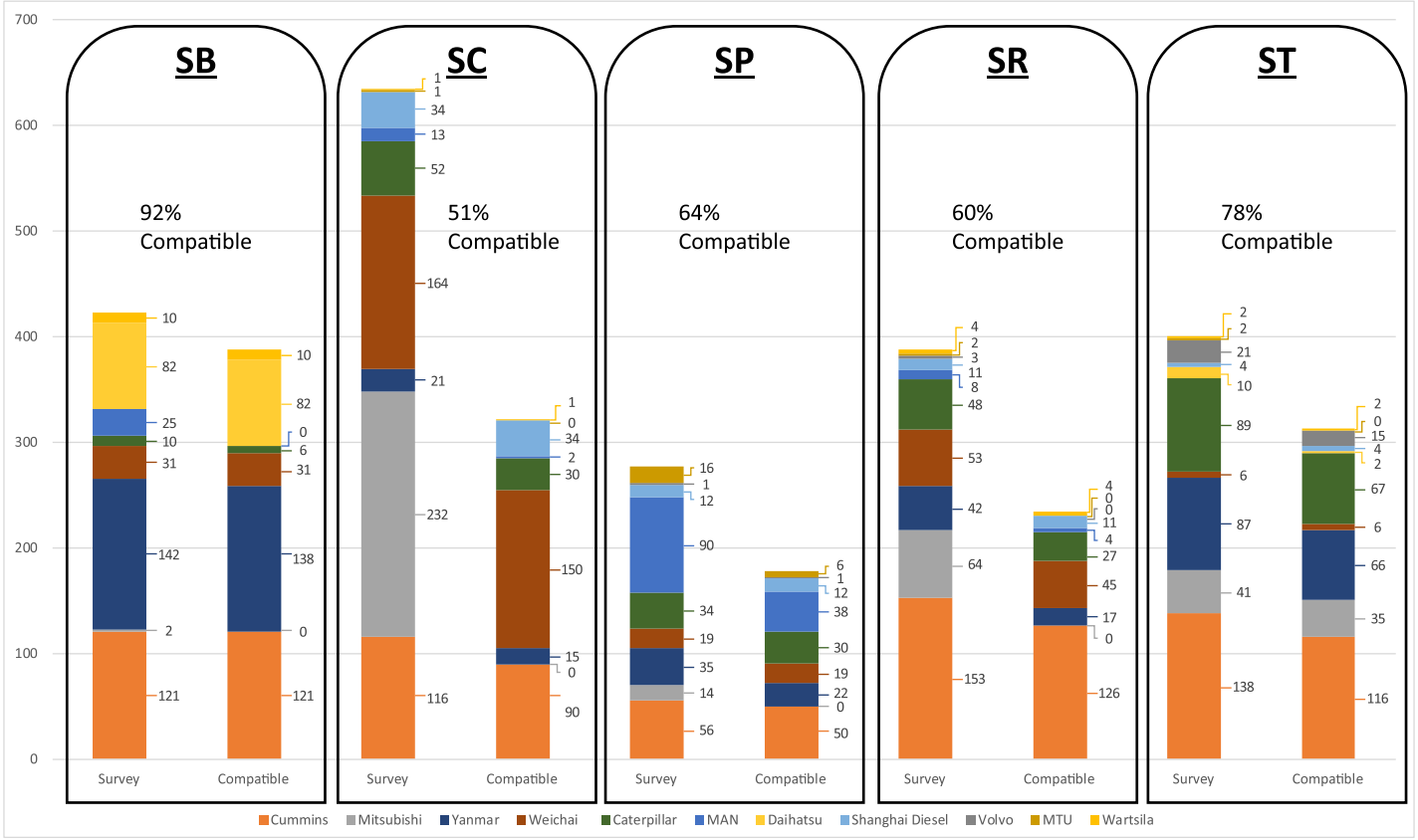

Figure 7.2 Distribution of biodiesel compatible engines for all prefixes of Singapore harbour craft

CHAPTER 8
CONCLUSION

The study has assessed the regional biofuel supply chains and presented three supply chain pathways for Singapore. The production of PME from the three main regional producers (Indonesia, Malaysia, Thailand) is the dominant supply of biofuel in Southeast Asia and has increased for the last 10 years, except for 2020 when the Covid-19 pandemic broke out. However, exports do not follow the production trend due to the strong domestic demand in compliance with the national mandates of the three regional producers. Exports from Thailand are negligible, while Indonesia is mandating higher biofuel blends for local use. Singapore, as a global bunkering hub, requires strategic planning to source and test new feedstock and develop close collaboration with suppliers to increase the availability of biofuel. Increased production of 2nd or 3rd generation biofuels, such as UCOME or advanced biofuels will lead to a more sustainable pathway.

Biofuel bunkering operations largely share the same infrastructure as conventional marine fuel. Before a larger scale adoption, the unique properties of biofuel, such as the storage stability, material compatibility, corrosiveness, heating value and miscibility with fossil diesel, shall be studied and addressed. Fortunately, a literature review shows a biodiesel spill during bunkering will cause a lesser environmental burden than hydrocarbon-based diesel fuels.

The lack of marine standards in terms of bunkering operations and fuel quality is a challenge. ISO 8217 is being revised to allow a higher percentage of FAME to be blended into distillate and residual fuel, setting benchmarks for both bunker sellers and buyers. Besides ISO 8217, it is found that EN standards provide good coverage and that parameters affecting cold flow and filter blockage are additional requirements as far as biodiesel is concerned.

Five parameters, which include viscosity, water content, acid value, oxidation stability by sediment, and oxidation stability by induction time (Rancimat test), were chosen to determine the biofuel storage stability. HVO blends met specifications during the 4-month long storage but PME and UCOME blends gave mixed results. Although the acid value and viscosity of all biofuel blends stayed within specifications over 4 months, the ingress of moisture was hard to avoid as B20 and B30 (PME and UCOME) went out of specifications after 2 months. The oxidation stability, as indicated by the Rancimat test, is equally challenging if the more stringent EN standard is referenced. The B100 PME, however, exhibits satisfactory stability even after four months, which highlights that cleanliness during blending and a well-maintained environment is critical for long-term biofuel storage.

The GHG emission savings can be estimated from methods that take full or partial consideration of the life cycle. There are three methods used: LCA, ISCC and IPCC. Although LCA provides a comprehensive analysis, there is no harmonised LCA approach for marine fuels. On the contrary, the GHG analysis by ISCC and IPCC provides more practical insights for industry and government agencies to shape their future strategy. Therefore, the study presents the ISCC and IPCC results. Based on ISCC guidelines, the GHG emission savings over the fossil fuel comparator by neat PME, UCOME and HVO are found to be at least 52.5%, 84% and 91.6%, respectively. Under the IPCC scheme, the GHG emission savings of the biofuel blends B20/R20 are around 18%.

Hands-on experience with biofuel running on an operational marine engine provides valuable information. It is necessary to prepare the vessel by taking into consideration of all potential compatibility issues. Good practices, such as re-calibrating fuel oil gauge, replacing fuel filters and lube oil and material compatibility checks on fuel storage and supply line were conducted prior to sea trial.

The sea trials have led to several observations on operation and maintenance. The test engine, Weichai WD-10 ran smoothly with all three biofuels at all blending ratios (B0 to B100) without retrofitting. Fuel injectors do not show significant change in atomisation, spray pattern, pressure of injection from those of MGO after sea trials, nor are there any abnormalities observed. The fuel oil filter and lube oil filter worked properly during the entire sea trial. However, bubble test during the maintenance reveals that the coarse fuel oil filter exhibits a minor leak from the end cap. In contrast to the common understanding that NBR material is non-compatible to biodiesel, the NBR seals and gaskets found on fuel oil filter and lube oil filter do not lose integrity except for a minor hardening upon physical inspection. The finding may deserve further investigation because materials used in dynamic conditions may undergo a much-retarded degradation than those in a stagnant environment. Throughout the sea trials, the fuel oil pumps do not show any abnormalities, which is further confirmed by maintenance inspection. Last but not the least, the engine wear and tear are monitored by analysing metal content from the lube oil samples from time to time. The concentration of worn-off iron in the lube oil only shows a slow and gradual increase after biodiesel blends are used. Lube oil testing shows a normal degradation, indicating that all biofuels used for the sea trial are compatible with existing lube oil.

An important observation from the sea trials is the change in specific fuel oil consumption. In the presence of many uncontrollable variables during a sea trial, the study relies on regression analysis to identify the significant impact factors from the use of biofuel. The LHVs of all biofuels, expressed volumetrically, affect the SFOC. Biofuel blends with higher LHV consistently exhibit lower SFOC and vice versa. Generally, FAME-based blends with MGO show higher SFOC than MGO, while HVO blends perform slightly better. Additional regression analysis also reveals that engine maintenance, engine speed and engine room temperature are significant factors affecting SFOC, as these are associated with the efficiency of the thermodynamic cycle. Similarly, the significant variables of exhaust gas emissions are identified. Engine speed or engine load affects CO_2, NO_x and CO emissions. Engine room temperature is positively associated with CO_2 and CO emissions and negatively associated with NO_x emissions. Maintenance is associated positively with CO_2 and NO_x emissions but not with CO emissions, which suggests that a comprehensive engine maintenance could help reduce CO_2 and NO_x emissions. Higher blends of HVO are found to have no significant impact on CO_2 and NO_x emissions and a slightly positive impact on CO emissions. Higher blends of FAME (PME and UCOME) are found to emit a slightly higher amount of CO_2 and NO_x, with a slight reduction in CO emission.

The key finding from assessing the potential economic factors is that the industry needs a clear and realistic mandate to use biofuels to account for the increase in fuel costs between MGO and biofuels. A push for a higher biofuel blend may not be viable without any economic incentives. Thus, the industry may initially use sustainable PME due to its high availability and lower cost. However, the use of waste and residues will lead to long-term sustainability and much lower GHG emissions based on ISCC guidelines.

The highlights from the survey with engine manufacturers and mapping exercise provide a snapshot of the current biofuel landscape in Singapore. Engine manufacturers express caution and additional maintenance in switching to biofuels but support biofuel-compatible engines at least up to B20. Shipowners are recommended to approach their engine manufacturers to confirm the biofuel compatibility of their current engines and consider implementing all additional cautions. The operational and maintenance requirements are largely in line with open literature and the findings from MESD's sea trial.

The future development of biofuel-compatible engines is positive as engine manufacturers have mostly supported to adapt to B30 and B50 with long-term tests. Doubts on the sustainability and availability of feedstock are a concern for engine manufacturers with net-zero carbon sustainability goals, and the preference is to support the use of higher blends on a demand basis.

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