

PERFORMANCE TESTING OF LIQUID FUEL PRODUCED FROM WASTE PLASTICS IN DIESEL ENGINE



By

Birhanu Adisie Fentaw

A Thesis Submitted To the Department of Mechanical Systems and Vehicle
Engineering

School of Mechanical, Chemical and Materials Engineering

Office of Graduate Studies

Adama Science and Technology University

May 2020

Adama; Ethiopia

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APPROVAL PAGE

We, the undersigned, members of the Board of Examiners of the final open defense by Birhanu Adisie Fentaw have read and evaluated his thesis entitled “Performance Testing of Liquid Fuel Produced from Waste Plastics in Diesel Engine” and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirement of the degree of Master of Science in Automotive Engineering.

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DEDICATION

This work is dedicated to my family for their steady and solid support, love, and encouragement in the course of my study. Dear friends I want to reach my extended dedication to all of you also. MAMA how could I forget you, being you above all.

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NOMENCLATURE

ASTM	American Society for Testing Materials
bsfc	Brake Specific Fuel Consumption
B0	100% diesel fuel
B20	20% waste plastic and 80% diesel fuel
B30	30% waste plastic and 70% diesel fuel
B50	50% waste plastic and 50% diesel fuel
CI	Compression ignition
CR	compression ratio
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DF1	Grade No.1 Diesel Fuel
DF2	Grade No.2 Diesel Fuel
Ea	Activation Energy
HC	Hydrocarbons
HDPE	High Density Polyethylene
IC	Internal Combustion
kg	kilogram
kW	kilo Watt
kWh	kilo Watt-hour
LDPE	Low Density Polyethylene
LPG	Liquefied Petroleum Gas
M ₁	Mass of Liquid (Condensate)
m ³	cubic meter
min	minute
ml	Milli Liter
MSW	Municipal Solid Waste
NA	not available
NC	None Condensate
N.m	Newton meter
NO	Nitrogen Monoxide
NO ₂	Nitrogen Dioxide
NO _x	Nitrogen Oxides

P_b	brake power
PE	polyethylene
ppm	Parts per Million
PS	Polystyrene
rpm	revolutions per minute
T_b	brake torque
UHC	unburned hydrocarbon
v_f	Volumetric flow rate of fuel
WPO	Waste Plastic Oil
WTE	Waste to Energy
ρ_f	Density of fuel

ABSTRACT

Conventional fossil fuels are widely used as a source of energy for prime movers like IC Engines. The efficient prime movers like diesel engines are usually find applications in a wide array of areas, including industrial, agricultural and transport sectors. However, the demand for diesel and other petroleum-based fuels across the globe, especially in developing nations such as Ethiopia, has been rising steadily leading to concerns for long-term energy security. In addition, the increased use of hydrocarbon fuels leads to air pollution, both at local and regional levels, ultimately leading to climate change. Due to a combination of these factors, various research initiatives aimed at developing suitable alternative sources of energy continue to be accepted and this is one of such initiatives. This study investigated the appropriateness of the use of waste plastic oil as an alternative fuel for diesel engine and effect of blending waste plastic oil with diesel (B0, B20, B30 and B50) on fuel properties, engine performance and engine emissions characteristics. The liquid fuel was produced using pyrolysis process from waste plastic collected from Adama and the test was conducted on a single-cylinder direct injection diesel engine in Addis Ababa Science and Technology University. Fuel Properties like density and kinematic viscosity were evaluated and compared to those of baseline data obtained with pure diesel (B0). Engine performance like brake power (P_b), brake torque (T_b) and brake specific fuel consumption (bsfc) and emissions such as CO, CO₂, HC and NO_x are also evaluated. Both density and kinematic viscosity observed to be decreasing as the waste plastic fuel proportion increases in the blend and the values are less than that of pure diesel but higher than the minimum standard value up to B50. The maximum gap between the pure diesel and its blend at peak points for brake power and brake torque is 11.9% (B30 at 3600 rpm) and 16.3% (B50 at 1150 rpm) respectively in which diesel fuel is on the top. However, in terms of bsfc, B50 gives the lowest consumption which can reduce up to 7.4% of fuel. In case of emission, the waste plastic blend improves NO_x emission (except B50), carbon dioxide, and unburned hydrocarbons by 2.8% (B20 at 3600 rpm), 9.8% (B50 at 1300 rpm), and 18.7% (B300 at 1000 rpm) respectively but the emissions of CO are slightly higher at low speeds and almost close to each other at higher engine speeds.

Keywords: Emission, Engine performance, fuel, pyrolysis, waste plastic

CHAPTER ONE

1. INTRODUCTION

1.1 Background

Diesel engines are the most popular prime movers, and regularly find application in a wide array of areas, including manufacturing, agriculture, and transport sectors, among others. As a result, diesel, and other petroleum-based fuels demand across the globe, particularly in developing nations like Ethiopia, has been rising steadily leading to concerns for long-term energy security. Ethiopia, like other non-petroleum producing countries, continues to import vast amounts of petroleum from the Gulf region leading to high energy cost, which in turn leads to high production costs and ultimately high cost of living (Macharia E. 2018).

On the other hand, the way Municipal Solid Waste (MSW) of Addis Ababa currently handled is unsustainable, shapeless, inefficient, uncoordinated, and unrepresentative. The solid waste generation is increasing, as the trend promises even vigorously fueled by a population boom and business expansion in volume, type, and level of hazard. There are obvious problems in the collection, transportation, and final disposal. The scattered solid wastes are creating environmental pollution posing health risks for human beings, domestic, and wild animals. The poorly managed open dumping site, which is currently no more at the periphery, is causing air, land, and water pollution. The site brings practical health risks particularly to the inhabitants surrounding it. It is open for all kinds of scavengers, human beings, domestic and wild animals (Tekahun B. 2007).

However, waste is now not only an undesired product of society but a valuable energy resource as well. Energy recovered from waste especially waste plastics of municipal solid waste can solve two problems at once:

- ✓ treating non-recyclable and non-reusable amounts of waste and
- ✓ Generating a significant amount of energy that can be included in the energy production mix in order to satisfy the consumers' needs.

The communication between waste management solutions and energy production technologies can vary meaningfully, depending on multiple factors. Different countries across the world select to implement different strategies, depending on social, economic, and environmental criteria, and limitations. These decisions can have an impact on energy safety,

energy equity, and environmental sustainability when looking at the future of the energy sector. If waste to energy (WTE) technologies are industrialized and executed following viable principles, then an accurate waste treatment strategy and an environment-friendly energy production can be realized at the same time. This solves challenges in both the waste management and energy sectors.

1.2 Physical composition of MSW

One can clearly see from Table 1.1 below that there is a change in the percent composition of wastes from year to year. Some constituents of solid wastes such as paper, plastics, and ferrous metals showed an increase in percent composition. These types of wastes are more public in developed nations. Therefore, this might be a sign for the city to be on the way to development. But from the recycling point of view, all of the three ingredients are recyclable materials, and hence it shows that recycling practices are not effectively practiced, and this is why a lot of paper and plastic substances found thrown out in river banks, ditches and open areas (Nigatu et al. 2011).

Table 1. 1: Percentage composition of MSW in Addis Ababa at three different years (Nigatu et al. 2011).

Major constituents	Weighted percent composition by weight and year of information		
	1982	1994	1995
Vegetables	8.7	4.185	2.90
Paper	2.2	2.47	3.37
Rubber	0.5	1.0	0.28
Wood	N.A	2.33	2.29
Bone	N.A	1.06	1.62
Plastics	0.7	1.93	1.98
Textiles	1.5	2.37	1.44
Ferrous metals	0.8	0.9	1.16
Aluminum	N.A	N.A	0.02
Glass	0.5	0.445	0.80
Combustible (leaves, grasses)	25.2	15.13	22.63
Non-combustible	6.3	2.53	2.96
Fines < 10mm	N.A	29.93	28.04
10 < fines < 55mm	N.A	35.65	31.43
All fines	53.6	65.58	59.44
Total	100	100	100

The physical composition of Addis Ababa city solid waste is summarized as shown in table 1.2 below (Organic 60%, Recyclables 15 %, others 25%) (Tekahun B. 2007).

Table 1. 2: MSW composition of Addis Ababa.

No.	Major constituents	%
1	Ash, dust, fines	65
2	Combustible leaves and grasses	15
3	Vegetables and fruits	4.2
4	Rubber and plastics	2.9
5	Non-combustibles	2.5
6	Papers	2.5
7	Textiles	2.4
8	Wood	2.3
9	Bones	1.1
10	Metals	0.9
11	Glasses and ceramics	0.5

1.3 Statement of the Problem

Municipal solid waste, which is a consequence of the day-to-day activity of humankind, needs to be managed properly. Ethiopia, like other developing countries, faces problems associated with poorly managed solid waste operation, especially waste plastics. If for example in the capital Addis Ababa, more than 1750 tons of MSW added to koshe/reppie each day according to the UN report of 2014. This poor waste management has different problems like an increase in the landfill and high methane emission to the environment.

On the other hand, the depletion of world petroleum reserves and an increase in environmental concerns have stimulated the search for alternative and renewable fuels that are capable of fulfilling an increasing energy demand. The environmental concerns not only due to the accumulation of wastes but also due to the release of toxic substances while using petroleum products for IC engines.

Therefore, production of alternative and renewable fuel from plastic wastes is the most feasible and reliable way of finding a solution to the above-mentioned problems.

1.4 Objectives

1.4.1 General Objective

The general objective of this thesis work is to produce alternative fuel from waste plastics and testing its performance in diesel engine.

1.4.2 Specific Objectives

The specific objectives of this study are:

- ✓ To construct a simple batch reactor for plastic pyrolysis.
- ✓ To produce alternative liquid fuel to diesel fuel from waste plastics.
- ✓ To measure different characteristics of the produced fuel like kinematic viscosity, and density.
- ✓ To test the performance of the fuel produced in diesel engine.
- ✓ To compare the performance characteristics of the produced fuel with base line diesel fuel.

1.5 Significance of the study

The main significance of this work is in the following two main areas:

1. Economical
 - ✓ Increase in fuel supply
 - ✓ Save foreign exchange
 - ✓ Motivates the microeconomic sector
2. Environmental
 - ✓ Control illegal dumping of waste and landfill.
 - ✓ Reduces methane emission and thus greenhouse gases due to the increment of landfills.
 - ✓ More environment friendly than petroleum fuel and this will lead us to keep clean our environment.

Therefore, the aggregate effect of this significance can boost the economy of the country.

1.6 Beneficiaries

Automotive industries, vehicle owners, researchers, society, and country as a whole get benefitted from this work.

1.7 Scope

This study is delimited to the production of liquid fuel from municipal solid waste plastics using pyrolysis, studying the properties of the fuel, and testing the performance in the diesel engine.

1.8 Limitations

Unlike diesel and biodiesel, there exist no standards for the production of waste plastic oil under pyrolysis, which in turn affects various properties of the fuel including the density, viscosity, heating value, and so on. This is one of the biggest limitations. Financial problems are other limitations that set back from evaluating all the physical properties of the produced fuel.

1.9 Organization of the thesis

The first chapter deals with a general introduction including statement of problem, objectives, the significance of the study, beneficiaries of the work, scope, and limitations.

The second chapter, which is a literature review, reviews and explains some other researchers works previously done related to this title. Not only this but also the research gap was also highlighted.

Chapter three describes the materials and methodology used to accomplish this work. All the materials needed and the workflow including the test itself is properly listed and described in this chapter.

The results gained in chapter three are given in chapter four with a detailed discussion of the results whether it brings the desired result or not and why.

In the last chapter, chapter five, the conclusions drawn based on the results obtained. The recommendations and future works are also clearly given.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Overview

An overwhelming majority (99%) of internal combustion engines employ liquid fuels that are fossil-based (Taylor et al. 1985). Products arising from petroleum refinement are often classified according to their use and their volatility and specific gravity, as determined by distillation at sea-level atmospheric pressure. “The main products obtained through this process include natural gas, kerosene, gasoline, fuel oils, diesel oils, and lubricating oils” (Guibert et al. 1997). This chapter compares different fuel properties and performance test of diesel fuels obtained from crude oil against waste plastic pyrolysis oil and their blends.

2.1.1 Diesel Fuels

Diesel fuels refer to the liquid petroleum fuels that are usually employed in compression or diesel engines. The American Society of Testing Materials (ASTM) standard D 75 characterizes diesel fuel in the United States, and currently identifies five grades of diesel fuels.

Grade No.1-D (DF1) and Low Sulfur 1-D:

This is a light distillation fuel for applications that involve a high volatility fuel for intermittent speeds and loads as in light buses and trucks. The specifications of this type of diesel fuel overlap with those of jet fuel and kerosene, and all the three fuels are often obtained from the same stock. One of the major uses of No. 1-D diesel is blending with No. 2-D to offer enhanced low-temperature properties during winter. In addition, No. 1-D diesel is necessary for highway use due to its low sulfur content of less than 0.05%.

Grade No. 2-D (DF2) and Low Sulfur 2-D

This type denotes a middle distillation fuel for uses that do not require a high volatility fuel. Typical usages include high-speed engines that operate at high loads for constant periods. Low Sulfur No. 2-D fuel is essential for use on the highway due to its low sulfur content of less than 0.05%.

Grade No. 4-D

This grade refers to a heavy distillation fuel that is viscous and may need fuel heating to achieve proper atomization. This grade of fuel discoveries usage in engines of low speeds.

2.1.2 Biodiesel Fuels

Conventional sources of biodiesel oils such as cottonseed, sunflower, castor, palm, and linseed have become leading candidates for alternative sources of fuel for use in diesel engines. According to Munavu et al. (1984), several indigenous and non-edible vegetable oil sources can also be used as alternative fuel sources in Kenya. Their physical and chemical properties are analogous to those of conventional vegetable oils. One such source for nonconventional vegetable oils is *Jatropha curcas*.

Pramanik et al. (2002) studied the properties and use of unmodified *Jatropha* oil and diesel-blended fuels in compression ignition found that between 40 and 50% of unchanged *Jatropha* oil can be substituted for diesel without the need for preheating of fuel blends and engine modification. Kumar et. al. (2001) stated that diesel engines can use original *Jatropha* oil without a major drop in engine performance. However, the studies established that while the performance of the *Jatropha* methyl ester was better than that of original *Jatropha* oil, its performance was still inferior to that of pure diesel. Therefore, it is significant to explore the properties of pyrolysis oils, particularly WPO, to determine if they are superior alternatives than biodiesel. The properties of *jatropha* biodiesel are given in table 2.1.

Table 2. 1: Physical and Chemical Properties of *Jatropha* biodiesel.

Properties	Liang et al. (2006)	Lin et al. (2007)	Sangha et al. (2004)
Density (g/cc), 300 °C	0.9180	0.93292	0.9135
Kinematic viscosity (cSt), 30 °C		52.76	26.22 @ 25 °C
Cetane number	51	38.00	
Flash point °C	240	210.00	
Calorific value, MJ/kg	39.62	38.20	
Saponification value		198.00	185.2
Iodine number		94.00	92.1
Acid value			3.52

2.1.3 Pyrolysis Oils

Pyrolysis refers to the chemical degradation of organic substances using heat in the absence of oxygen. Usually, pyrolysis is the first chemical reaction that occurs in the burning of various organic fuels in solid form, including wood, cloth, paper, tires, and some types of plastic. An anhydrous pyrolysis process can be employed to make liquid fuels from waste plastics with similar characteristics to those of diesel (Yoshida et al. 2015).

The pyrolysis of tires aims to convert waste tires into potentially recyclable materials such as pyrolysis oil, flammable gas and carbon black. Tire pyrolysis oil is associated with a high gross calorific value (GCV) of between 41 and 44 MJ/kg (Lee et al. 2007). Various plants for producing tire pyrolysis oil exist around the world with many producing pyrolysis oil as a substitute for heavy fuel oil used for heating purposes in industrial applications. Usually, the waste tire needs to be shredded before the pyrolysis process can begin. The maximum yield of tire pyrolysis oil occurs at 350°C and decomposes rapidly above 400°C. In addition, desulphurization becomes a necessity during the pyrolysis process in order to eradicate sulfur content. Frequently the products of tire pyrolysis on a weight basis consist of 35% tire pyrolysis oil, 56% residue, and 9% gases (Miller et al. 2005).

High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Propylene (PP), and Polystyrene (PS) are all hydrocarbons that entirely consist of hydrogen and carbon, which are similar to hydrocarbon fuels such as gasoline, diesel, and liquefied petroleum gas (LPG). Undeniably plastics are derived from petroleum and the range of their calorific values is like that of diesel, petrol, and LPG as shown in Table 2.2 below (Baines et al. 1993).

Table 2. 2: Comparison of the Energy Density of Plastics and other Hydrocarbon Fuels.

Material	Calorific Value (MJ/kg)
Polyethylene	46.3
Polypropylene	46.4
Polystyrene	41.4
Polyvinyl chloride	18.0
Coal	24.3
Liquefied petroleum gas	46.1
Petrol	44.0
Kerosene	43.4
Diesel	43.0
Light fuel oil	41.9
Heavy fuel oil	41.1

The production process usually involves the collection and segregation of waste plastics. The segregated waste plastics are then washed, dried, and stored. The waste plastics are then shredded and fed into the hopper of a pyrolysis reactor or directly into the reactor where they flow into the heating chamber in the presence or absence of a catalyst. The plastic waste is decomposed into liquid vapor which flows into a condenser and liquid and tarries waste which is tapped and collected in containers. The condensed liquid vapor is then tapped and collected as the waste plastic oil (WPO).

2.2 Comparison of Fuel from Waste and crude oil Used in IC Engine

Based on the diesel regulation, the important properties of plastic derived fuels are surveyed in most studies because the diesel fuel is produced from synthetic hydrocarbon polymers that do not comprise any other elements except for carbon and hydrogen. Therefore, some of the miscellaneous properties are not central for the diesel from plastic pyrolysis, such as sulfur content and water content. The class of the liquid fuels from the pyrolysis of plastics will vary with pyrolysis procedures, reactor type, and types of plastic feedstock. However, evaluation of the plastic pyrolysis fuels and petroleum-derived fuels has both been found in the literature review and this study will summarize some of them as follow.

The quality of plastic derived fuels differs basically based on the process and the feedstock type. The diesel range products in the LDPE derived fuels hold the same linear chain alkanes

as those in the fresh diesel. The content of alkene in LDPE derived products is considerably higher than that in diesel, which decreases the storage stability of fuel (Kumnesky et al. 2004). Compared to naphtha, aromatic compounds, and branched hydrocarbons, linear alkanes have a relatively higher cloud point with the same carbon number or density.

Therefore, many catalysts and processes were used to reduce linear hydrocarbons and increase the proportion of others (Kaminessky et al. 2004). According to this journal by (Kaminessky et al. 2004), It was found that plastic derived diesel contains a high proportion of linear alkane that has low solubility in diesel. This can significantly increase the cloud point that is the temperature at which the first crystals appear in diesel. De-waxing, hydrogenation, isomerization, and cyclization are normally used in the pyrolysis processes to change the chemical composition in the products. Some other properties of plastic derived fuels are controlled in the production processes such as distillation range and carbon residue in the fuel.

Using this fuel oil in 100cc Passion Plus bike, after converting the **plastic** waste by pyrolysis (310 to 355 °C) and the **non-plastic** waste by Bio-Fuel Formation from Biomass of agricultural and perishable waste (140 to 170 °C), it increases the efficiency of the bike by 25 to 30% as compared to petrol used in the bike. Engine fueled with waste plastic oil exhibits higher efficiency, but it gets its performance better when mixed with a suitable mixture with the fuel made from day to day waste material. By comparing the density of waste oil with petrol, it gives approximately the same value. It could be concluded that the thermal pyrolysis of plastic mixed with perishable waste fluid in a given ratio leads to the production of fuel oil, valuable resource recovery, and reduction of the waste problem. Thermal pyrolysis of waste plastic has also several benefits over other alternative recycling methods. It has been shown that the conversion at a lower temperature in the presence of catalyst into liquid is a feasible process. The use of a perishable based fluid with Pyrolysis fuel enhances its quality to an extent that its mileage is improved by about 10 to 15% more (Parishwang et al. 2016).

The experimental study by Ankit et al. (2018) was conducted on a single-cylinder, 4-stroke, multi-fuel, research diesel engine to appraise the effects of performance and exhaust emission operating with Waste Plastic Oil and its blends with diesel. For fuel production 200 grams of waste transport plastic which is used for packaging is used at a temperature of 400-500 °C. Based on this experimental study:

1. The use of Waste Plastic Oil blended fuel in a diesel engine causes improvement in engine performance and exhaust emissions. Plastic oil is safe to use up to 40% blended with diesel without loss of power, and its trend does not differ with variation in the compression ratio.
2. Waste Plastic oil addition results in the increase of Brake Thermal Efficiency (BTE) and a decrease in the specific fuel consumption. BTE for diesel and B40 are 33.33% and 38.7% at CR 18:1 at maximum load. The bsfc reduces with an increase in CR. The deviation in bsfc detected at maximum load for diesel and B40 is 0.26 ± 0.04 kg/kWh at CR 18.
3. Waste plastic oil addition results in a significant reduction in exhaust emissions. Carbon monoxide (CO) decreases with an increase in load, an increase in blend ratio up to 40% of WPO, and an increase in compression ratio. NO_x emission of B40 is very close to pure diesel at a lower load up to 50% and higher for further increased load for all CR. CO₂ emission of B40 is lower for all compression ratios when compared with diesel. CO₂ emissions increase with respect to load for all blends, and at maximum load emission for diesel and B40 are almost the same.

2.3 Suitable plastic types for pyrolysis

Thermal and catalytic pyrolysis of all plastic types such as PS, PE (HDPE, LDPE), PP, PVC, and PET as a single substrate has been carried out in the last few years. Lee et al. (2009) and Miskolczi et al. (2009) carried out pyrolysis of mixed municipal plastic waste that was encompassed of almost all types of plastics. In addition, a few studies were carried out on the pyrolysis of polymethyl methacrylate (Kaminsky et al. 2004) and polyurethane (Miskolczi et al. 2004). Sakata et al. (1996) and Lopez et al. (2012) studied the pyrolysis of PVC that produced dangerous chlorine gas. Therefore, the de-chlorination step at a low temperature was recommended to stop the hazardous chlorine as a processed product in the form of HCl (Lopez et al. 2011). Suitability of different plastics for pyrolysis is given in table 2.3 below.

Table 2. 3: Suitability of different plastics for pyrolysis.

Resin	Suitability for pyrolysis	Remark	References
	Not suitable	✓ Contains hetero atom's	Thorat et. al. (2013)
  Polyethylene	Very good	✓ Required temperature is higher than 500 °C due to its branched chain structure. ✓ In thermal pyrolysis it converts into wax instead of liquid oil ✓ In catalytic pyrolysis wax formation is occurred on external sites of catalyst while further cracking of wax into gases and liquid occurred in internal site of pyrolysis.	Miskolezi et al. (2009) Lee (2012)
 Polyvinyl chloride	Not suitable. only few studies was carried out by different scientists	✓ Produce hazardous chlorine gas ✓ De-chlorination via low temperature (250-320 °C) or physical or chemical absorption ✓ In catalytic pyrolysis presence of chlorine and deposition of coke affect the catalytic activity of catalyst.	Lopez et al. (2011) Lopez et al. (2012)
 Polypropylene	Very good	✓ Required high temperature ✓ After PE it is difficult to degrade thermal pyrolysis of PP. ✓ In catalytic pyrolysis produces liquid yield with high aromatic compound	Miskolezi et al. (2009)
 Polystyrene	Very good and gives excellent fuel properties	✓ Low temperature required as compared to PE and PP. ✓ Produce less viscous oil as compared to PE and PP.	Lee et al. (2007) Sidliqi et al. (2009)

According to Mantesh et al. (2017), Low-density polyethylene (LDPE) is selected for such an experiment and the thermal cracking process without catalyst was used. 6.5 Kg waste plastics which were cut into 3-5 cm size started heating from 100 °C to gradually up to 400 °C. Between 100 and 250 °C 20-30% of waste plastic fuel is collected, and when the temperature increased to 325 °C the next 40% and at 400 °C the harvest was fully complete. Before filtration and purification, the yield percentage was 90% and the rest 6% was light gases and 4% solid black residue in the reactor. Finally, 4 liters of plastic fuel was collected. The values of specific gravity, density, viscosity, gross calorific value, flash point, and fire point for this waste plastic fuel found to be in between the regular petrol and diesel values.

According to Vikas et al. (2015) closed combustion chamber with an electronic heater of 2000 watt is used and high-density polythene and low-density polythene is converted into recycled fuel by pouring in the close combustion chamber, then by heating the close combustion chamber in a temperature range of 110 to 300 °C for approximately 30 minutes to 1 hour. Approximately 500ml of fuel is collected after 2 hours.

A transparent bottle which is airtight and half-filled with water is used for both condensing the gasified fuel and collecting the waste plastic fuel after liquefied. The density of HDPE and LDPE oil found in this paper is approximately the same value to that of petrol and diesel, respectively. Other properties like viscosity, specific gravity, flash point, fire point, cloud point, or pour point are also investigated and the values are almost the same as that of the conventional fuels.

Based on the study of Ojolo et al. (2005) a well dried municipal solid waste consisting of food waste, fruit/vegetable, paper, plastic, and textile mixtures was used as a raw material. The experiment was held four times in which 12 kilograms of waste was used in each experiment for four hours at a temperature range of 400-650 °C. After the four experiments an average yield and energy of tar oil found to be 52.19%, char 24.23%, and that of pyro gas 22.58% by weight. Based on these results it was concluded that taking proper distillation of tar oil some useful petroleum products can be derived but the char cannot be used due to low energy in it.

Liquid fuel was produced from different mixtures of land fill plastics i.e. PP, LDPE, HDPE, and mixed plastics as a raw material in which conventional slow pyrolysis in a batch reactor between 250 to 350 °C as experimental conditions. In the study different maximum yield of liquid fuel was found. When PP was used as a raw material which is 80% and the least was

mixed plastics, which is 46% by weight. The Distillation temperature of pyrolysis liquid fuel varies from 191 °C (mixed plastics) to 207 °C (HDPE) on average but when the distillation temperature was raised above 250 °C all except LDPE (35%) yields approximately 40% of distilled fuel by volume. Finally, it is stated that the obtained liquid fuel (after distillation) was similar to that of petroleum diesel oil (Chung et al. 2003).

Dianta et al. (2015) tried to explain the importance of waste plastic pyrolysis at higher temperatures typically 900 °C than using at a temperature range of 350-500 °C in terms of carcinogenic reduction and increase of flammable compounds (2-propane). Accordingly, a calorific value of 46,848 kJ/kg which is greater than those waste plastic fuels obtained at 425 °C mostly not more than 41,870 kJ/kg. not only this the level of carcinogenic compounds (boric acid and cyclopentanone) is reduced and it is concluded that at 900 °C fuel properties of waste plastic can be more secured.

According to this research article by Khan et al. (2016), HDPE waste plastic was converted in to waste plastic oil as an alternative fuel, characterized in detail, and compared with conventional fuels used. The experiment was carried out in a batch reactor between 330 and 490 °C for two hours and forty minutes of retention time. The effect of temperature on total product yield, the effect of distillation temperature on crude waste plastic pyrolysis oil, and physicochemical analysis was carried out in detail. In percentage by weight 77.03% product was found and can be used as furnace oil by blending with petroleum oils even though further study is also needed.

Antony et al. (2011) studied the difference between non-catalytic pyrolysis and catalytic pyrolysis cracking and how the fuel grade can be upgraded using catalyst cracking. According to this study when no catalyst was used, the temperature for pyrolysis is higher and all the reactive time is longer. Due to this the octane number of gasoline will be relatively lower and the pour point of diesel will be high. Additionally, using catalyst cracking can maximize the yield capacity and reduces those additives used in the process of purification relatively to those of regular fuels obtained from crude oil.

Khaing et al. (2015) studied a sample of 200 grams of mixed plastics consisting of HDPE, LDPE, PP, PS, and PET as a raw material in which 40%, 22.5%, 30%, 5% and 2.5% by weight shares each according to their listing order. In each experiment 20 grams of natural catalysts like Shwedaung clay, Mabisan clay, Bentonite clay, Dolomite, and synthetic catalyst like zinc oxide were used with 1-gram starch powder and starch powder binder 1% by weight

of the catalyst. For catalyst pelletizing 10 ml of water was added into the catalyst mixture and the temperature range was 32 to 380 °C. The final yield of liquid fuel ranges from 63.76% to 67.06% and that of gas was from 19.92% to 28.5%. Among those results mentioned above the maximum fuel and minimum gas yield i.e. 67.06% and 19.92% respectively were found while Mabisan clay catalysts were used in the temperature range of 220 to 370 °C for one and a half hours.

Miteva et al. (2016) analyzed the effect of the PID temperature control program with different proportions of Al_2O_3 and SiO_2 catalysts to convert HDPE and PP into liquid fuel. The pyrolysis experiment was carried out from 180 to 550 °C for three hours of retention time in a semi-batch reactor equipped with temperature measuring instrument and control system i.e. PID control. Among those parameters mentioned above retention time, SiO_2 , and PID program have a predominant effect on the product yield. The maximum yield of liquid fuel (88% by weight) obtained when the catalyst SiO_2 was used at a suitable PID program to it.

According to Sonawane et al. (2016) 100 grams of well washed and dried HDPE milk garbage was used as a raw material in a shredded form with silica and alumina catalysts each weighing 5 grams. The experiment was carried out in a temperature range of 430-470 °C in five different ways. First without catalyst, second and third with 5% silica and 5% alumina catalysts and the last two with 5% silica and alumina mixture in 7:3 and 8:2 weight ratios. In order to create an inert atmosphere nitrogen gas was purged before the experiment started for about 2 minutes with a 50 ml/min flow rate. The maximum yield of HDPE liquid fuel 87.34% and minimum yield 54.64% by weight were obtained with 5% Silica Alumina (7:3) and 5% silica respectively. Finally the calorific value for that maximum product 87.34% was 43,000 KJ/Kg which is a close value to that of petroleum diesel oil having a calorific value of 45,000 KJ/Kg.

Siddhant et al. (2016) identified different types and classes of hydrocarbon groups from PP waste plastic once the necessary purification method carried out. Once the PP was converted into liquid fuel and distilled in five-stage fractional distillation for further purification, PP waste plastic fuel in the first fraction (40-60 °C) consists of very light groups of hydrocarbons from C_3 - C_{10} and density of 0.72 gm/ml. As stated in the research, sulfur, and other harmful contents are very low, and due to this reason the obtained fuel can be considered as a clean product with almost similar properties to gasoline with slightly higher molecules in PP waste plastic fuel C_3 - C_{10} than gasoline C_3 - C_9 .

2.4 Factors affecting Plastic pyrolysis

The main causes influencing the plastic pyrolysis process and pyrolysis product molecular distribution include chemical composition of the feedstock, cracking temperature and heating rate, operation pressure, reactor type, residence time, and application of catalyst. These factors are shortened and presented in this section as follows.

2.4.1 Chemical composition of the feedstock

The pyrolysis products are directly associated with the chemical composition and chemical structure of the plastics to be pyrolyzed. In addition, the chemical arrangement of the feedstock also affects the pyrolysis processes. In reality, waste plastics are possibly contaminated before recycling which could also have effects on the pyrolysis process, and products (McMurry et al. 2000).

2.4.2 Cracking temperature and heating rate

Temperature is one of the most important operating variables since the temperature dominates the cracking reaction of the polymer materials. But not all of the polymer materials can be cracked by increasing the temperature.

The other operating thermal dynamic parameter is the heating rate. The term “heating rate” in this field means the increase in temperature per unit time. The effect of the heating rate on the plastic pyrolysis process and product distribution differs in different studies due to the differences in the pyrolysis reactor, operation conditions, like temperature, and pressure, and temperature measurement location (Serrano et al. 2003).

In a batch process, the plastic is typically heated from room temperature to the cracking temperature in numerous minutes. It is a slow pyrolysis process. Once the plastic feedstock is heated to the cracking temperature, the temperature remains comparatively constant until all feedstock has been pyrolyzed. Therefore, the heating rate is generally applied as the temperature indicator instead of the reaction temperature in a slow pyrolysis process (Hernández et al. 2007).

2.4.3 Type of reactor

Reactors can be classified into a batch, semi-batch, and continuous or can also be classified based on types of reactor beds.

Batch, semi-batch and continuous reactors

According to the feeding and product removal processes, the pyrolysis reactor is classified into a batch, semi-batch, and continuous reactors. In the batch reactor, the materials are fed into the reactor in batches for pyrolysis either at the start of the pyrolysis process or after all of the fed materials are processed. In the continuous reactor, the feedstocks are feed from one part and the products are led out from the other part of the reactor. A semi-batch reactor removes the pyrolysis products continuously once they are produced but the feed materials are added initially before the pyrolysis process starts (Mastral et al. 2006).

Some semi-batch process uses inert carrier gas to take out the pyrolysis products. Batch and semi-batch reactors are mainly applied to research and the continuous reactor is mainly used for industrial products such as Mitsui R21, Fuji, Toshiba, Veba Oel, PKA, etc (Ivanova et al. 1990).

2.4.4 Residence time

Residence time in fast pyrolysis or continuous pyrolysis process refers to the contact time of the plastic on the hot surface throughout the reactor but in slow pyrolysis and batch process, it is to mean the duration from the time when feedstock plastic starts to be heated to the time when the products are removed. Longer residence time favors a further conversion of the primary products thus yielding additional thermally unstable products such as light molecular weight hydrocarbons; non-condensable petroleum gases (Aguado et al. 2016). In slow pyrolysis, long residence time encourages the carbonization process and produces more tar and char in the products. The pyrolysis conditions, residence time, and target products are given in Table 2.4.

Table 2. 4: Pyrolysis processes and target products.

Process	Heating rate	Residency time	Temperature (°C)	Target product
Slow carbonization	Very low	days	450-600	Charcoal
Slow pyrolysis	10-100 K/min	10-60 min	450-600	Gas, oil, char
Fast pyrolysis	Up to 1000 K/s	0.5-5 sec	550-650	Gas, oil, char
Flash pyrolysis	Up to 10000K/s	<1sec	450-900	Gas, oil, char

Except for the batch pyrolysis reactor in a closed system, the residence time is difficult to be controlled directly but can be adjusted by changing other operating factors such as feeding

rate, carrier gas stream rate, and product discharge rate. The residence time was then calculated for these controllable operation parameters (McMurry et al. 2000). Secondary pyrolysis cracking occurs when residence time is long enough, which enhances the yield of gaseous products (Simon et al. 1996).

2.4.5 Use of catalyst

In order to enhance plastic pyrolysis reactions and adjust the distribution of pyrolysis products, catalysts are widely used in research and industrial pyrolysis processes. Petroleum fuels such as LPG, petrol, kerosene, and diesel, are hydrocarbons ranging from C₁ to C₂₄.

The PE pyrolysis products are mostly straight hydrocarbons from C₁ up to C₈₀, which encompass much heavier molecular weight components (Aguado et al. 2006). One of the main purposes of adding catalysts is to cut the carbon chain length of the pyrolysis products and thus to decrease the boiling point of the products. The main reason catalysts is applied to PE pyrolysis are because the primary product from other plastics such as PP, and PS are mainly light hydrocarbons, with similar carbon chain length to the range of commercial fuels. The products from non-catalytic PE pyrolysis enclose a high proportion of 1-alkenes and di-alkenes. Some catalysts are applied specifically to decrease the unsaturated hydrocarbons and stimulate the yield of aromatics and naphthenes. This can significantly increase the stability and cetane number of oil products. Furthermore, it is reported that activation energies (E_a) measured in the PE pyrolysis with catalysts (such as HZSM-5, HY, and MCM-41) were much lesser than those when no catalyst was added (Garforth et al. 1998).

Sonawane et al. (2015) tried to study the effect of a catalyst on retention time required, total yield, and quality of the product. For the experiment 200 grams of properly cleaned, washed, and shredded PP waste plastic was used as a raw material. For a clear understanding of the effect of catalysts, the experiment was held first without any catalyst and then using 10% of natural zeolite as a catalyst. The result shows that to start receiving the distillate and to complete the processes 25 and 90 minutes for non-catalytic pyrolysis and 20 and 65 minutes required for 10% natural zeolite catalyst respectively. Not only reduction of retention time by using a catalyst the total yield of pyrolysis oil with and without catalysts was 80% and 86% by weight respectively, and using natural zeolite as a catalyst improves the quality of the produced oil like physical appearance and calorific value.

Catalyst classification

Homogeneous and heterogeneous catalysts have been studied for the catalytic cracking of plastics. Homogeneous catalysts used for polyolefin pyrolysis have mostly been classical Lewis acids such as AlCl_3 (Ivanova et al. 1990). Generally, heterogeneous catalysts are preferred due to their easy split-up and recovery from the reacting medium.

Heterogeneous catalysts can be summarized as nanocrystalline zeolites, aluminum pillared clays, conventional acid solids, mesostructured catalysts, super acid solids, metals supported on carbon, and basic oxides (Aguado et al. 2006). Among the listed catalysts, Nanocrystalline zeolites have been widely studied for polyolefin pyrolysis.

2.4.6 Pressure

Operating pressure has a substantial effect on both the pyrolysis process and product types. The boiling points of the pyrolysis products are increased under higher pressure, therefore, under pressurized environment, weighty hydrocarbons are further pyrolyzed instead of vaporized at given operating temperature but under pressurized pyrolysis more energy is required for further hydrocarbon cracking. It was also found that high pressure increases the yield of non-condensable gases and decreases the yield of liquid products. The influence of pressure on the concentration of double bond, $\text{C}=\text{C}$, of the liquid product was not significant as reported by (Miranda et al. 2001).

2.4.7 Other Influencing factors

There are a number of other factors that also affect the pyrolysis process to a certain extent. For example, reactive additives such as air, oxygen, or hydrogen are sometimes present in the reaction for different purposes, which will interfere with the reactions and affect the quality of the products.

Further pyrolysis of the primary product occurs in most processes. Secondary cracking reactions were found in many reports which are enhanced by high pressure, long residence time, low heating rate, and high refluxes (Siddiqui et al. 2009).

2.4.8 Multi-factor effect on pyrolysis process

It is difficult to directly compare the product yields obtained for a specific plastic in different researches as the operating conditions and reactors can be very different. In general pyrolysis processes, thermal degradation occurs in the initial stages of the pyrolysis with the absence of oxygen. The pyrolytic products immediately after the pyrolysis consist of solid residue, oil vapor, and non-condensable gases among which the oil vapor will become liquid after cooling down. According to the residence time or the heating rate during the pyrolysis process, the pyrolysis can be classified into slow carbonization, slow pyrolysis, fast pyrolysis, and flash pyrolysis. With a slow heating rate (less than 10K/min), the carbonization occurs and the process proceeds from the outer surface to the core of the plastic particles with the local carbonization temperature of above 300 °C. The carbonization process is determined by the heat transfer rate to the material surface and the heat transfer rate within the material. At the given temperature and heating rate, the residence time is also the most important variable to achieve the desired carbonization (Jung et al. 2006). The residence time required is also related to the dimensions of the material. If the size of the material is too large which needs much longer residence time, incomplete carbonization may occur at the center of the plastic particles. In other extreme situations, if the operating temperature is very high, for example 800 to 1000 °C, the gasification process occurs and in this case, the plastics are directly converted to short-chain gases and the yield of non-condensable gases in the product is maximized. High heating rate is required to minimize the proportion of solid char production and rapid quenching favors liquid production before further cracking into gaseous products (Lee et al. 2007).

The above-mentioned processes are applied to all of the plastic types to be examined including HDPE, LDPE, PP, and PS all of which have similar cracking temperatures from 320 to 500 °C. However, in the pyrolysis of PVC the cracking temperature (250 °C) is much lower than that of other common plastics mentioned above (Kim et al. 2001).

In most practical pyrolysis processes, particularly those applied in industries, pre-heating and melting the plastic feedstock between 200 and 300 °C are applied in order to reduce the volume of the feedstock and to eliminate the oxygen from the feeding system. The melting temperature is also high and sufficient for PVC to crack and form hazardous gases and acid. Therefore, a pre-heating chamber is commonly used in the commercial process to remove gases generated from the PVC degradation in the pre-heating.

2.5 Existing Commercial Plastic Pyrolysis Technologies and Processes

The waste plastic pyrolysis plants are settled and built in many countries. The selection of the process and the plant is determined mainly on the feedstock composition and the target products.

2.5.1 Feedstock effects

To summarize existing processes and technologies reported by, the most important property of plastic feedstock is whether it contains PVC or not (Aguado et al. 2006). PVC pyrolysis has different thermal cracking processes and different products from those of other common waste plastics including PE, PP, and PS. In the PVC pyrolysis, the products containing HCl are particularly hazardous for fuels (Kim et al. 2001). If the feedstock contains PVC, the plants must have a re-treatment system to remove and a solvent scrubber to remove HCl from the pyrolysis products.

The other important property for some current processes is the size of feedstock. The requirement for the feedstock size is to avoid the feeding blockage and to enhance the heat transfer between the heating medium and the plastics particles. It was found that in most cases, the feedstock is a mixture of various waste plastic in municipal solid wastes or industrial residues. In the pyrolysis of the mixed plastics, interactive effects among the different plastic types may occur due to the difference in cracking temperatures and different products (Aguado et al. 2006).

The selection of pyrolysis technology is based on the characteristics of the feedstock and the target products. In general, each pyrolysis technology comprises of three parts: feeding system, pyrolysis reactor, and separation system.

Feeding system

In most marketable processes, the raw materials are firstly heated and melted in the feeding system before flowing into the reactor. The air, moisture, and other solid materials can be detached from the raw materials in the feeding system. In addition, the pre-treatment may be required for cracking the PVC at 250°C (Uemichi et al. 1999). In some rotary kiln reactors, solid plastic particles with suitable sizes can be extruded into the reactor directly. Most feeding systems transport the highly viscous melted plastics into reactors by its gravity or by an extruder. However, a mandatory temperature gradient should be maintained from the feeding system to the pyrolyzer although this may not be an issue for the rotary kiln reactors.

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The mandatory temperature gradient is to avoid melted plastic cracking before entering the pyrolyzer. For example, the cracking temperature of PS is 420°C thus any overheating in the feeding system should be avoided. The free-fall feeding system is widely applied in fixed bed and fluidized bed reactors.

Pyrolysis reactor

The continuous pyrolysis process is functional to most commercial plants with the capability to use catalysts in which the plastic retention time is comparatively short. Very few of the commercial plants use a high-pressure working environment and most of the plants operate at or slightly above atmospheric pressure. The operating temperature in the reactors varies fundamentally from 250 °C (Mazda fixed-bed catalytic process in Japan) up to 800°C (Compact Power fixed-bed pyrolysis in the United Kingdom), nevertheless most of the pyrolysis reactors operate between 400 °C and 550°C (Scheirs et al. 2006).

It must be noted that if the operating temperature is above 800°C, the process becomes gasification and the products are mainly short-chain hydrocarbons that remain as gases under room temperature and atmospheric pressure. All of the viable plants are fast or flash pyrolysis. Three types of reactors including fixed-bed, fluidized-bed, and rotary kiln can be found in the literature review (Kaminsky et al 2004).

Product separation and collection

The products from plastic pyrolysis are mainly combustible gases and liquids. The liquids can be either combusted for power generation or for further refining to produce high-quality fuels. In some plants, the pyrolysis products are simply separated into liquid, gas, and solid whereas others have a more complete separation system by feeding the mixture of liquid and gas into distillation columns. Diesel category products can then be distilled out as in an oil refinery process. The non-condensable gases are mainly made of hydrocarbons, and a minor amount of hydrogen and carbon monoxide. The gases can be liquefied as fuels, or used as fuels to heat the pyrolysis reactor, or if the amount is insignificant, the non-condensable gases are sent to an incinerator flaring off with the air (Williams et al. 1999). Ash may present in the non-condensable gases so most commercial processes have a gas scrubber for cleaning the gases.

2.6 Summary of the review

So far it is observed that different types of waste plastics can be used as alternative fuels for petroleum products. As it is observed from the study of Baines et al. (1999) different plastic products like HDPE, LDPE, PP, and PS have similar calorific value with diesel, petrol, and LPG.

Not only WPO but also blends of WPO and diesel have studied by different researchers. Ankit et al. (2018) investigate that blending up to 40% is safe without loss of power, and its trend do not differ with variation in the compression ratio. In addition waste plastic oil addition results in a significant reduction in exhaust emissions.

In terms of yield of liquid fuel Khan et al. (2016) found 77.03% from HDPE and Mantesh et al. (2017) found 90% from LDPE.

Product yield with and without catalysts has a significant difference. Sonawane et al. (2015) found that the product yield increases from 80% to 86% while using natural zeolite as a catalyst.

2.6.1 Research gap

Since there are no standards for the production of waste plastic oil under pyrolysis, different types of production methods followed by different researchers and so different products were found. Some of them found improved properties and performance of WPO while others found lower values and even there are some researches that recommend the WPO does not use in a diesel engine without engine modification. So this paper work tries to show which one is more reasonable and how.

The next chapter deals with the required materials and the details of the methodology followed.

CHAPTER THREE

3. MATERIALS AND METHODS

This thesis work is purely experimental based. The materials and equipment used and methodology followed are clearly described in this chapter.

3.1 Description of the Equipment (Materials)

REACTOR – This is an insulated stainless steel cylindrical reactor heated by charcoal to achieve a maximum heating temperature which is useful to melt the feedstock and convert into gaseous form. The necessary running is made on the reactor for mounting the gadgets for the collection of hydrocarbons from the reactor.

CONDENSER – The gaseous output from the reactor passes through a single-walled water pipe which passes in a bowl filled with water (condenser 1). The liquefied hydrocarbon now received in the first receiver and the gaseous one which still not condensed passes to the next condenser and receiver. Unlike the first condenser and receiver the second condenser and receiver are not different rather it is a plastic water container half-filled with water. The gaseous hydrocarbons at a temperature of around 350°C condensed to around 30-35°C.

RECEIVER – The condensed hydrocarbon within the liquid form is collected within the receiver. The second condenser and receiver not only receives the liquefied fuel but also the water inside washes and clean the non-condensable gases while escape to the atmosphere.

MASS BALANCE- It is used to measure the exact mass of feedstock for proper weight percentage as the feedstock contains different types of municipal solid wastes.

THERMOMETER – It is used to measure the temperature of the water which is used as a condensation media. Much of the literature on waste plastic pyrolysis in which water is a condensation media, recommended the temperature of the water should not be above 25°C in order to reduce the temperature of gaseous hydrocarbon below 40°C. So this thermometer is used to assist this task by measuring the temperature of the water.

A simple batch reactor with some of the equipment mentioned above is shown in Figure 3.1 below.



Figure 3. 1: Simple batch reactor for waste plastic pyrolysis.

3.2 Production processes and methods

Production of pyrolysis oil consists of the following seven key stages:

1. Feedstock Preprocessing and preparation
2. Pyrolysis set up
3. Pyrolysis oil production
4. Filtration & Purification
5. Characterization of liquid fuel
6. Testing the performance in diesel engine
7. Data analysis

3.2.1 Feedstock preprocessing and preparation

The major tasks under this category include the following steps.

Identifying and collecting municipal solid wastes that are compatible with pyrolysis: among the different compositions of municipal solid wastes; glasses, bones, metals, ceramics, ash, dust, and non-combustible wastes should not be used due to high melting point and non-combusting behavior. Others like vegetables, papers, wood, and textiles have low calorific value and can be easily decayed, which implies pyrolysis is not a better and viable option. Plastics, on the other hand are the most suitable and viable for pyrolysis oil production due to higher calorific value and great impact if stayed as landfill. Therefore plastics are the main

targets feedstock for this study. Plastics used in this study are waste plastics of HDPE and LDPE, plastic bags, PP, and PS of yogurt plastic cups. A total of 12 kg sample was used in which the sample is pyrolyzed in batches of each 4 kg sample used (three trials). All of these plastics were collected from the daily disposed waste of people in the city. PVC is excluded because it is normally used in long term applications making a low contribution in the waste stream, and its conversion through pyrolysis produces a high yield of very corrosive hydrogen chloride.

Dirt removal and cleaning: Once the viable sample is collected, it is cleaned from the dirt materials, washed and left to dry in ambient temperature.

Shredding: For ease of feeding and pyrolysis, the cleaned feedstock shredded into less than 5 mm small pieces. Shredded waste plastic is shown in Figure 3.2.



Figure 3. 2: Shredded waste plastic for pyrolysis.

Weighing: Before making ready for final feeding, properly measuring the weight of each plastic group of feedstock is very important for data analysis later in the final stage. The balance used for weighing is shown in Figure 3.3.

Note: Municipal solid wastes were collected at Adama, approximately 100 kilometers east of Addis Ababa, the capital city.



Figure 3. 3: Analytical precision balance.

3.2.2 Pyrolysis set up

Once the necessary materials and wastes are collected and prepared, the next step is setting up the pyrolysis equipment.

The pyrolysis setup used in this experiment is a batch reactor shown in Figure 3.1 above. It consists of a reactor made of stainless steel tube (length 70 cm, internal diameter- 25 cm and outer diameter- 30 cm) sealed at one end and an outlet tube at the other end for obtaining the volatile/gas/oil products of the reaction.

All the equipment on the reactor sealed properly not to leak to the outside environment or from outside to the inside.

Mix and then introduce the weighed feedstock to the reactor and close it tightly to prevent the back leak of gaseous hydrocarbons during pyrolysis.

A simplified schematics of simple batch reactor used in this experiment is shown in figure 3.4 below.

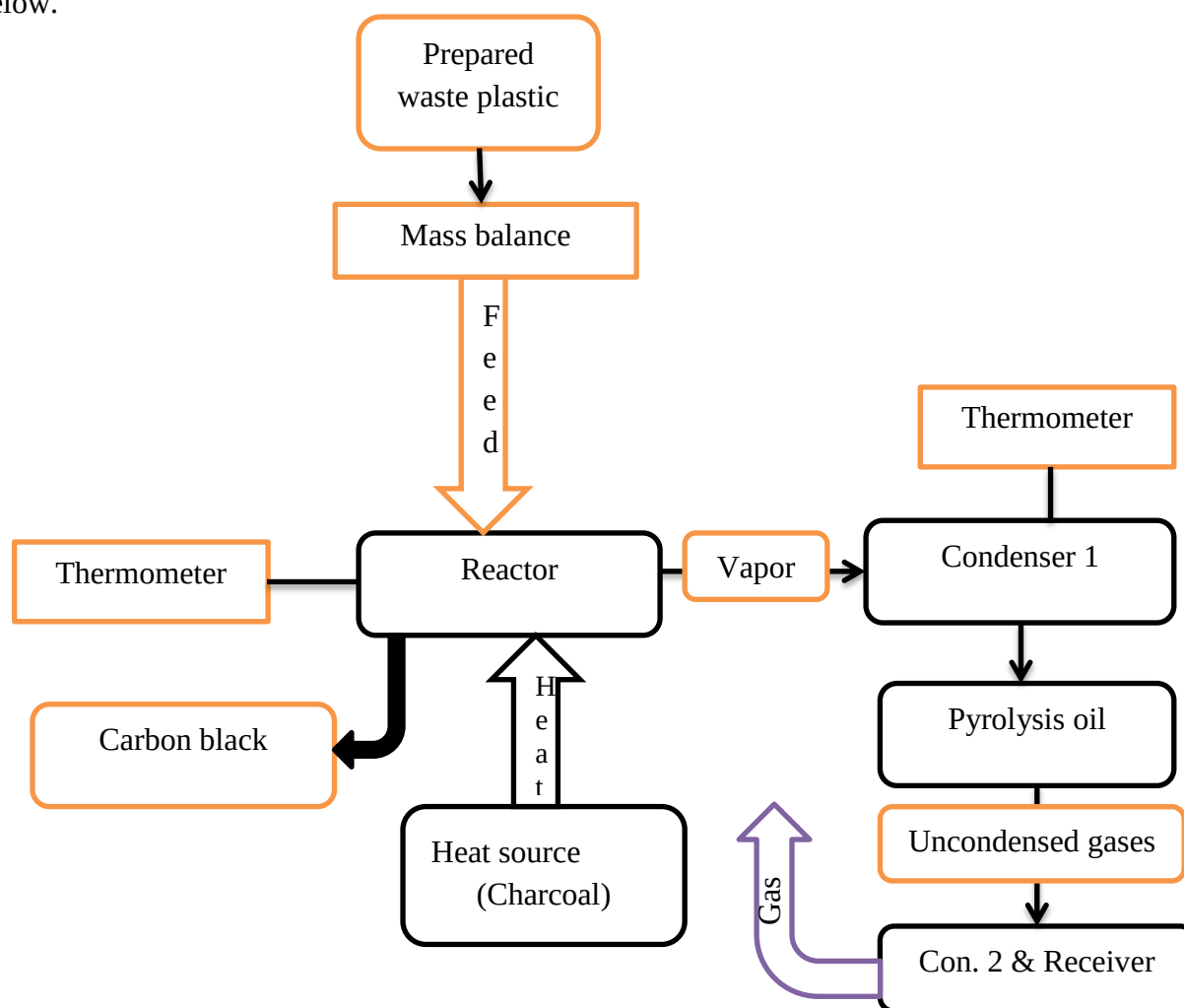


Figure 3. 4: Schematics of pyrolysis setup.

3.2.3 Pyrolysis oil production

The shredded feedstock was treated in a cylindrical batch reactor in a slow pyrolysis process of between 300°C and 450°C in the absence of oxygen for about 2 hours. But the temperature is increased slowly from ambient temperature to that of 300 to 450°C. No catalyst is used but as the temperature increases the waste can be gently cracked in to gaseous and the gases can be condensed into a series of gases, char and distillate oil, which is the main interest of the study. Feedstock can be added into the reactor in batches until to get the desired product both in quantity and quality. The qualities and quantities are checked using the product output gained after pyrolysis. The waste oil produced then stored ready for analysis and further distillation into petroleum oil application.

3.2.4 Filtration & Purification

The fuel collected in the receiver was impure. There was wax, grease, and other impurities. So to remove the impurities, the following processes were carried out.

- ✓ Gravity separation.
- ✓ Filtration with filter paper.

Gravity separation is the basic process. In this process the impure fluid is poured in a container in which the bottom part is like a funnel. So when the fluid is poured, the denser liquid will settle down below, most probably the water was found. Then the waxy and greasy substance which was pale greenish-yellow was found immediately above the water. Finally, most of the waste plastic oil is seen above in the topmost layer. So by opening the valve at the bottom, all the unwanted substances were removed and the remaining oil is processed further.

In the **filtration process**, the substances which are in the colloidal state can be removed. The filter paper will allow the molecules which are smaller than their pores. So the various sizes of smaller pores give more clean fuel.

The flow chart of the pyrolysis process is shown in Figure 3.5 below.

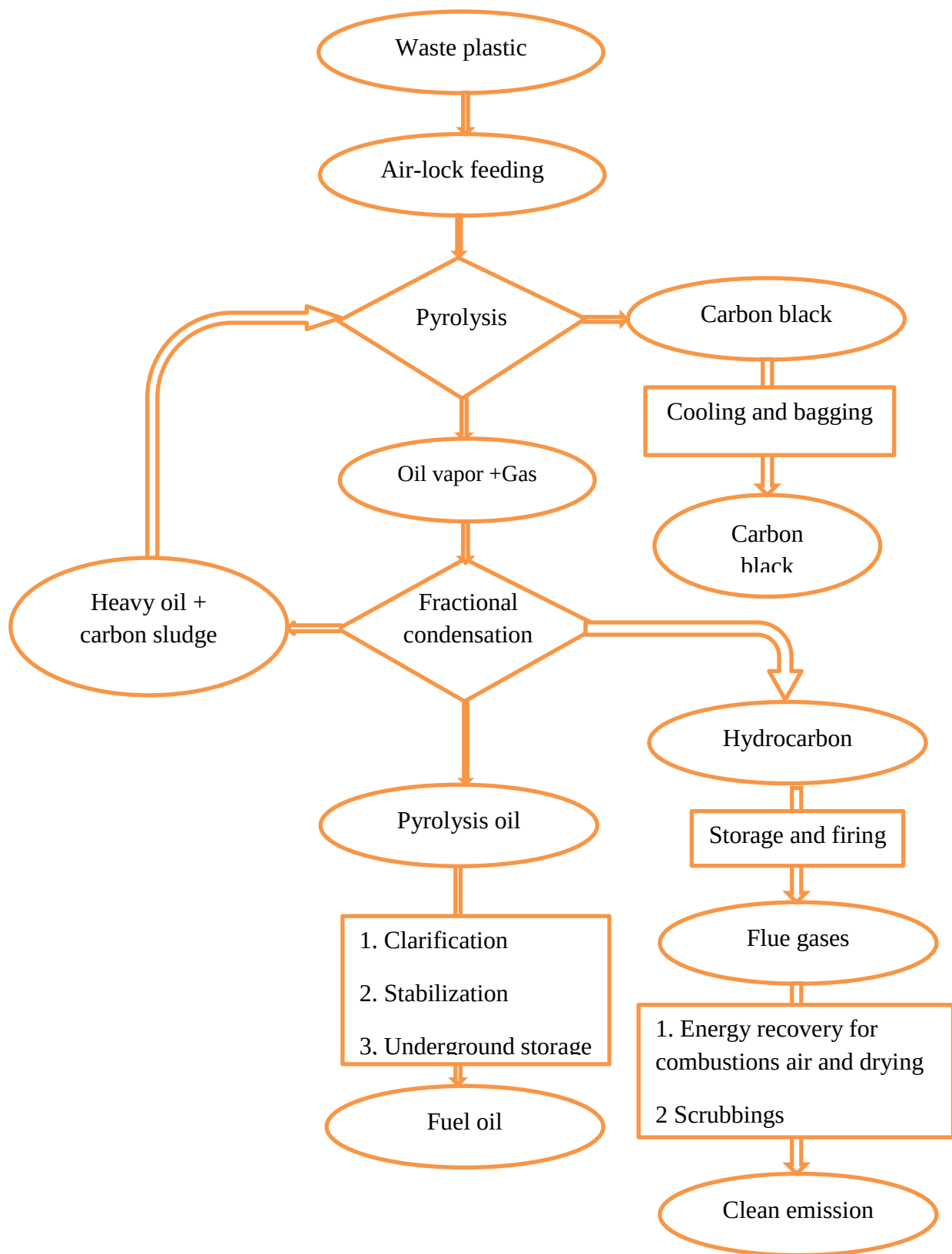


Figure 3. 5: Summarized overview of pyrolysis flow chart

3.3 Characterization of liquid fuel

Characterization of some of the waste plastic fuel to be tested in these experiments was carried out at Adama Science and Technology University (ASTU) chemical engineering laboratory. Fuel properties of the tested samples were determined in accordance with the American standard for testing materials (ASTM) procedures for petroleum products in the book of ASTM, 2002.

But before characterizing different properties of liquid fuel at operating conditions that had a higher yield was tested and compared with standard results. The yield of liquid fuel products from each experiment was calculated using the following equation 3.1.

$$\text{Condensate} = \frac{((R_1 + C_1 + RC_1) - (R_0 + C_0 + RC_0))}{M_s} \times 100 \dots \dots \dots \text{equation (3.1)}$$

Condensable=Yield of condensable volatiles (wt %).

R_0 = Mass of the reactor before the experiment (kg).

C_0 = Total mass of condensers before the experiment (kg).

RC_0 = Total mass of rubber connectors before the experiment (kg).

R_1 = Mass of reactor after the experiment (kg).

C_1 = Total mass of condensers after the experiment (kg).

RC_1 = Total mass of the rubber connectors after the experiment (kg).

M_s = Mass of the feed sample (kg).

The yield of char was calculated as the fraction of the difference in mass between the sample boat content before and after the experiment using Equation 3.2 below.

$$\text{Char} = \frac{(B_1 - B_0)}{M_s} \times 100 \dots \dots \dots \text{equ (3.2)}$$

Where:

Char= Yield of char (wt %)

B_0 = Mass of sample boat and sample before the experiment (kg).

B_1 = Mass of sample boat and char after the experiment (kg).

The gas yield (Gas) was calculated by the difference from 100 wt % of the condensable volatiles and char yield sum as illustrated in equation 3.3 below.

$$\text{Gas} = 100 - (\text{Condensate} + \text{Char}) \dots \dots \dots \text{equ (3.3)}$$

The overall conversion is the fraction of the feed that ends up as products in the pyrolysis process and it was determined using Equation 3.4 below.

$$\text{Conversion efficiency} = \frac{M_s - M_c}{M_s} \times 100 \dots \dots \dots \text{equ (3.4)}$$

Where:

M_c = Mass of char (kg).

M_s = Mass of the feed sample (kg)

Using the condensed liquid and feedstock, the percentage yield of liquid fuel can be calculated using equation 3.5 below.

$$\text{Yield of liquid fuel} = (M_1/M_s \times 100\% \dots \dots \dots \text{equ (3.5)})$$

Where:

M_1 = Mass of liquid condensate (kg).

M_s = Mass pyrolysis feedstock (kg).

The reactor was emptied after every run to accumulate char product inside and solidified oil (wax) that remain on its inner walls. Respective masses measured after weighing the samples were then used to estimate the amount of non-condensable (NC) gas product from the experiment as shown in equation 3.6.

$$\text{NC} = \text{M. pyrolysis feed stock} - (\text{M. char} + \text{M. liquid fuel}) \dots \dots \text{equ (3.6)}$$

The properties like density and kinematic viscosity of the purified fuel were measured using ASTM standards.

1. Density

A small volume of liquid sample was introduced into the density meters oscillating sample tube. The change within the oscillating frequency of the tube, caused by the increased mass of the tube, was employed in conjunction with calibration data to see the density of the sample.

Density could also be determined by using the relation below:

$$\rho = (M.liquid\ sample)/(V.liquid\ sample)$$

10 ml volume can be taken and using an analytical precision balance (can measure up to 0.0001 g) we can measure its mass and using the above relationship so the density. In this case care should be taken for ambient temperature.

2. Kinematic Viscosity

Kinematic viscosity of plastic fuel similar to diesel was determined using ASTM D562, standard test methods for kinematic viscosity of transparent and opaque liquids.

Table 3. 1: Features and specifications of the viscometer.

Feature	
Method	ASTM D562
Units	KU, g, cP
Manual mode	for all manually operating with all samples and containers
Automatic mode	for only available for 600ml standard beaker with 450 to 460 ml sample on pin adapter
Specifications	
Speed	200 rpm
Accuracy	+ or – 1% of full scale
Repeatability	+ or – 0.2%
Power	100 – 240V, 50/60Hz
Viscosity	• KU:40.2 to 141 • g: 32 to 1099 • cP: 27 to 5274

The kinematic viscosity of the sample was measured in automatic mode with units of cP and the viscometer is shown in Figure 3.6 below.



Figure 3. 6: Kinematic Viscometer

3.4 Performance Test

In this section performance characteristics are clearly stipulated. The Engine performance test was conducted in Addis Ababa Science and Technology University, School of mechanical and electrical engineering automotive workshop laboratory on the TBM3-02 Computer Controlled Test bench for a single-cylinder diesel engine. The test machine is very modern; all the test results including the exhaust or emission properties are directly read from the computer; that is integrated with the test bench. As shown in figure 3.7 below, the main parts of the machine that the complete test stand consists; an air-cooled diesel engine (1), Asynchronous motor (2), fuel tank (3), SCADA software control system (4), computer (5), and exhaust gas analyzer (TBM3_AGE) (6).



Figure 3. 7: Experimental setup of TBM3-02 test bench for single-cylinder diesel engine

In this investigation, pure diesel fuel and a blend of diesel fuel and waste plastic oil (20%, 30%, and 50% by volume) were tested. Performance and emission tests for each fuel were tested on the same engine at the same time (it is to mean that once the engine starts to run, the computer using the integrated software recorded both the performance and engine emission). After checking the engine condition along with the lubricating oil level, the fuel tank is filled with fuel. Then the engine is run and the experiments are conducted using the test bench.

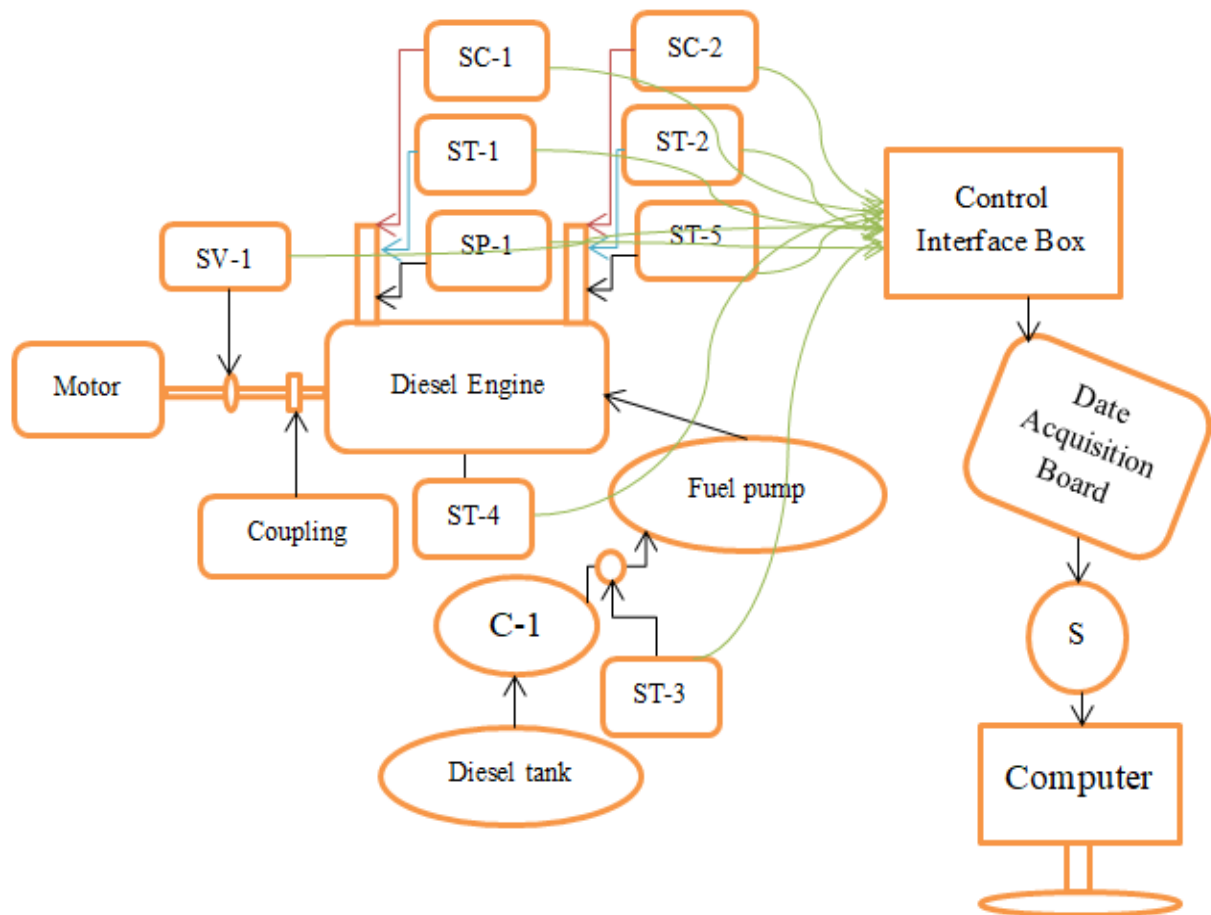


Figure 3. 8: Schematic diagram of the experimental setup.

1 & 2 = Air Inlet and Exhaust Gasses respectively.

ST-1 & ST-2 = temperature sensor at the air inlet and exhaust respectively.

ST-3 = temperature sensor between the flow meter and the fuel pump.

ST-4 = temperature sensor inside the combustion chamber.

ST-5 = temperature sensor at the cylinder head.

SC-1 & SC-2 = flow sensor at the air inlet and exhaust gasses respectively.

SP-1 = pressure sensor at the inlet of the cylinder.

SV-1 = speed sensor.

S = software for computer control, data acquisition, and data management.

But before continuing to the detailed test procedures let's see first some of the specifications and other basic parameters of the test stand. The Specifications of the test engine and the main screen of SCADA test bench are given in Table 3.2 and figure 3.9 respectively.

Table 3. 2: Specification of Test engine.

Engine Manufacture	Edibon
Type of engine	Compression ignition
Fuel type	Diesel
Number of cylinders	1
Number of strokes	Four
Type of air intake	Naturally aspirated
Type of cooling	Air cooled
Start	Computer controlled / manual
Compression ratio	21:1
Maximum power	4.2HP/3.13kW @ 3600 rpm
Cylinder bore	69 mm
Stroke	60 mm

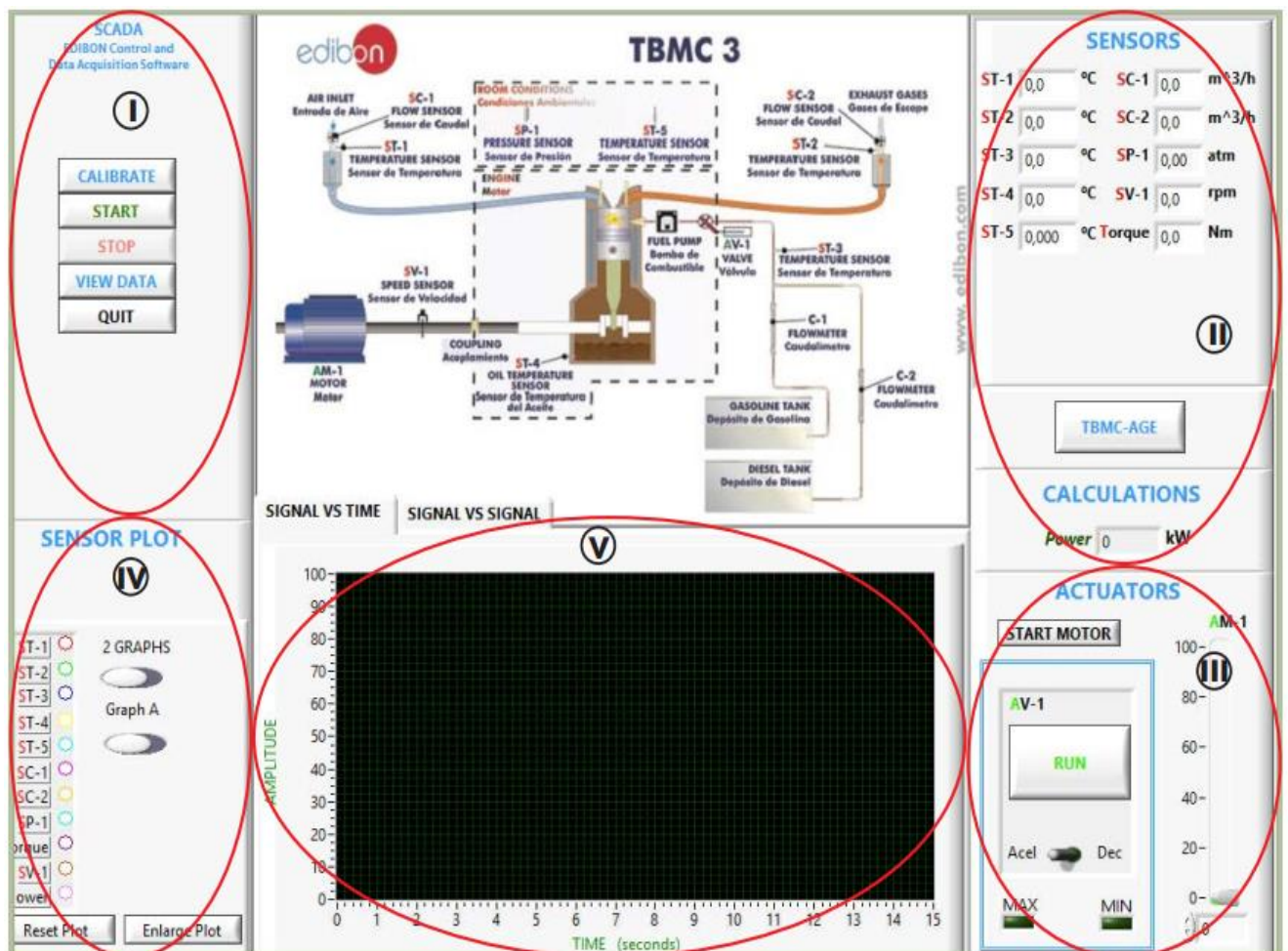


Figure 3. 9: SCADA main screen of the test bench (edibon).

I. Main software operations

Using the software we can operate the engine. Data logging and viewing are possible. SCADA's main screen is shown in Figure 3.9.

II. Sensor displays

As its name indicates the different parameters like temperature, airflow, pressure, speed, and torque sensors read from different places like intake and exhaust. ST=Temperature sensor, SC= Flow sensor, SP=Pressure sensor, and SV=Speed sensor.

III. Actuator controls

The software allows both accelerating and decelerating the internal combustion engine via the actuator (AV-1). Besides, the braking torque can be increased by acting on the electric motor (AM-1).

AV-1=Control valve (for accelerating and decelerating), and AM-1=Electric motor control.

IV. Channel selection and other plot parameters

The representative curves of the internal combustion engine, such as turning speed against developed power and turning speed against torque can be plotted with the software and matched with the operation theoretical curves.

For example the turning speed against the developed torque characteristic curve can be plotted as follows shown in Figure 3.10.

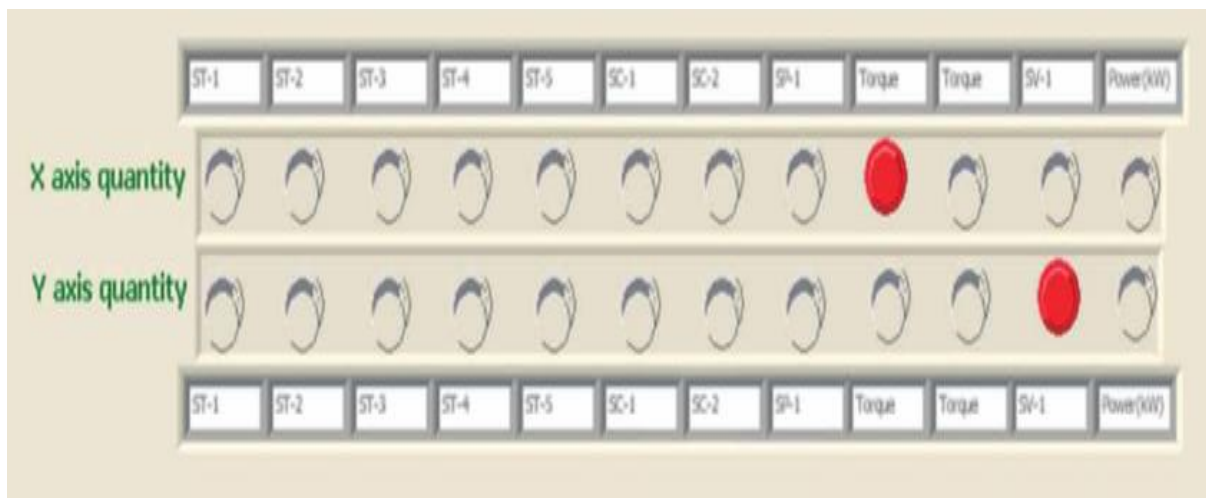


Figure 3. 10: A sample of speed Vs torque graphing method.

V. Real-time graphics display

Several data collected by sensors can be characterized against time in real time graphics display.

3.4.1 Exhaust gas analyzer

Currently, the internal combustion engines are one of the main poisoning agents. Although the pollution values are not individually representative, they are a poisonous focus when referring to all of the groups. A gas analyzer unit allows us to measure consistently the different gaseous polluting agent concentration, which is emitted to the atmosphere by a focus. The gas analyzer is shown in Figure 3.11 below.



Figure 3. 11: Edibon Exhaust gas analyzer (TBCM-AGE).

The specifications of the above exhaust gas analyzer are given in Table 3.3 as follows.

Table 3. 3: Specification of Edibon exhausts gas analyser (TBCM-AGE).

Measurements	✓ Carbon monoxide CO (%). ✓ Carbon dioxide CO₂ (%). ✓ HC (ppm). ✓ Oxygen O₂ (%). ✓ Lambda calculation. ✓ Oil temperature.
Technical Data	✓ Power Supply: 115/230 VAC - 50/60 HZ - 68 W. ✓ Measure time: 12 seconds (maximum). ✓ Warm Up time: 6 minutes (from 25 °C). ✓ Work Temperature: from +2 °C to +40 °C. ✓ Humidity: 95 % max (non-condensed). ✓ Pressure: 800-1060 mbar ✓ Lambda: from 0 to 9.999 rmp. ✓ Oil temperature: 0 - 200 °C.
Control software	TBMC-AGE
Dimensions	600 x 200 x 300 mm approx.
Weight	5 kg approx.

3.4.2 Test procedure

Primarily the experiments were carried out on the engine with diesel fuel to develop optimum cooling rate and by maintaining this optimum rate of engine cooling all the experiments were conducted on the engine. The performance and emission tests were conducted using diesel-waste plastic oil blends without any nano particle additive to the blend. The step by step procedures followed during the experiment are listed and described as follows.

1. Check all the necessary electrical connections to the panel.
2. Check the lubricating oil level in the engine
3. Fill the tank with the fuel
4. Start the SCADA TBMC3-02 software on the computer
5. Press “**start**” in the screen to start the engine
6. Run the engine under idling condition (no load) for 8 to 10 minutes to ensure warm and steady operating conditions.

7. Then increase the engine speed little by little from minimum to maximum and record the performance and emission parameters for each increment.
8. Check that the data is saved after the test is completed before shutting down the engine
9. After the completion of the test release the load to zero and then shut down the engine.

The next chapter deals with the detailed discussions on the results obtained from the experimentation.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

This chapter illustrates and discusses the results of the study in line with the objectives of the study. It outlines product types with their percentage shares, the fuel properties of diesel, and WPO blends as determined during laboratory tests. Next to this the chapter deals with the results of the performance tests with the goal of determining the appropriateness of WPO and its blends with diesel as alternative fuels to diesel. Thirdly, the chapter discusses the emission results obtained during the analysis conducted with the aim of determining the most suitable fuel running an engine with minimal adverse impact on the environment.

4.1 Product Types and Their Shares

The measured amount of different parameters before and after the pyrolysis is stated as follows.

As it is stated in chapter three subtitle 3.2.1, the experiment is conducted in three trials (the 12 kg sample is divided into three in which each sample contains 4 kg), the results for each trial are summarized in table 4.1 as follow and the average values are taken for later calculations.

Table 4. 1: Experimental values of pyrolysis under three trials.

Parameters	Trial 1	Trial 2	Trial 3	Trial Average
Ro	11.12	11.28	11.296	11.232
Co	0.804	0.914	0.919	0.879
RCo	0.251	0.2548	0.2532	0.253
R1	11.28	11.618	11.662	11.52
C1	3.78	3.79	3.80	3.79
RC1	0.2544	0.2549	0.2557	0.255
Mc	0.3189	0.321	0.3201	0.32
B0	12.175	12.4488	12.4682	12.364
B1	12.4939	12.7698	12.7883	12.684

NB: Unless and otherwise it is specified, the unit for each mass of sample or equipment is in kilograms (kg).

Mass of reactor before the experiment (R_0) = 11.232 kg

The total mass of condensers before the experiment (C_0) = 0.879 kg

The total mass of rubber connectors before the experiment (RC_0) = 0.253 kg

Mass of reactor after the experiment (R_1) = 11.52 kg

The total mass of condensers after the experiment (C_1) = 3.79 kg

Total mass of rubber connectors after the experiment (RC_1) = 0.255 kg

Mass of the feed sample (M_s) = 4 kg

Mass of char (M_c) = 0.32 kg

Mass of sample boat and sample before the experiment (B_0) = 12.364 kg

Mass of sample boat and char after the experiment (B_1) = 12.684 kg

$$\begin{aligned}\text{Condensable} &= \frac{((R_1 + C_1 + RC_1) - (R_0 + C_0 + RC_0))}{M_s} * 100 \\ &= \frac{((11.52 + 3.79 + 0.255) - (11.232 + 0.879 + 0.253))}{4} * 100 \\ &= 0.80075 * 100\end{aligned}$$

Condensable ~ **80 %**

$$\begin{aligned}\text{Char} &= \frac{(B_1 - B_0)}{M_s} * 100 \\ &= \frac{(12.684 - 12.364)}{4} * 100 \\ &= 0.08 * 100\end{aligned}$$

Char = **8 %**

Gas = 100 – (Condensate + Char)

$$= 100 - (80 \% + 8 \%)$$

Gas = **12 %**

$$\begin{aligned}\text{Conversion efficiency} &= \frac{M_s - M_c}{M_s} * 100 \\ &= \frac{4 - 0.32}{4} * 100\end{aligned}$$

Conversion efficiency = 92 %

$$\text{Yield of liquid fuel} = (M_1/M_s) \times 100\%$$

But; $M_1 = C_1 - C_o = 3.79 - 0.879 = 2.881 \text{ kg}$

$$\text{Yield of liquid fuel} = 2.881/4 \times 100\%$$

Yield of liquid fuel ~ 72 %

$$\begin{aligned} \text{NC} &= \text{M. pyrolysis feed stock} - (\text{M. char} + \text{M. liquid fuel}) \\ &= 4 - (0.32 + 2.881) \end{aligned}$$

$$\text{NC} = 0.799 \text{ kg}$$

As it's seen the results here and those of different kinds of literature in the literature review, the values for condensable liquids, conversion percentage, the yield of liquid fuel, char remained in the reactor, the gas liberated, and masses of char and non-condensable gasses are very satisfactory. For comparison let's see some of them as follows.

According to Mantesha et al. (2017), from 6.5 kg sample of LDPE, 90% was liquid oil, and the rest 6% light gasses and 4 % solid black residue. On the other hand Ojolo et al. (2005) found that 52.19% of oil, 24.24% char, and 22.58% gas by weight from municipal solid wastes consisting of food wastes, fruit and vegetables, papers, plastic, and textile mixtures. Khan et al. (2016) also found 77.03% by weight of liquid oil from LDPE waste plastic that can be used as furnace oil by blending with petroleum oils.

One more thing to be known is that the percentage of char (8%) stated above is the maximum expected value. This is because it is calculated by assuming the total mass remained in the reactor after pyrolysis is mass of the char. But some liquefied fuels may remain in the reactor especially on the inner walls of the reactor. Such liquid fuels must be subtracted and the net mass of char should be taken.

Therefore the percentage of char is less than 8% and as a result, the percentage of non-condensable gasses will be affected which is surely a little more than 12%.

4.2 Properties of Diesel, and WPO Blends

4.2.1 Density and kinematic viscosity

The density of crude oils and oil products is dependent upon temperature and degree of weathering. The understanding of density is useful for quantity calculations and evaluating ignition quality.

The limits for the viscosity of fuels ensure that fuel will flow easily during cold starting. Often, a minimum limit is specified to avoid the possibility of a serious power loss at high temperatures.

Both density and kinematic viscosity were tested in Adama Science and Technology University, Material Science department laboratory. The properties of fuel were tested as per ASTM standards.

Table 4. 2: Density and kinematic viscosity of Pure Diesel, WPO and Blends.

No	Property	Test method	ASTM limits	Test Results				
				Diesel	WPO 20%	WPO 50%	WPO 80%	WPO
1	density@15°C (g/ml)	D4052		0.848	0.836	0.824	0.804	0.789
2	density@20°C (g/ml)	D4052	0.820 -0.870	0.842	0.833	0.810	0.795	0.781
3	Kinematic viscosity @32°C (mm ² /s)	D562	1.9-6 mm ² /s (@40°C)	4.5	3.8	3.32	2.52	2.13

It was observed that the densities of the blended fuel samples decreased with an increase in the percentage of WPO in the blend at all temperatures and decreased with an increase in temperature for all the fuel samples under test. The results that were obtained clearly indicate that the density of pure diesel oil is higher than the density of WPO and their blends. Lee et al. (2015) established the same finding. There was a decrease in density with an increasing ratio of WPO fuel in the blended fuel while keeping the temperature constant as shown in Figure 4.1.

The American standard methods specify the range of density of pure diesel as 820-870 kg/m³ at 20 °C. Obviously, the obtained WPO is the lightest (first) fraction with a density of 781 kg/m³ at 20 °C. The densities of both pure Diesel and WPO blends up to 37.3% were within the specifications of all the standards at a temperature of 20 °C. This result shows that WPO can be used for blending with thicker diesel fractions with a density of around 850 kg/m³ and above in order to obtain a fuel with a higher density.

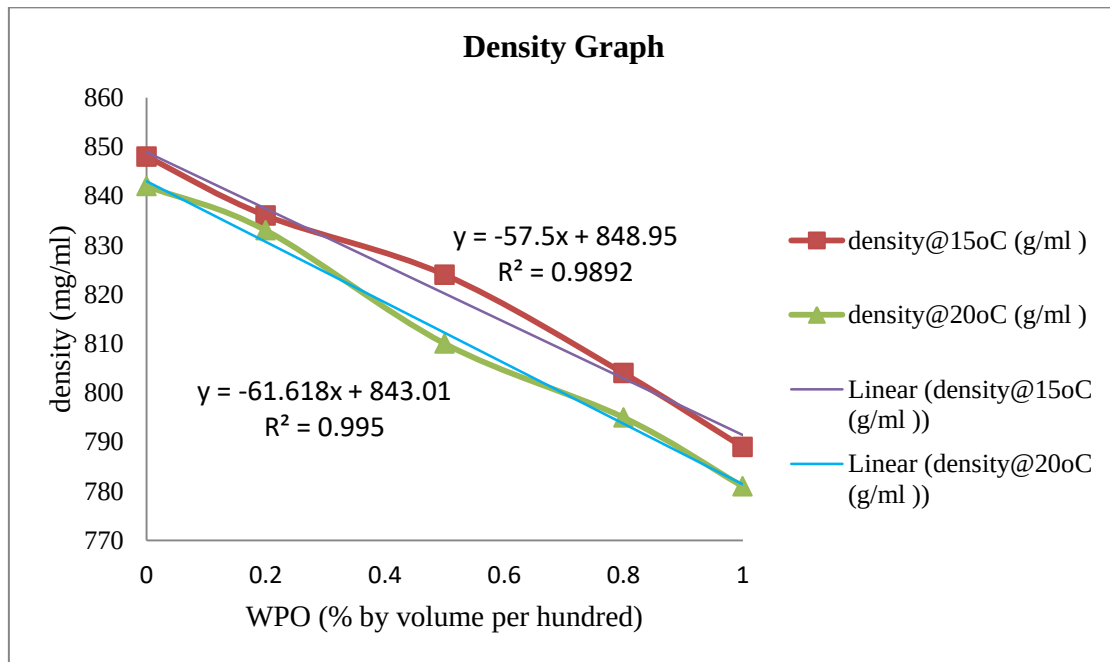


Figure 4. 1: Regression Analysis of Density of WPO-Diesel Blended Fuels.

Note: In order to get the maximum blend in which that satisfies the minimum range it is recommended to use the approximate linear equation of the above graph:

$$y = -61.618x + 843.01$$

$$820 = -61.618x + 843.01$$

$$61.618x = 843.01 - 820$$

$$x = 23.01/61.618 = 0.37343 = 37.3\%$$

The viscosity of pure diesel is higher than the viscosity of the obtained WPO and its blends. The blending of alternative waste plastic fuel with pure diesel has a quantifiable effect on the viscosity of the blended fuels. The variation for the experimental value of kinematic viscosity for pure diesel, blends, and WPO is shown in figure 4.2 below.

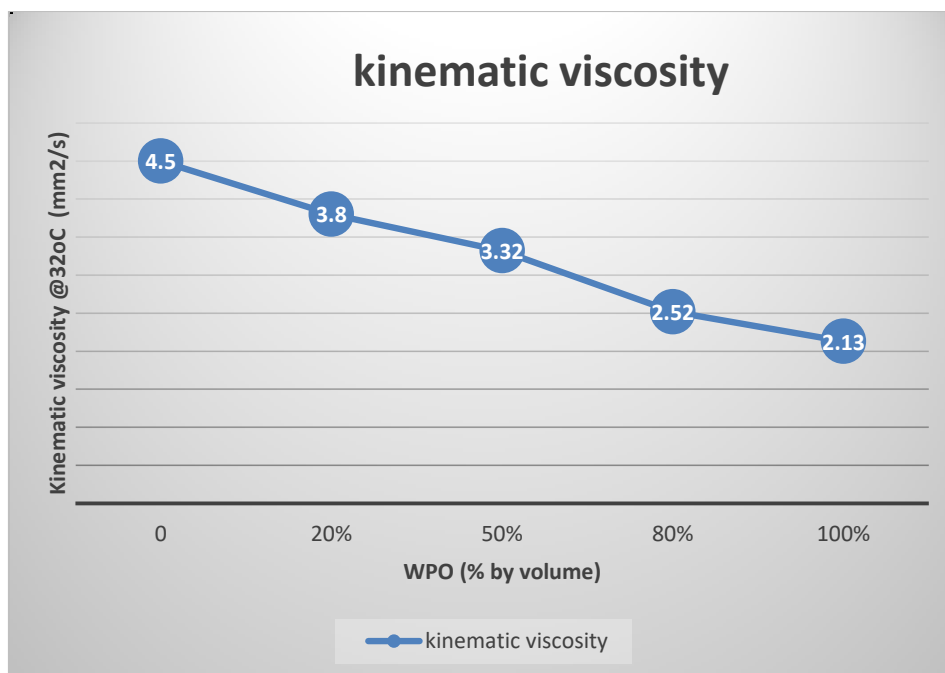


Figure 4. 2: Viscosity of WPO-Diesel fuel blends at 32 °C.

As observed in Figure 4.2, the viscosity of the fuel blends decreases with an increase in the fraction of WPO in the blends. But, the outcome of the occurrence of WPO in fuel blends is less weighty in the middle fractions of between 20% and 60%. Even though the test was done at @32 °C and the limits are based on 40 °C, the viscosity reading of 2.13 mm²/s @32 °C is not expected to fall below 1.9 mm²/s @40 °C (the minimum requirement).

Therefore the final values of kinematic viscosity obtained from the experiments indicate that all the WPO-Diesel blends are within the limits of the standard ASTM D 562.

4.3 Engine Performance

The performance of the engine when using diesel and WPO blends with diesel was evaluated with respect to brake specific fuel consumption, brake power, and brake torque. The experiments were conducted with Varying engine speed. The parameters such as brake power, brake torque, and brake specific fuel consumption were evaluated for different engine speeds as a result of varying engine load.

Table 4. 3: Results of fuel and airflow rates for B50.

No	Engine speed (rpm)	Fuel volume flow rate (ml/min)	Air inlet flow rate (m ³ /h)
1	1000	4.21	21.5
2	1150	4.15	23.12
3	1300	4.07	29
4	1500	4.02	34.5
5	2000	4.01	42
6	2300	4.00	50
7	2500	3.99	52
8	3000	3.99	58
9	3400	3.98	62
10	3600	4.00	62
11	3800	4.05	62.8

4.3.1 Brake power (P_b)

Brake power is the power available at the delivery point; at the engine crankshaft. The brake power of the engine at different operating conditions was determined and read directly from the integrated software on the computer screen. Thus as the other testing systems of the past, we do not need of calculating it from engine speed and torque.

Figure 4.3 and Table 4.4 show the variation of brake power with respect to engine speed. It indicates that the brake power increases with an increase in engine speed up to some points and attains maximum point and starts to fall down. The figure concludes that the blending of waste plastic oil (WPO) with pure diesel can give us a close trend with pure diesel corresponding to the variation of engine speed. Even though Figure 4.3 shows some variation of power and the time to reach maximum power, it is possible to say that waste plastic fuels

can be a better alternative fuel in terms of fulfilling the required brake power. The maximum power drop here is registered while using B30 and it is 11.9% at the maximum brake power of base line diesel fuel (3600 rpm).

Table 4. 4: Test results of engine brake power with respect to varying engine speeds.

No	Engine speed (rpm)	Brake power (kW)			
		B0	B20	B30	B50
1	1000	0.52	0.56	0.51	0.58
2	1150	0.85	0.82	0.8	0.82
3	1300	1.15	1.09	0.95	0.92
4	1500	1.4	1.32	1.22	1.12
5	2000	1.9	1.78	1.71	1.55
6	2300	2.18	2.04	1.97	1.92
7	2500	2.55	2.41	2.21	2.25
8	3000	2.87	2.75	2.62	2.6
9	3400	3.06	2.85	2.76	2.89
10	3600	3.11	2.86	2.74	2.86
11	3800	3.01	2.81	2.68	2.68

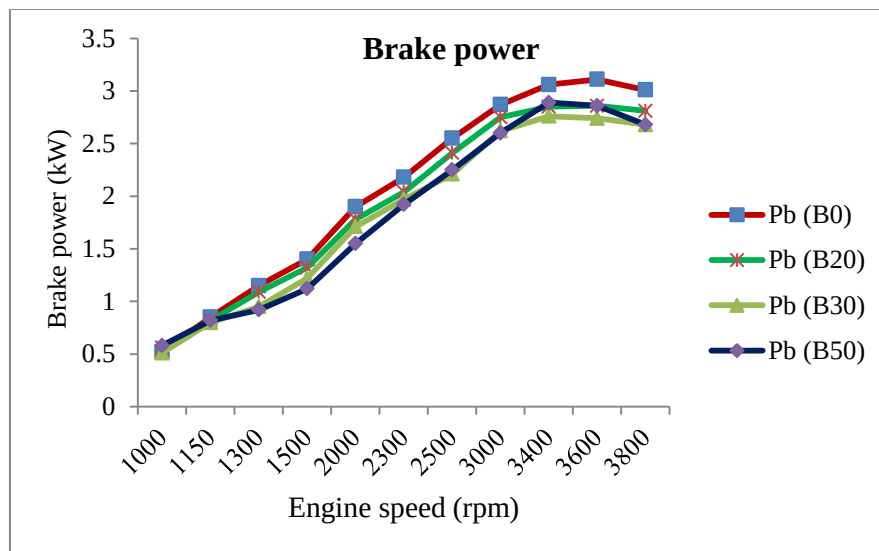


Figure 4. 3: Engine speed Vs brake power.

4.3.2 Brake Torque (T_b)

This torque is the torque available at the flywheel. The brake power was recorded for each test fuel at various engine speeds. At the same time brake torque is also recorded directly in the same way as that was described in brake power.

The trend of the graph (Figure 4.4) shows all the blends have a very close value with each other and compared to the pure diesel form, the WPO blends have a little bit lower especially in the middle speeds but very close at lower and higher speeds. Compared to the brake torque

of the base line diesel fuel, a maximum drop of 16.3% is recorded at 1500 rpm while using B50 but at 1000 rpm B30 increases the brake torque by 11.7%. For more and detail it is possible to check and see Table 4.5 below.

Table 4. 5: Test results of engine brake torque with respect to varying engine speeds.

No	Engine speed (rpm)	Brake torque (Nm)			
		B0	B20	B30	B50
1	1000	1.51	1.69	1.71	1.68
2	1150	2.14	2.05	2.01	1.95
3	1300	2.56	2.25	2.17	2.15
4	1500	2.7	2.39	2.32	2.26
5	2000	2.75	2.45	2.43	2.35
6	2300	2.74	2.45	2.53	2.48
7	2500	2.79	2.49	2.58	2.54
8	3000	2.77	2.52	2.55	2.51
9	3400	2.61	2.42	2.51	2.46
10	3600	2.5	2.33	2.4	2.3
11	3800	2.3	1.99	2.22	2.04

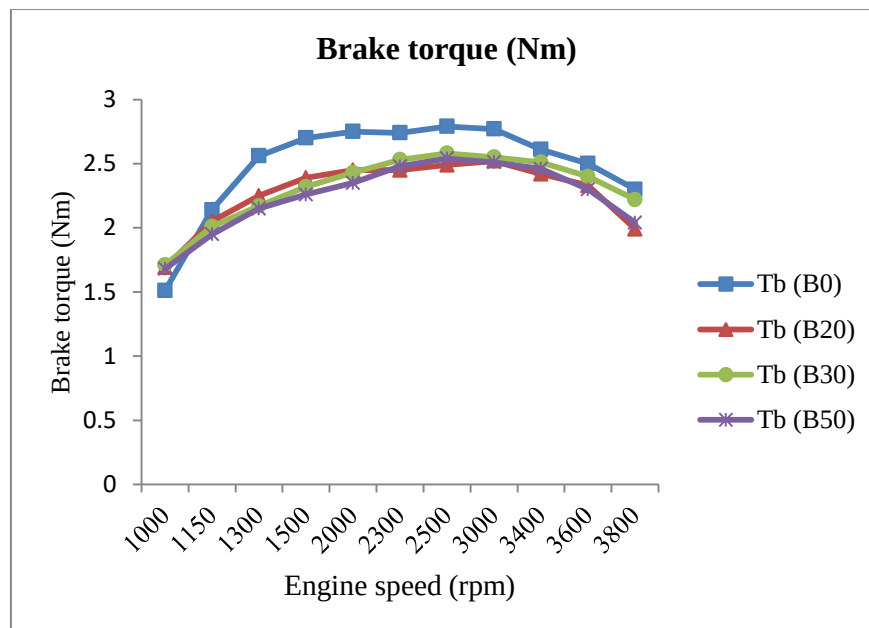


Figure 4. 4: Engine speed Vs brake Torque.

4.3.3 Brake specific fuel consumption (bsfc)

Unlike brake power and torque, specific fuel consumption cannot read directly from the test bench. So we need some calculations which can be stated as follow.

This equation is used to calculate the bsfc values and all the bsfc values of table 4.6 were found using this equation.

$$\text{bsfc} = \frac{V_f \times \rho_f \times 60}{P_b \times 1000} \text{ kg/kWhr} \dots\dots\dots 4.1$$

Where;

V_f is the volume flow rate of the fuel in ml/min.

ρ_f is density of fuel in g/ml (810 g/ml @20 °C)

P_b brake power in kW

The brake specific fuel consumption of the engine is the ratio between the fuels consumed per hour to the brake power. The brake specific fuel consumption decreases as the engine speed or brake power increases. This is because when the power increases, the temperature inside the cylinder increases, the delay period reduces, total combustion timing increases, and results proper combustion of fuel. But this is true only up to a certain limit and then starts to increase.

As shown in the graph (Figure 4.5) and Table 4.6, the bsfc for pure diesel and WPO blends with diesel decreased with increasing engine speed up to about 2500 rpm after which it leveled. The bsfc subsequently started rising when the engine speed exceeds the limit where the engine brake power is maximum, which is a typical trend of the bsfc curve for the CI engine. This shows that the bsfc of both pure diesel and WPO blends decreases and follows a constant path up to the maximum brake power and then starts a slight increase.

Comparing bsfc of the two fuels (pure diesel and blends), the pure diesel bsfc is higher in the middle engine speeds but almost the same at the start and end (lower and higher engine speeds). The higher bsfc value for diesel is may be due to its high density compared to the densities of WPO blends. As the fuel injection system of the engine is calibrated to inject a fixed volume of fuel, the use of the less dense WPO blends resulted in less fuel mass to be injected into the engine leading to lower bsfc. When comparing the bsfc of the pure diesel and the blends, it ranges from the same bsfc (B30 at 1150 and 1300 rpm) to a decrease by 7.4% at 2300 rpm while using B50.

Table 4. 6: Test results of engine brake torque with respect to varying engine speeds.

No	Engine speed (rpm)	bsfc (Kg/kWh)			
		B0	B20	B30	B50
1	1000	0.38	0.37	0.36	0.37
2	1150	0.35	0.35	0.35	0.34
3	1300	0.33	0.32	0.33	0.32
4	1500	0.3	0.29	0.29	0.28
5	2000	0.28	0.28	0.27	0.26
6	2300	0.27	0.27	0.26	0.25
7	2500	0.26	0.26	0.25	0.25
8	3000	0.26	0.26	0.25	0.25
9	3400	0.26	0.26	0.25	0.25
10	3600	0.26	0.26	0.25	0.26
11	3800	0.27	0.27	0.26	0.27

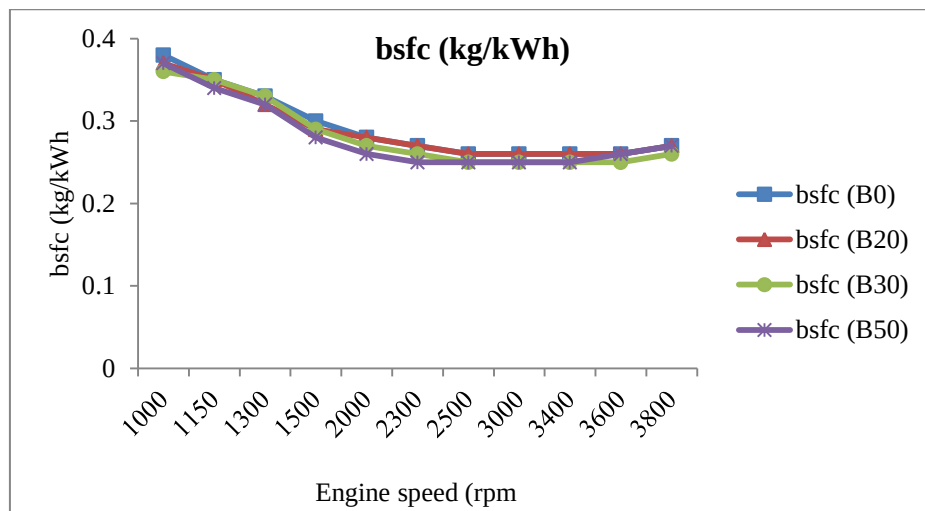


Figure 4. 5: Engine speed Vs brake specific fuel consumption (bsfc).

Joining Figure 4.3, 4.4, and 4.5 by keeping the values of Figure 4.3 and 4.5 as it is but reducing the values of Figure 4.4 by the same percentage (around 330 %), the engine performance curve looks like as graphed in Figure 4.6 (blue lines for pure diesel and red lines for WPO blends of B50).

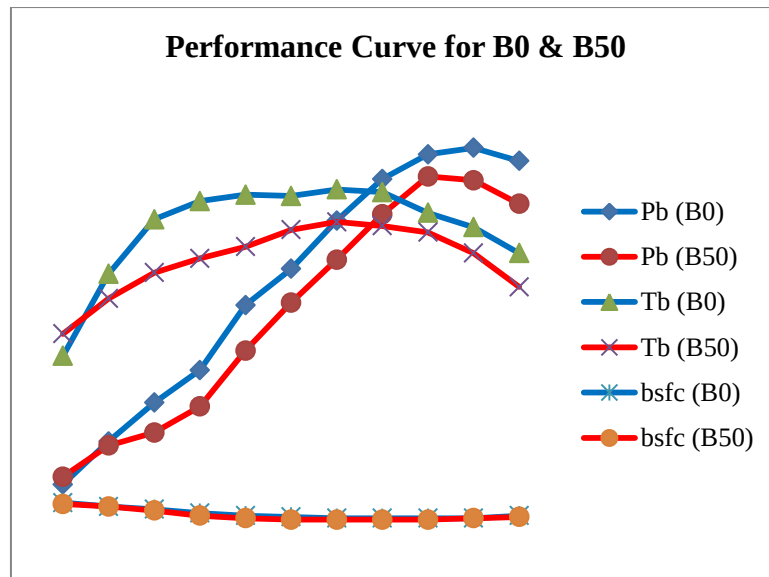


Figure 4. 6: Engine performance curve.

Finally Figure 4.7 shows the variation of inlet air flow rate with respect to the engine speed. Engine speed increased means the more and more air-fuel mixture is fed into the engine cylinder per unit time. This is because as speed increases more strokes happened per unit time and this leads to more air fuel mixture to burn per unit time. Due to this fact engine speed and inlet air flow rate have a direct relationship as depicted in the graph.

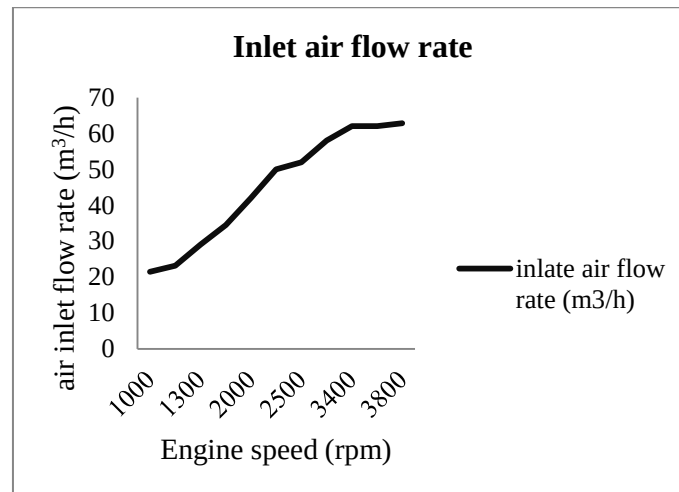


Figure 4. 7: Engine speed Vs inlet air flow rate.

4.4 Engine Emission characteristics

The emissions of the engine when using diesel and WPO blends with diesel were evaluated with respect to oxides of Nitrogen, carbon monoxide, carbon dioxide, and unburned hydrocarbons. The emission data obtained is given in Table 4.7.

Table 4. 7: Engine emission characteristics table.

Engine speed (rpm)	CO emission (% vol)				CO ₂ emission (% vol)				NO _x emission (ppm)				HC emission (ppm)			
	B0	B20	B30	B50	B0	B20	B30	B50	B0	B20	B30	B50	B0	B20	B30	B50
1000	0.063	0.065	0.066	0.07	2.23	2.17	2.15	2.12	150	151	153	152	16	14	13	13
1150	0.06	0.058	0.059	0.067	2.35	2.24	2.2	2.13	165	163	166	170	16.5	14.5	13.5	14
1300	0.057	0.057	0.058	0.063	2.44	2.31	2.27	2.2	185	179	189	195	17.01	15	14.5	14.67
1500	0.055	0.056	0.057	0.059	2.56	2.47	2.42	2.35	210	207	214	220	17.87	15.65	15.04	15
2000	0.053	0.054	0.055	0.057	2.76	2.66	2.59	2.55	240	231	241	245	18	16.62	16	15.98
2300	0.054	0.055	0.054	0.056	2.87	2.79	2.7	2.68	275	274	275	280	18.75	17	16.32	16.55
2500	0.058	0.057	0.059	0.06	2.91	2.84	2.8	2.79	307	299	302	310	19	17.58	16.98	17
3000	0.063	0.06	0.066	0.065	2.96	2.94	2.89	2.87	325	320	330	335	19.32	18.09	17.4	17.65
3400	0.069	0.068	0.072	0.071	3.01	2.95	2.93	2.94	345	342	350	361	20	19	17.93	18.44
3600	0.075	0.074	0.078	0.076	3.12	3.04	2.98	2.98	355	345	357	358	21.5	20	18.5	20
3800	0.083	0.081	0.083	0.08	3.3	3.18	3.01	3.04	340	334	355	345	24	22	21	22.94

4.4.1 Nitrogen Oxides (NO_x) Emissions

The oxides of nitrogen in the emissions comprise nitric oxide (NO), and nitrogen dioxide (NO₂). Figure 4.8 shows the variation of Nitrogen Oxides with an Engine speed for diesel and WPO blends with diesel. It can be observed that the amount of Nitrogen Oxide increases with an increase in engine speed for diesel and WPO blends with Diesel. This is because as the speed increases so does the engine power and it is associated with high peak pressures, and thus temperatures, leading to increased levels of Nitrogen Oxides. Further, it was observed that the level of nitrogen dioxide emission for WPO blends with diesel when the blending exceeds 30% was a little bit higher in the entire loading range compared to the level of pure diesel NO_x emission. The cause for this is the advanced heat release rate of WPO which is associated with higher aromatic content and a ring structure. According to Mani et al. (2011), fuels with a ring structure often possess a higher adiabatic flame temperature thus leading to higher heat release rates. Because of the high heat release rate, the in-cylinder temperature

increases with an increase in the fraction of WPO in the WPO-Diesel blend. Increased ignition delay of waste plastic oil promotes premixed combustion, by allowing more time for fuel to be injected prior to ignition, may also be another reason for increased NO_x. After the engine attains its maximum power the peak pressure so does temperature decreased. This leads to the decrease of NO_x emission as shown in the graph. The maximum NO_x emission improvement is recorded when B20 was used at 3600 rpm and it is about 2.8% but B50 increases the emission up to 4.6% at 3400 rpm.

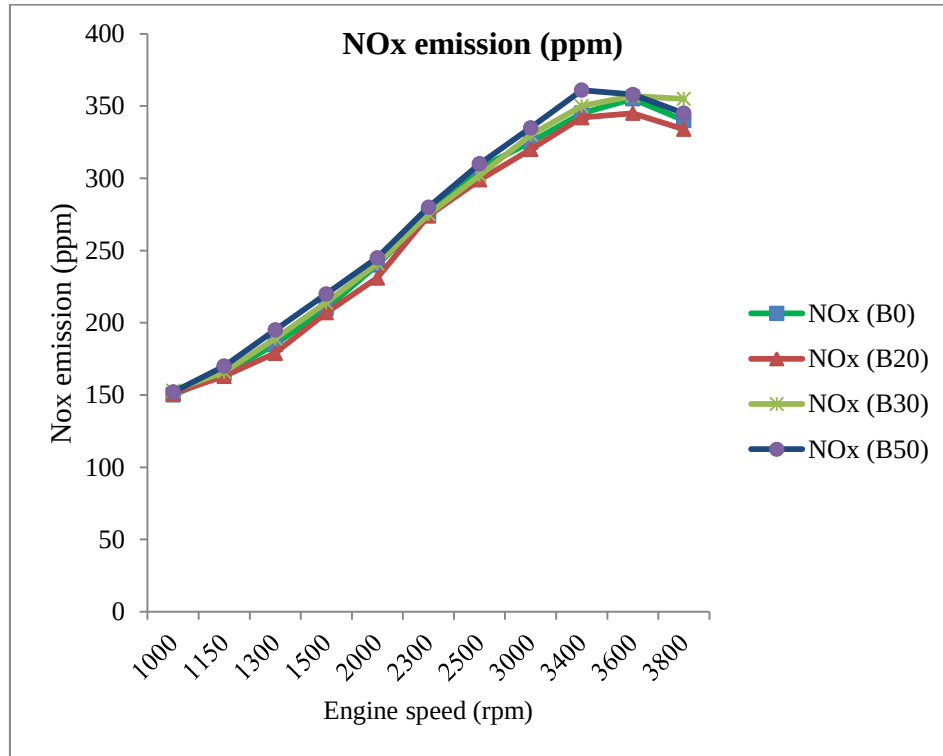


Figure 4. 8: NOx emission Vs Engine speed.

4.4.2 Carbon Monoxide Emissions

The emission of Carbon Monoxide (CO) is primarily because of the lack of Oxygen, poor entrainment of air, preparation of the mixture, and incomplete burning during the combustion process (Mani et al., 2011). Consequently, the emission of carbon monoxide is highly dependent on the equivalence ratio; a rich mixture results in a high CO emission level, and vice versa. But usually the level of emission of CO will be low because CI engines were run with lean mixtures.

Figure 4.9 shows the variation of carbon monoxide emission with an engine speed for diesel and WPO blends with diesel. It was observed that CO emissions for all types of fuels were higher at lower speeds before decreasing up to some range of operation. This is due to air and

fuel achieving a stoichiometric ratio which leads to lean combustion. In this region of the graph except B20 the CO emission of WPO blends with diesel is higher than that of pure diesel CO emission. This is because at lower engine speeds hence lower engine power, the inside cylinder temperature to ignite WPO blends with diesel is less favored than a pure form of diesel. Not only this comparing to pure diesel WPO blends with diesel have less oxygen and as a result more incomplete combustion occurs. Further, it was observed that the amount of CO emission for diesel and WPO blends with diesel starts to increase at a higher rate due to incomplete combustion as the engine speed increases the rate of fuel consumption is higher than the rate of inlet oxygen intake.

One more thing that can be observed from the graph is after stoichiometric ratio, the incremental rate of CO emission is higher for pure diesel compared to WPO blends with diesel and at the very end of the graph the amount of CO emission for pure diesel is higher than that of WPO blends with diesel. This is because in this region the inside cylinder temperature is higher and more comfortable for WPO ignition. But in the general case, the CI engine operates with lean mixtures, and hence the CO emission would be low. Compared to the base line diesel CO emission, B20 improves by about 4.8% at 3000 rpm but B50 increases the emission by about 11.7% at 1150 rpm.

To sum up, for better environmental protection and less emission of CO the middle range engine speeds are favorable.

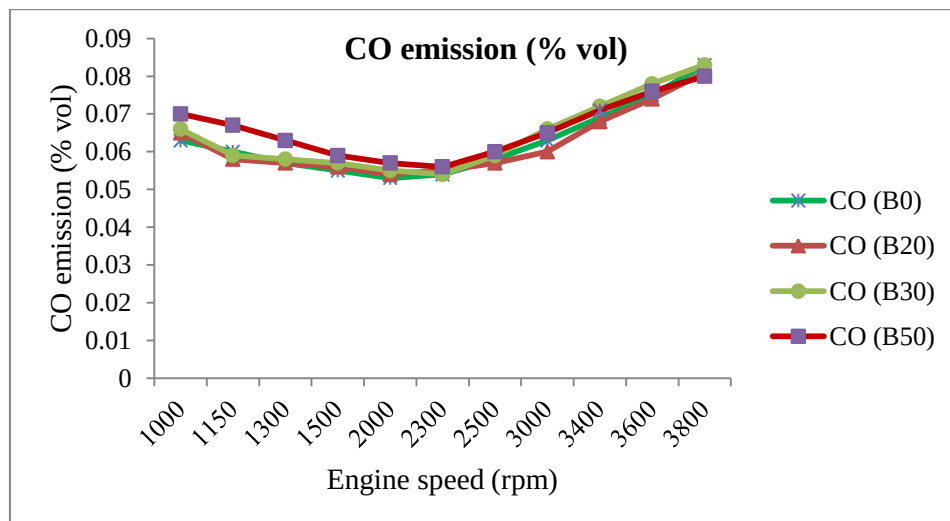


Figure 4. 9: CO emission Vs Engine speed.

4.4.3 Carbon Dioxide Emissions

Figure 4.10 shows the variation of carbon dioxide emission with an engine speed for diesel and WPO blends with diesel. It was observed that CO₂ emission for diesel and WPO blends with diesel were lower at lower engine speeds and higher at higher. This can be credited to the lean running of the CI engine. Additionally, it was detected that the levels of CO₂ emitted during operation WPO and its blends with diesel were lower than the levels of CO₂ emission during diesel operation throughout the entire engine speed. This observation was attributed to delayed ignition of fuel resulting in incomplete combustion because more CO₂ is formed if more complete combustion of fuel takes place (Mani et al., 2011). From the blends B50 decreases the emission by about 9.8% at 1300 rpm.

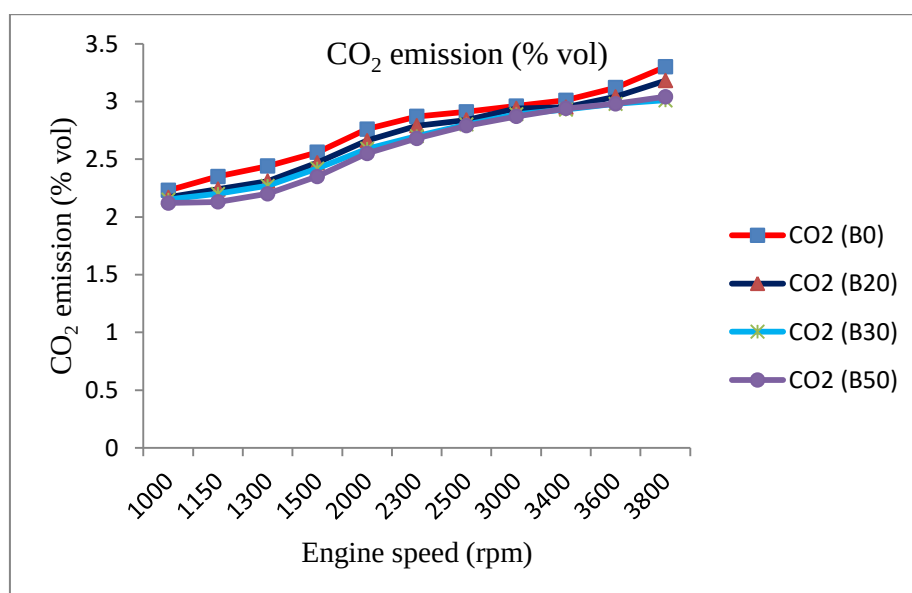


Figure 4. 10: CO₂ emission Vs Engine speed.

4.4.4 Unburned Hydrocarbon (UHC)

Unburned hydrocarbon is a useful measure of combustion efficiency. Unburned hydrocarbon comprises of fuel that is partly burned.

The variation of unburned hydrocarbon with an engine speed for tested fuels is shown in Figure 4.11. At low speeds due to large amounts of excess air, low exhaust temperature, and lean fuel-air mixture, the amount of UHC formation is minimum for both types of test fuels. Even though the less availability of oxygen in WPO blends fuel expect the formation of higher UHC than pure diesel, because of its lesser density compared to pure diesel, which favors better fuel atomization which leads to lesser UHC emission due to more complete combustion. As the engine speed increases the amount of oxygen admitted to the engine

reduces and thus the amount of UHC formation increases for both test fuels. Compared to the pure form blended fuels have lower HC emission and this may be due to their less density which is more favorable for complete combustion and these less unburned HC. A maximum emission improvement of 18.7% occurs from B30 at 1000 rpm.

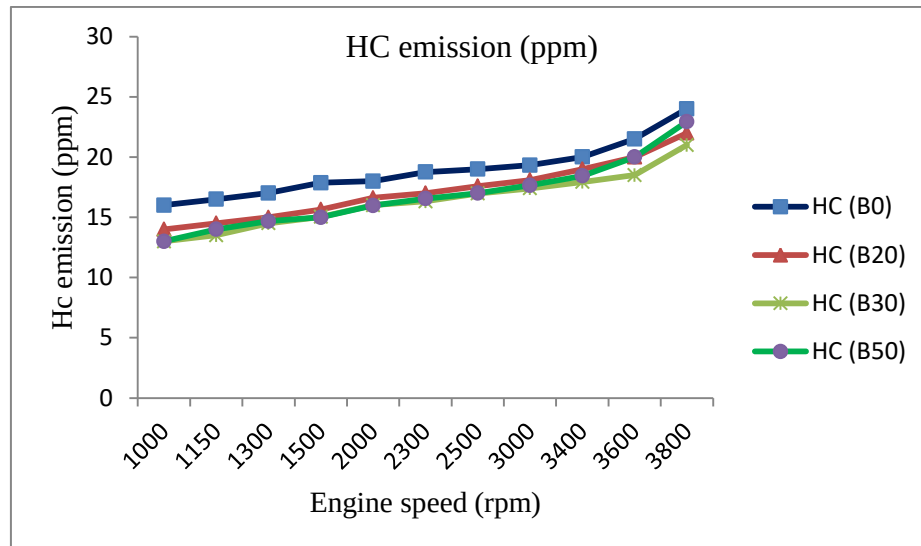


Figure 4. 11: UHC emission Vs Engine speed

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Summery

This study investigated the appropriateness of the use of waste plastic oil as an alternative fuel for diesel engines and the effect of blending waste plastic oil with diesel (B0, B20, B30, and B50) on fuel properties, engine performance, and engine emissions characteristics. The waste plastic fuel was produced from the waste plastics collected from Adama town through the pyrolysis process and the test was conducted on a single-cylinder direct injection diesel engine. Fuel Properties like density and kinematic viscosity were evaluated for all blends and compared to those of diesel. Engine performance like brake power (Pb), brake torque (Tb), and brake specific fuel consumption (bsfc) and emissions such as CO, CO₂, HC, and NO_x are also evaluated.

5.2 Conclusion

The concept of waste to energy especially the conversion of waste plastics into an alternative source of energy allows us to determine a specific contribution to waste management. By converting waste plastics to alternative fuel, we solve problems of fuel shortage as well as environmental pollution at the same time. By taking into account that low-cost production process, it would be a great support to our economy.

The study and analysis of this paper showed that waste plastics of municipal solid wastes can be used as alternative fuels for the Diesel engine. The results found in the experiment can be concluded as follows.

- ✓ A maximum of 80% condensable liquid fuel, 8% char, and 12% gas by weight were achieved in the experiment. The maximum conversion efficiency that the mass sample can be converted into gaseous forms during pyrolysis was 92% and even if 80% were condensable the collected liquid fuel was 72%.
- ✓ Both density and kinematic viscosity decrease as the waste plastic fuel blend increases and the values are less than that of pure diesel but higher than the minimum standard value up to B50. The maximum gap between the pure diesel and its blend at peak points for brake power and brake torque is 11.9% and 16.3% respectively in which

diesel fuel is on the top. However in terms of bsfc, B50 gives the lowest consumption which can reduce up to 7.4% fuel. In case of emission, the waste plastic blend improves CO₂ emission and unburned hydrocarbons by 9.8% and 18.7% respectively but the emissions of CO and NO_x are slightly higher at low speeds and almost close to each other at higher engine speeds.

- ✓ Blends of WPO and diesel can be used in diesel engines without a major drop in brake power and brake torque and exceeding emission limits, as their emission characteristics and levels are comparable to those of diesel operation.

From the above results it can be concluded that the fuel obtained from waste plastics of municipal solid wastes present potential solutions for both the environment and economy and more studies on this topic should be considered.

5.3 Recommendations

The conversion of waste plastics of municipal solid wastes into alternative liquid oil and other valuable products is getting significant attention both as waste management and an alternative energy generation technology. Related to this work some recommended points to be put a due focus on the following ideas:

- ✓ Due to leakages or lack of proper sealing, condensable and non-condensable gaseous fraction moves out from the system. The release of such gaseous products has an effect on the environment. The gaseous fraction had high calorific value, so the system must be sealed properly.
- ✓ Even though the results found showed that the waste plastic fuel can be used as an alternative fuel for a diesel engine without major modification, it is highly recommended more experiments to be conducted (future works) by considering all engine working parameters like what would happen if the weather is too cold.

5.4 Future Work

The study recommends that further work be carried out to investigate the suitability of waste plastic oil as an alternative fuel for diesel engines. Among the reasons that a further study needed it is because unlike diesel and biodiesel, there exist no standards for the production of waste plastic oil under pyrolysis, which in turn affects various properties of the fuel including the density, viscosity, heating value, etc.

Hence, further work includes:

- ✓ Waste plastic oil production using different catalysts and test performance and emission using different nano particles.
- ✓ Test of other fuel properties like a flashpoint, calorific value, cloud point, total acidity, etc.
- ✓ Prepare more blends in short-range and test fuel characteristics, performance, and emission characteristics.
- ✓ Cost-effective scaling of technology to demand including evaluation of socioeconomic and environmental impacts in field studies
- ✓ Integration of other renewable energy forms (solar water heater, biogas as co-fuel or initial fuel) in large scale application of the technology for distillation, dryer, and baking
- ✓ Impacts and complexities linked to a profitable entrepreneurial application are needed to generate baseline data for large scale production and marketing.

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