CHARACTERIZATION AND THE EFFECT OF WASTE PLASTIC OIL IN A DIESEL ENGINE

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RESEARCH REPORT SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

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ABSTRACT

The world currently relies heavily on conventional fuels such as diesel and petrol for its main source of energy supply. This has affected the environmental balance as has caused climate change and environmental pollution. Pollution such as plastic waste is also very common, leading to ocean bio habitat and ecosystems damage. Currently the solution to such plastic pollution is by burial in large landfills or by incineration. An innovative idea has come up in recent years in utilising the waste plastics into usable fuel, solving two of the largest issues faced by the global community with a solution. The purpose of this study is to investigate the suitability of Waste Plastic Oil (WPO) and various proportions of blends between WPO and Waste Cooking Biodiesel (WCB) as fuel in diesel engines. Sample of Malaysian pump diesel of B10, 100% Waste Plastic Oil (WPO) as well as samples of blend WPO 90 (90% waste plastic oil, 10% waste cooking biodiesel), WPO 80 (80% waste plastic oil, 20% waste cooking biodiesel) and WPO 70 (70% waste plastic oil, 30% waste cooking biodiesel) were tested for lubricity. The samples tested were then further analysed and undergone engine testing to determine the engine performance running on the respective fuels. Among the tested samples, all well capable of achieving the lubricity and performance similar to or better than of the B10 diesel. The fuels calorific values showed a decreasing trend with increasing WCB content. Content on pollutants such as eicosane tend to be higher with blends with lower WCB content. The physical property of the WPO 90 and the added advantage in terms of its fuel consumption placed it the most suitable fuel to replace the currently available B10 diesel in the market.

ABSTRAK

Dunia pada masa ini sangat bergantung kepada bahan api konvensional seperti diesel dan petrol daripada sumber utama bekalan tenaganya. Ini telah menjejaskan keseimbangan alam sekitar kerana telah menyebabkan perubahan iklim dan pencemaran alam sekitar. Pencemaran seperti sisa plastik juga sangat biasa, menyebabkan habitat bio lautan dan kerosakan ekosistem. Pada masa ini penyelesaian kepada pencemaran plastik tersebut adalah dengan pengebumian di tapak pelupusan besar atau dengan pembakaran. Idea inovatif telah muncul dalam beberapa tahun kebelakangan ini dalam menggunakan sisa plastik menjadi bahan api yang boleh digunakan, menyelesaikan dua daripada isu terbesar yang dihadapi oleh komuniti global dengan penyelesaian. Tujuan kajian ini adalah untuk menyiasat kesesuaian Minyak Plastik Sisa (WPO) dan pelbagai perkadaran adunan antara WPO dan Biodiesel Minyak Masak Sisa (WCB) sebagai bahan api dalam enjin diesel. Sampel pam diesel Malaysia B10, 100% Minyak Plastik Sisa (WPO) serta sampel campuran WPO 90 (90% sisa minyak plastik, 10% biodiesel minyak masak sisa), WPO 80 (80% sisa minyak plastik, 20% biodiesel minyak masak sisa) dan WPO 70 (70% sisa minyak plastik, 30% biodiesel minyak masak sisa) telah diuji untuk pelincirannya. Sampel yang diuji kemudiannya dianalisis dan menjalani ujian enjin untuk menentukan prestasi enjin yang berjalan pada bahan api tertentu. Di antara sampel yang diuji, semuanya berkemampuan untuk mencapai pelinciran dan prestasi yang serupa atau lebih baik daripada diesel B10. Nilai kalori bahan bakar juga menurun dengan penigkatan kandungan WCB. Bahan kimia pecemaran seperti eicosane juga meningkat apabila kandugan WCB menurun dalm sampel. Sifat fizikal WPO 90 dan kelebihan tambahan dari segi penggunaan bahan apinya meletakkannya sebagai bahan api yang paling sesuai untuk menggantikan diesel B10 yang sedia ada di pasaran.

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LIST OF SYMBOLS AND ABBREVIATIONS

WPO	:	Waste Plastic Oil
WCB	:	Waste Cooking Biodiesel
HFRR	:	High Frequency Reciprocating Rig
GC-MS	:	Gas Chromatography Mass Spectroscopy
BSFC	:	Brake Specific Fuel Consumption
DI	:	Direct Injection
IDI	:	Indirect Injection
EGT	:	Exhaust Gas Temperature
COF	:	Coefficient of Friction
PE	:	Polyethylene
PP	:	Polypropylene
UDPE	:	Used Low Density Polypropylene
IICS	:	Indirect Injection Combustion System
DICS	:	Direct Injection Combustion System
NOx	:	Oxides of Nitrogen
VGT	:	Variable Geometry Turbo

CHAPTER 1: INTRODUCTION

1.1 Background

A diesel engine is a type of heat engine developed by its inventor Rudolph Diesel in the late 19th century (Lynwood, 1976). This form of engine has been powering the machinery and industry of the modern world. The diesel engine in its infancy was powered by peanut oil as its source of fuel (Ayhan, Progress and recent trends in biodiesel fuels, 2009; Mohd Noor, Noor, & Mamat, 2018). However, diesel engines now are primarily powered by petroleum diesels. This however is not practical as the source of fossil fuel is depleting. Fossil fuels reserve were estimated to be depleted by the year 2040 (Shahriar & Erkan, 2009). This effect is also driven by the fact that the discovery of new fossil fuel reservoir peaked in the 60s and 70s, and hence steadily plateaued since (Inigo, Margarita, Carlos, Oscar, & Luis, 2014). Also the consumption of oil and other fossil fuel are expected to increase to 106 million barrels daily by the year 2030 (Hisham, Ayub Khan, A.Aljilil, & Ghasemi, 2019). Hence, this undoubtedly requires alternative fuel to run our current infrastructure and the machines of industry.

The goal of this current research is to study on "The Characterization and Effectst of Waste Plastic Oil in a Diesel Engine. An alternative or a substitute to the current petroleum-based diesel fuel has been the interest of many industrialists and scientist. The most common alternative suggested by expert is there of a palm oil-based diesel, a form of biodiesel, or a blend of both petroleum diesel and biodiesel (Ayhan, 2009). This option is widely preferred in tropical countries, whereas soybean oil is commonly used in the Americas and rapeseed oil in Europe (Ayhan, 2007). This option whilst being popular and currently available in the consumer market, has a few drawbacks. Biodiesel or blends of biodiesel generally has lower heating value or more commonly known as energy density (Yaakob, Mohammad, Alherbawi, Alam, & Sopian, 2012).

Another common issue raised with the current industries is the amount of plastic waste being produced and accumulated as waste, with majority polluting the aquatic environment. Despite our mitigation, experts estimate nearly 23 million metric tons of plastic waste will end up in the ocean by the year 2030, a mere 11% of the total plastic waste our industrialized society generates (B. Borrelle, et al., 2020). Industries prefer plastics due to its corrosion resistance, durability, lightness, and cheap cost (G.B Derraik, 2002). Due to this advantages, plastic waste production has been steadily increasing from 1.5 million tonnes in the 1950s to 299 million tonnes in 2013 (Li, Tse, & Fok, 2016). The cumulative plastic production around the world has now exceeded 7 billion tonnes from the year 1950 to 2015 (Geyer, Jambeck, & Law, 2017). Experts even estimates our annual plastic production to exceed the 600 million tonnes mark by the year 2040. (Shams, Alam, & Mahbub, 2021)

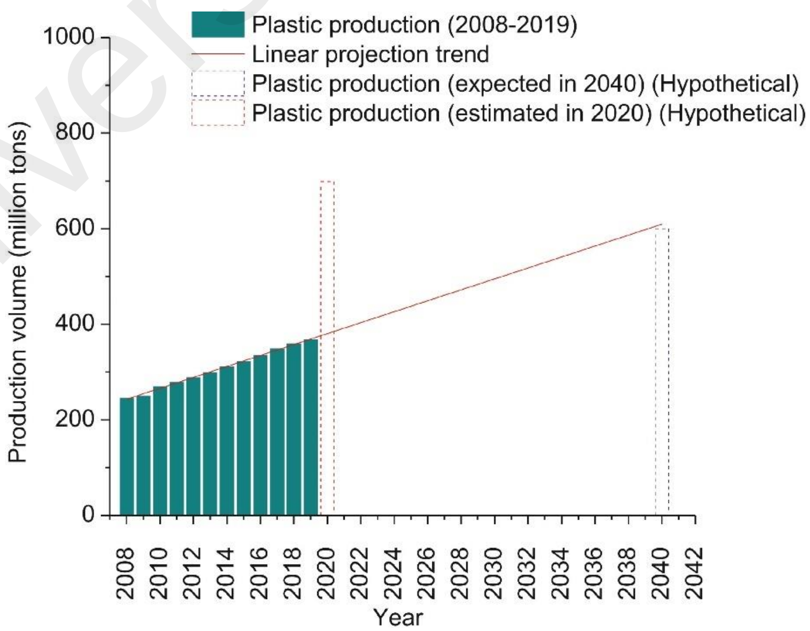

Figure 1: Expected Plastic Production by the Year 2040 (Shams, Alam, & Mahbub, 2021)

The current methods available in disposing of plastic waste is by landfills, incinerations, or recycling (Wong, N., Abdullah, & Inuwa, 2015). However, this current methods of disposing plastic waste comes with problems of its own. Excluding the quaternary chemical recycling, the other method of recycling is far from a sustainable solution. In chemical recycling, the goal is to convert the waste plastic polymers into monomers. This monomer is then used a feedstock for industrial processes or as fuels (Achyut, Singh, & Mishra, 2010).

Therefore, in recent times there has been a surge in the scientific and the engineering community to produce liquid fuels from plastic waste that are suitable, relatively clean and provides reliable power especially in diesel engines without major modifications or alterations in the current engine architecture. This research therefore approaches the matters stated above by utilising plastic waste as a source of fuel to overcome our societies and industry's heavy reliance on fossil fuel.

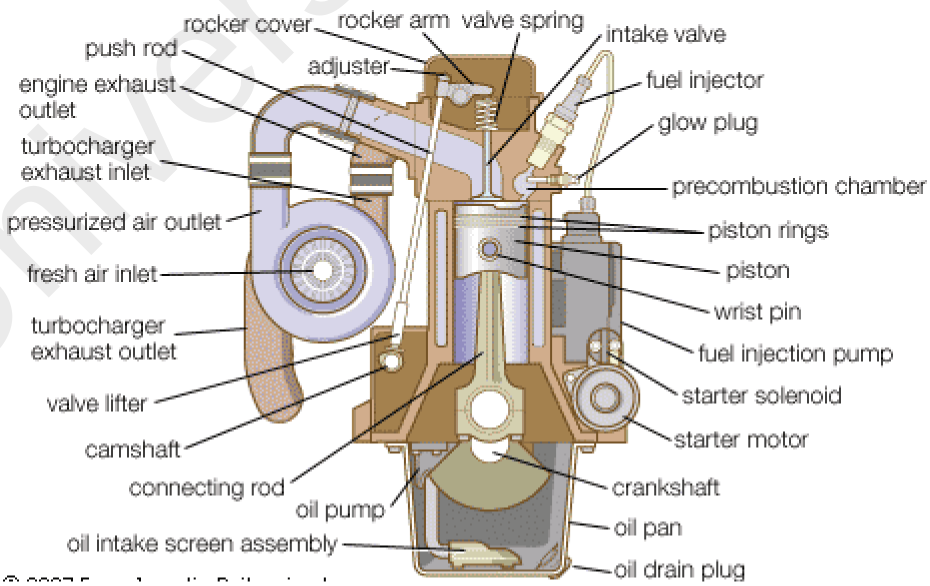

Figure 2: Typical Layout of a Modern Diesel Engine

1.2 Research Background

Diesel engine is the most common source of fuel in the industrial and commercial sector. This includes the marine, trucking and even remote electricity generation facilities. The current diesel engines rely heavily on petroleum-based diesel, despite the introduction of biodiesel blends. Common biodiesel also has inherent disadvantages does prevent a 100% adoption of the said fuel. Biodiesel especially sourced from soy and palm oil has shown signs of swelling of nitrile rubber and polychloroprene, a common material used automotive and industrial machinery hoses. This is mainly due to the elastomers being degraded when in contact with solvent such as biodiesel (Coronado, et al., 2014). Studies also indicate biodiesel tends to be more corrosive to engine metallic parts (Haseeb, Fazal, Jahirul, & Masjuki, 2011). This effect hinders the mass adoption of a 100% biodiesel fuel in diesel engine. Aa alternative to this problem would be using Waste Plastic Oil (WPO) or its blends.

WPO is a form of oil produced by a process of pyrolysis. Pyrolysis is process in of thermally degrading polymers with long chain molecules into smaller, simpler molecules through a high temperature and high-pressure process at oxygen free environment (Anuar Sharudin, Abnisa, Wan Daud, & Aroua, 2016). There are 3 products produced in the pyrolysis process, namely oil, gas and char. Pyrolysis is often the preferred technique as if has the highest oil yield, compared to other methods. Research has shown a yield of 80% WPO from the pyrolysis process (FakhrHoseini & Dastanian, 2013). In this process it is common to utilise catalyst as a method to further increase the WPO yield, however the catalyst used varies from the type of plastics used as the pyrolysis process feed stock (Singh & Ruj, 2016). Other common method of converting waste plastics to WPO are namely catalytic cracking, vacuum cracking, and thermal cracking (Kundan, T.T.M. Kannan, & Ashutosh Das, 2020)

The commonly used catalyst is such as zeolite and silica alumina for WPO made from Used Low-Density Polyethylene (UDPE) (Soundararajan, Devan, & Pitchandi, 2020). The other common type of catalyst used, are like Iron, Copper, and Nickel for the pyrolysis process (Yamada, Kiatkittipong, & Tagawa, 2022). Another common type of catalyst used for WPO made from High Density Polyethylene (HDPE) are metal oxide impregnated waste brick kiln dust (Ahmad, et al., 2016). catalyst used can improve the yield of WPO from the feedstock immensely. The mass adoption of WPO is also highly driven by the applicability and availability of the catalyst for the suitable fuel.

1.3 Research Problem

Developing a commercial mass consumption fuel is very challenging. Besides the current lack of infrastructure to organize such level of adoption, there is also the problem of technical and regulatory requirement. Diesel engine may be a common sight in around the world, however there is the problem of compatibility of WPO to these engines. The WPO proposed should also be able to perform all the function or perform better than the current petroleum-based diesel available at the pumps or in the consumer market without side effects such as low reliability or high emission. The nature of WPO or its blends may impose great threat to this. This paper discusses in detail the suitability of WPO in terms of, performance, automotive part compatibility, calorific value and lubricity of WPO and its blends in a common diesel engine.

1.4 Research Objective

- To investigate the lubricity of WPO and its blends as diesel fuel in a compression ignition diesel engine
- To investigate the performance of diesel engine running on WPO and its blends

1.5 Research Significance

This research will contribute the knowledge pool in the field of diesel engines focusing on the WPO as its fuel. This paper then takes into consideration the operational conditions, reliability, and the emission compliance of this fuel with the modern emission regulation as well as a comparison with the currently available petroleum-based pump diesel. Issues studied includes whether WPO or any of its blends affects on the lubricity of the moving metallic parts in engine while providing adequate power.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, this paper will discuss on the current technology, theories and experimental outcome on diesel engine running on WPO and its various blend of WCB at a molecular level. The fuel reaction must be studied as it indicates the diesel engine performance and general operating conditions. The environment in the combustion chamber in a diesel engine warrants various sorts of fluctuations in engine performance. A common diesel engine running on petroleum-based pump diesel operates at a cylinder temperature of 1500°C or 1770°K and at a cylinder pressure of 7MPa (Moldovanu, Baldean, Burnete, & Jurchis, 2018).

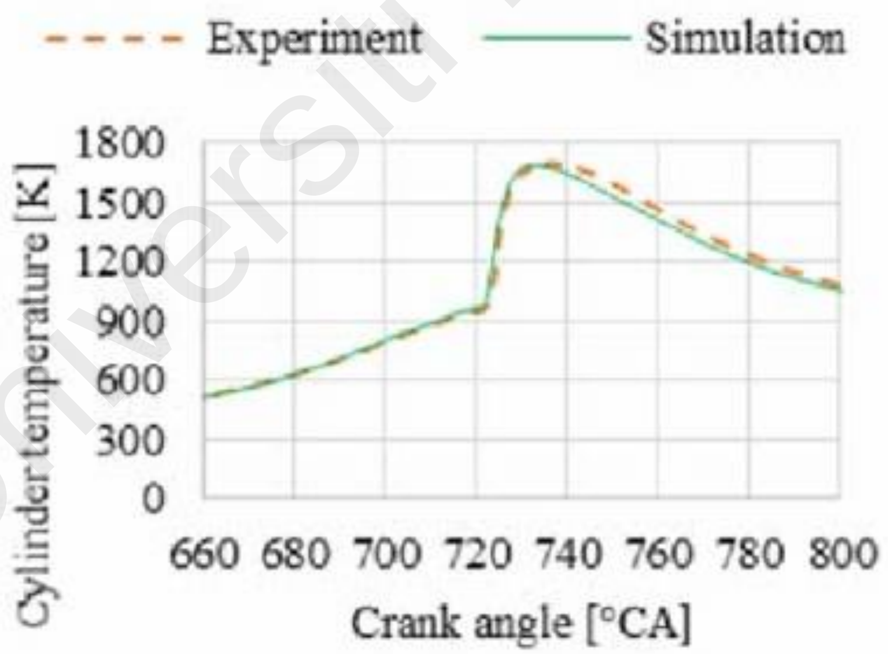

Figure 3: Cylinder Temprature in a Common Diesel Engine

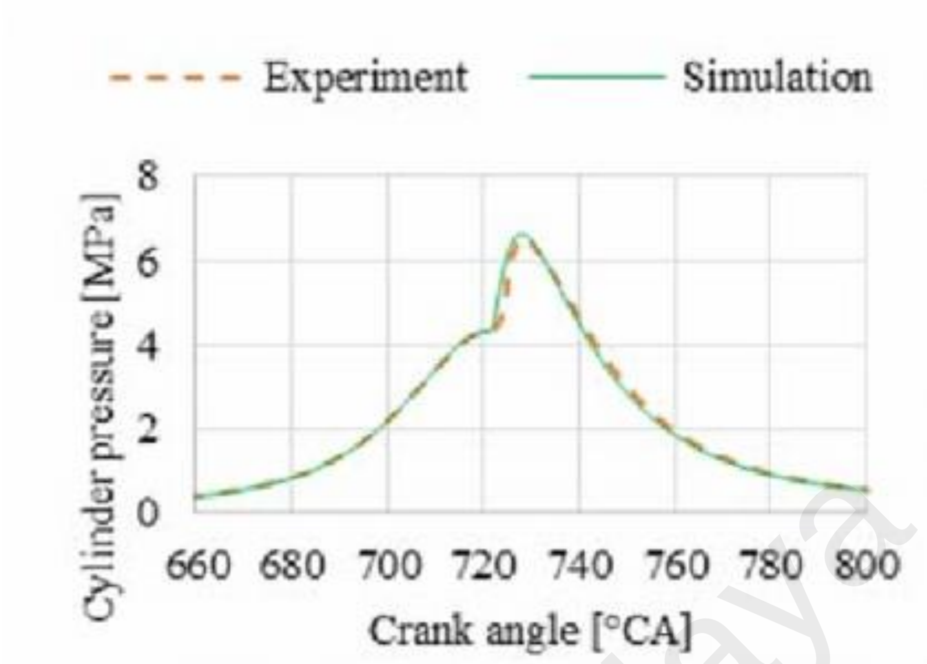

Figure 4: Cylinder Pressure in a Common Diesel Engine

This chapter discusses the various factors governing the suitability of a diesel engine running on WPO and its blends with WCB. The governing factors discussed will be on the fuel delivery system, engine aspiration, types of fuel blends and rection with automotive fuel line parts.

2.2 Fuel Delivery System

Diesel engines are the driving force of our economy. There are commonly 2 types of diesel engine fuel delivery system configuration namely the Indirect Injection Combustion System (IICS) and Direct Injection Combustion System (DICS) (Huang, et al., 2011). Of course, these systems were available in the market decades after the inventor, Rudolph Diesel's solid injection system (Lynwood, 1976). However, the antiquated solid injection system would not be discussed further as the system is now obsolete and not currently actively present in the mass consumer market nor the industrial market.

Among the 2 types of fuel delivery system stated earlier, the IICS is of a older design (Huang, et al., 2011). As the name would suggest the IICS system utilises and pre chamber before the charged is delivered to the main combustion chamber. Research has shown that the IICS system generally has a lower thermal efficiency, hence resulting in higher fuel consumption. However, due to the lower injection pressure, this fuel delivery system is much more robust and function well on lower quality fuel such as high sulphur content, impurities and relatively lower lubricity. Due to the reliance of ignition delay, the IICS systems could not operate at high revs since the effects of ignition delays becomes less significant at those speeds. (Huang, et al., 2011; Rakopoulus, Antonopoulos, Rakopoulos, & Giakoumis, 2006). Research has also shown, at high loads an engine equipped with the IICS system, the Brake Specific Fuel Consumption (BFSC) also increases when the Exhaust Gas Recirculation (EGR) is present (Ghazikhani, Feyz, & Joharchi, 2010; Jafarmadar, 2013). These limits balance out the NOx emission control and engine efficiency target. This may indicate to reason why IICS systems are currently falling out of favour in diesel engine application.

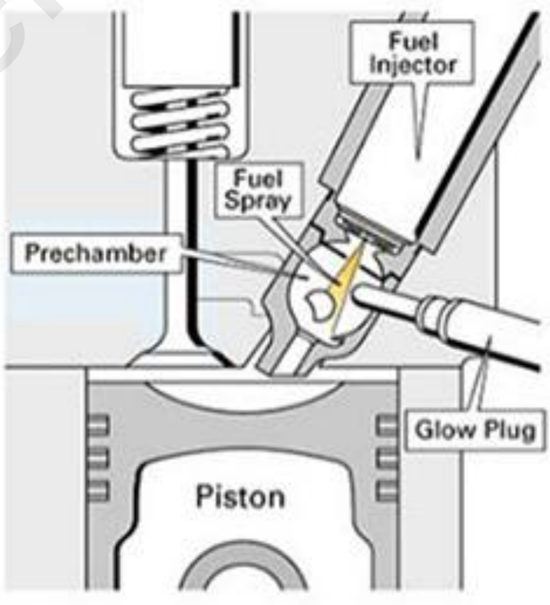

Figure 5: IICS Fuel Delivery System

The other common type of fuel delivery system in diesel engine in the DICS system. The DICS negates the need for a pre-chamber altogether, as the fuel is atomized and injected directly into the combustion chamber of the engine at very high pressure. It is not uncommon to find DICS systems operating at a pressure of 1600 bar (Guerrassi & Dupraz, 1998). DICS systems unlike the older IICS systems has much higher thermal efficiency, Research has shown the DICS system provides a 10% improvement in fuel economy compared to the IICS systems, an indication to the prior's better thermal efficiency (d'Ambrosio, Ferrari, Mancarella, Manco, & Mittica, 2019; Monaghan, M L;, 1981). Another common advantage of DICS system is the implementation of implementing different injection strategy, a technique which in incapable to be replicated in the IICS system (Fayad, 2019). The DISC system, with its high fuel atomization and good fuel oxygenation, has very good fuel efficiency and low soot, however it's also increases the engine's Oxides of Nitrogen (NOx) emission. This is known as the Soot/NOx trade-off (Rakopoulos, Antonopoulos, Rakopoulos, Hountalas, & Giakoumis, 2006). A common method to circumvent this issue in DISC equipped engines is by installing an Exhaust Gas Recirculating (EGR) system, however this system too has drawbacks such as increased particulate emission, increase fuel consumption while reducing lubricity (Cadman & Johnson, 1986; Gan, Ng, & Pang, 2011; Ladommatos, Abdelhalim, & Zhao, 2000). This will result in low engine durability an effect that would be further compounded with running on fuels with lower lubricity. Despite this, DISC equipped diesel engine are the most common type of diesel engines for passenger cars and light utility vehicles. This is mainly due to the emission control advantage and the better fuel efficiency provided by the DISC systems.

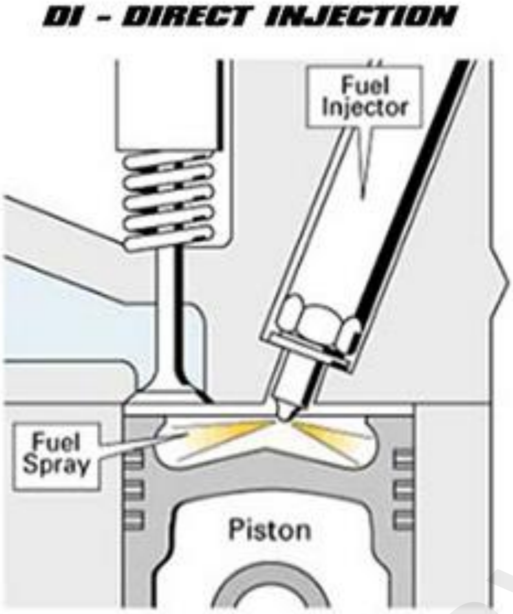

Figure 6: DICS Fuel Delivery System

2.3 Engine Aspiration Systems

In this section, the types of engine aspiration will be discussed. In diesel engines, there are 2 types of engine aspiration. Namely, natural aspiration and force inductions, Diesel engine has by design suitable for force induction in terms of additional supply of air into the fuel mixture meant to be combusted, especially turbocharging. Turbocharging is a form of force induction utilises the expansion gasses in the turbine of the exhaust leaving the cylinder to compress air leading to the inlet to the cylinder (Giakoumis, 2016).

Previous studies utilising naturally aspirated and turbocharged diesel engines running on palm biodiesel to obtain higher thermal efficiency in an turbocharged setting compared to a non-turbocharged setting (Arbab, et al., 2015). This reflects as a general reduction in fuel consumption. A turbocharged diesel engine however undergoes a large power transient period especially to engine load and speed changes, unlike its naturally aspirated counterpart which provides a liner power delivery (Rakopoulos & Giakoumis, 2006).

During this transient period, the diesel engine undergoes increase in emissions, reduce drivability and performance. This phenomenon is commonly referred to as turbo lag (Wrinkler & Angstrom, 2008). The main cause of turbo lag is attributed to the increase in exhaust gas power generated being incapables to instantaneously increasing the torque at the turbine, an effect mainly causing by increase loss of heat to the exhaust manifold and cylinders (Mavropoulos, 2011). This parameter is crucial in determining the engine performance.

2.4 WPO and WCB Blends

In this section, the different aspect of WPO, WCB and its blends are discussed. Key parameters such as the fuel lubricity and fuel calorific value will be analysed in further detail.

2.4.1 Fuel Lubricity

Diesel engine utilises many moving parts to function. As these parts are often metal to metal, lubrication is a key criterion. Also as discusses in the previous sections. Modern DICS fuel delivery system function on very key pressures. This then compounds the need for proper fuel lubricity to fuel pump or other internal fuel delivery system damage. In a diesel engine, the fuel pump bearing, and assembly is self-lubricating, while being submerged in the diesel fuel in the tank (Awang, et al., 2021). According to previous research conducted, mixing biodiesel or castor oil biodiesel increase the blends overall lubricity between 10% to 15% compared to plain WPO comprising of polyethylene and polystyrene. When ran on a High Frequency Reciprocating Rig (HFRR), the wear scar diameter was greatly reduced up to 2.62% when a blend of WPO and biodiesel is used compared to plain WPO (Kaewbuddee, et al., 2020).

Another study comparing 3 samples namely pyrolysis oil comprised of plastic from Low Density Polyethylene (LDPE), Polyolefin 8 and trimethyl propane trioleate. In this case, the pure plastic pyrolysis oil displayed the worst lubricity. It was also found that, the lubricity of the fuel decreases with increasing percentage of plastic oil in the blend. However, it should be noted that the blends of plastic oil did have better than the petroleum-based diesel (Awang, et al., 2020). This phenomenon can be explained by the fact that the long chain polymers from the plastic waste. Previous studies have proven than synthetic based oil can reduce the coefficient of friction (COF) by providing enhanced lubrication (Wang, et al., 2019; Zhang, Tan, & Spikes, 2017).

Another key reason to why blends of biodiesel improve the lubricity of fuel is the fact that fatty acids has better lubricating features than hydrocarbons due to the imparting oxygen atoms. This feature is also present in monoacylglycerols and glycerol where their free OH group. Research has also show that among the OH, NH_2 and SH groups, oxygen leads to the best lubricity compared to nitrogen or sulphur (Hu, Du, Li, & Min, 2005; Knothe & Steidley, 2005).

2.4.2 Fuel Consumption and Calorific Value

For automotive and industrial application, diesel engines are required to operate for adequate time under relatively high speeds. Research conducted in the Nordic region has shown that range anxiety is one of the main reasons hindering the adoption of electric vehicles in that region (Sovacool, Kester, Noel, & De Rubens, 2019). This indicates the need for vehicular range in mass adoption alternative fuels. Fuels that could provide longer range or operating times, has lower downtime due to the refuelling process. The key item driving the range is the fuel consumption and the fuel calorific value. In this section, these items are discussed and analysed in detail for WPO and its WCB blends.

Fuel calorific value of fuel measures the energy content in the fuel. The calorific value of WPO is heavily dependant of the raw feed of plastic used in the pyrolysis process. Previous studies have shown as follows:

Table 1: Calorific Value of WPO and it's Feedstock

No	WPO Composition	WPO Calorific Value (MJ/kg)	Control Diesel Calorific Value (MJ/kg)	Source
1	1. Polyvinyl Chloride 2. Polypropylene	43.5	44.2	(Kaimal & Vijayabalan, 2015)
2	1. Various Plastic Waste	43.388	42.5	(Senthilkumar & Sankaranarayanan, 2016)
3	1. Polyethylene 2. Poly-ethene terephthalate	41.254	42	(Singh R. K., Ruj, Sadhukhan, Gupta, & Tigga, 2020)
4	1. Municipal Solid Plastic Waste	41.585	42	(Sachuthananthan, Raghurami Reddy, Mahesh, & Dineshwar, 2018)
5	1. Styrene Butadiene 2. Polyester 3. Clay 4. Ethylene-Vinyl Acetate 5. Rosin 6. Polyethylene 7. Polypropylene	38.3	42.9	(Kalargaris, Tian, & Gu, 2017)
6	1. Low Density Polyethylene	40.37	45.5	(Singh, Rajak, Dasore, Muthukumar, & Verma, 2021)

Table 1 shows that the calorific value of WPO is highly driven by the types of plastic used in the feedstock but generally has a lower calorific value than pure petroleum-based diesel.

The calorific value of biodiesel is generally lower than of WPO or petroleum-based diesel. However, Table 2 indicates all the relevant types of biodiesels and its calorific value.

Table 2: Types of Biodiesel and it's Calorific Value

No	Type of Biofuel	WPO Calorific Value (MJ/kg)	Source
1	Soybean	39.48	(Oliveira & Da Silva, 2013)
2	Jatropha	39.455	
3	Rapeseed	39.458	
4	Crambe	40.564	
5	Palm Oil	38.5	(Bari & Hossain, 2019)
6	Sunflower Oil	37.1	
7	Waste Cooking Biodiesel (WCB)	37.2	(Sahar, et al., 2018)

Referring to Table 2, it is common for biodiesels to have lower calorific value compared to the petroleum-based diesel fuels. This can be explained by the fact that caloric value of fuels are directly proportional to the size of carbon chain of ethyl ester in the fuel. Unlike petroleum diesels, biodiesel is a mixture of different ethyl ester compound leading to the lower calorific value (Oliveira & Da Silva, 2013). Previous researchers has concluded that, biofuels such as palm oil are suitable alternative fuel to the existing diesel engines (Kalam & Masjuki, 2002). However, it should also be well noted, that that due to biodiesel's generally lower calorific value, the fuel consumption of a diesel engine running on any biodiesel tends to have higher fuels consumption. Previous research has found the BSFC of biodiesel to be 10% higher than of petroleum-based diesel engines. Despite the fact that biodiesels have additional availability of oxygen in the fuel molecules and potentially assist in the combustion process's efficiency (Bari & Hossain, 2019). This paper than would looking further into the calorific value and fuel consumption of diesel engines running on WPO and WCB.

2.5 The Effect of WPO on Automotive Fuel Line Components

Fuel compatibility is a key factor in determining the suitability of fuels in engines. In a diesel engine, fuel goes through 3 different system in a full cycle. Namely fuel feed, combustion, and exhaust system (Haseeb, Fazal, Jahirul, & Masjuki, 2011). Based on previous research conducted, the position, engine block and other internal system on a diesel engine is made from aluminium and cast iron (Cole & Sherman, 1995). For the fuel injector and pump, it is common to use materials from copper and its alloys (Sgroi, Bollito, Sarraco, & Specchia, 2005). Common part such as the fuel nozzles, valves and fuel filter as made of stainless steel (Fazal, Haseeb, & Masjuki, 2011). Meanwhile, fuel liner a commonly made from cast iron (Shahabuddin, et al., 2021). Previous research has also indicated that materials made from copper and aluminium has the highest susceptibility of reaction with biodiesel, however, stainless steel materials was not as affected (Fazal, Haseeb, & Masjuki, 2010). All these different materials react differently to the WPO and WCB resulting in corrosion and other types of failure depending on the material. However, not much research has been conducted on the effects on pure WPO on automotive parts. Despite this, previous research has indicated a generally lower lubricity value for lubricity for WPO compared to petroleum-based diesel (Sharma, Moser, Vermillion, Doll, & Rajagopalan, 2014).

Several corrosion inhibitors can be used to mitigate corrosion on cast iron part. Research has shown that tert-butylamine has the best corrosion inhibition properties. This can be explained by the fact that the corrosion inhibitors adsorbed to the reactive surface of the metal, effectively preventing oxygen and water reacting on the metal surface, forming oxide layer (Fazal, Haseeb, & Masjuki, 2011). This then in turn reduces the corrosion rate on the metallic parts in the fuel delivery system and internal parts for the engine.

2.6 Summary

In this section, it was investigated, studies and analysed the different parameters that is playing a key parameter for WPO in diesel engine. Previous studies have indicated that the key parameters to consider in determining the applicability of WPO and WCB blends are driven by the type of fuel delivery system, type of engine aspiration, type of fuel blends and the overall reaction of the said fuel on the engine parts. The result of this parameters are highly dependent on each other and would reflect the ability of WPo and WCB blends to be a viable alternative to the current petroleum based diesel fuels aviable in the market.

This paper will then discuss the laboratory experiment and result in testing the WPO and WCB blends in determining the lubricity of the fuel, fuel consumption and power generation. The experimental setup will be the discussed in depth in the upcoming section.

CHAPTER 3: METHODOLOGY

3.1 Flow Chart

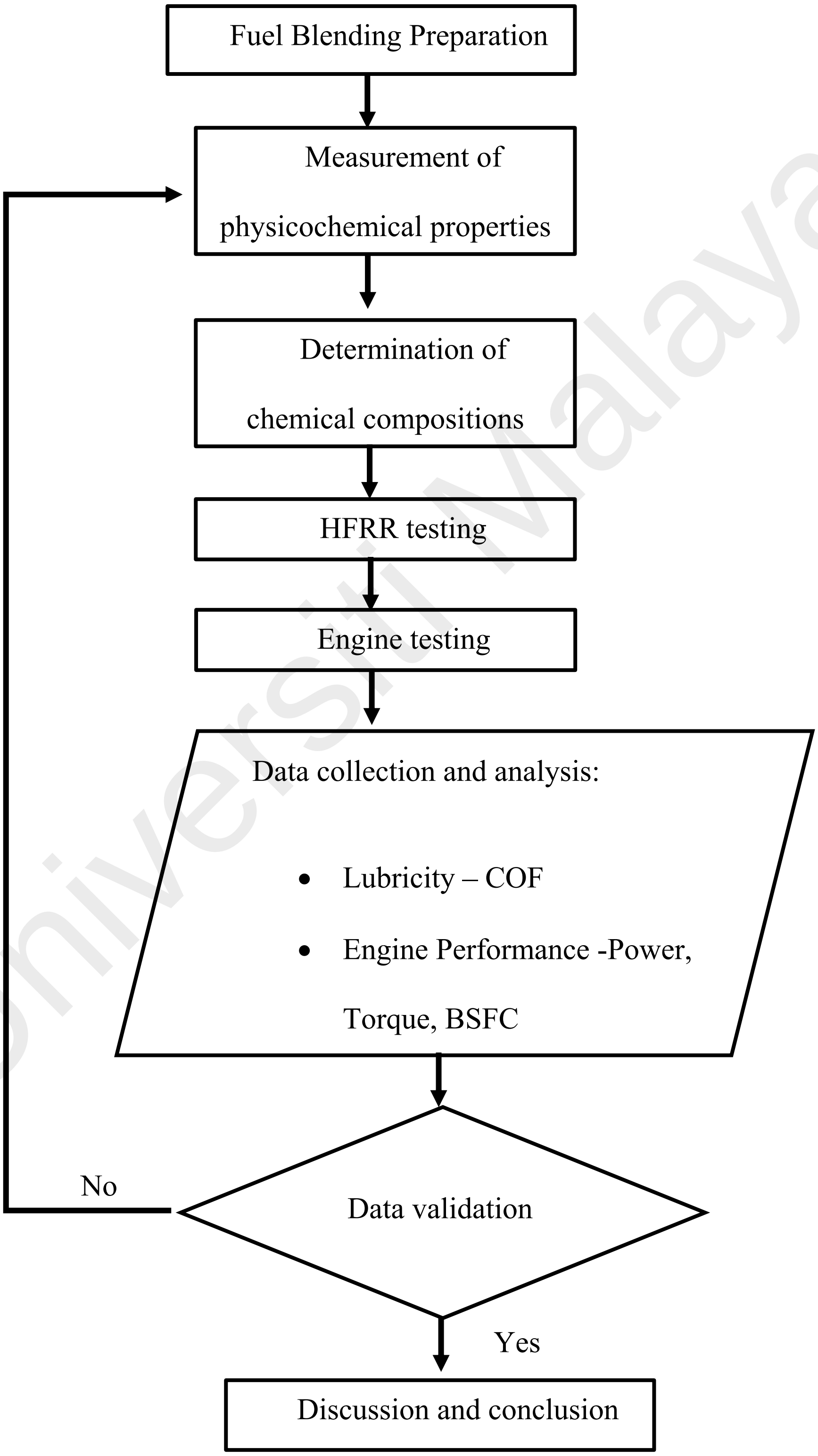

Figure 7: Flow chart of research methodology

3.2 Sample Preparation

The sample for WPO 90 ire prepared by the following steps and procedures:

I. A sample of total 1000ml is required

II. Measure a WPO of 900ml in a measuring cylinder (90% WPO)

III. Measure WCB of 100ml in a measuring cylinder (10% WCB)

IV. Fix both WPO and WCB into fluid container.

V. Stir the mixture using a magnetic stirrer for 30 minutes

VI. Upon stirring, separate the mixture to 200 ml for lubricity test and 800 ml for engine testing

VII. Repeat above steps for WPO 80 and WPO 70 with the appropriate WPO to WCB ratio

For WPO 100 , B10 Malaysian pump diesel samples, 1000 ml is required. No blending and stirring is required for sample preparation. While for the WPO 0 sample, only 200 ml is required as this sample will not undergo engine testing. A detail analysis shall be discussed in the upcoming sections.

Figure 8:Magnetic Stirrer

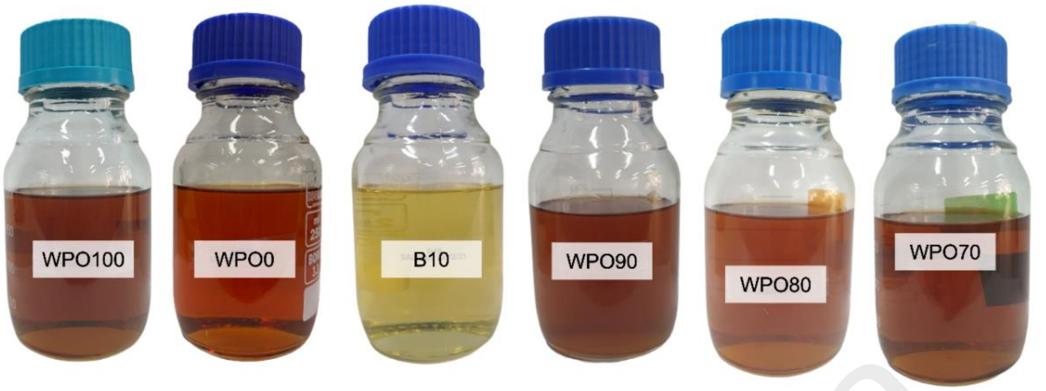

Figure 9:Prepared Fuel Samples

Malaysian standard B10 pump diesel and 100% WCB (WPO 0) will also be used as a control sample. The details of the samples are indicated in the table below:

Table 3: Fuel Samples

No	Label	Composition
1	WPO 100	100% Waste Plastic Oil
2	WPO 90	90% Waste Plastic Oil, 10% Waste Cooking Biodiesel
3	WPO 80	80% Waste Plastic Oil, 20% Waste Cooking Biodiesel
4	WPO 70	70% Waste Plastic Oil, 30% Waste Cooking Biodiesel
5	B10 Malaysia Pump Diesel	90 % Petroleum Diesel, 10% Palm Oil Diesel
6	WPO 0	100% Waste Cooking Biodiesel

3.3 WPO and WCB Source

As discussed earlier the samples used will be based on blends on WPO and WCB. WPO used is based on polypropylene and polyethylene-based waste plastic.

Figure 10:Waste Plastic Oil Sample

Lubricity of these fuels will be tested on a High Frequency Reciprocating Rig (HFRR) to determine the scar formation. The fuel consumption and power will be tested using a single cylinder DI diesel engine.

3.3.1 WPO Source

WPO was produced by Syngas Sdn Bhd, Terengganu, Malaysia, meanwhile B10 were purchased from Petron, Jalan Universiti, Kuala Lumpur, Malaysia. Waste Cooking Oil (WCO) was obtained from a local restaurant at Taman Jaya Setapak, Kuala Lumpur, Malaysia. WCO was used as a feedstock to produce biodiesel in the laboratory. In the current study, WPO and WCB were used to prepare the binary fuels, and B10 was used as the reference fuel. AISI 52100 Chrome hard polished steel balls with a diameter of 6.2 mm was obtained from SKF Malaysia Sdn Bhd and 15 mm SAE-AMS 6440 steel smooth diamond polish plate from the local market, according to ASTM (D6079-11) dimensions.

3.3.2 WCB Production

To decrease the moisture content, the collected WCO was heated up to 100 °C for 10 min. The heated WCO was allowed to reach room temperature before undergoing the filtering procedure to remove solid particles. The transesterification was done in a glass reactor with a heating jacket that linked to a heated thermostatic bath, reflux condenser and mechanical stirrer. The 1000 ml WCO was heated to 60 °C first. Within this process, 90 g of methanol (30 wt% of WCO) and 3 g of sodium hydroxide (NaOH) (1 wt% of WCO) were mixed in a beaker. Next, the NaOH pellets were dissolved into the methanol, forming a methoxide solution by using a stirrer at 1100 rpm. The transesterification reaction was carried out by mixing 300 g of WCO and methoxide solution by using a mechanical stirrer (at 830 rpm) and heated at 60 °C for 1 h. After that, the product was placed in a separating funnel and left for 24 hours. There were two distinct layers of biodiesel and glycerol. The glycerol layer, which was on the bottom, was removed. To obtain the pure biodiesel, the top layer of biodiesel was rinsed with warm water.

3.4 Gas Chromatography and Mass Spectrometry (GC-MS)

The samples of WPO 100, WPO 0, B10, WPO 90, WPO 80 and WPO 70 was arranged for GC-MS using a Hawlett-Packard HP 7860 with a 5975-quadrupole detector. The measurement of the capillary column of the GC-MS machine was at 30m of length and a diameter of 0.25mm. The column was also covered in 0.25 µm of 5% phenyl polysiloxane

(HP-5) layer of film. Before the reading are taken, the initial temperature of the oven was set to 50 °C. This temperature will be held constant for the next 2 minutes. The temperature will be then increased to a final temperature of 290 °C at a rate of 5°C / minute at a liner rate of increment. The final temperature is then held constant for a period of 10 minutes before data collection. The collection of data in the full scan mode between m/z 33 and 533 with a solvent interval of 3 minutes. The chromatographic peaks were cross referred with the existing NIST08 based spectrum database. This database is the base point for all reference to the collected data in the Gas Chromatography and Mass Spectrometry machine. This was computed from total ion chromatogram, peak area. (Awang, et al., 2021; Juwono, et al., 2018).

3.5 Lubricity Test

Lubricity of the fuels tested on a High Frequency Reciprocating Rig (HFRR). In this case, the HFRR used is a DUCOM brand, TR-281-M8 model equipment. To test the lubricity of the fuel, several specimens of 15mm x 15mm test plates were prepared. The plates were than polished with silicon carbide paper ranging from 600 to 2000 rating. An additional layer of polish is also added on the specimen, namely 1 μm x 3 μm diamond suspension. The surface roughness of these samples was then measured and ensured to be between 0.03-0.04 (Ra). In order to the lubricity of the fuel, a steel ball would be let to rotate an move on the steel plate specimen prepared earlier. The ball will be submerged partially in a fuel sample of 5ml. The table below indicates the conditions in which the HFRR run was conducted.

Table 4: HFRR Test Condition

No	Conditions	Value
1	Sample test duration	75 minutes
2	Applied load	5 N
3	HFRR frequency	10 Hz
4	Sample fuel temperature	60 °C
5	HFRR stroke length	2 mm
6	Sample fuel volume	10 ml

The test standards is in compliance with the ASTM D6079-11 standards. Upon the HFRR test an optical microscopy (OM) test is used to calculate the Coefficient of Friction (COF) (Awang, et al., 2021; Mujtaba, et al., 2020). The COF is calculated by the formula as follows:

Equation 1: Calculating Coefficient of Friction

$$COF = \frac{Actual\ Frictional\ Force\ (N)}{Applied\ Force\ (N)} \quad (1)$$

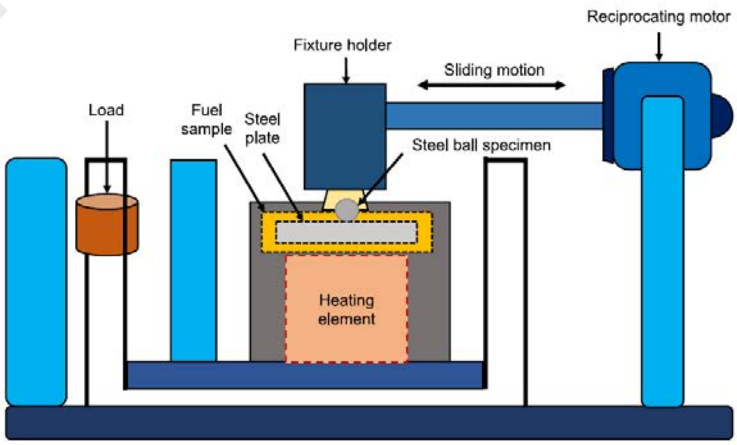

Figure 11: HFRR Test Setup

3.6 Engine Test

In this section, the engine testing for the fuel blends will be discussed. For the engine test fuel sample of B10, WPO 100, WPO 90, WPO 80 and WPO 70 will be used. Pure WCB (WPO 0) will not be discussed further as this in beyond this study's scope.

By conducting this engine test. The goals are to test for the fuels and engine's power rating and torque curve. These will be obtained by the dynamometer coupled to the stationary diesel engine of the test rig. The fuel consumption could also be calculated will the engine testing is done on all the samples at hand.

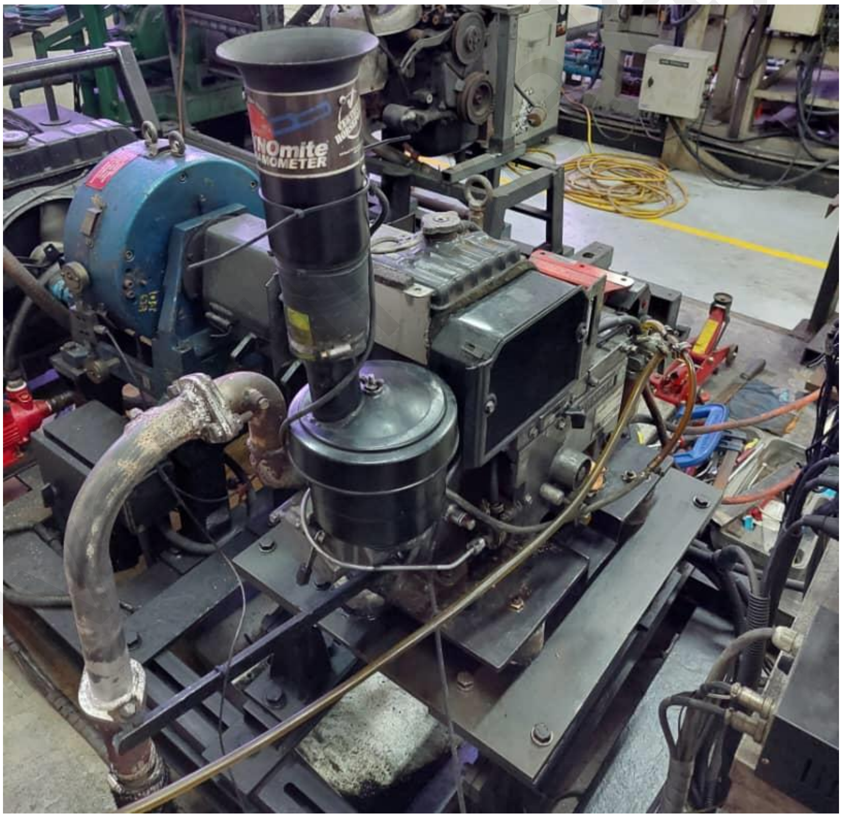

Figure 12: Test Engine

For this a single cylinder diesel engine (Yanmar model TF 120M) is used. The engine specification are as follows:

Table 5: Test Engine Specifications

No	Specification	Details
1	Injection System	Direct Injection
2	Cylinder	1
3	Cooling	Liquid Cooled
4	Rated Power	10.5 HP @ 2400 rpm
5	Max Power	12 HP @ 2400 rpm
6	Engine Aspiration	Naturally Aspirated

The procedure for the engine testing is as follows:

1. Bleed the diesel engine fuel line system and refill the tank with B10 grade diesel
2. Warm-up the engine on B10 diesel for 3 minutes on full engine load
3. Upon warm-up, replace fuel filter on fuel line a replace fuel in the fuel tank with WPO 100.
4. Bleed the fuel in the fuel system to prevent air bubble in the fuel line
5. Push throttle control to half load and start engine and start dynamometer.
6. Engage full engine load and start auto test cycle with engine speed starting from 2400 rpm till 900 rpm, with a 300 rpm interval
7. Note the time lapse for every 10ml of fuel consumed during the test
8. Collect engine power and torque curve data from dynamometer
9. Repeat step 3 till 8 with fuel blends of WPO 90, WPO 80, WPO 70 and B10 diesel
10. Upon completion run engine with B10 grade fuel to prevent residual oil in the engine

Figure 13:Diesel Fuel Pump and Fuel Delivery

Figure 14: Engine and Computerized Dynamometer

Figure 15:Test Engine Manufacturer Specifications

3.7 Summary

In this section this paper has looked into the experimental setup and the step by step procedure in conducting the experiment. The experiment as stated above will be focusing on the lubricity of the fuel as well as the performance of the engine running on the various blends of WPO and WCB blends. In the upcoming section, the paper will look into and analyse in detail the experimental results and trends obtained in this methodology and experimental procedure.

CHAPTER 4: RESULT AND DISCUSSION

4.1 Fuel General Properties

Upon conducting the study, the results from the physicochemical, lubricity and engine test was analysed. In this section, the result of the experiment would be discussed. Below are the general properties of the WPO and blends fuels.

Table 6: General Fuel Properties

Properties	B10	WPO100	WPO90	WPO80	WPO70	WPO0
Density at 15 °C (kg/m3)	0.832	0.8026	0.8125	0.8201	0.8287	0.8805
Kinematic viscosity at 40 °C (mm2/s)	2.905	2.9181	3.161	3.3091	3.5363	4.9641
Kinematic viscosity at 100 °C (mm2/s)	1.1999	1.2449	1.3211	1.3716	1.375	1.8343
Dynamic viscosity at 40 °C (mPa.s)	2.3649	2.2901	2.5116	2.6543	2.8667	4.2795
Dynamic viscosity at 100 °C (mPa.s)	0.92521	0.92366	0.99299	1.0409	1.0553	1.5002
Viscosity index	167.5	282.6	243.2	237.5	135.4	181.3
Calorific value (MJ/kg)	45.614	45.828	44.8562	44.6784	44.1695	40.9787
Flash point (°C)	80	40	61	67	76	180
Oxidation stability at 110 °C (induction time/hr)	-	37.56	-	-	-	3.07

From the table above. it was found that the calorific value of the pure WPO 100 has similar to the commercially available B10 diesel in Malaysia. Adding WCB to the WPO blend also shows in decrement in the calorific value of the fuel. This trend is similar to the findings in previous research where there is a decrease in calorific value of WPO blends compared to pure WPO 100. It should also be noted that the biodiesel in this experiment was based oil palm oil and castor oil (Kaewbuddee, et al., 2020).

In addition to this, it was also noted that the kinematic and dynamic viscosity of WPO blends decreases with the increase in WCB content. Pure WPO 100 has higher viscosity than Malaysian standard B10 diesel available at the pumps. This effects the fuels' ability to flow especially at location where sub-zero temperature is prevalent. This trend is in contradiction with other research, where engine oil was compared to WPO from HDPE (Sikdar, Siddaiah, & Menezes, 2020). This may however be due to the viscosity modifiers used in the 10W-40 engine oil used as benchmark in this experiment.

The density of the WPO 100 is also the lowest among the sample. The density then increases with the content of WCB in the blends. It should be noted that the density of the B10 Malaysia diesel is similar to the WPO 70 blend. This result was very similar in the experiment conducted earlier, where the WPO had lower density compared to the 10W-40 engine oil. However there are post-treatment methods in achieving similar density to B10 diesel (Sharma, Moser, Vermillion, Doll, & Rajagopalan, 2014; Sikdar, Siddaiah, & Menezes, 2020).

The flash point of pure WPO is very low at only 40 °C compared to the B10 diesel at 80 °C. It is also noted that the flash point of the WPO blend increases with the increase of WCB content in the fuel. This is a key parameter, since if a fuel with lower flash point to the external temperature may lead to a safety hazard (Abdullah & Kalghatgi, 2016; Fahim, Taher, & Elkilani, 2010). This trend is also seen in previous research utilising blends of WPO, WCB and Palm Oil Biodiesel. The research shown an increase in flash point with WPO content (Awang, et al., 2021). The parameter may also restrict the use of such fuel as it does not meet the current fuel regulation. As an example, the European diesel regulation EN 590 specification calls for a 55 °C flash point on diesel fuels (Murphy, Devlin, & Mcdonnell, 2013).

4.1.1 Gas Chromatography and Mass Spectrometry

The sample of B10, WPO 100, WPO 90, WPO 80 and WPO 70 had also undergone a Gas Chromatography and Mass Spectrometry (GC-MS) test to determine the key component in the WPO fuel and its blends. This paper will than analyse the result in conjunction to the engine testing and tribological results conducted on the fuel blend. The results of the GS-MS are as follows:

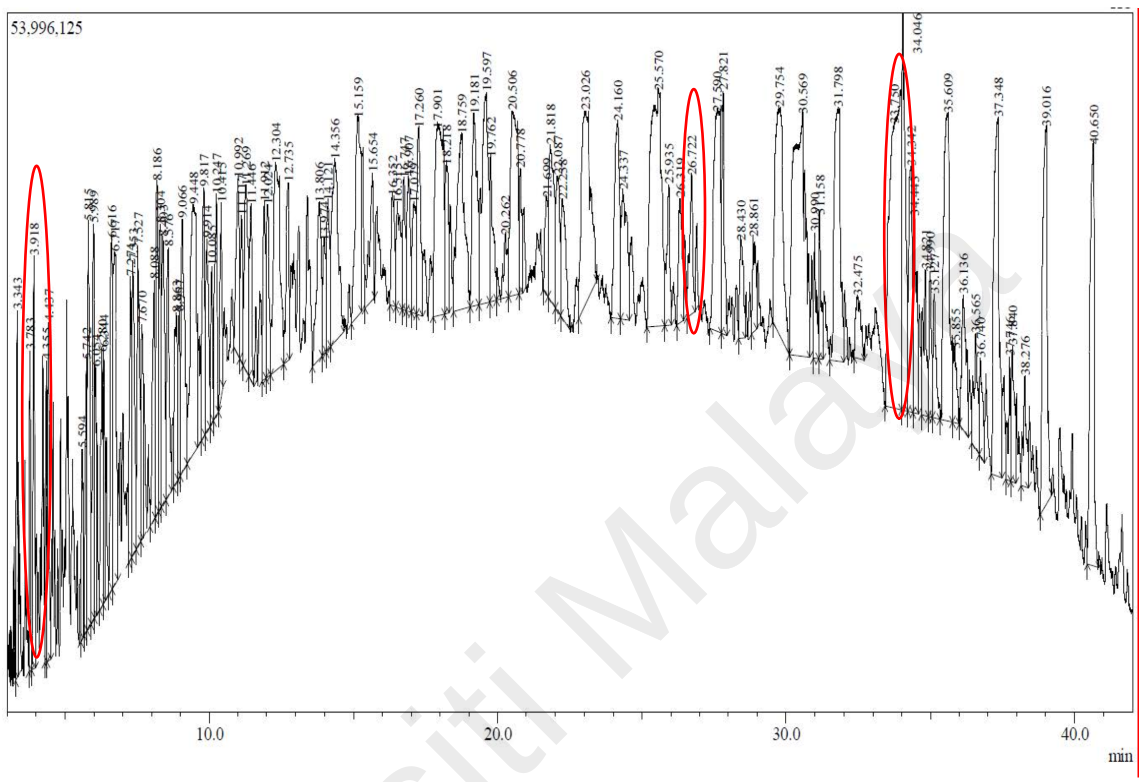

Figure 16: B10 GC-MS results

Table 7: Key compounds in GCMS of B10 sample

No	Particles	Peak Number	Height
1	Eicosane	26.722	10710926
2	Esters	33.75	21994489
3	Xylene	3.918	31867662

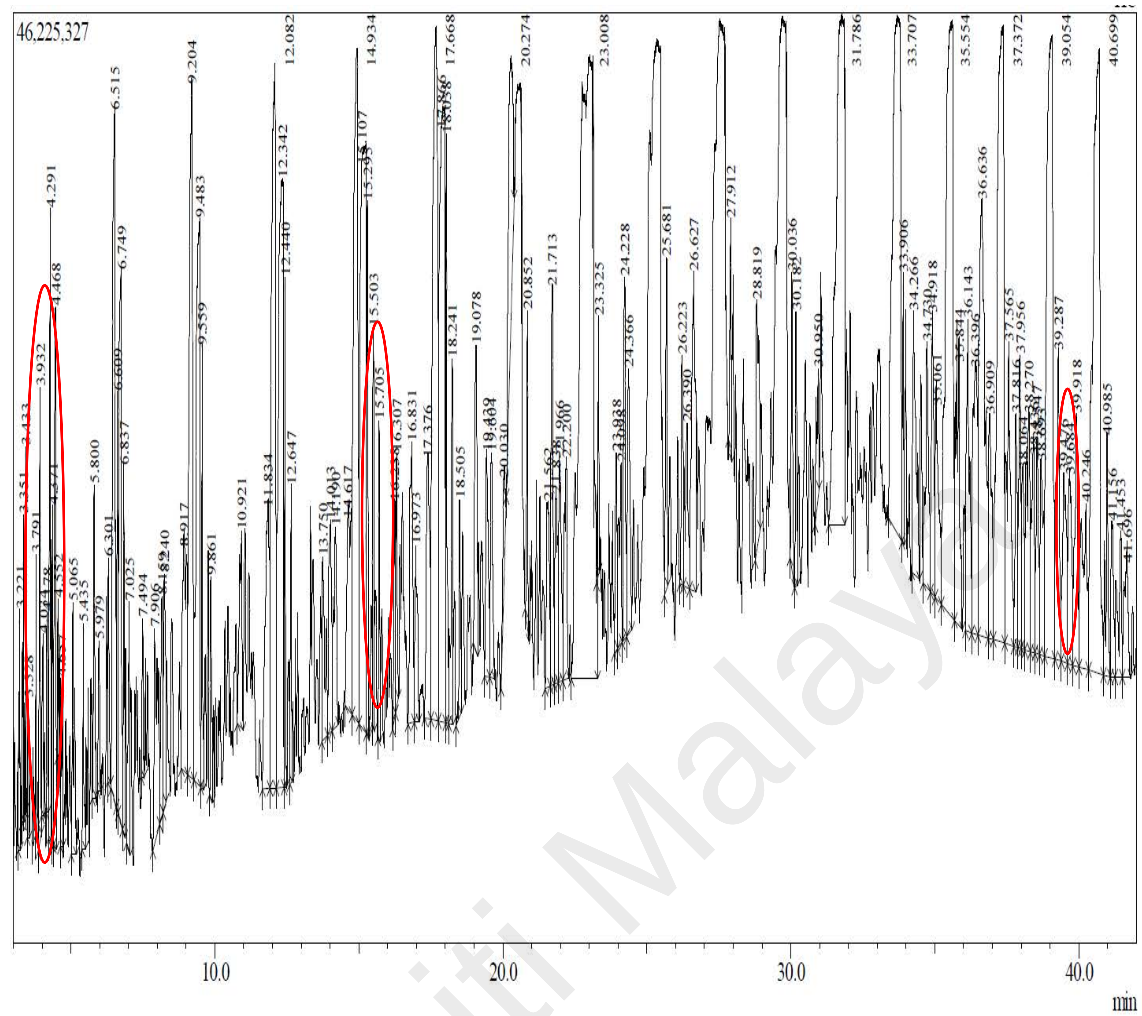

Figure 17: WPO 100 GC-MS results

Table 8: Key compounds in GCMS of WPO 100 sample

No	Particles	Peak Number	Height
1	Eicosane	15.705	15756994
2	Xylene	3.932	22489319
3	Sulfureous acid	39.684	9428311

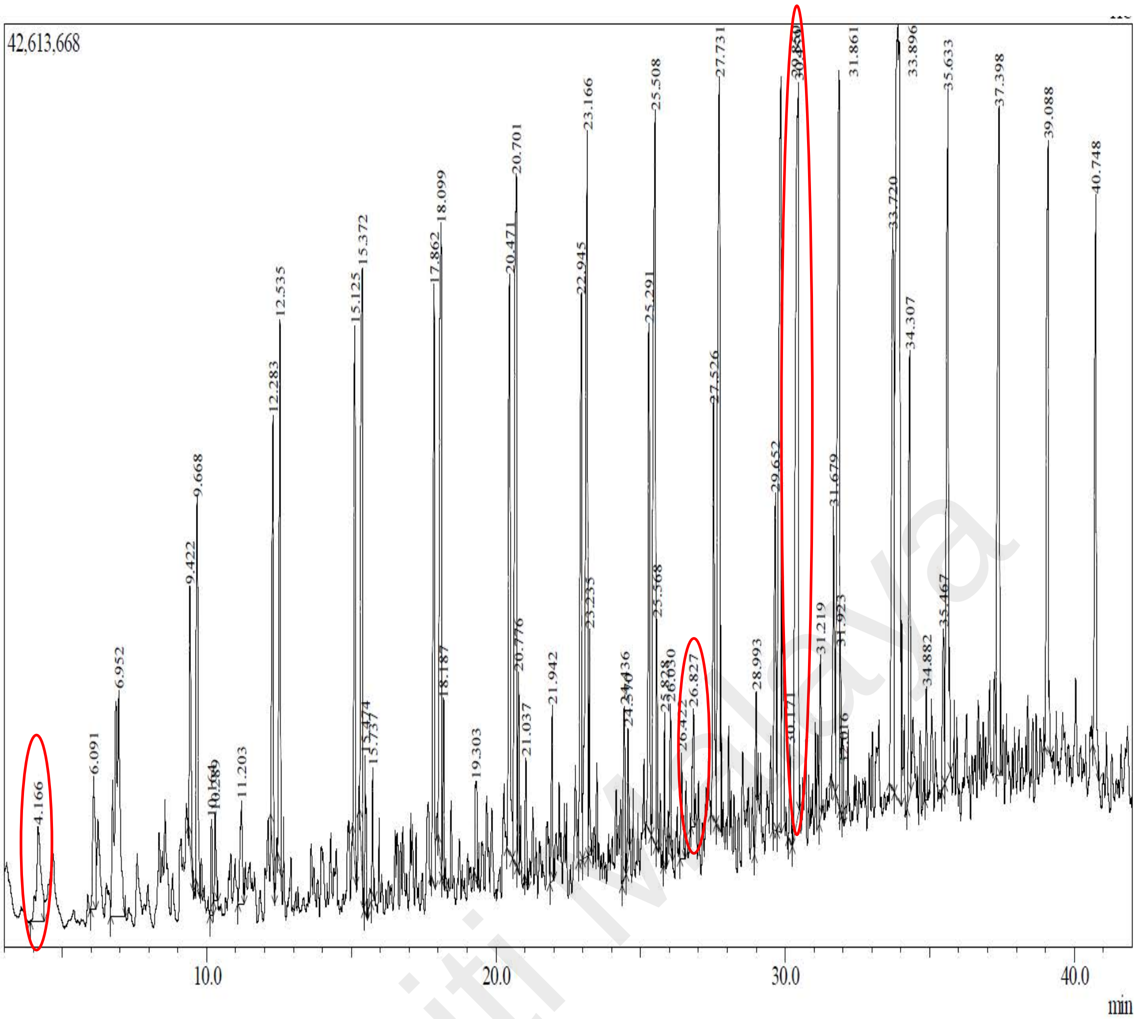

Figure 18: WPO 90 GC-MS results

Table 9: Key compounds in GCMS of WPO 90 sample

No	Particles	Peak Number	Height
1	Eicosane	26.827	5407330
2	Esters	30.459	33539853
3	Xylene	4.166	4389027

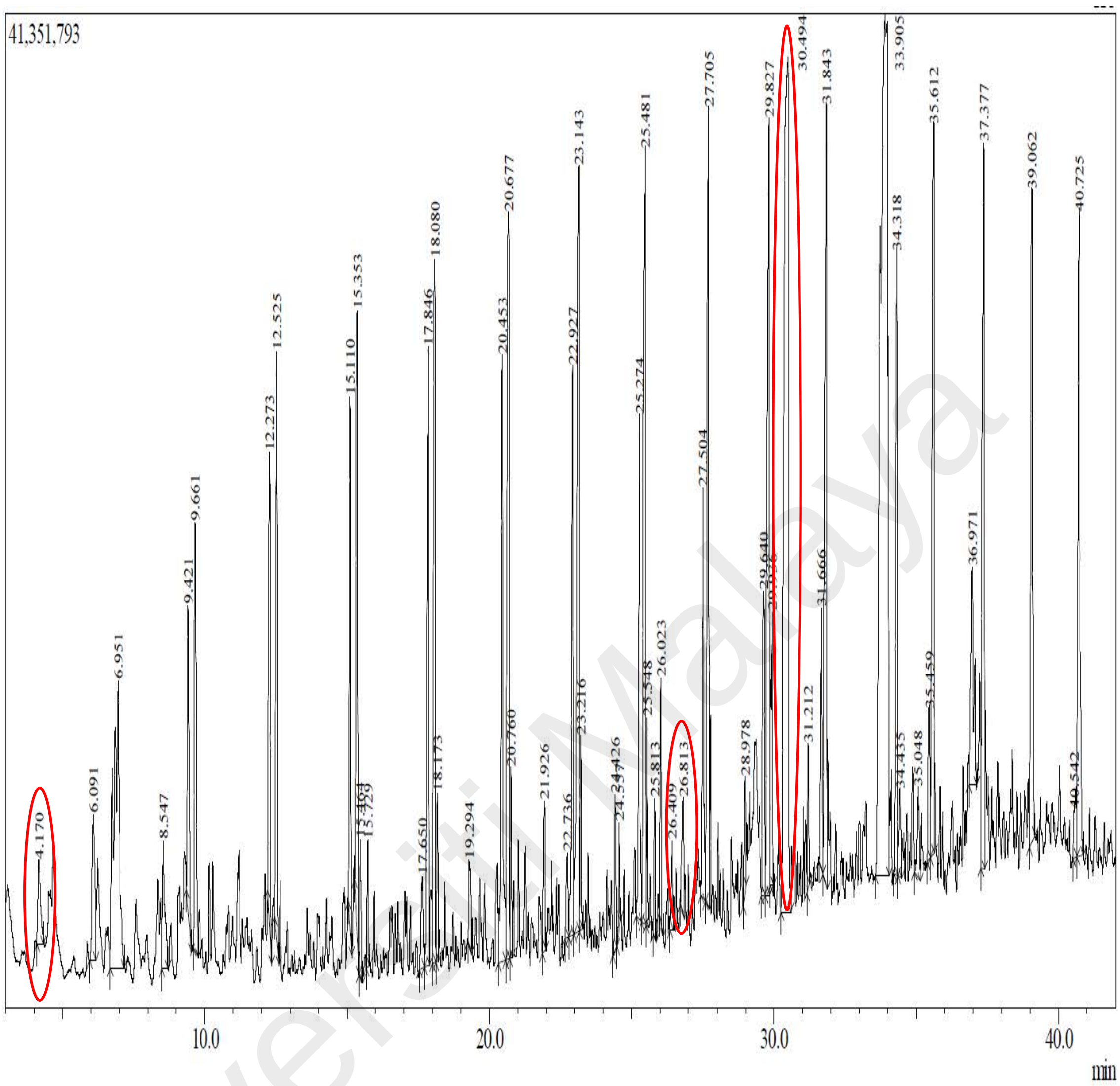

Figure 19: WPO 80 GC-MS results

Table 10: Key compounds in GCMS of WPO 80 sample

No	Particles	Peak Number	Height
1	Eicosane	26.813	4694305
2	Esters	30.494	355824481
3	Xylene	4.17	3495264

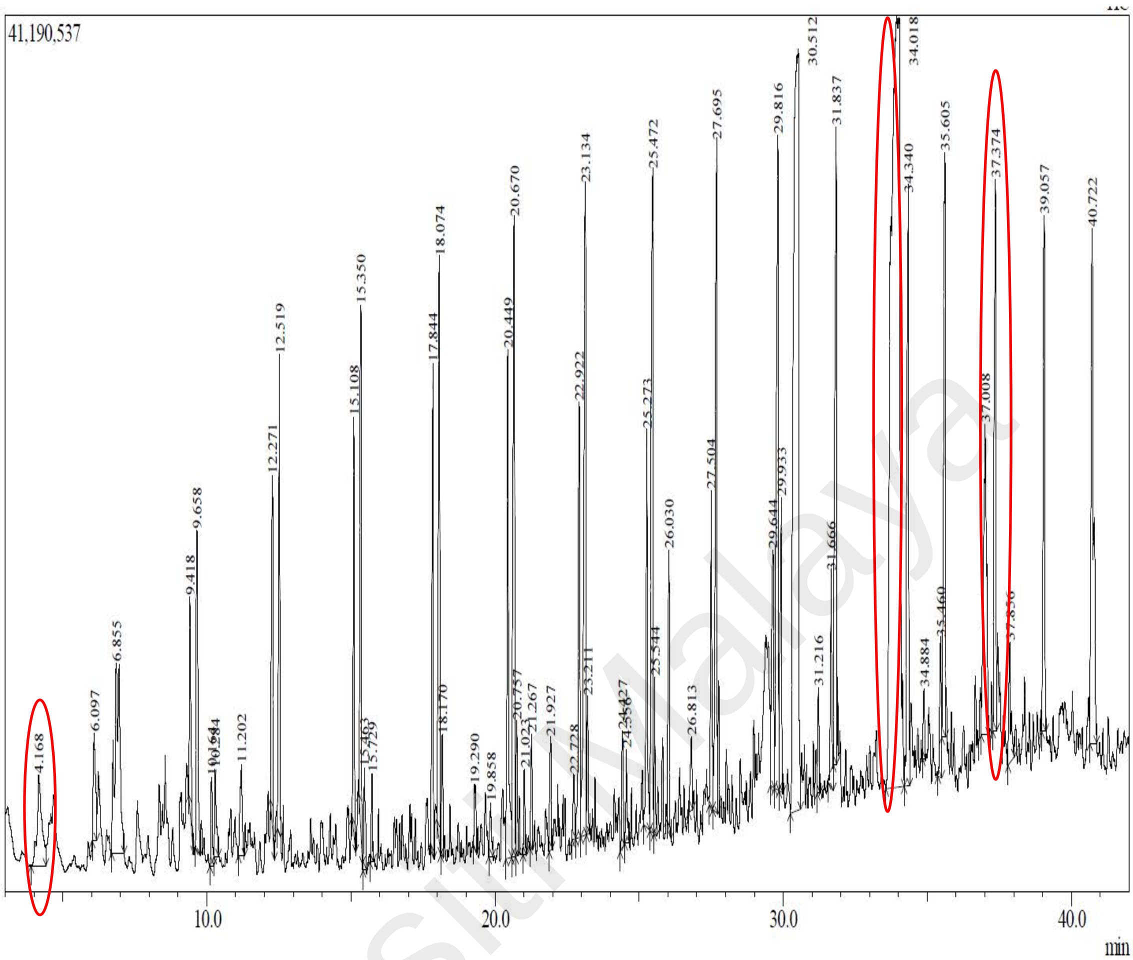

Figure 20: WPO 70 GC-MS results

Table 11: Key compounds in GCMS of WPO 70 sample

No	Particles	Peak Number	Height
1	Eicosane	37.374	25866750
2	Esters	34.018	36091810
3	Xylene	4.168	4265562

Referring to the GC-MS results as shown above, there are several noteworthy trend is analysed in this section of this study. In the B10 commercial diesel sample, we can note that the sample is rich in various range of hydrocarbon particles. Particles such as eicosane, a straight chained n-alkanes were also present in this sample. This particle is often attributed to diesel nanoparticle emission that detrimentally effects human pulmonary system (Kanno, Furuyama, & Hirano, 2008). It should be noted that the WPO sample has the highest content of eicosane. The concentration of eicosane the reduces with the increment of WCB content in the samples, with the WPO 70 sample being the lowest among all 5 tested samples. This can be explained by the fact that eicosane being commonly found in the tailed of crude oil distillation curve. A region where raw feeds for thermoplastics such as polyethylene and polypropylene originate (Mueller, et al., 2016).

Another key component noted was the present of esters. Esters was present in all of the samples except WPO 100. The B10 sample, despite being petroleum diesel, it should be noted that the commercial diesel in Malaysia is 10% palm methyl-esters. This therefore explains the presence of esters in the B10 samples, WPO 90, WPO 80 and WPO 70 has increasing ester content with increasing WCB percentage. This is definitely is due to the concentration of esters in WCB. Despite having minimal harm to human health or the environment. High concentration of esters reflects less desirable properties in fuel especially at low temperatures especially cloud point, pour point and the ability to flow. In a temperate climate such as in Malaysia, such features does not affect the day to day use of this fuel, in colder climates, starting and supplying a steady flow of fuel to the engine is a challenge (Dunn, Shockley, & Bagby, 1996). It should also be noted that esters also adversely effect the components in a diesel engine, especially on the fuel hoses (Christensen, Williams, Paul, Burton, & McCormick, 2011).

The GC-MS results also shows xylene particles. Xylenes are a highly flammable colourless liquid. The concentration of xylene is the highest in the WPO 100 sample. The concentration then subsequently reduces as the percentage of WCB increases in the samples. The commercial B10 diesel has relatively low concentration of xylene. Previous studies have shown that the concentration of xylene is directly proportional to the flame speed in compression ignition engines (Pei, et al., 2015).

Sulfureous acid is also a common particle found in the GC-MS result. The value for sulfureous acid is the highest in the WPO sample. However, this particle does not appear in the B10 commercial diesel sample. Sulfureous acid is a common product from the pyrolysis process in preparing WPO from plastic waste. The absence of sulfureous acid in the B10 sample can be explained by the fact that diesel is extracted from lighter component during the refining process while sulfureous acid occurs from oily petroleum sludge. A part of the lower and heavier component extracted from the refining process (Wang, et al., 2022). Sulphur too aids in enhancing the lubricity of fuel. However, with the increasing concern on the environmental impact, low sulphur fuel is commonly introduced such as the Euro 5 B10 diesel used in this experiment. This paper will study in detail the lubricity of fuel in the coming section.

4.2 HFRR Results

The samples were tested using a HFRR machine. Lubricity of fuel is important as it leads to the reliability of the fuel system of the engine. After the lubricity test conducted for the fuel sample using a HFRR machine, the following results for the Coefficient of Friction (COF) were generated as follows:

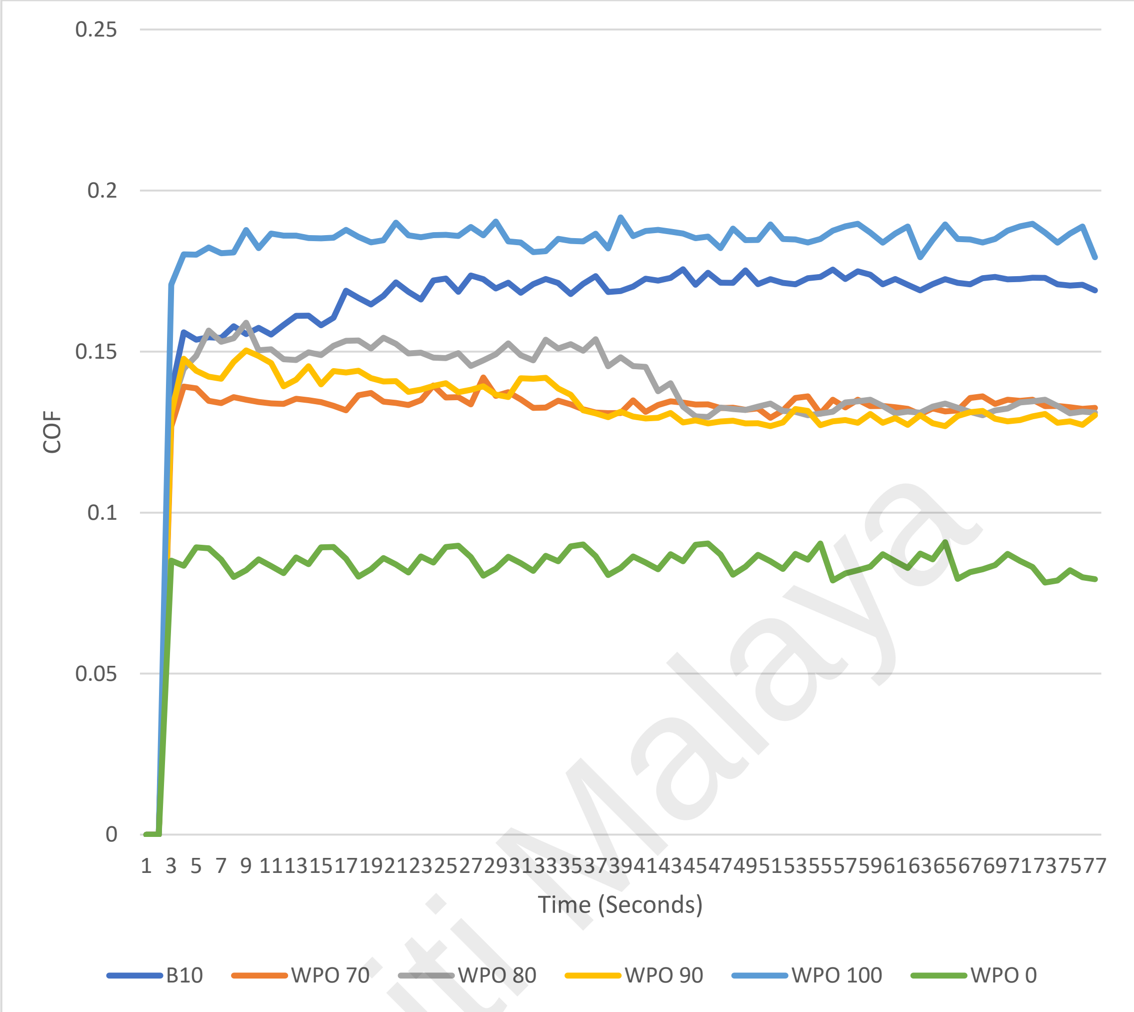

Figure 21: Graph of COF for Various Fuel Samples

The average COF for the fuel sample can be then calculated, the results are tabulated as follows:

Table 12: Table of Average COF values for various samples

Sample	Average COF
WPO 100	0.185333
WPO 90	0.135926
WPO 80	0.134467
WPO 70	0.133892
WPO 0	0.083505
B10	0.168398

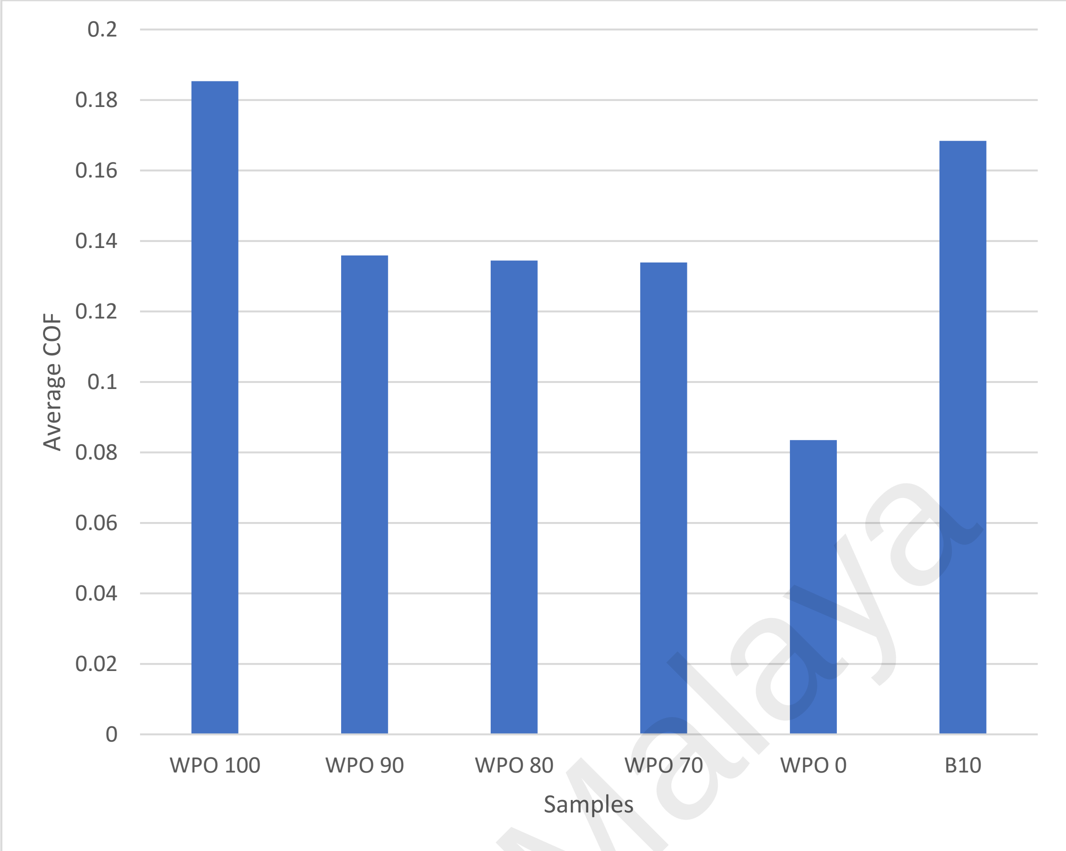

Figure 22: Average COF for various samples

Referring to the table and graph illustrated, it is determined that the lubricity of the fuel increases with the increase in WCB composition in the fuel. This also explains, the result of WPO 0 to have the best lubricity as it contains pure WCB. It should also be noted the drop in COF is very drastic from WPO 100 and WPO 90, with a drop of 26.65%. The subsequent increase in lubricity was only ranging from 0.5 – 1%. This phenomenon can be explained by the fact that WPO 100 lacks any lubricating element in it. This trend can be further explained by the lack of nitrogen or methyl ester particles, a common lubrication enhancer, in the GC-MS result (Anastopoulos, Lois, Karonis, & Kalligeros, 2005). Despite, the presence sulphur related compounds in the WPO blends used in this study.

The results on the Euro 5 B10 petroleum diesel used in this study performed slightly better than the WPO 100 sample. It is commonly understood that the lubricity of fuels increases with its viscosity. However, in this case, the lubricity of the B10 diesel performed better than the WPO 100, despite the latter's higher viscosity. This can be explained by the long-chained alkanes present in the B10 fuel. Previous studies have indicated that fuels with long alkanes chains had higher lubricity compared to shorter ones (Lapuerta, Garcia-Contreras, Compos-Fernandez, & Dorado, 2010; Lapuerta, Sanchez-Valdepenas, & Sukjit, 2014). This trend is despite the fact that the low-sulphur diesel available in the Malaysian fuel pumps.

4.3 Engine Testing

In this section, this study would further analyze the power and performance of the fuel through engine testing. The parameters of this test have been defined in the previous chapter under methodology. The fuel consumption of the engine running on the various fuel samples were also collected during this engine test. The result for the engine test are as follows:

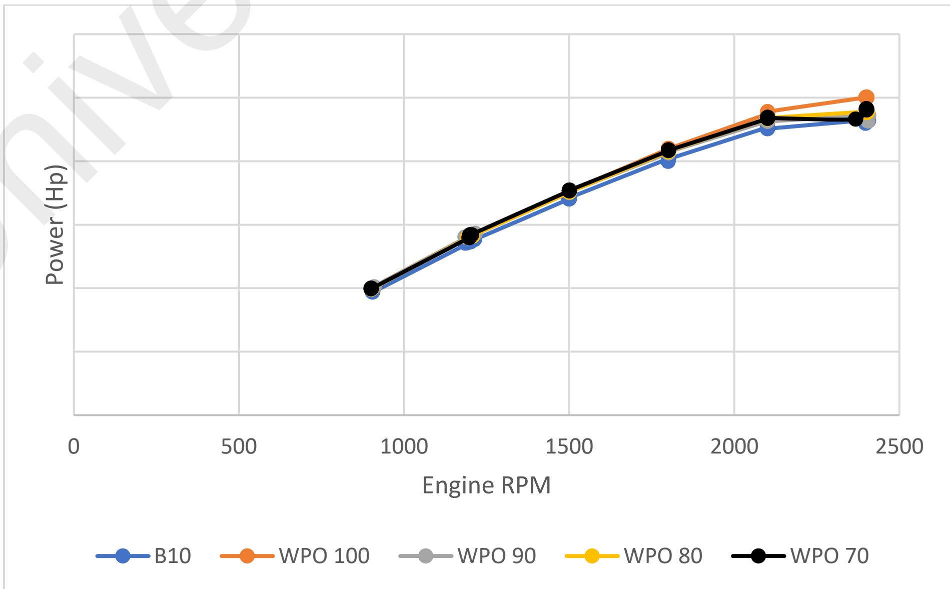

Figure 23: Graph of Power (Hp) against RPM for Various Samples

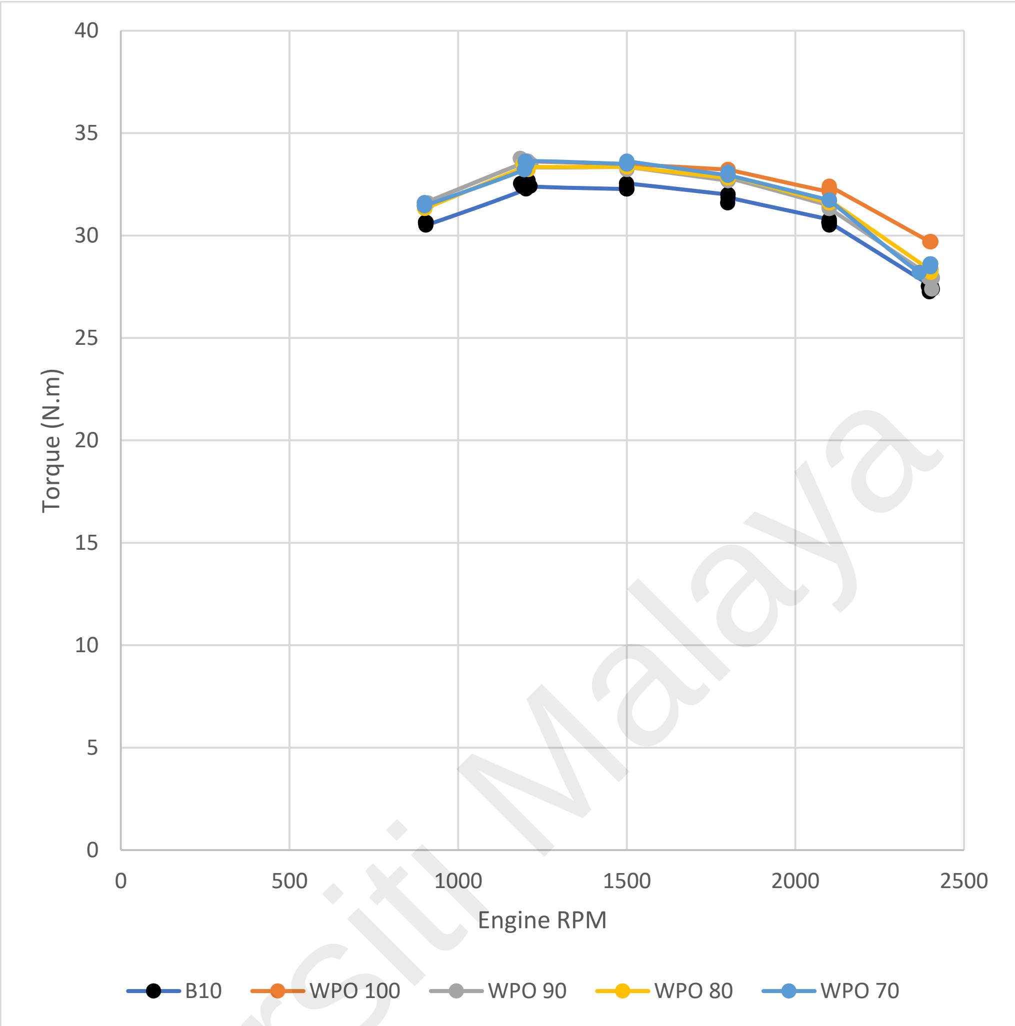

Figure 24: Graph of Torque (N.m) against RPM for Various Samples

Referring to the torque and horsepower curve shown above, it is determined that the test diesel engine had the highest torque and power running on the WPO 100 sample. The performance then drops with the increment of WCB percentage in the fuel sample. The B10 performed poorest in terms of the power and torque generated by the engine. However, it should also the noted that the variation in power generation is minimal between the best and worst performing fuel. There is a variation of 3% in terms of torque generated and only 2.4% for the power generation. These results are inline with previous research conducted on similar setting (Awang, et al., 2021).

As these tests were conducted, the fuel consumption of the engine was also monitored. As discussed earlier, the samples were collected at an interval of 10 ml. The duration were monitored and noted. The results obtained for various fuel samples are tabulated as follows:

Table 13: Engine Fuel Consumption Running on B10 Fuel

RPM	Test cycle	Duration	Average Duration	Fuel Consumption (liter/min)
2400	1	10.48	10.56	0.057
	2	9.57		
	3	11.63		
2100	1	13.89	13.3	0.045
	2	12.44		
	3	13.56		
1800	1	13.03	14.7	0.041
	2	16.03		
	3	15.03		
1500	1	15.04	15.2	0.039
	2	14.75		
	3	15.8		
1200	1	16.42	17.07	0.035
	2	15.7		
	3	19.09		
900	1	20.04	23.41	0.026
	2	22.47		
	3	27.72		

Table 14: Engine Fuel Consumption Running on WPO 100 Fuel

RPM	Test cycle	Duration	Average Duration	Fuel Consumption (liter/min)
2400	1	12.63	12.19	0.049
	2	12.5		
	3	11.44		
2100	1	12.63	12.64	0.047
	2	12.81		
	3	12.47		
1800	1	15.74	15.52	0.039
	2	15.99		
	3	14.83		

1500	1	16.43	18.42	0.033
	2	18.44		
	3	20.39		
1200	1	21.34	22.67	0.026
	2	24.34		
	3	22.32		
900	1	27.4	28.9	0.021
	2	29.73		
	3	29.57		

Table 15: Engine Fuel Consumption Running on WPO 90 Fuel

RPM	Test cycle	Duration	Average Duration	Fuel Consumption (liter/min)
2400	1	10.2	10.75	0.056
	2	10.85		
	3	11.2		
2100	1	13.3	13.3	0.045
	2	14.1		
	3	12.5		
1800	1	16.3	17.6	0.034
	2	17.7		
	3	18.8		
1500	1	22.52	21.74	0.028
	2	20.8		
	3	21.9		
1200	1	23.6	24.83	0.024
	2	25.6		
	3	25.3		
900	1	29.72	30.15	0.02
	2	29.08		
	3	31.65		

Table 16: Engine Fuel Consumption Running of WPO 80 Fuel

RPM	Test cycle	Duration	Average Duration	**Fuel Consumption (liter/min)**
2400	1	10.09	10.99	0.055
	2	11.11		
	3	11.77		
2100	1	11.74	12	0.05
	2	12.06		
	3	12.2		
1800	1	16.5	16.67	0.036
	2	17.43		
	3	16.09		
1500	1	18.92	19.19	0.031
	2	19.74		
	3	18.92		
1200	1	24.81	25.09	0.024
	2	25.46		
	3	25.01		
900	1	28.49	28.99	0.021
	2	29.92		
	3	28.56		

Table 17: Engine Fuel Consumption Running of WPO 70 Fuel

RPM	**Test cycle**	**Duration**	**Average Duration**	**Fuel Consumption (liter/min)**
2400	1	11.86	12.77	0.047
	2	13.58		
	3	12.88		
2100	1	13.91	13.58	0.044
	2	12.04		
	3	14.78		
1800	1	14.78	16.75	0.036
	2	18.68		
	3	16.78		
1500	1	18.56	19.4	0.031
	2	19.88		

	3	19.76		
1200	1	22.7	24.46	0.025
	2	26.39		
	3	24.3		
900	1	28.76	31	0.019
	2	33.45		
	3	30.79		

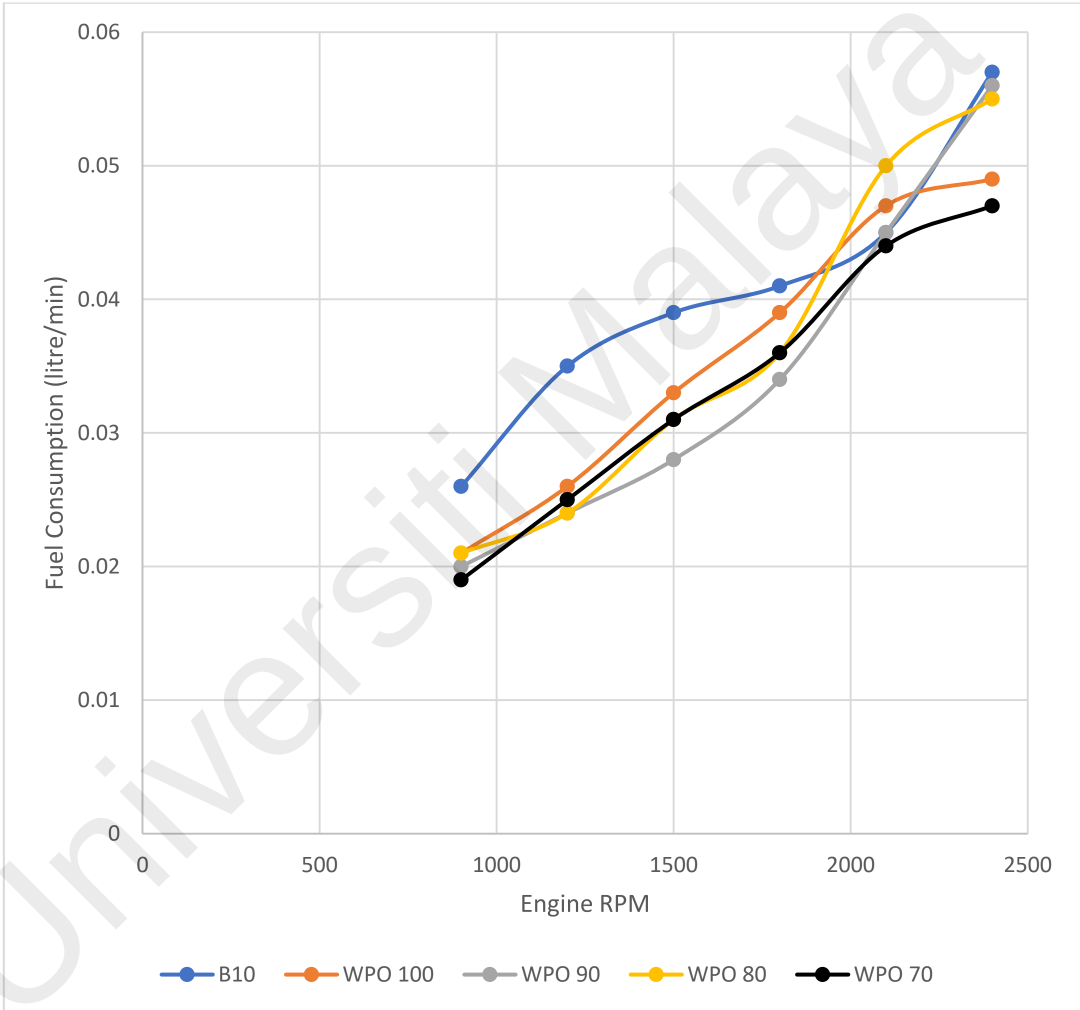

Figure 25: Graph of Fuel Consumption (Litre/min) for Various Fuel Samples

From the tables and graphs illustrated above, the analysis can be broken into 2 sections, namely at low speed and high speed. The results during the engine testing had significant different at both conditions. It should be noted that, the engine fuel consumption if consistently highest when running on B10 diesel fuel. This is despite the fact that, B10 sample having higher fuel calorific value. This trend will be explained and analysed in detail in the following section. For the WPO 100 and other blends, the fuel consumption difference is negligible at lower engine speed. However, the trend changes at higher engine speed. At higher engine speed, the fuel consumption increases with the decrease in proportion of WCB in the fuel sample. This is inline with the calorific value of the fuel sample.

Further analysis was then conducted, by calculating the Brake Specific Fuel Consumption (BSFC) of the engine test. The BSFC will normalize the fuel consumption by basing it on the power generated in the engine test. The result of the BSFC test analysis are as follows:

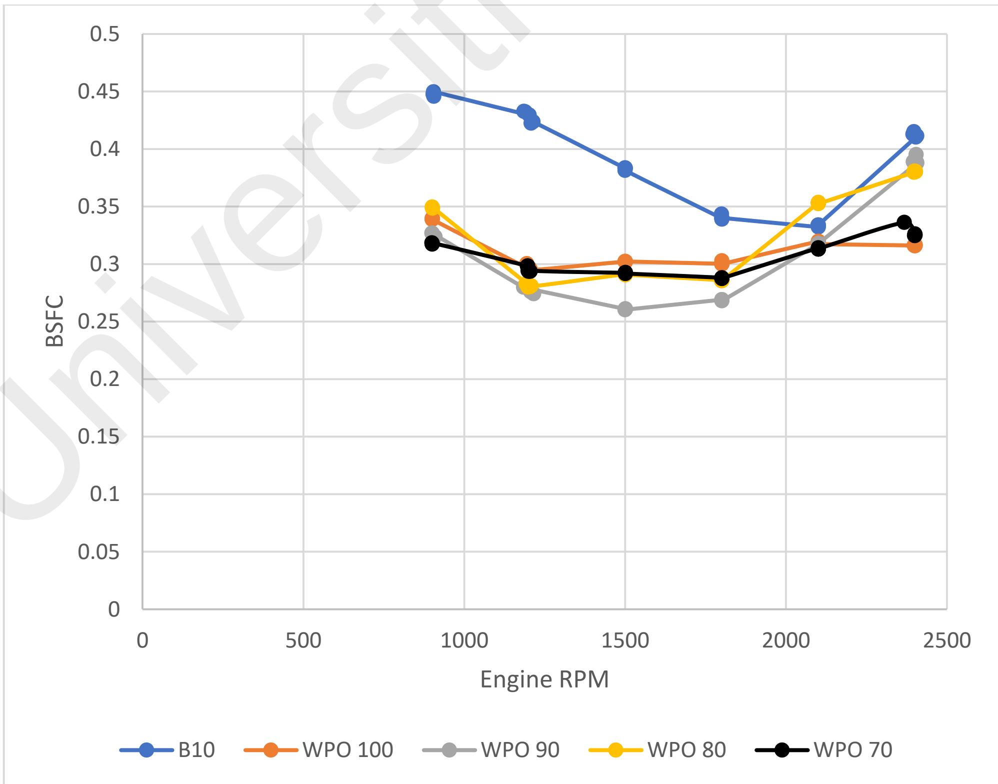

Figure 26: BSFC (g/kWh) against engine speed for various fuel samples

Referring to the graph illusterated, we can determine that the BSFC for the B10 is highest in the lower engine speeds. The BFSC then drops at 2100 rpm, then increases thereafter. The shows the engine running on B10 is the most optimum at the 2000 rpm mark unlike the other. This may be explained by the high flash point for the B10 diesel engine. Therefore, increasing the speed required for optimum combustion. It should be noted that, most common diesel fuels are catered for turbocharged engines, in a non-turbocharged engine the fuel combustion will undergo incomplete combustion. Since the difference in the Exhaust Gas Temperature (EGT) for the various fuel is negligible, it can be theorized that the fuel is exhausted unburnt while running on B10 fuel. However, this scope of study is beyond the research parameters in this paper. Therefore, no further analysis will be conducted to this matter.

For the engine test running on WPO 100 and other WPO blends, it can be noted that the general trend is that the BSFC of the fuel is higher when the blend of WCB in the fuel sample is lower. A trend that is inline with the calorific value of the fuel tested. Despite this, all fuel sample have higher BSFC at lower engine speed and has an optimum engine speed of 1500 to 1800 rpm for all WPO fuels tested. These results are in line with previous research conducted on similar materials (Awang, et al., 2021).

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Regarding this study's objective regarding the fuel lubricity. Among the 5 samples tested in the paper, the lubricity increased with the increase in WCB content. This confirms that adding WCB into WPO samples would increase the overall lubricity of the fuel. All but WPO 100 fuel sample had COF as well as or better than the B10 diesel sample. This allows the conclusion that blends of WPO 90, WPO 80 and WPO 70 are suitable to be used in existing diesel engines, in terms of fuel lubricity.

The second objective of this study regarding the engine performance running on WPO and its blends was achieved by the engine test conducted. The 5 samples tested in this paper, all WPO samples have performed better than the currently available B10 diesel. The WPO 100 performed the best in this test, with the best torque and power delivery. From this test, this study concludes that the WPO samples are capable, or delivery similar or better performance compared to the B10 diesel sample.

A further analysis of the BSFC of the fuels have shown that the all the fuel samples had lower BSFC compared to the B10 diesel conducted on a naturally aspirated DI diesel engine. This indicates that WPO blends can deliver similar performance and fuel consumption compared to B10 fuel.

Among all the samples tested in this study. This paper concludes that the WPO 90 blend performs most favourably to the test objective. The WPO 90 sample not only managed to perform better than the B10 sample in the lubricity, engine performance and fuel consumption test, but also has the most similar calorific value of the fuel. The WPO

90’s calorific value of 44.8562 MJ/kg compared to B10 fuel sample’s 45.612 MJ/kg. A difference of only 1.6%. The viscosity of the fuels is also very similar, with a difference of 8%. These similarities would allow the current diesel engines and other fuelling infrastructure to readily adapt and utilise the WPO 90 fuel without major modification or alterations required.

The samples for WPO 80 and WPO 70 has performed equally well. However, there will be additional modifications to the fuel or to the current facility that would be required. The WPO 70 fuel especially had low calorific value and BSFC figures. The density for both aforementioned fuels are similar to the B10 diesel. While the viscosity being much higher than of the B10 diesel. Despite this the fuels performed similarly to the WPO 90 in the lubricity test, without a significant notable advantage for the WPO 80 and WPO 70 fuel samples.

5.2 Recommendations

There are several recommendations that this study would like to recommend to future researchers in this field. The recommendations are af follows:

1. Repeat this study utilising a diesel engine equipped with a Variable Geometry Turbo (VGT) to reflect the effects of WPO blends on modern diesel technology.
2. Conduct engine exhaust emission testing during variable load engine test
3. Conduct research on engine oil dilution tendency, when WPO and its blends are used as fuel
4. Repeat experiment with variable fuel spray pattern to determine positive crankcase ventilation and intake valve carbon build up tendency of the WPO fuel.

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