Thermo-economic analysis of diesel engine fueled with plastic waste oil blends

A Thesis

Submitted in partial fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

(Mechanical Engineering)

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LOVELY PROFESSIONAL UNIVERSITY, PUNJAB
2025

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis, entitled "**Thermo-economic analysis of diesel engine fueled with plastic waste oil blends**" for the fulfilment of the requirements for the award of the **Degree of Doctor of Philosophy (Ph.D.)** and submitted in the **School of Mechanical Engineering** of Lovely Professional University, Punjab, India is an authentic record of my own work carried out under the supervision of **Dr. Ravinder Kumar**, Professor, School of Mechanical Engineering, Lovely Professional University, Punjab, India and **Dr. Upendra Rajak**, Associate Professor, Department of Mechanical Engineering, Rajeev Gandhi Memorial College of Engineering & Technology, Nandyal, Andhra Pradesh, India. The thesis is an original piece of research work and embodies the findings made by me.

The matter presented in this thesis has not been submitted in part or in full for the award of any other degree/diploma of this or any other University/Institute.

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CERTIFICATE

This is to certify that the thesis entitled “Thermo-economic analysis of diesel engine fueled with plastic waste oil blends”, being submitted by Mrs. Dunga Simhana Devi (Reg. No. 41800373) to the School of Mechanical Engineering, Lovely Professional University, Punjab, India for the award of Degree of ‘**Doctor of Philosophy’ (Ph. D.)** in Mechanical Engineering, is a bonafide research work carried out by him under my supervision and guidance. His thesis has reached the standard of fulfilling the requirements of regulations relating to degree.

The results presented have not been submitted in part or in full to any other University/Institute for the award of any other degree or diploma.

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ABSTRACT

It has been an eternal longing for research community to look for alternative options for fossil fuels in order to stop the never-ending cycle of global warming and pollution caused by fossil-fuelled internal combustion engines. Another factor about fossil fuels is economic instability due to geopolitical reasons. The goal of this study is to find a way to use mixed fuels instead of standard diesel.In contemporary society, there has been a notable surge in the recycling of waste plastic, driven by the pressing need to manage environmental concerns. Simultaneously, the escalating demand for energy parallels the rapid expansion of the global population. Conventional energy sources like petroleum and its derivatives are finite and fail to adequately meet the escalating demand, leading to concerns about fuel scarcity. To address this challenge, there is a growing interest in finding alternative, sustainable, and cost-effective fuel options. One promising avenue is the conversion of waste plastics into fuel oil, offering a potentially endless and readily available energy source.

Plastic has become very important in today's world because of what it can do and how it can be used. Plastics are cheap, easy to use, and don't react with chemicals. Plastics are now used for a wide range of things in everyday life, both at home and in the workplace. Plastic trash takes almost 100 years to break down on Earth's surface. Plastic trash stays on the surface of the earth for longer amounts of time, which is bad for the environment because it releases chemicals into the air and hurts the ozone layer.The process of converting waste plastics into fuel oil involves subjecting them to pyrolysis in a reactor, a method explored in various experimental studies. These studies typically evaluate the physio-chemical properties of the resulting plastic oil and

compare them with established standards such as those set by ASTM. Observations often include a change in viscosity and the presence of carbon residues, indicative of the transformation process.

One common approach involves blending waste plastic oil with diesel, creating fuel mixtures with different ratios, such as 80% diesel and 20% waste plastic oil, or 60% diesel and 40% waste plastic oil. These blends are then subjected to combustion analysis in the ignition chamber of a diesel engine. The findings of such analyses frequently demonstrate a moderation in thermal efficiency when utilizing waste plastic oil-diesel blends compared to pure diesel fuel. Reduction in thermal efficiency was noted in such studies when employing waste plastic oil-diesel blends. Additionally, parameters like peak rate of pressure rise, peak cylinder pressure, and smoke emissions experienced marginal decreases, further highlighting the impact of waste plastic oil on combustion dynamics. While waste plastic oil exhibits slightly higher values compared to diesel, there is also an increase in specific fuel consumption, indicating a complex interplay between the physio-chemical properties of the fuel and engine performance characteristics.

The conversion of waste plastics into fuel oil presents a promising solution to address energy demands while mitigating environmental concerns. However, further research is warranted to optimize the process and maximize the efficiency and sustainability of waste plastic-derived.This study looks at how well waste plastic fuel mixed with pure diesel works in a diesel engine, as well as how waste plastics can be turned into fuel oil. In this study, WPO20D80, which is made of 20% waste plastic oil and 80%clean diesel, is used to test how well it works. By looking at its physiochemical qualities.The primary objective of this study is to enhance both the performance and

emission parameters of a diesel engine by utilizing waste plastic oil as a fuel source through experimental methods. With traditional fuel sources being depleted, there is a pressing need to address fuel scarcity while also considering emissions and environmental impact. The results indicate a reduction in smoke emissions and engine torque, alongside a slight increase in volumetric efficiency and NO emissions when utilizing a blend of 80% diesel and 20% waste plastic oil (WPO20D80) compared to conventional diesel fuel.

Cost analysis for the production of precision components used for the combustion of plastic fuel, where increasing reliability requirements result in higher production costs. Conversely, an increased level of dependability would lead to decreased expenses for maintenance and replacement parts. Several economic analysis techniques have been devised to assess the total cost during the lifespan and determine the payback period, which was determined to be 11.5 years. The experimentation was conducted at 1500 rpm while subjecting the system to different loads. An investigation was conducted to examine the impact of varied loads and mixes on braking power (BP), cooling water losses (Q_w), exhaust gas losses (Q_{exh}), and unaccounted losses Q_{un}. The exergy efficiencies of pure diesel and WPO20D80 are approximately 33.9% and 33.0%, representing the highest and lowest values, respectively. It has been observed that both BP and Q_w rise as the load increases, but Q_{exh} and Q_{un} exhibit a declining pattern. Furthermore, it was noted that when blending grows, the value of Q_w rises while the value of Q_{exh} declines. During the exergy analysis, it was noted that the rate of exergy efficiency reaches a maximum of 30.9%, 30.0%, and 29.8% of the input exergy values for diesel, WPO20D80, and WPO100DP0, respectively.

Key words: Compression ignition engines; Waste plastic oil; Compression ratio; Emission analysis; Cost analysis; Energy analysis; Exergy analysis.

Acknowledgement

It is my great pleasure to record profound gratitude to my research supervisor, **Dr. Ravinder Kumar**, Professor, School of Mechanical Engineering, Lovely Professional University, Punjab, India, and **Dr. Upendra Rajak**, Associate Professor, Department of Mechanical Engineering, for their constant inspiration and invaluable guidance throughout the course of investigation. I gratefully acknowledge his painstaking efforts in thoroughly going through and improving the manuscript, without which this work would not have been completed. The numerous discussions I had with Dr. Ravinder Kumar and Dr. Upendra Rajak instilled in me the confidence needed to crack formidable problems in the present field of research.

I wish to thank **Dr.Ankur Bahl**, HoS, School of Mechanical Engineering, Lovely Professional University, Punjab, India, and **Dr. Sudhanshu Dogra**, HoD, Thermal Engineering, Lovely Professional University, Punjab, India for the administrative support during the execution and completion of this thesis for their kind cooperation, support and continuous guidance. I would also like to thank all the end term presentation panel members, faculty, and staff members of the Mechanical Engineering Department, Lovely Professional University, Punjab, India, for their valuable advice during the completion stage.

My gratefulness, a hearty and special measure of thanks, is due to my Husband and Son for their patience, love, and encouragement during this course of work, just for being themselves. Finally, I owe the entirety of my academic achievements to my grandmother and parents. Before all and after all, the main thanks should be to the Almighty God.

(Dunga Simhana Devi)

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NOMENCLATURE

CIS	Commonwealth Independent States
US	United States
CI	Compression Ignition
SI	Spark Ignition
FSSAI	Food Safety and Standards Authority of India
USFTP	US Federal Test Procedure
DEE	Diethyl ether
UHC	Unburned hydrocarbons
HC	Hydrocarbons
HDPE	High density polyethylene
LDPE	Low density polyethylene
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
PET	Polyethylene terephthalate
EGT	Exhaust gas temperature
DI	Indirect Injection
PBDF	Petroleum-Based Diesel Fuel
WOME	Waste Cooking Oil Methyl Ester
PM	Particulate Matter
DS	Dry Soot
NSF	Non-Soot Fraction

TDC	Top dead centre
BDC	Bottom dead centre
AOF	Adsorbed organic fraction
WCO	Waste cooking oil biodiesel
ASTM	American Society for Testing and Materials
FFA	Free fatty acid
FAME	Free acid methyl ester
D100	Diesel
IR	Infrared
DAS	Data acquired sensors
HRR	Heat Release Rate
MROPR	maximum rate of pressure rise
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CR	Compression Ratio
SFC	Specific Fuel Consumption
SFC	Specific energy consumption
BTE	Brake Thermal Efficiency
CO_2	Carbon dioxide
CO	Carbon monoxide
HC	Hydrocarbon
NO_x	Nitrogen Oxide
NO	Nitric oxide
O_2	Oxygen
H_2SO_4	Sulphuric Acid
HCl	Hydrochloric acid
H_3PO_4	Phosphoric acid
CH3OK	Potassium methoxide
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
SOx	Sulphur oxide

WPO10D90	10% WPO and 90% diesel
WPO20D80	20% WPO and 80% diesel
WPO30D70	30% WPO and 70% diesel
WPO40D60	40% WPO and 60% diesel
WPO20D80	20% WPO and 80% diesel
WPO40D60	40% WPO and 60% diesel
WPO100	100% WPO and 0% diesel
VCR	Variable compression ratio
PPM	Part per million
IP	Injection pressure
EGT	Exhaust gas temperature
L	Low load (25%)
M	Medium load (50%)
H	High load (100%)
WPO	Waste plastics oil

CHAPTER 1

INTRODUCTION

1.1. Fossil fuel scenario

Fossil fuels are going to deplete sooner than expected, based on global usage. It can be easily predicted that the world's supply of fossil fuels will eventually run out. When fossil fuels are used, they deliver emissions that lead to air pollution, and ultimately, global warming [1]. As a result, a lot of countries are trying to find a way to replace fossil fuel with alternative fuel. To keep diesel emissions under acceptable limits, many scientists are focused on finding not just one, but a wide variety of alternative fuels. Using plastics is on the rise in both commercial and home settings because of their low production cost, lightweight, and convenience of use [2].

1.2. Global Energy scenario

The global energy distribution for 2023 is indicated in Fig.1.1. The figure shows that coal accounts for 27%, oil for 33%, and natural gas for 24% of the world's total energy consumption; these three fuels account for the majority of the market share. Despite the efforts that have been made to transition to cleaner energy sources, fossil fuels still hold a large role in the energy landscape of the world. Some areas do get their electricity from nuclear power plants, which contribute 5% to the overall energy mix and contain a minimal carbon dioxide footprint. Energy proportion that comes from renewable sources, notably the sun, the wind, energy from geothermal, and biomass, has reached 11% and is rapidly increasing. Solar and wind energy will respectively account for 36% and 32% of the global segment of renewable energy sources in the year 2023, according to the most recent forecasts shown in Fig. 1.2.The sun’s rays are converted into electricity by photovoltaic cells to produce solar power, while wind energy is produced by rotating wind turbines [3]. Hydropower, which derives its energy from moving water sources, accounts for twenty percent of the mix. The remaining 12% is accounted for by the group labelled "Other," which very certainly includes non-conventional energy sources: geothermal, biomass, and tidal power.

The data points to a positive trend towards cleaner and more sustainable energy sources, with solar and wind playing key roles in the current global energy transition away from fossil fuels. This trend implies a favourable shift towards cleaner and more sustainable energy sources [4]. Even though there has been some progress achieved in the promotion of non-conventional energy, the data underlines the continued dependence on fossil fuels and the need for further measures to diversify and transition towards more sustainable and low-carbon energy sources [5].

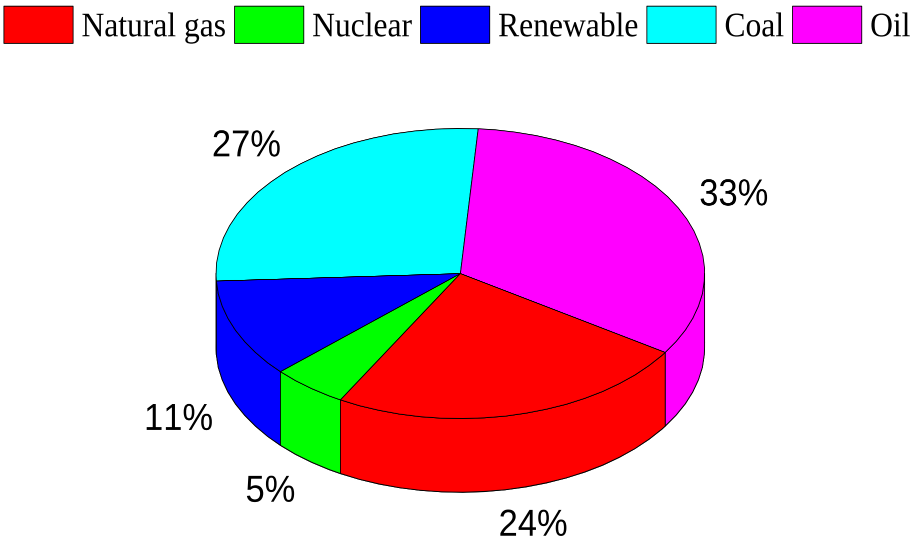


Fig.1.1 Global energy share

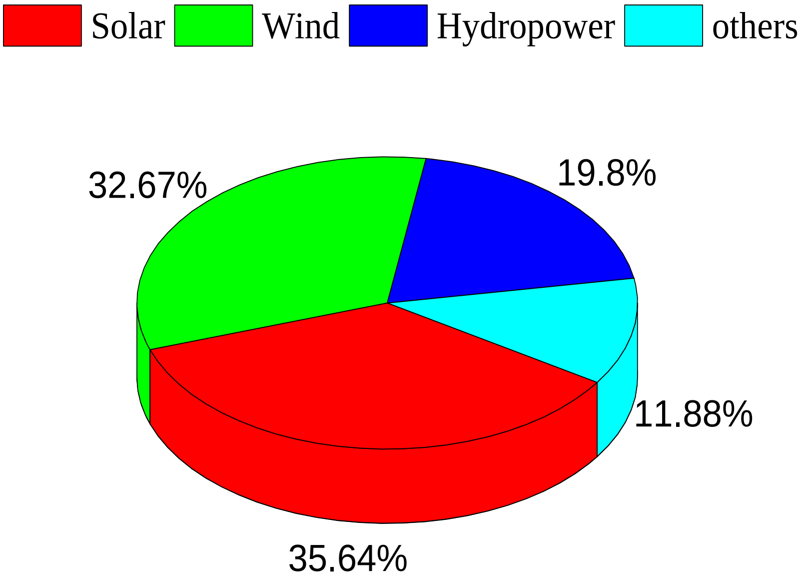


Fig.1.2.World-wide renewable energy share

Figure 1.3 reveals the daily oil consumption in millions of barrels for several countries, along with their respective shares of global oil consumption as of year 2022 [6]. The United States leads with 19 million barrels per day, accounting for approximately 21% of global consumption, followed closely by China at 14 million barrels per day, representing around 14.2% of the global share. India ranks third with 4.9 million barrels per day, making up about 5% of global consumption. Japan and Russia each consume 3.7 million barrels per day, accounting for approximately 3.8% of global consumption. Germany's consumption stands at 3.1 million barrels per day, representing around 3.2% of the global share. South Korea, Brazil, and Canada have consumption figures of 2.8, 2.7 and 2.3 million barrels per day, respectively, with shares of about 2.9%, 2.7%, and 2.4% of global consumption. The data highlights the varying levels of oil consumption among nations, with the United States, China, and India leading the world in daily oil usage, collectively accounting for approximately 40% of global oil consumption.

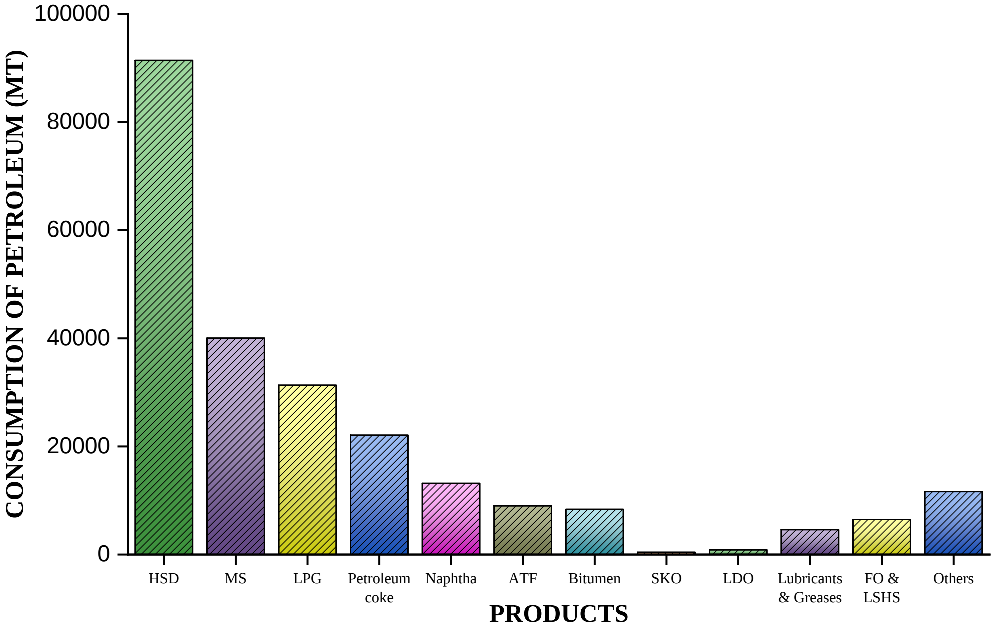


Fig.1.3. Share of global oil consumption

Figure 1.4 shows the daily oil consumption in millions of barrels for various countries as of year 2022. The United States tops the list with a consumption of 19 million barrels per day, reflecting its significant energy demand and large population [6]. China follows closely behind at 14 million barrels per day, which is expected given its rapid industrialization and economic growth. India ranks third, consuming 4.9 million barrels per day, driven by its expanding population and increasing energy needs. Both Japan and Russia consume 3.7 million barrels per day, with Japan relying heavily on imported oil for its energy requirements. Germany follows closely behind, consuming 3.1 million barrels per day, reflecting its industrialized economy. South

Korea, Brazil, and Canada have oil consumption figures of 2.9 million, 2.7 million, and 2.4 million barrels per day, respectively. These numbers highlight the varying levels of oil consumption among nations, with the United States, China, and India leading the world in daily oil usage.

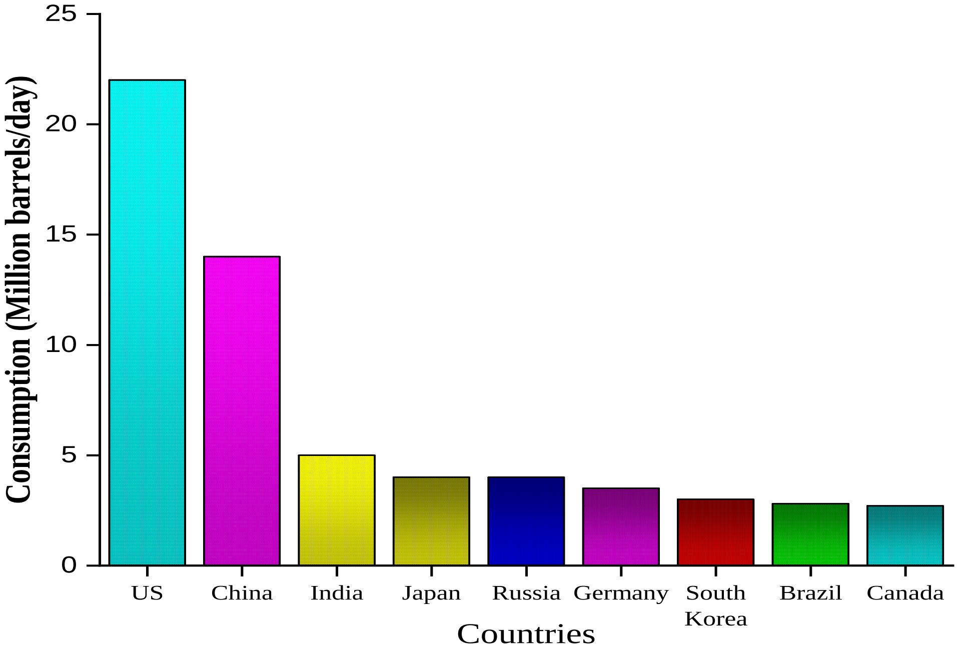


Fig.1.4. Global oil consumption in millions of barrels per day

Energy is crucial to the development and maintenance of every contemporary economy. The availability of reliable, low-cost, and easily accessible energy sources is critical for future of the economy [6]. It is very necessary for power plants to be designed with sustainability in mind in order to adequately address rising concerns over climate change and air pollution. Since India is the 6thmajor user of energy in the domain, India places a significant amount of importance on its domestic energy resources. The country of India has enough amounts of coal deposits. It also has an abundance of clean energy sources such as the sun, wind, water, and biomass. However, estimates put India's hydrocarbon reserves at a pitiful 0.4% of the world's total. As a result, India and other developing nations must import hydrocarbon fuels to meet their main energy demands. India’s reserves provide for less than 25% of these needs, which mostly import crude oil and natural gas as their commercial energy source.

Inadequate foreign currency resources are substantially to blame for energy supply constraints, and the growing oil import cost is a major cause for worry.

Dependence on oil-producing countries is inevitable due to oil imports. Petroleum products have widespread use in transportation, agriculture, and industry. Figure 1.5 outlines India's petroleum products consumption [7]. Over the last decade, there has been a sharp rise in the proportion of crude oil supplied by imports. Figure 1.6 displays the breakdown of petroleum product usage among industry types in India [7]. India has less than 1% of the world's known energy reserves yet 17.5% of the world's population. There is a peak deficit of around 12.5% and an energy shortfall of 7.5% in India's power industry with the current installed capacity of 1, 47,000 MW [8]. About 1,000 MW of extra capacity is needed to keep up with this rising demand. By contrast, the United States uses just around 3% as much energy per person as India does, while Japan uses only about 7% [8].

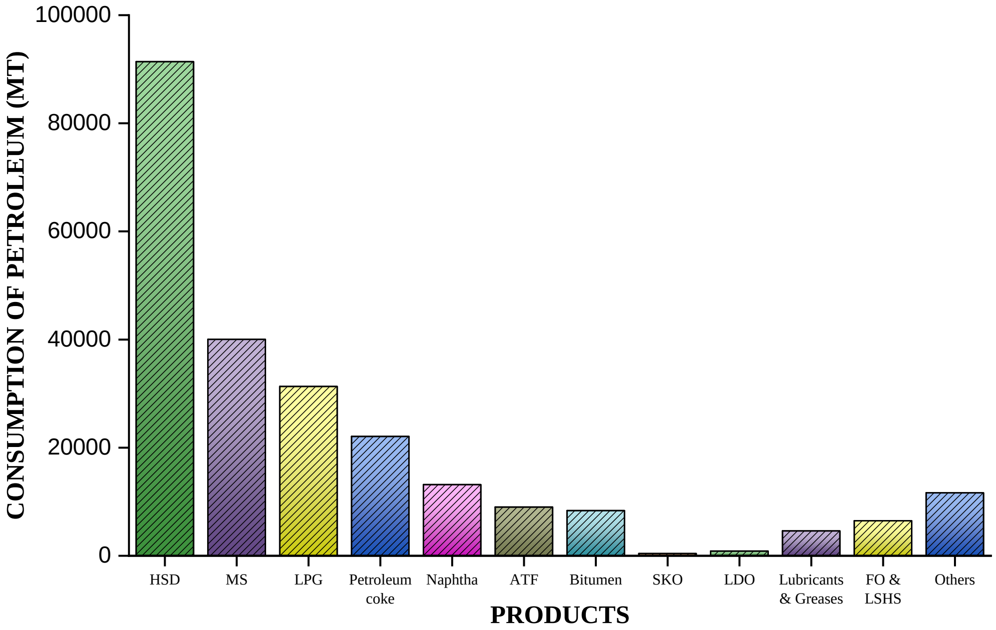


Fig 1.5 India's petroleum products consumption year 2022-2023

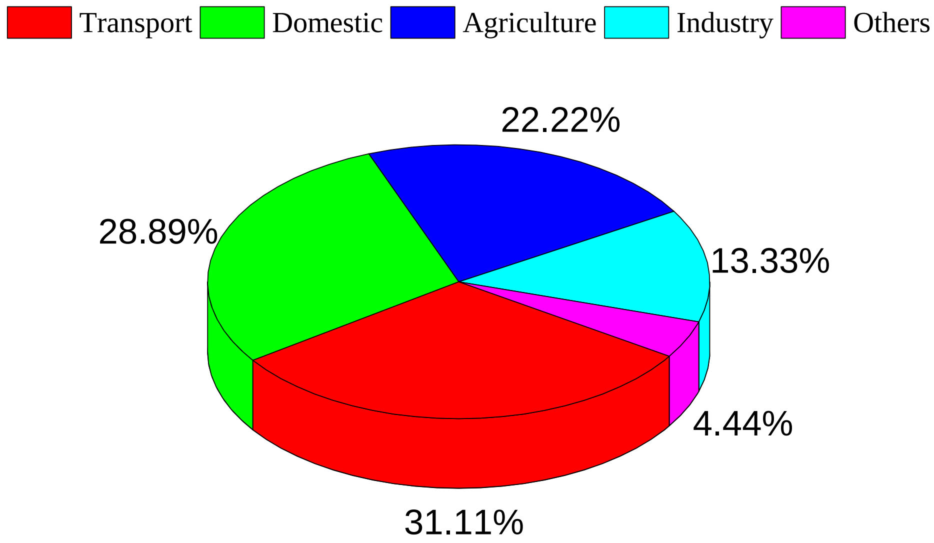


Fig.1.6 Breakdown of petroleum product usage among industry types in India

The following are four options for meeting India's anticipated energy needs in the future:

- Innovations in technology that make using current energy sources cleaner and more reliable are needed.
- Incorporating renewable energy sources as a supplement to, or as a replacement for, traditional energy sources via the development of suitable technologies.
- Creation of energy-saving tools and methods; this is particularly important regarding updating numerous outmoded manufacturing procedures.
- Effective and efficient management of energy resources.

Consequently, it is crucial to investigate alternative energy sources, particularly renewable ones, while still preserving traditional energy resources. Particularly in poor nations, biofuel energy has the potential as an alternative source of energy.

1.3. Sustainable development Necessity

Sustainable growth necessitates making efficient use of the resources that already exist. It also includes using renewable energy sources efficiently and fuel-efficient equipment. One of the most crucial needs for long-term sustainability is access to renewable energy. Renewable energy refers to any of many different types of energy that may be replenished indefinitely. Renewable energy has several benefits, including lowering emissions both locally and globally, providing reliable power for the future, and opening new career paths. In addition, since they don't rely on the imports that characterise the supply of fossil fuels, renewable energy resources open opportunities for local production and supply security. Important solutions must be explored in conjunction to address the current energy issue. These methods are storage of natural resources and the protection of the ecosystem. The first approach is to abandon the managed pricing system and instead set fair prices for finite or non-renewable resources. The second approach is to create and spread suitable technologies for tapping into unconventional energy sources to meet the total energy crisis. Rapid increase in fuel costs, the paucity of traditional petroleum-based fuels, and the hydrocarbon reserves of the globe have prompted the search for adequate technologies and alternative fuels to encounter the growing needs of the segment.

1.4. Internal combustion engine (ICE)

The growth of ICE was crucial to the expansion of manufacturing. Compression ignition (CI) and spark ignition (SI) are the two main categories used to describe I.C. engines. The employment of compression ignition engines in the public transit, agriculture, and power generating sectors has increased dramatically in recent years. Diesel fuel is 20% more expensive per mile than regular gas. These engines are more efficient, but the pollution they produce necessitates strict global emission regulations when fuelled by diesel generated from petroleum.

1.5. Pollutants emitting from diesel engines

Pollutants in the environment have increased because of industrialization, which negatively impacts the ecological system. Vehicle emissions account for 60% of urban air pollution, followed by those from factories and other sources (20 to 30 %) and fossil fuels (10 to 15 %). When environmental pollution occurs, it becomes much more hazardous when it reacts with other pollutants (via processes like photochemical reactions, for example). Table 1.1 Represent pollutants emitted from diesel engine [9].

Table 1.1 Pollutants emitting from diesel engines

Pollutant	Description
PM	Tiny particles are released during the incomplete combustion of diesel fuel. They pose a risk to human health and are a contributor to a variety of respiratory problems.
NO_x	Resulting from the combination of nitrogen in the air and oxygen during the high-temperature combustion that takes place in diesel engines. NO_x is a pollutant that may be hazardous to human health and is a contributor to both smog and acid rain.

	An invisible and odourless petrol that is produced when diesel fuel is not burned to its entire extent.
CO	Burning carbon-based fuels releases the colourless, odourless, and toxic gas known as carbon monoxide (CO). Vehicles, power plants, wildfires, and household appliances are just a few of the many sources of CO emissions.
HC	Unburned or partially burned fuel hydrocarbons are released into the atmosphere, contributing to the formation of ground-level ozone and smog.
SO_2	Some diesel fuels contain sulphur, which is released as SO_2 during combustion. Sulphur dioxide is a respiratory irritant and contributes to air pollution.
VOCs	Emitted during the combustion process, volatile organic compounds (VOCs) contribute to the creation of ozone.
GHGs	Diesel engines emit CO_2 and other greenhouse gases (GHGs), contributing to climate change.

1.6. Alternative fuels for diesel engines

Diesel fuel is the primary source of energy for transportation, agricultural industries; thus, it is crucial to research and develop diesel fuel alternatives. Several measures have been attempted to encourage the reduction of petroleum use. Some examples include making refineries more energy efficient and reducing fuel waste in the transportation industry. However, the contaminants in the air are accumulated by the engine exhausts. Diesel specifically needs an alternative fuel to help mitigate exhaust gas pollution's negative effects on the environment and fossil fuel depletion. Such substitutes should work with already installed engines and their ancillary equipment (such as injectors, fuel tanks, and delivery systems). When choosing on a replacement fuel for current engines, the following features should be considered.

- To be competitive with petroleum fuel, the operation's upfront costs must be lower, namely the additional expenditure on the current engine.
- Existing engine upgrades should be straightforward, cost-effective, and reversible.
- Engines' ability to run on either diesel or alternative fuels should not be compromised by such a change. It should be simple to go from using alternative fuels to using diesel.
- When an alternative fuel is used, the efficiency of the engine should increase, leading to lower emissions.
- Equipment longevity, dependability, and functionality must not be compromised by using alternative fuels, under the manufacturer's warranty. The alternative fuel must

be easily accessible, and its upkeep and running costs must be comparable to those of traditional Diesel.

Alternatives to diesel fuel include hydrogen, compressed natural gas (CNG), alcohols, biogas, producer gas, and vegetable oils. Biofuel provides a practical way out of the energy dilemma for emerging nations like India. Alcohols, vegetable oils, biomass, and biogas all fall under the category of bio-origin fuel. Table 1.2 describes the alternative fuels for diesel engines [10]. Some of these fuels may be utilised in their unrefined state, while others need further processing to get qualities more like those of conventional fuels. The feasibility and practicality of utilising biofuel made from vegetable oils is the primary subject of this investigation. The great majority of automobiles on the road today are powered by the internal combustion engine, which requires fossil fuels to operate. However, increased efficiency and decreased emissions are also possible with the use of substitute energies. The characteristics of many substitute energies and technologies are still in the early phases of development [10].

Table 1.2 Substitute energies for diesel engines

Fuel	**Description**
Biodiesel	Derived from renewable sources, typically vegetal oil or animal fat. Classified based on the feedstock used.
Synthetic	Produced through a Fischer-Tropsch process from natural gas, coal, or Hydro treated
Vegetable oil (HVO)	Derived from various vegetable oils through hydro treatment, resulting in a high-quality diesel-like fuel.
Dimethyl ether (DME)	Produced from various feed stocks, such as natural gas, biomass, or waste. Known for high cetane number and low emissions in compression ignition engines.
Natural Gas	Composed mainly of methane, extracted from natural gas reserves.
Hydrogen	An emission-free fuel that can be used in CIEs with certain modifications. Utilized in hydrogen-diesel dual-fuel engines or hydrogen fuel cells.
Methanol	Produced from biomass or renewable sources. Can be used as a blend.

1.7. Utilization of waste plastic oil in diesel engines

Diesel engines are the most common choice for automobiles because of their superior thermal efficiency and good output. Their benefits are outweighed by the negative effects on human health from the NOx and smoke emissions. To reduce these airborne toxins, strict emission standards have been implemented. In addition, the rising demand for oil is a direct result of the expanding number of automobiles used for transportation. Diesel engines need an alternative fuel source due to the depletion of petroleum fuel. Table 1.3 represents an advantage of exploring the application of waste plastic oil in diesel engines [11-12]. Most nations have struggled greatly with how to properly dispose of their garbage. This research investigates the feasibility of using oil from waste products in diesel engines. Oil refined from plastic waste has been combined with heavy oil for marine use in a few studies. The findings show that the viscosity of the mixture was significantly reduced, and the engine's performance was much improved. However, testing their use in high-speed diesel engines has gotten far less attention than testing other applications. Plastics such as Dacron, nylon, polypropylene, polyethylene, and Teflon, [12] etc., every year cause the death of tens of thousands of marine creatures and seabirds due to entanglement in bottles, nets, plastic bags, and ropes. Some of these rare sea creatures are on the verge of extinction. Using plastic waste not only would solve the issue of excess clearance, but also forms a part of usable energy if oil were to be extracted from these wastes. In India, a trial recycling programme turns trash into oil [13].

Table 1.3 Advantages of utilization of waste plastic oil in diesel engines

Waste reduction	
Energy recovery	Converting waste plastics to fuel reduces the consumption of fossil fuels.
Lower greenhouse gas emissions	When compared to more conventional ways of waste disposal, the usage of plastic oil may result in fewer overall emissions of greenhouse gases.
Renewable energy source	Plastic oil comes from a continuous stream of plastic waste, making it a form of renewable energy.
Energy efficiency	Plastic oil has a relatively high energy content.
Potential cost savings	Contributing to efficient energy conversion.

1.8. The problem of plastic waste disposal

1.8.1. Global status

The dumping of waste plastics is a growing threat to the world's ecosystems. Plastic's adaptability, longevity, and low cost have led to a meteoric growth in the material's customer base. Although Waste plastic management research is being conducted in several different countries, only a few waste plastic disposal/conversion technologies are efficient or cost-effective, and industrialization of them is an area of concern. Due to their inert nature, plastics accumulate as landfill material. Each year, globally, more than 400 metric tonnes of plastic are produced. Plastics have made many useful innovations, but they have also become an environmental and health problem. Figure 1.7 represents a landfill for waste plastic disposal [14]. The global problem of plastic waste disposal continues to be a major environmental challenge. Plastic waste has become pervasive in various ecosystems worldwide, causing significant harm to the environment, wildlife, and human health [14]. Here's an overview of the global status of the problem:

- An Increase in the formation of Plastic trash. Production of plastic throughout the world has been gradually rising, which has led to an increase in the formation of plastic trash. Each year, the globe generates hundreds of millions of metric tons of garbage made of plastic.
- Inadequate Waste Management: Many countries, especially developing nations, face challenges in managing the vast amount of waste plastic effectively. Inadequacy of proper wastage collection, recycling infrastructure, and disposal facilities contributes to plastic pollution.
- Ocean Plastic Pollution: An alarming quantity of plastic garbage makes its way into the seas of the globe due to insufficient waste management, littering, and incorrect disposal. This is a problem that has to be addressed immediately. Because of this, there has been increase in the amount of pollution caused by plastic in the water, which has an effect on marine life, ecosystems, and coastal communities.
- Micro plastics: Plastic waste breaks down into tiny particles known as micro plastics, which are found in various water bodies, soil, and even the air. Because marine species are able to consume these micro plastics, there is a possibility that they could enter the food chain, which raises worries about the effect they will have on human health.
- Recycling Challenges: While recycling efforts exist, the global recycling rate for plastic remains relatively low. The complexity of plastic types, contamination issues, and economic factors contribute to recycling challenges [13].

- International Waste Trade: Some countries have been exporting plastic waste to other nations for recycling. However, instances of illegal or unregulated waste trade have led to environmental and social problems in recipient countries.
- Plastic Bans and Regulations: Several countries and regions have implemented plastic ban or restrictions on single-use plastics to curb plastic waste. However, enforcement and adoption vary, and more comprehensive measures are required.
- Global Clean-up Initiatives: Various global organizations and initiatives are working to clean up plastic waste from oceans and beaches. These efforts aim to raise awareness and mobilize action to address the issue on a global scale.
- Public Awareness and Advocacy: Growing public awareness of the plastic waste problem has led to increased advocacy for more sustainable practices and policies.
- Circular Economy and Innovation: The concept of a circular economy, promoting recycling, reuse, and sustainable design, procured traction as a possible elucidation to the problem. Additionally, innovative technologies and materials are being explored to reduce plastic waste.

Fig.1.7. Waste plastic landfilling

1.8.2. Status of waste material in India

According to a study that covered the whole of India and was conducted in 2003, even though India generates more than 3.4 million metric tonnes of plastic waste every single day, only 30 % tonnes of it is recycled. The other 70% act as landfilling material [15]. About 81.5% by weight and twice that by volume, plastic garbage is a contributor to the world's solid waste streams [16]. It was predicted in the survey that by 2030 the amount of plastic trash generated by consumers was expected to rise to 3.6 million tonnes annually [17]. With garbage production rising at such a startling rate, India must make extensive plans for waste recycling and disposal. The increasing rates of trash production have prompted several procedures and solutions. However, there were several operational, economic, and budgetary constraints that made all the processes less than ideal. Rapid global depletion of petroleum reserves and consistent increases in crude oil prices has a negative impact on the economies of nations. Lack of fuel energy is a major issue in India. Petroleum and crude oil are imports for India. Only a miniature percentage of the country's fuel needs are met by domestic supply [18]. India faces significant challenges related to the problem of plastics dumping. The country generates a massive amount of plastic waste due to its large population and increasing urbanization. Here are some key points about India's status in the plastic waste disposal problem [19].

- India is among the world predominant manufacturers of plastic garbage, producing millions of tons of plastic every year. The vast majority of this garbage is produced by one-time use plastic items such as bags, bottles, and packaging.
- Inadequate Waste Management Infrastructure: India's waste management infrastructure, especially for plastic waste, has struggled to keep pace with the increasing amount of waste generated. Many cities and towns lack proper waste collection, segregation, and recycling facilities.
- Littering and Pollution: Due to the inadequate waste management system, a significant amount of plastic waste ends up littering the streets, rivers, and other public spaces. This leads to environmental pollution and poses serious threats to wildlife and marine ecosystems.
- Recycling Challenges: While some efforts are being made to recycle plastic waste, the recycling rate remains relatively low. Many recycling units are informal and inefficient, leading to limited plastic waste being recycled effectively.
- Limited Plastic Bans: Several Indian states have imposed partial bans on certain single use plastic items, but the implementation and enforcement of these bans vary. There is no nationwide ban on single-use plastics.
- Plastic Waste in Water Bodies: India faces a significant issue of plastic waste in its water bodies, especially in rivers and coastal areas. This not only harms marine life

but also affects the quality of water and poses health risks to communities relying on these water sources.

- Government Initiatives: The Indian government has recognized the problem of plastic waste and has launched various initiatives to address it. These include the Swach Bharat Mission and Plastic Waste Management Rules that aim to enhance waste management methods.
- Challenges in Behavior Change: Change in behavior of the public towards responsible plastic use and waste disposal remains a challenge. Awareness campaigns and education on plastic waste management are crucial for long-term solutions.

1.8.3. Problem Identification

The mismanagement of plastic waste along with depleting sources of fossil fuel is the problem which is inherently related. The drastic uptrend in demand of fossil fuel led jump in fuel prices and eventually leads to depletion of resources, moreover the environmental pollution is major concern due to over usage of fossil fuels. On the other hand, plastics which are inherently the petroleum products, and are causing havoc in terms of environmental pollution. One of solution of could be reusing plastic for production oil, which further partially replaces some percentage of original diesel fuel. This investigation explores the aforementioned problem and its potential solution.

1.9. Thesis Organization

The thesis is divided in to six chapters, the chapter focuses on background, motivation behind using plastic waste fuel as alternative source of fuel and problem associated with fossil fuels.

- The second chapter outlines the previous experimental investigations conducted using conventional fuels, waste plastic, and biofuel.
- The third chapter focuses on the preparation and evaluation of fuel properties.
- The fourth chapter deals with testing and evaluation methodologies of performance aspects. The fifth chapter discusses the results obtained from experimental evaluation methodically.
- The thesis concludes with summary of the experimental outcomes and their future direction.

CHAPTER 2

LITERATURE REVIEW

The rising levels of pollution in recent years have made it unavoidable to discuss the relevance of plastic trash and the many strategies now available to combat the problem posed by plastic waste. The chapter also provides a concise description of the literature those evaluated in relation to the management of plastic trash and the methods that are included in the forthcoming sections.

2.1. Overview of plastics

Plastics are made from fossil fuels like crude oil, gas, and other hydrocarbons and are created with precise properties that make them perfect for their intended use. Materials known as thermoplastics may be melted and reused. Thermoplastics include, however are not limited to acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS),polymethyl methacrylate (PMMA), expanded polystyrene (EPS), and polyvinyl chloride (PVC) [20]. Table 2.1 categorises plastic according to their use. Plastics known as thermosets change chemically when heated and cannot be re-melted or reformed. Thermosets include substances including vinyl esters, phenolic resins, silicone, melamine resins, and epoxy resins. 360 million tonnes of plastic were produced worldwide in 2018. According to the dissipation of plastic production worldwide, The North American Free Trade Agreement (NAFTA), Europe, the Middle East and Africa, Latin America, and the Commonwealth of Independent States (CIS) each contribute for 7% of the total, while Asia accounts for 51% of the total [21]. The demand for plastic in different industries reveals that 36% of plastic is used in the packaging industry, 16 % in construction of the building, textiles 14 %, 10% in automotive, 5% in electrical and electronic, 4% in the agricultural industry, 16% for other uses like appliances, mechanical, among others [22]. As a result, they produce large amounts of plastic garbage, which stimulates the creation of effective and cutting-edge techniques for recycling and reusing plastics.

Table 2.1. Classification of plastic by its usage

Type	Common uses	Recyclability

PET	Water bottles, soda bottles, food packaging	High
HDPE	Milk jugs, detergent bottles, toys	High
PVC	Food packaging, piping, siding	Low
LDPE	Plastic bags, cling wrap, food packaging	High
PP	Yogurt containers, straws, ketchup bottles	High
PS	Styrofoam, disposable cups, food packaging	Low
Others	Miscellaneous plastics	Varies

In 2019, the collective plastics production was 368 million metric tons and in India was 28 million metric tons [23]. PET, HDPE, and PVC were the most widely used types of plastics, accounting for over 70% of global and Indian plastic usage [1] [24]. These plastics are used for a variety of applications, including water bottles, soda bottles, food packaging, and construction materials. The increasing usage of plastics is a major environmental concern, and to decrease usage of plastics to recycle plastics whenever possible. Figure 2.1 and Figure 2.2 represent the global and India plastic production in percentage of share.

It is not required for the quantity of plastics produced to be equal to the volume of plastic trash produced since various plastic goods have varying life cycles. According to estimates, 9% of the plastic garbage that is collected is transferred to recycling facilities and 50 % is deposited of in landfills [25]. Zero landfilling is attained in nations like Switzerland, Austria, and the Netherlands to preserve the circular economy of plastics. In the middle of the 1980s, plastics started to be recycled when post-consumer garbage was transported to state-level waste deposit schemes. The domestic plastic garbage is collected via curb side programmes and sent to a material recovery facility (MRF) [26].

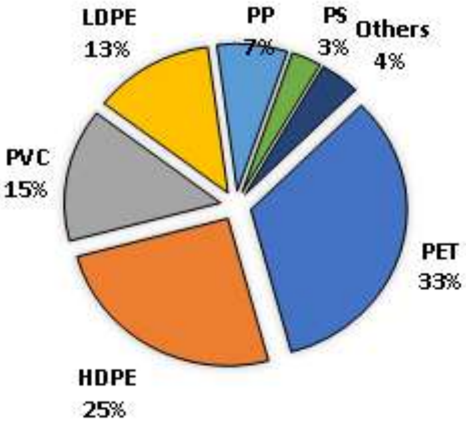


Fig.2.1. Global plastic production

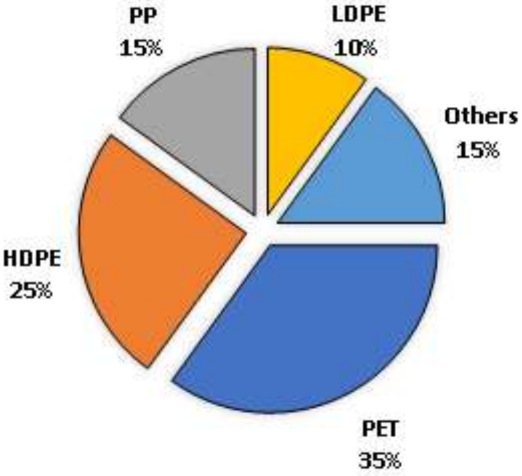


Fig.2.2. India plastic production

In MRF, the plastic waste is processed for reuse after being separated using an optical sensor that classifies it based on the kind of resin. The next step is waste plastic reclamation, when the plastic waste is broken down into tiny pieces, cleaned to remove impurities, and then sold to be used in the creation of new items. Significant material is lost when plastic garbage is sent to a landfill. Burning plastic garbage is not a good idea either since it releases potentially dangerous carcinogens including polychlorinated biphenyls and dioxins.

2.2. Plastic Waste Management Scenario in India

Over 9.4 million tonnes of plastic garbage are estimated to be produced annually in India. A total of 5.6 million tonnes plastic garbage are recycled each year, while 3.8 million tonnes are dumped in landfills [27]. Due to their dense populations, urban areas like Delhi, Mumbai, Kolkata, and Chennai have been among the leading producers of municipal solid waste (MSW). 429 tonnes of plastic garbage are produced daily in Chennai. According to statistics on plastic trash output, Chennai is the second-largest generator of plastic garbage. The foremost to ban, plastic is Sikkim in India: water bottles and disposable foam to minimise the use of plastic trash. Disposable items made of polystyrene are now forbidden by Maharashtra's government in India. 14 different categories of plastic garbage, including plastic sheets, cups, foam items, and carry bags, are now prohibited by Tamil Nadu government in India [27].

Plastic is a deteriorating environmental calamity. Plastics are not biodegradable by nature; therefore, they stay as landfills and at recycling centres for a long time. If not disposed of properly, plastic bags which are used to convey food and other items take 500 years to degrade. Numerous marine and terrestrial creatures often ingest plastic garbage, which may have devastating health impact. The procedure has grown to be burdensome for municipal trash management organisations. At the Perungudi and Kodungaiyur dump sites in India, the Central Public Works Department (CPWD) conducted an assessment and quantification of plastic waste in 2015 [27]. The results showed that an average of 95.42 kg/metric tonnes of the total municipal solid waste generated each day, or about 4500 MT/day, was made up of plastics. Municipal solid waste (MSW) collection efficiency is projected to be 80.28%, of which only 28.40% has been treated and the remainder has been disposed of immediately without first going through the pre-treatment process. HDPE, PP, and PET made about 94% of the recyclable garbage that was collected [27].

2.3. Waste plastic disposal methods

To utilise plastic trash for advantageous purposes like building roads, processing, and turning it into liquid fuel, etc., Source segregation is necessary for plastic waste management. Some techniques for treating plastic trash include land substantial, burning, thermo-chemical behaviour, and natural reprocessing [28]. The benefits and drawbacks of each strategy are shown in Table 2.2[28].

Table 2.2. Waste Plastic disposal methods advantages and disadvantages

Method	Advantages	Disadvantages
Landfilling	Cost-effective for non-recyclable waste. Requires minimal initial investment and technology. Can handle large quantities of waste with low labour requirements.	Produces greenhouse gases and leachate, potentially polluting soil, and groundwater. Limited space availability, leading to potential land use conflicts. Long-term monitoring and maintenance of landfill sites are needed.
Incineration	Reduces waste volume significantly, saving landfill space. Generates energy through heat recovery, contributing to electricity generation. Suitable for waste with high calorific value and non-recyclable materials.	High capital and operational costs. Releases air pollutants (e.g., dioxins, heavy metals) if emission controls are inadequate. Public concerns over emissions and potential health impacts.
Blast furnace	Utilizes waste as an alternative raw material in steel production, conserving natural resources. Reduces dependence on virgin raw materials for steelmaking. Lower CO2 emissions compared to traditional iron ore-based steelmaking.	Limited applicability to specific waste types and suitable furnace facilities. Energy-intensive process, impacting the overall environmental footprint. Requires waste pre-treatment and quality control to ensure suitable feedstock.
Gasification	Efficient energy recovery, producing syngas for electricity and heat generation. Reduces waste volume and potential for hazardous emissions. Can handle a wide range of waste types, including hazardous materials	High initial capital investment and operating costs. Requires advanced technology and skilled operators. Complex waste sorting and preparation processes are needed
Recycling	Conserves natural resources by reusing materials. Reduces energy consumption and greenhouse gas emissions during production. Supports the circular economy and reduces waste disposal needs.	Initial collection and sorting infrastructure require investment and maintenance. Some materials are challenging to recycle efficiently and economically. Contamination of recyclables can reduce the quality and value of recycled materials

2.3.1. Land filling

Waste plastic materials are disposed of in landfills where they "mummify" over time. Plastic is not biodegradable; thus, it contaminates the soil and, over time, creates serious environmental risks including lowering soil fertility and contaminating surface and subsurface water. In addition to the negative aspects, the plastic loses its embodied energy.

2.3.2. Incineration

Mixed plastics may be burned in an incinerator to produce electricity. The off-gas pollutants, such as dioxins and fleuron, cannot be reduced to appropriate levels in this way, however. As a result, this approach of managing plastic garbage is typically not favoured. The expense of treating the gases is often more than the energy gained.

2.3.3. Blast furnace

If waste plastic is formed into the necessary-sized particles and then put into the blast furnace, it may be utilised in lieu of coke and pulverised coal. Reducer gas ($CO + H_2$) is created when the injected plastic is broken down. This gas released through the furnace's raw materials and interacts with the iron ore. Hydrogen chloride is produced when polymers with chlorine, such poly vinyl chloride, are injected into the furnace. Hydrogen chloride in the furnace is neutralised by the limestone used in the blast furnace to regulate the composition of the slag, lowering its concentration. However, the percentage of Coke that can be replaced by plastic is only around 40% by weight.

2.3.4. Gasification

In essence, gasification is the thermal breakdown of organic matter in an airless atmosphere or with a finite amount of oxygen. When PVC is gasifier at a lower temperature to remove chlorine from the input, it includes chlorinated compounds, thus the temperature is increased to convert higher hydrocarbons. Controlling the combustion temperature and the volume of unburned gases, however, presents challenges.

2.3.5. Recycling

Recycling the plastics garbage is not the only option for its disposal. After the third or fourth round of recycling, the plastic is no longer suitable for use and is eventually disposed of in landfills. There are certain plastics that cannot be recycled. But scattered municipal waste plastic cannot be processed using this technology; it is only appropriate for separated plastic materials. The following are the issues with the recycling process:

- There are several varieties of plastics in use, making it challenging to separate them for certain purposes.
- There are many different fillers and additives in plastics.
- Plastic’s sorting is costly and technically challenging.
- Plastic recycling lowers the product's quality.

2.4. Pyrolysis Process

Environmental degradation and low quality of life are caused by significant deficiencies in starting place segregation, selection, transportation, treatment, and scientific waste disposal [29]. New approaches have sometimes been developed to address the problems posed by plastic trash, including mechanical recycling, landfill disposal, house building using plastic bottles, and feedstock recycling. Waste plastics are converted into liquid fractions using pyrolysis, which has an advantage over combustion technology in terms of pollution output. For oil-based compounds, the less stringent approach, in which plastic waste is thermo-treated without oxygen to break long-chain hydrocarbons into intermediate and short-chain hydrocarbons, is an appropriate technique [30].

The heating rate, residence duration, and temperature determine whether pyrolysis is gradual, fast, or flash. Gasification as a means of handling plastic rubbish only became a problem in India in the late 1990s [31]. The manufacture and use of plastics have been expanding at a rapid pace. The most cutting-edge technique for treating the co-pyrolysis of plastic waste demonstrates an adequate liquid output level. HDPE, LDPE, PP, PS, PVC, and Polyethylene Tetra phthalate all are employed as feedstock in thermal pyrolysis [32]. Researchers were intrigued by the higher yield of pure distillates produced by pyrolyzing plastic waste compared to alternative organic feedstock. The needed output is achieved by optimising the process parameters and the types of plastic feedstock used. The pyrolysis products are similar to fossil fuels because of the high carbon and hydrogen content of the polymers. Polyethylene and polypropylene have a carbon percentage between 83.1% and 86.1% [33]. However, PS and PVC have a high aromatic content since naphtha is used in the polymerization process. There may be a wide range of volatile substances and solid residue in the final product [34]. In a semi-batch reactor, polyethylene is pyrolyzed to create low molecular weight paraffinic hydrocarbon, which is then refined into diesel fuel. Using zeolite from the earth as catalyst, used polystyrene may be refined into oil. The oil is a mixture of aliphatic and aromatic hydrocarbons. Using fly ash as a catalyst in a multistage catalytic pyrolysis of waste polyethylene, scientists were able to recover benzene, toluene, ethyl benzene, and xylene at a rate of 21.34% and increase the liquid yield by 78.20% [35].

2.4.1. Thermal pyrolysis

During the well-researched process of endothermic thermal pyrolysis of synthetic polymers and plastic waste [36], various different polymer materials, including polystyrene, polypropylene, polyethylene, poly vinyl chloride, and polyethylene terephthalate, are analysed. These are just some of the many polymer materials that are examined. During the thermal pyrolysis process, the polymer is heated, and the oil that is produced comes from the condensed vapours. While the non-condensable vapour is allowed to leave as if gas is extracted, the residue will be left at the reactor's base. The temperature is consistently maintained within the range of 500–600°C, throughout the process of polymer breakdown [37]. The by-products of thermal pyrolysis have the potential to significantly decrease the dependability of products that are processed from petroleum. Products are comparable to those manufactured using fossil fuels.

Additionally, while pyrolyzing plastics, as opposed to other feed sources like biomass, pure distillates are produced. To get the required outputs, extensive research has performed for improving the pyrolysis reaction situation along with feedstock kind. PET preferred in food wrapping, electrical wiring or medical equipment. PET is pyrolyzed to give a 42% liquid yield, a 42% gas yield, and a 16% char product [38]. The polycyclic aromatic compounds (PAH) produced by PET pyrolysis may interfere with the human immune system. PET is thus not appropriate for pyrolysis reactions. Thermal breakdown of polyethylene (PE) converts it to oil, yielding 74.12% liquid, 22% gas, and 3.88% residue [39]. PE is a fully branched hydrocarbon that must be heated to degrade. One of the most popular polymers, polyvinyl chloride (PVC), is mostly utilised in the building industry. When polypropylene is pyrolyzed, it yields gases and liquids in proportions of 83.6 and 16.4 respectively. Good sources of pyrolysis liquid yield include polypropylene and polystyrene [40].

Pyrolysis investigations are based on the impact of operational factors such as temperature and time, reactor type, feedstock composition, fuel quality, and resource recovery [41]. Polypropylene, polyethylene, and virgin polystyrene were used to study how temperature and time affect the pyrolysis process [42]. The investigation reveals temperature has a higher effect on individuality of liquids and a more diverse impact on gases as well as residues. Oil becomes very viscous and has a lengthy chain of hydrocarbons around 460°C, and it becomes more aromatic at higher temperatures of

600°C [43]. Since a longer reaction time has no influence on the conversion or properties of the product, it has a less significant effect than temperature intervention. The investigations also demonstrate that the best reaction temperature for the breakdown of plastic garbage is 500°C [43].

The pyrolysis testing technique has been applied to a broad variety of polystyrene varieties, such as pure polystyrene, expandable polystyrene, and polystyrene containers. The results of these tests have been analysed. The pyrolysis of expanded polystyrene indicated that aromatic compounds were generated at the beginning of the process and aliphatic were produced at the end of the procedure; nevertheless, the product flow of unused polystyrene and polystyrene containers is made up entirely of aromatic compounds. This is despite the fact that pyrolysis of expanded polystyrene revealed that aromatic compounds were formed at the beginning of the process and aliphatic were produced at the conclusion of the method [44]. This is in contrast to expanded polystyrene, which indicated that aliphatic compounds were produced at the end of the procedure. According to the investigations, the pyrolysis of HDPE at heats ranging from 400-450 °C results in the production of char that is composed of 52% volatile matter, 45% fixed carbon, 2.411% moisture remaining 0.116% ash. It has been shown that the density of char is 1.59 grams per cubic centimetre and that its calorific value is 4500 calories per gram [45]. They came to the conclusion that the HDPE char that was generated during the pyrolysis process will be fuel during the combustion procedure.

The HDPE fluid oil that came when used shopping bags were paralyzed has a hydrocarbon boiling range that extends from 190 to 290 °C and has the potential to be employed as qualified mix ingredient for diesel fuel. 0.6% of the hydrogen in the liquid oil is aromatic, 2.6% of the hydrogen in the liquid oil is aliphatic olefin, and 96.8% of the hydrogen in the liquid oil is saturated aliphatic paraffinic [46]. The evaluation of the phase change characteristics of polymers during the pyrolysis process experimented in reactor that consisted of a vertical falling film. The volume of fluid (VOF) model, which effectively transforms everyday plastics such as household packaging and water containers to spectrum of petrol-like hydrocarbons, was used to study the pyrolysis of molten polypropylene. Plastic oil was used in diesel engines as part of an experiment, and the results showed that the substance has qualities that were similar to those of diesel fuel [46]. Elevated temperatures ranging from 400 to 900 °C are required for thermal pyrolysis process, which is temperature-dependent and results in the decomposition of polymers into liquid, residue, and gas. They are bound to a few limitations, including the presence of layers in the produce oil, extended reaction times and higher temperatures, and decreased product selectivity. In order to circumvent these limitations, the pyrolysis process might benefit from the use of a catalyst [46].

2.5. Catalytic pyrolysis

Recent studies have concentrated a lot on the catalytic pyrolysis of plastic trash. It gives polymeric waste a better chance of being used effectively. It has found that HZSM-5 can be used to catalyse the pyrolysis of laminated aluminium plastic, producing higher levels of aromatics. The pyrolysis of polystyrene uses a heterogeneous acidic catalyst. MCM-41 made of sepiolite from nature is one of the most popular acidic catalysts. Red mud and ZSM-5 were used as a catalyst to pyrolyzed mixtures of plastics such as polystyrene, polypropylene, and polyethylene [47]. It was discovered that ZSM-5 had an important influence on the supply and possessions of the pyrolysis harvests.

In a liquefied bed reactor, plastic waste is paralyzed catalytically utilising PP, PET PS, and PVC as the plastic waste materials. Acidic catalysts like ZSM-5, FCC-R (fluidized catalytic cracking of recycled materials) silicate allowed for plastic waste hospital pyrolysis, which resulted in the creation of a greater number of gases than was previously possible. To be more specific, the utilisation of catalyst ZSM-5 was responsible for 88.3 weight percent of gases, 3.5% weight percent of fluid, and 6.5 weight residues [48]. As test materials for the process of assessing sequential pyrolysis, catalytic reforming of HDPE, polyethylene, HDPE were utilised. This kind of plastic trash that is used has a sizeable impact, not only on the manufacture of the product, but also on the high quality of the oil and residue that are generated as a by-product of the process. The oil that was created as a by-product of the pyrolysis of HDPE had a heavy oil fraction. On the other hand, the oil that was generated as a by-product of the pyrolysis of polyethylene contained a much greater number of diesel components. It has been shown that natural zeolite is an even more effective catalyst than Y-Zeolite for boosting oil production. It has been found that there is a ratio of 1:3 between the amount of silica and alumina in the nickel silica-alumina catalyst that is used to pyrolysis PE, PP, and PS [49]. This discovery was made after it was found that there is a ratio of 1:3 between the amount of silica and alumina in the nickel silica-alumina catalyst [49].

The catalyst with nickel loading slows the aromatics production in Diesel. The research reveal that the product yields and catalytic acidic property are related. As a result, an important criterion for hydrogen transfer process is acidic property. Lewis and Bronsted acid sites may be found on silica-alumina catalysts [49-50]. The chars that are created when biomass and polymers are pyrolyzed together may prove to be a valuable starting material for the production of activated carbon. Desiccant, molecular sieve, catalyst carrier, thermal energy converter, and energy storage are some of the many uses that have been found for the synthetic mesoporous silica material that has been created. It has been investigated how the presence of biomass changes the catalytic activity of waste plastic using zeolite HZSM-5 catalyst. This study found that the presence of biomass decreased the production of aromatic chemicals. Copper-supported catalysts, such as copper alumina (Cu-Al), Cu-montmorillonite (Cu-Mmn), and Cu-activated charcoal (Cu-AC), are used in the pyrolysis of waste expanded polystyrene. The use of $Cu-Al_2O_3$ as a catalyst may be responsible for the elevated styrene, toluene, and benzene ethylene found in the product stream [51].

In a quartz glass reactor, $Al-Al2O_3$ was used as a catalyst for the purpose of researching PET impact on polystyrene as well as its reactivity. The findings revealed that the yield of the product was affected by factors such as temperature, reaction duration, and the proportion of polymer to catalyst [52]. The temperature of the polystyrene reaction was lowered thanks to the use of a catalyst. Toluene, naphthalene derivatives, indene, methyl styrene, styrene, and benzene are among the many compounds that have been seen forming in the product stream. Other molecules that have been observed include toluene and indene. Using a catalyst that is based on barium titanate (BaTiO3), the HDPE pyrolysis demonstrated that the lead-cobalt/barium titanate (Pb-Co/BaTiO3) catalyst produces 84.2 weight percent oil, 5.13 weight percent residue, and 10.1 weight percent gases [53]. The catalyst resulted in an increase in the creation of paraffin while simultaneously lowering the generation of olefin and naphthenic. Uplifted-density polyethylene catalytic process combined with maize stalk is examined as a means of producing a greater quantity of aromatic compounds. The study makes use of activated carbon. According to the findings of the study, the 600– 700 degrees Celsius activation temperature, impregnation percent (0.0–2.0) chemical activating agent possess all contributed to an improvement in the synthesis of aromatics [54]. The formation of aliphatic along with aromatic compounds by catalyst HZSM-5/MCM41 has revealed that the catalytic activity of bio char on the pyrolysis process was impacted by the absence of functional groups containing phosphorous in the bio char [55]. This was proved by the fact that the catalytic activity of bio char was not influenced by the lack of functional groups containing phosphorous in the bio char. Used polyethylene greenhouse film is pyrolyzed with rice husk at 600 degrees Celsius, and the major vapours are then filtered through layer of composite sieve with micro mesoporous characteristics. This method is responsible for producing 71% of the total amount of hydrocarbons [56].

The employment of a ZSM-5+Ca $(OH)_2$ + red mud artificial catalyst allows for the pyrolysis of a wide range of waste plastics, includes polyethylene with low density, polyethylene with high density, polypropylene, cardboard. It is been shown that a catalyst with a high alkali content has the ability to increase both the total acid number and the characteristics of corrosion [47]. It is possible that the use of zeolite catalyst will bring about a reduction in both the viscosity and the density of oil. Carboxylic acids, Aldehydes, alcohols, ketones, and phenol derivatives are some of the several components that make up oil. Other components include ketones. Char is a carbon-rich residue that is produced as a solid by-product during the pyrolysis process. This kind of feedstock affects composition of the char in different ways. The surface area of char is rather enormous at 589 m^2/g, and its micro pore volume is 225 mm^3/g. Char is utilised as a sorbent and in catalytic usage to remove pollutants like sulphur dioxide and nitrogen oxides from water and flue gas. Catalytic pyrolysis relies heavily on catalyst regeneration. Coke built on the catalyst's surface cause deactivation of catalyst. The catalyst's pores will get clogged because of coke production, which lowers the catalyst's activity. Therefore, catalyst renewal is carried out to increase activity [56]. In an oxidative environment, regeneration takes place. The catalytic activity of a new catalyst could not be entirely recovered during regeneration.

2.6. Microwave pyrolysis

Because microwave pyrolysis can heat materials quickly, it has drawn a lot of interest. Federal communication controls the distribution of frequencies for household and commercial use. GHz (2.45) is used for residential purposes, whereas GHz (0.915) is used for industrial purposes [57]. Microstructure, temperature, and frequency all affect how deeply a microwave may penetrate a material. Deep within the particle, microwaves interact with matter to produce heat energy. A tried-and-true method for turning waste materials including polymeric waste, sewage sludge, and forest and agricultural wastes into fuels is microwave irradiation. Major benefits of microwave heating include:

- Quicker completion of reactions
- Less energy is needed
- A productive heat transfer
- Cost-effective

The management of solid waste and environmental remediation may both benefit from the use of microwave pyrolysis as a heating source. Implementing the process of pyrolysis in the management of plastic trash will cut down on the quantity of garbage dumped in landfills. Additionally, important hydrocarbons like low-sulphur naphtha and diesel may be made from the microwave pyrolysis product oil by refining it. Because polymers are poor microwave conductors, microwave pyrolysis requires the use of an absorbent/suspect or to accept the heat and then transport it to polymer being pyrolyzed. Because absorbers and susceptors tend to be dielectric, they are receptive and transparent; the interaction of the material's charged particles and the electron's electric field components is what causes the heating of the dielectric [58]. Both the material apt in convert incoming electromagnetic energy to heat, which is referred to as dielectric loss, and the capacity of the material to absorb microwave radiation, which is referred to as dielectric constant, are examples of the dual dielectric properties that may be found in absorbers or susceptors.

Silicon carbide, iron and cobalt, carbon, iron powder, and activated carbon are some of the susceptors that have been used as microwave absorbents. Other susceptors include iron and cobalt. The relationship between microwaves and carbon was investigated using a fluidized bed reactor equipped with microwaves [58]. While the light-dependent resistor (LCD) has been utilised to measure the plasma production, the charge coupled device (CCD) camera has been employed to capture the digital image. According to the findings, the formation of plasma is brought about by a combination of the temperature at which carbon is activated and the trace elements presence, such as Si, K, and Cu.

For a variety of feedstock, including lignite, Indian and Indonesian coals, switch grass, soap stock, microalgae and scum, lignin, and polypropylene, and maize Stover, microwave-assisted pyrolysis has been used. The findings of experiments on the microwave-induced pyrolysis of plastic waste, including polystyrene, with involvement of aluminium, how microwaves interact with it demonstrate that reaction probably be managed by modifying the structure and dimensions of the metal antennas inside the reactor [59]. These studies were conducted to better understand how microwaves interact with the material. Recovering the monomer styrene is by the reverse polymerization of polystyrene. Styrene production was found to vary depending on the microwave power and absorber ratio. One of the quickest methods to turn waste polystyrene into oil is the microwave metal interaction of a copper coil, which yields 66 wt. % liquid oil. Low-rank coal has been pyrolyzed in a microwave oven using a FeS_2 (iron disulphide) catalyst [60]. The coupling of the microwave and catalytic processes has improved the production of light oil. Quartz reactors are used for microwave analysis because they have low tangent loss and function as insulator for microwaves.

For the purpose of determining the temperature contained inside the microwave reactor, it is possible to make use of thermocouples, sensors based on infrared light, and optical fibre. Research was exhaustive and meticulous, using a local chrome-lume thermocouple of microwave power, a variety of subsectors, and feedstock polymer mass [61]. In order to keep track of the temperatures in both the reaction closet and the reactor tanker during the plastic pyrolysis in microwave, two thermocouples have been deployed. Pyrolyzed polystyrene was used with a thermometer with a wide-angle scale to determine microwave temperature while it was in the microwave absorbents' presence, such as graphite and SiC. According to the results, using carbon as the absorbent and running the microwave oven at a temperature ranging from 300 to 520 degrees Celsius has the potential to produce 94 weight percent of liquid [62]. According to the residence period, it was found that the product composition differed. It is also possible to utilise the char created by microwave pyrolysis as fuel or microwave absorbent. The impact of the pyrolytic conditions has been thoroughly investigated in the microwave pyrolysis of maize Stover. When low density polyethylene and lignin were heated in a microwave, more aromatic compounds were generated than phenol compounds.

In a microwave pyrolysis reactor, an investigation into the tyre powder power level is being carried out. It has been shown that it is possible to attain an utmost fluid yield at 45 wt. % when using particular microwave energy of 14 W/g, and the circumfluent oil preferred in this process is commonly an aromatic molecule. The formation of 18.5 weight percent of gases is caused by a microwave power that is particular to a gram and measures 24 W/g. Methane (CH_4), ethylene (C_2H_4), and hydrogen (H_2) are examples of gases that may be found in the lighter fractions. The method of microwave pyrolysis may be used to produce mesoporous activated carbon [63] that has a surface area that is much more than 1038 m^2/g. This activated carbon may also be used as an absorber for microwaves in certain applications.

2.7. Properties and Composition of waste plastic oil

Plastic oil that has been used has a variety of chemical compounds with carbon numbers ranging from C10 to C30. Both calorific value and the quantity of sulphur that WPO contains is diminishing than those of diesel. Diesel has a higher heating value. WPO has a ring structure and a higher proportion of aromatic components than other fuels. Table 2.2 presents the feed composition, the catalyst goal, the process parameters, and the product distribution that result from the conversion of several kinds of waste plastic into liquid, gas hydrocarbons, and residue [64]. The procedure is carried out at temperatures ranging from 300 to 400 degrees Celsius and at atmospheric pressure; the batch cycle duration is between three and four hours. The catalyst's objective is to convert 1 weight percent of the feed into gas, whereas the final products include 10 to 20 weight percent gas, 60 to 80 weight percent liquid hydrocarbons, and 7 to 10 weight percent residue.

Table 2.3 compares the properties of WPO (waste-plastic), diesel. WPO is a liquid fuel prompted from the waste-plastics pyrolysis. It has lower specific gravity and higher aromatic content than diesel, but a lower flash point [65]. Gasoline is a clear, colourless liquid fuel that is typically derived from petroleum. It has a lower specific gravity and lower aromatic content than WPO, but a higher flash point. It also shows that WPO has lower sulphur content than diesel. It means WPO is a cleaner-burning fuel and produces fewer emissions. However, WPO also has an inferior cetane value than diesel, which means that it is not as easy to ignite. Overall, WPO is a promising an alternative fuel with the capability to decrease emissions and improve air quality. However, more research is needed to develop WPO into a commercially viable fuel.

The gaseous bi-products of discarded plastic oil are outlined in Table 2.4 [66]. Propylene is the most prevalent gaseous product, making about 29.1% of the total gaseous products. It is also the most reactive gaseous product. Methane accounts for

6.6% of the total gaseous products, followed by n-butane (0.9%), ethane/ethylene (10.7%), propane (7.3%), hydrogen (2.5%), iso-C5-n-C5 (0.1%), C4 (unsaturated) (24.6%), and C5+higher (15.4%) [66]. The ratio of CO to CO2 is lower than 400 parts per million (ppm) [67]. The kind of plastic waste that is utilised, the circumstances of the pyrolysis, and the presence of any catalysts all have a role in the composition of the gaseous products that are obtained from waste plastic oil. In general, the gaseous products of waste plastic oil are a combination of light hydrocarbons, which may include alkanes, alkenes, and aromatics. These compounds are released into the atmosphere during the combustion process. These gaseous products have several applications, including as fuels and as feedstock for the production of other types of chemicals.

The chemical make-up of waste plastic oil is shown in Table 2.5 [68]. C_{10} is the most common kind of chemical compound, making up 61% of all the different kinds of chemical compounds. C_{10} to C_{13} accounts for 2.4% of all chemical compounds, C_{13} to C_{16} accounts for 8.5%, C_{16} to C_{20} accounts for 4.1%, C_{20} to C_{23} accounts for 7.6 %, and C_{23} to C_{30} accounts for 16.4%. The kind of plastic waste that is utilised, the circumstances of the pyrolysis, and the presence of any catalysts all influence the chemical makeup of the WPO that is produced. In general, waste plastic oil's chemical makeup is a combination of aliphatic and aromatic hydrocarbons. However, there are certain exceptions to this rule. Fuels may be made from these chemical compounds, or they can be utilised as feedstock for the production of other chemicals. It also demonstrates that the theoretical values of the chemical composition are somewhat off from the measured values of the composition of the substance. This is due to the fact that the actual pyrolysis process is not a flawless process, and some chemical components are lost throughout the process [69].

Table 2.3. Product yields and process parameters

Feed	**Assorted waste plastic**
Goal	10 wt.%
Pressure	Atmospheric
Temperature	300-400 °C
Catalyst	1 wt.% on feed
Gas	10-20 wt.%
Batch cycle time	3-4 hrs
Residue	7-10 wt.%

Liquid hydrocarbons	60-80 wt.%

Table 2.4. Comparison of WPO and diesel

Properties	**WPO**	Diesel
Colour	Pale black	
Kinematic Viscosity, cSt @ 40°C	3.4	2.5-3.0
Cetane number	51	55
Bulk modulus [10^9 Pa, N/m^2]	1.52	1.49
Sulphur Content (%)	<0.002	<0.035
Fire Point °C	45	56
Flash Point °C	42	50
Aromatic content, %	55	20
Pour Point °C	<-7	6
Gross Calorific Value (kJ/kg)	44340	45500
Specific Gravity at 30°C	0.8355-0.870	0.8300

Table 2.5.Waste plastic oil gaseous products

Component	**Quantity (%wt.)**
Propylene	29.1
Methane	5.5
n-Butane	0.9
Ethane/ethylene	11.7
Propane	6.4
Hydrogen	2.5
Iso C5-n-C5	0.1
C4 (unsaturated)	26.6
C5+higher	15.3
CO/CO_2	<400 ppm

Table 2.6. Waste plastic oil chemical composition

Composition	Percentage
C_{23} to C_{30}	16.4
C_{20} to C_{23}	7.6
C_{16} to C_{20}	4.1
C_{13} to C_{16}	8.5
C_{10} to C_{13}	2.4
C_{13}	61

2.8. Utilisation of Waste Plastic Oil in Diesel Engine

WPO performance characteristics have been compared to those of conventional diesel engines by researchers [70]. They have tried everything, including WPO that has been mixed with diesel and WPO that has been laced with other poisons. In this part, we will discuss the many components that contribute to the performance characteristics of a system. Some of these components include the system BTE, cylinder pressure, EGT, ignition delay and heat release rate, SFC, and SEC.

2.8.1. Engine performance characteristics

According to research [71], using biodiesel and WPO blend successfully enhanced BTE by around 15.7% as compared to diesel. This was done by burning waste plastic oil molecules that contain the oxygen-rich ester (AOME). Researchers [72] discovered that using WPO and diesel combinations increased brake thermal efficiency. Increased heat release rates contributed to a decrease in efficiency and an increase in the amount of heat that exhaust gases transported away. Additionally, when the proportion of WPO in the mixture climbs as a outcome of a surge in oxygenated compounds, the combustion heat rises, which in turn causes an increase in BTE. WPO and diethyl ether (DEE) were mixed in order to get an even higher level of BTE [73]. Because the oxygen included in DEE assists during full combustion, an increased proportion of DEE results in an increase in BTE. In addition to this, it was shown that the BTE is greater than diesel while operating at full load when DEE is annexed to WPO at a rate of 10%. Atomization increases as DEE% increases; it reduces the surface tension between liquids [74]. This results in an increase in the rate of combustion. Because the micro-burst of water droplets found by WPO emulsions results in the fragmentation of transforming large oil droplets into smaller particles, using WPO emulsions rather than diesel might result in an increase in BTE. As a direct consequence of this, air mixing and fuel evaporation were accelerated, which led to a quicker rate of combustion and an increase in BTE [75]. According to the author [76], n-butanol improves the air-fuel combination by reducing density, improving spray atomization, and increasing ignition delay in blends with WPO and diesel. WPO's capacity to vaporise is improved when DEE is added to the mixture because DEE has the ability to absorb heat and reduce the viscosity of the WPO [77]. BTE rises with increasing load because of greater cylinder temperature, a quicker rate of fuel vaporisation, decreased heat loss, and improvement in power [78-80]. The same reasons, higher cetane number, lower viscosity, and higher velocity, also explain why improvements in DEE in a mixture of WPO and DEE boost Brake Thermal Efficiency, leading to a quicker combustion rate [78].

The BSFC is greater when WPO is mixed with diesel and n-butanol than it would be with pure diesel because Pure Plastic Oil possesses a subsidiary calorific value than diesel [80]. This is so that WPO may provide the same amount of power as diesel while burning a greater volume of fuel. WPO and DEE blends have better BSFC than diesel due to their lower heating value, greater density, alongside bigger bulk modulus (which allows furthermore propelling discharge per injection pump plunger displacement) [81]. Researchers [82] found that WPO had a higher BSFC than diesel because of the combination of Pure Plastic Oil and JME. WPO also had a larger bulk modulus and lower calorific value than diesel. In lieu, research indicates that WPO has a greater BSFC than diesel [83]. Because of this, a greater amount of fuel is required while producing the same amount of energy with WPO as opposed to diesel [84]. According to the findings of the research, WPO had a greater BSFC than diesel blends of any kind, and the lower heating value of WPO might be the cause. Author [85] says that the amount of petrol that the engine must burn in order to run at a fixed speed generates a larger BSFC as EGR levels grow because the air in the combustion chamber is replaced by exhaust gas, which results in improper combustion and loss of torque.

Using a vital statistic known as brake specific energy consumption, it is feasible to evaluate the impacts of using two different fuels in an engine that has various viscosities, heating values, and densities. This is possible because brake particular energy consumption is an important metric. In addition to this, it was found that an increase in the quantity of the blend of pure plastic oil led to an improvement in BSEC. This was due to the engine's increased fuel consumption, which was brought on by the low calorific value of the WPO. According to the author [86], WPO-diesel blends have a lower density and viscosity than simple WPO, which improves the air-fuel combination and helps the combustion process. WPO was shown to have a higher BSEC compared to diesel while operating at rated power, as discovered by the researcher [87]. BSEC for diesel fuel, WPO, and three more WPO blends (Plastic Oil 25, Plastic Oil 50, and Plastic Oil 75), each of which comprises 25, 50, and 75 percent WPO, as well as diesel with variable load, was recently updated.

2.8.2. Engine combustion characteristics

The temperature of the exhaust gas is a significant component in determining how well combustion operates. Low exhaust temperatures are a sign of improved combustion performance and efficient cylinder fuel combustion. Increased exhaustion pipe heat loss suggests a slight shift of heat to work [88]. Because more fuel must be consumed to provide the same amount of power, the exhaust gas temperature rises as well as the load. Exhaust temperature of pure plastic oil exceeds that of diesel [89]. Due to its oxygen content, WPO tends to promote more efficient combustion, which can lead to higher exhaust gas temperatures compared to diesel fuel.[90]. Additionally, WPO has a higher fuel to air ratio. WPO has a greater exhaust temperature due to the delayed ignition, which enhances diffusion combustion for variation in braking power and exhaust temperature for pure Diesel as well as for pure plastic oil.

Ignition delay is the time needed to prepare fuel-air for combustion between fuel injection and combustion [91]. WPO burns longer compared with diesel because of greater viscosity, auxiliary cetane value, volatility depletion, spray properties, outstretched hydrocarbon chains that need more energy to break, and high electron affinity chemicals. Beginning combustion rates affect peak cylinder pressure in CI engines. Diesel engines' maximum cylinder pressure depends on the fuel-air mixture's ignition time. Longer ignition delays allow more diesel to burn uncontrollably, raising peak cylinder pressure [92]. Increased viscosity and decreased volatility delay the air-fuel mixture preparation in premixed combustion, raising peak cylinder pressure. According to many studies, WPO has a higher peak cylinder pressure than diesel [93], which might be attributed to its higher viscosity, more ignition delay, and preparation of the fuel mixture during the ignition delay period. Additionally, WPO had a higher heating value. Because of the biggish ignition delay induced by the higher viscosity, precocious cetane number, and elevated heat release during combustion of pure plastic oil, the peak cylinder pressure for a mixture of WPO and diesel fuel is raised, and this rise continues to occur when the quantity of WPO in the diesel fuel is increased. On account of the existence of vapour content inside the combustion chamber and the quick combustion rate (emulsions), the researcher [94] also demonstrated a rise in peak cylinder pressure for WPO and its mixes. This was caused by the combination of the two factors. Instead of only using WPO, using a combination of WPO and WPO, JME led to a reduction in the maximum cylinder pressure that could be achieved.

2.8.3. Engine emission characteristics

CO is created as a result of an incomplete combustion of hydrocarbons, a lack of oxygen, inadequate air entrainment, incorrect preparation of the mixture, and other factors [5]. Since Carbon Monoxide is a product of burned hydrocarbons, it must be controlled [87]. Raising the temperature of the combustion chamber (to 1200 °C for CO_2 oxidation) may lower CO emission because of the propensity for more complete combustion [7]. According to studies [85], WPO fuel emits higher carbon monoxide than diesel. The increased CO in WPO, according to the study, is caused by the low cylinder temperature [95]. Additionally, the researcher [93] discovered that using WPO and diesel mixtures produced greater CO emissions than diesel.

CO_2 ranks as the second most prevalent exhaust gas following nitrogen., accounting for 13% of total exhaust gas [58].WPO emits lower CO_2 emissions than diesel fuel does. By absorbing heat, CO_2 decreases the peak combustion temperature due to its intrinsic higher heat capacity. According to research [94], WPO emits less CO_2 than diesel because of combustion instability and a lack of oxygen. Incomplete combustion was also facilitated by higher viscosity. The reduction in CO_2 emission that results from increasing WPO levels in WPO-diesel blends may be caused by incomplete CO oxidation brought on by delayed fuel combustion [86]. Using an EGR system with WPO alone can lead to unstable combustion and reduced oxygen availability within the engine cylinders.. Due to the improved combustion that occurs when diesel fuel is used, researchers [95] have shown that utilising a combination of

WPO and diesel results in lower levels of carbon dioxide emissions than using commercial diesel fuel in its purest form.

The particulate matter present in exhaust gas and suspended as solid soot particles is commonly known as smoke [83]. Because the engine cylinders don't have a homogeneous charge, the combustion process burns more rapidly, and the flame spreads further WPO and WPO and diesel mixtures produce more smoke [98]. Additionally, the researcher [96] found that biodiesel and biodiesel plus WPO mixes produced more opaque smoke. Weak volatility and increased viscosity, which led to the mixing of gas droplets with air, were blamed as the reason. Additionally, heavier WPO molecules are mentioned by the author [94]. Smoke emission increases when the WPO percentage in WPO and diesel mixes increases as a result of WPO's increased viscosity and low volatility, which have an influence on spray characteristics, mixture formation, and combustion efficiency. Similar justifications for the increase in smoke from WPO vs. diesel fuel were offered by the researcher [97]. When used in blends with diesel, WPO with a greater aromatic concentration could also emit more smoke. Researcher [98] attributed the waste plastic oil's higher smoke opacity as a pre-mixed inside the combustion chamber to the fuel's early evaporation as the cause.

The two substances that make up NO_x are nitric oxide (NO) and nitrogen dioxide (NO_2), which are produced when nitrogen is burned. NO_x generation is influenced by temperature, reaction residence time, oxygen content, and the air/fuel mixture ratio. The quantity of free oxygen atoms that may interact with nitrogen to form NO_x increases when combustion is adequate, which also boosts temperature [85]. Due to the low air-fuel ratio used by CI engines, NO_x emissions are higher. Although the thermal mechanism dominates NO_x production in diesel engines, NO_x is produced during combustion by three diverse mechanisms, namely thermal, quick, and fuel [96]. Numerous studies have shown that WPO has greater NO_x emissions than diesel fuel at all loads due to its ring structure [89]. WPO emits more NO_x than diesel because of the greater peak cylinder pressure and heat[87]. WPO emits more NO_x than diesel because of its greater nitrogen concentration, claims the researcher [90]. When it comes to measuring how efficiently a fuel-air combination burns, one of the most important factors to look at is the emissions of unburned hydrocarbons. These pollutants are a by-product of incomplete combustion, which causes them to be produced. Gaseous forms of organic substances known as hydrocarbons may be found in [87]. The petrol that has been trapped in cracks associated with combustion is the primary contributor to the presence of unburned hydrocarbons in exhaust gases [93]. A researcher found that WPO and diesel blends have higher UHC emissions than diesel alone due to incomplete combustion, un reacted hydrocarbons, WPO's higher aromatic content, and their high density, lower viscous nature, and higher cetane value, which causes an extended ignition delay [86]. Diesel fuel has less unburned hydrocarbon than WPO and diesel mixes. WPO has unsaturated hydrocarbons that do not break down during combustion [90], a greater fumigation rate [107], and fuel leakage through injector nozzles owing to the less viscous diesel and WPO blend [99] fuel.

2.9. Research gaps

As a result of a review of the relevant literature, it was determined that very little experimental research was carried out on investigating the characteristics of an engine employing oil derived from waste plastic materials in WPO in a DI engine. The following topics have received inadequate attention and are potential areas of research.

- Numerous researchers have worked on biodiesel, but only a few have experimented with diesel and waste plastic oil blends as an alternative fuel and cost analysis.
- Locally accessible, unattended waste plastics should be located and examined for their potential to be converted into oil in order to broaden the scope of plant-based fuels and also to protect biological diversity.
- Therefore, in order to lessen our reliance on one specific form of WPO, we need to conduct an experiment with a blend of several types of WPO and do a cost analysis.

2.10. Research objectives

The proposed research work consists with the following objectives

- Energy analysis of a diesel engine fuelled with fuel obtained from waste plastics.
- Exergy analysis of a diesel engine fuelled with fuel obtained from waste plastics.
- Economic analysis of a diesel engine fuelled with fuel obtained from waste plastics.

CHAPTER 3

FUEL PREPARATION AND CHARACTERISATION

In this chapter, plastic trash, catalysts used in the study, and the diesel-WPO mixture are characterised. The raw material gathering process and the experiments that were conducted are explained in the subsequent section. A broad description of pyrolysis experiments is given in this chapter. Also included are the technical details of the waste plastic oil. ASTM D975 and EN 590 standards are preferred for WPO conversion.

3.1. Production of waste plastic oil

The liquid fuel that results from conventional pyrolysis techniques may be polluted with by-products and is temperature sensitive. The pyrolysis process often leads to an uneven distribution of products due to its low selectivity. Furthermore, conductivity in temperature-dependent processes without catalysts is difficult because of crossed-chain hydrocarbon structures of polyolefin-based polymers, including HDPE, LDPE, and PP. To ensure the financial sustainability of pyrolysis facilities, it is essential to use a catalyst to create products. Research on the use of catalysts to enhance product distribution, along with selectivity, has gathered over the last 20 years. There are many different catalysts, domestic and commercial activated carbon, modified natural zeolite (NZ) catalyst, two-stage catalysis using mesoporous catalyst, potassium hydroxide, sodium hydroxide, zeolite (ZSM-5), nitric acid, sodium hydroxide, zeolite (HZSM-5), zinc oxide, magnesium oxide, and zinc oxide. These catalysts are used to greatly reduce energy expenditures by accelerating reaction times, lowering process temperatures, and increasing product dispersion. Compared to thermal degradation, catalytic pyrolysis offers a substantial benefit due to its exceptional selectivity, which resembles isomerization. Catalytic reactions may be loosely divided into homogeneous and heterogeneous groups. A homogeneous catalyst only exists in one phase, whereas a heterogeneous solid catalyst is recommended.

According to what has been discussed so far, the catalyst utilised is a more important variable. Plastic water bottles, one-use juice cups, plates shopping bags and other items made of PE, PP, PS, and PET were gathered locally and used as feedstock in the catalytic pyrolysis process. The reason these polymers were selected is because they make up most of the plastic waste. To guarantee a uniform mix, all the waste samples were pulverised before being pyrolyzed.

In a batch reactor, waste plastic oil was created. Fig. 3.2 flaunts the WPO pyrolysis waste in oil. Fig.3.3 Hydrotreatment process of waste plastics-to-waste plastics oil**.** The concentrations of free fatty acids (FFA) in waste plastic oil are to be less than one. In this experimental test, waste plastics are sent into the melter, wherein solid waste plastic is converted into liquid fuel; this liquid fuel is sent to the pyrolysis reactor through extrusion. The main purpose of the extrusion is to feed molten fuel at the same time it eliminating hydrocarbons. Further reaction takes place in the pyrolysis reactor, moving on to the catalytic reactor, then to the condenser, and finally to the fractionating to wear. We conducted all the experiments at Hydroxy Power Plant, at Hydroxy Power Plant, Hydroxy Power Plant, RC Puram, Hyderabad.

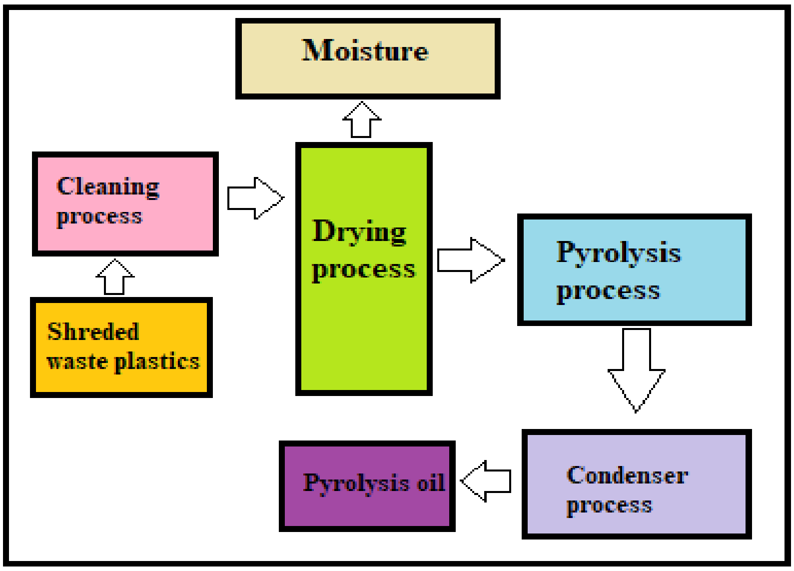


Fig.3.1.Conversion of waste plastic oil pyrolysis oil

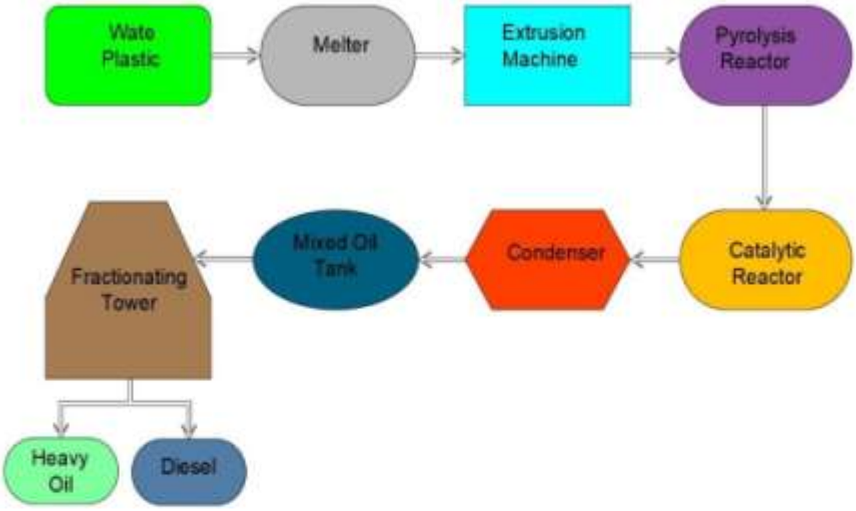


Fig.3.2.Pyrolysis process of waste to oil

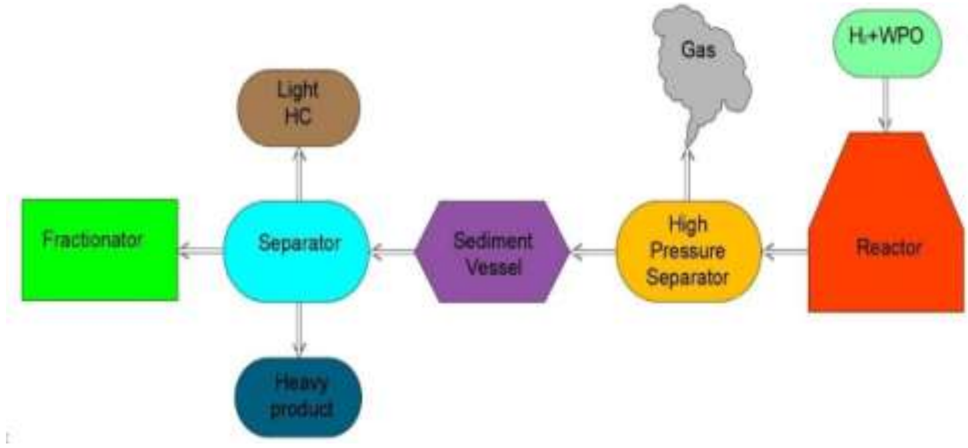


Fig.3.3.Hydro treatment process for waste-to-waste plastics oil

3.2. Blending of waste plastic oil and diesel

To obtain WPO, measured amounts of diesel and WPO were combined (by volume) in a glass container for five minutes. By adjusting the ratios of WPO/diesel, the same process is utilised to make WPO. Two different WPO blends are created, WPO20D80 and contain 20% waste plastic oil blended with 80% diesel. WPO40D60 is the designation for the second blend, which contains 60% diesel and 40% waste plastic oil. Table 3.1 describes the properties of waste plastic oil [85].

Table 3.1. Properties of waste plastic oil and blends.

Properties	**Diesel**	**WPO**	**WP10D90**	**WP20D80**	Standard
Density; kg/m^3	838	850	839.24	840.48	D4052
Flash point; °C	53	42	51.81	50.72	D93
Fire point; °C	57	45	55.8	54.6	D92
Calorific value; MJ/kg	46.5	39-44.3	46.3	46.07	D5865
Viscosity; cSt @ 40°C	3.0	3.4	3.04	3.07	D445

3.3. Gas Chromatography Analysis

It is a technique used to identify the individual compound in a mixture of compounds; this technique is applicable even for gases and liquids too. In this process, specific mixtures are segregated. Gas chromatography is conducted under similar conditions**.** The results show that the molecular weight of waste plastic oil is 176.52 g/mol, whereas for diesel it is228.67 g/mol, and the distribution of chemical compounds of C_6-C_{26} with a molar ratio of 1.67 [95].

3.4. Comparison of Diesel and WPO Properties

Waste plastic oil, which is made by pyrolyzing plastic waste, has qualities comparable to those of diesel. It has a high calorific value (about 40-46 MJ/kg), a density of 0.81-0.85 g/cm^3, a kinematic viscosity of 1.6-2.5 cSt, and a flash point that is usually between 50 to 60 °C. The cetane number is usually between 40-60. However, depending on the type of plastic and the pyrolysis process, it may need to be further refined [12].

CHAPTER 4

EXPERIMENTATION AND METHODOLOGY OF PRESENT WORK

Due to the fact that it offers data that is essential for the investigation, the equipment plays a key part in the investigation that is being conducted. Before beginning an experimental research endeavour for the first time, it is essential to get all of the relevant knowledge on the apparatuses that are required for the experimentation, as well as particulars regarding their working principles, uncertainties, accuracy, and range of the experimental test engine range, etc. Acquiring this expertise entails being familiar with the many instruments that will be put to use in the experiment.

4.1. Preparatory Work for Investigation

As a direct consequence of these findings, preparatory actions were taken before the inspection even began:

- For this investigation, a diesel engine that had a naturally aspirated, four-stroke, direct injection, water-cooled, single-cylinder, 3.5 kW of output, and 1500 rpm was used.
- An experimental setup was enhanced to assess the adaptation of the engine under a different load, with or without modifications to the engine and fuel.
- The cylinder head is housed with a piezoelectric pressure transducer to valuable the pressure within the combustion cylinder. The pressure sensor and the charge amplifier are both connected with a temperature-resistant, strong, integrated Viton connection.

4.2. Experimental Setup and Test Procedure

In this research, various test procedures are conducted, such as engine performance, exhaust gas temperatures, and emission measurements. The equipment that was utilized in this experiment was assembled and placed as shown in Fig. 4.1. Technical information of the engine is provided in Table 4.1. Engine with four strokes, direct injection, water cooling, and a single cylinder, which is functioning at its maximum injection pressure of more than 230 bar. As a result, the engine is producing its maximum power of 3.5 kW while also operating under its maximum load. Each test was run using the test engine in its basic setup, without any modifications. The test vehicle's engine can satisfy the standards of the Euro 4 emission standard. The test engine employed a pilot injection methodology aimed at minimizing the generation of unwanted noise because of the combustion. When diesel engines utilize indirect injection, this is a standard strategy they use. 24^o before top dead centre, this engine's pilot fuel injection started (TDC). Very near TDC, the pilot injection should occur concurrently alongside the first peak combustion pressure. The combustion pressure signal's subsequent hump, which indicates the major injection, can be observed. The full-load curve served as a test for establishing the precision with which the engine had been set up, which was the objective of this investigation.

To clearly see how the various fuel mixes under test affect the engine operating characteristics, it is essential to operate the engine at maximum load. This explains why this is the case; engines use the most fuel while operating at full load, which is when they are producing their highest output. The engine is maintained at a constant speed of 1500 rpm. Using an eddy current dynamometer, the engine torque and brake power were measured while it was working at full load. At this point in time, a gas analyser was equipped to monitor the waste gas concentrations that were being expelled into the atmosphere. A smoke metre was used to record not just the reports from the gas analysers but also the smoke-gaseous emissions that were unleashed by the engine.

Fig.4.1. Pictorial setup of experiment

4.3. Exhaust Gas Measurements

Exhaust flue gas emissions were tested for concentrations of CO_2, CO, NO, HC, O_2, and lastly NOx using aTesto-350 emission monitoring analyser. A central processing unit, a condensate trap, a condensate pump, a cable, a gas pump, a prime gas pump, a feed pump, a battery, six different sensors, a module, a probe handle, and an air supply cooling system are all included with the Testo-350. Several infrared (IR) sensors were employed for the measurement of CO_2, CO, O_2, and HC. In contrast, a photochemical sensor was used to determine NO levels.

Table 4.1.Engine technical specifications

Model	TV-1
Engine Type	Single cylinder, four stroke, naturally aspirated
Injection type	direct
Brake power, kW	3.5 kW
Rated speed, rpm	1500

Cooling system	Water
Displacement volume, cm^3	662
Stroke, mm	110
Bore, mm	87.5
Injection nozzle hole	3 holes
Injector nozzle hole diameter, mm	0.25
Nozzle opening pressure, bar	200
Injection timing,	23.0
Compression ratio	15.5:1-19.5:1

4.3.1. CO and CO_2 Measurements

The infrared gas analyser is used to determine the exact percentages of each gas emitted by the motor. It is a dual-head instrument, with two separate inspection heads controlled by a single body. This allows for simultaneous carbon monoxide and carbon dioxide detection. All gases in the sample absorb infrared light at a certain frequency. The IR identifier can measure the volumetric grouping of the CO or CO_2 in the sample by shining an infrared beam through the cell (which contains CO or CO_2) and measuring the amount of infrared absorbed by the sample at the fundamental wavelength. This helps establish whether CO_2 or CO is present. The IR method for measuring the CO/CO_2 is represented in Fig. 4.2.

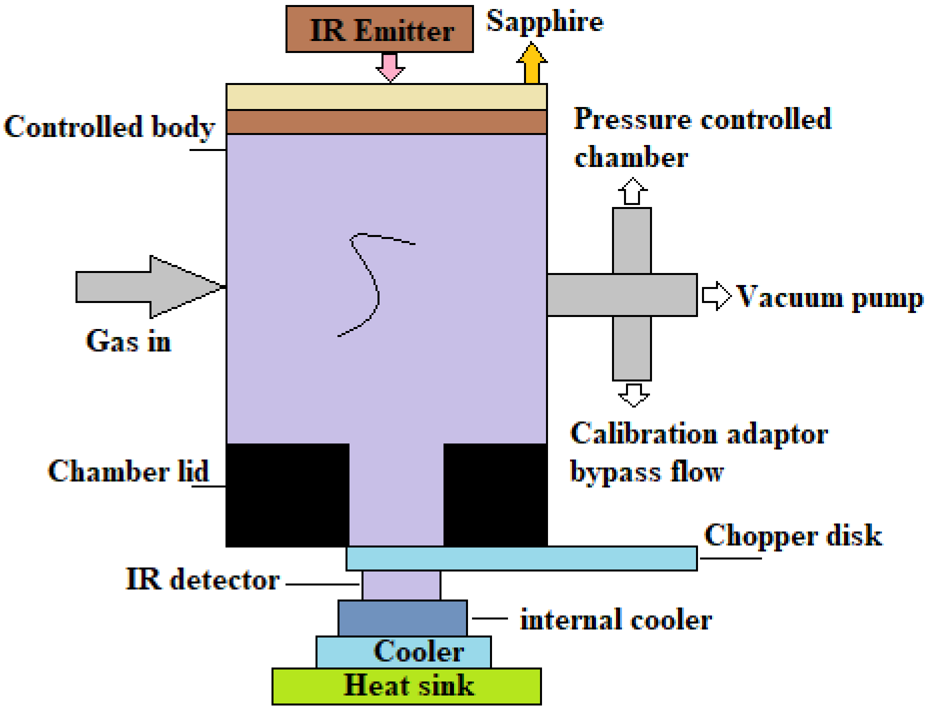


Fig.4.2. CO/CO_2 measuring principle

4.3.2. HC Measurement

Dilution factor dependent techniques are used to quantify HC concentrations. By burning the sample, ions will be generated as a by-product of the hydrocarbons. Pellistor gas sensors (catalytic bead gas sensors), have dominated the market ever since their introduction in the 1960s. These sensors are widely regarded as the most accurate technique to identify potentially hazardous chemicals. There has been research conducted on the subject by detecting touchy gases and unsettled organic chemicals; however, a significant number of chances for mistakes in this process. Pellistor makes use of Wheatstone bridge circuits, which are characterised by two "beads" that each encapsulate a platinum coil inside their interior. A Pellistor has a total of four platinum coils inside it. The "active" bead is identified by a process of random selection, and the catalyst is then administered to that specific bead. Because of this, the temperature at which the gas in the surrounding area may ignite is reduced. Combustion generates a lot of heat; hence, the temperature of this activity is different from that of the other "reference" bead. This difference in resistance allows us to roughly estimate the concentration of the gas in question as a fraction of its lower explosive limit. The current diesel concentration is directly proportional to this. Before entering the housing for the flameproof sensor, the gas must first pass through a sintered metal flame arrestor, which is sometimes referred to as a sinter. This container serves as a home for the electrical components as well as the heated bead. Fig. 4.3 illustrates the Pellistor's working principle for HC measurement. The sensor housing is kept at a constant temperature to allow for controlled combustion to take place within. If the concentration of gases in the active bead is high enough to prevent complete combustion from taking place, then a layer of soot may accumulate on the surface of the active bead. There will inevitably be a drop in efficiency because of this. When the percentage below the lower explosive limit is more than 70%, there should be areason for alarm.

4.3.3. NOx Measurement

The electrochemical NO estimate standard is used to determine whether discharges from ignition sources (heaters, turbines, and engines) are genuine and unrelated. This is done so that an exact NO value can be determined. In proportion to the attention paid to NOx, NO, NO_2, and total emissions are monitored. For the most part, this is correct. Electrochemical sensors are used to detect the presence of a gas by emitting an electrical signal proportional to its concentration in the air. It has been shown that this approach works. A small amount of electrolyte separates the sensing anode and the counter electrode. Measurement of NOx is based on an electrochemical concept, which is shown in Fig. 4.4.

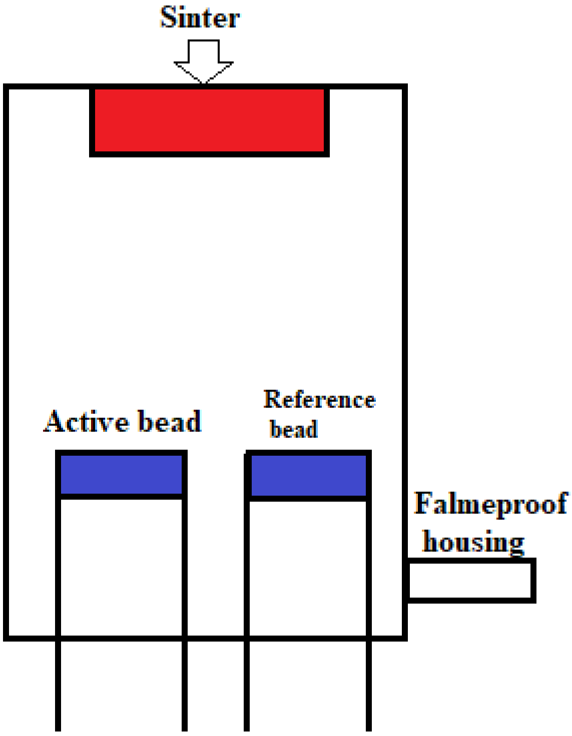


Fig.4.3. HC measurement principles

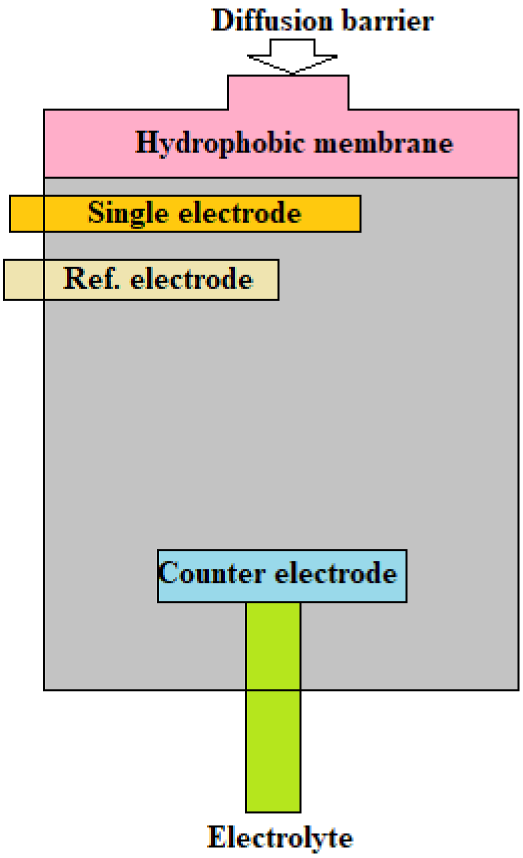


Fig.4.4 NO measurement principle

Fume gas may reach the anode via an opening in the anode, bypassing the hydrophobic barrier that normally surrounds it. Using these steps may prevent electrolyte from leaking out of the sensor. If the gas diffuses past the obstacle, a device that measures oxidation or reduction can record a reading at a location that is not the detecting terminal. This hypothesis provisions the assumption put out by Curiosity's ideal gas that the reactions are triggered by the terminal elements. When a resistor is placed in series with both the anode and the cathode, a constant gas flow is ensured. It is widely believed that electric current is the most important component in influencing the gas-fixation process. Since flow is always being generated, the electrochemical sensor is often modelled after an aerometric gas sensor or a miniature power module. Both models accurately reflect the reality that flow is always being created. Fume gas may reach the anode via an opening in the anode, bypassing the hydrophobic barrier that normally surrounds it. Using these steps may prevent electrolytes from leaking out of the device. If the gas diffuses past the obstacle, the device that is monitoring oxidation or reduction can produce a reading that is outside of the detection range. This hypothesis provisions the assumption put out by Curiosity's ideal gas that the reactions are triggered by the terminal elements. When a resistor is placed in series with both the anode and the cathode, a constant gas flow is ensured. It is widely believed that electric current is the most important component in influencing the gas-fixation process. Since flow is always being generated, the electrochemical sensor is often modelled after an aerometric gas sensor or a miniature power module. The pressure transducer's technological merits are summarised in Table 4.2.

Table 4.2. Pressure transducer specification

Type	**Specification**
Cooling	Air
Transducer	Piezoelectric
Range	0-100 bar
Make	Kistler
Sensitivity (±0.5%)	25 mV/bar
Calibration at 200 °C	0-100 bar
Linearity (% FSC)	≤ ± 1.0
Frequency range	0.016-20,000 Hz
Operating temperature range (Viton cable connection)	200.0 °C
Shock	2000.0g

4.3.4. Smoke Measurement

When calculating smoke output, we factor in the results of using injected fuel. It is hypothesised that the generation of soot particles involves the processes of elevated thermal polymerization, the dehydrogenation process within the liquid-vapor core of dispersed beads, ruinous chain alterations of fuel drop alongside the expansion of fuel bead facade towards the flame front are subjects of experimental investigation. All the processes take place at high temperatures. Both mechanisms are pivotal in the birth of soot particles. An analogous method to the combustion of soot particles and the decrease in volume concentration due to progress is presented. During the light termination testing method, the percentage of a light bar's force humiliated by smoke is referred to as the power of the smoke. The procedure for measuring smoke and the analyser used to do so are shown in Fig. 4.5displays the AVL 444 exhaust gas analyser’s specifications and principle as shown in Fig.4.6.Table 4.3 displays the circumstantial technical features of the AVL smoke metre, while a Testo-350 flue gas analyser was cannibalized to ascertain NO_x, HC, and CO.

Fig.4.5. Smoke meter.

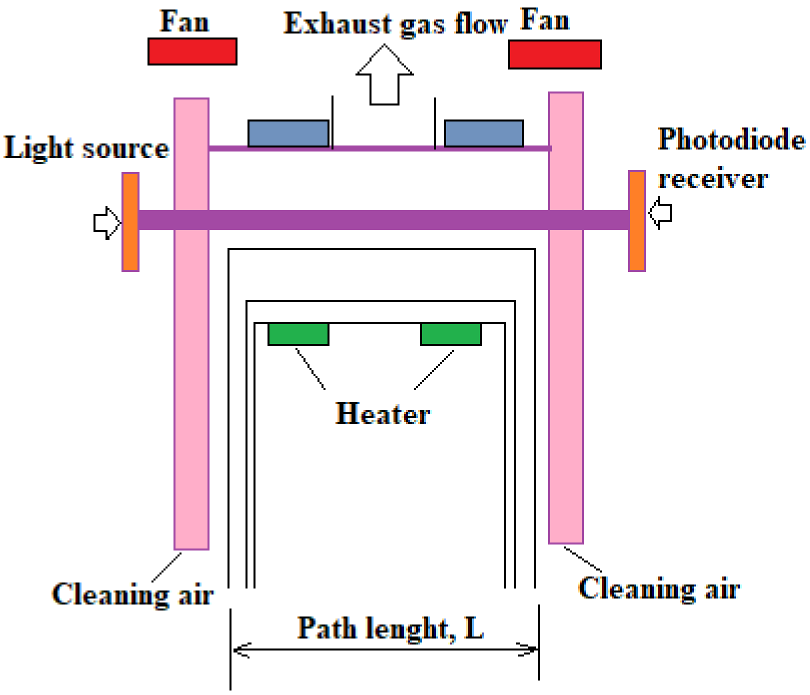


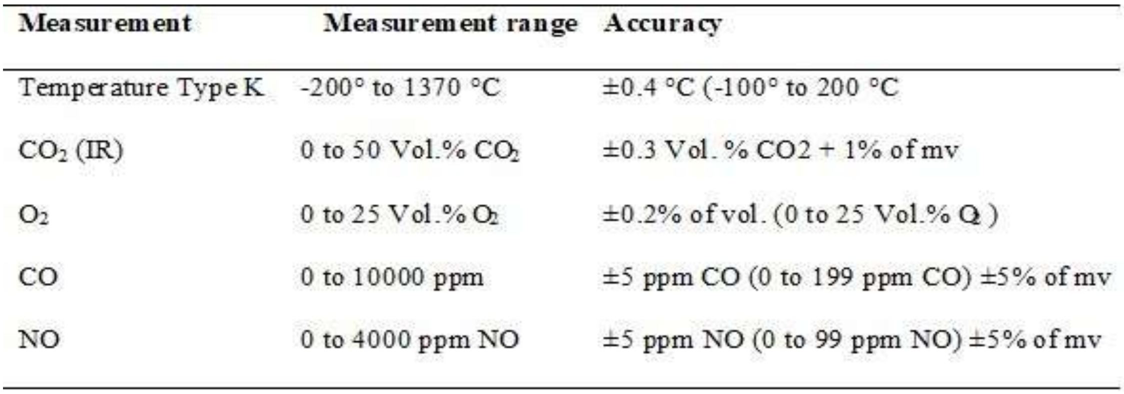
Fig.4.6. Smoke measurement principle

Table 4.3. Smoke meter specification

Instrument model	Smoke meter
Measuring rang, % opacity	0-100
Weight, kg	24
Resolution, %	0.1
Accuracy and repeatability, %	±1
Application	For free acceleration test only
Smoke inlet	Through a control valve
Linearity check, %	48.4 – 53.1
Smoke temperature at entrance, ^{0}C	250
Sensor	Selenium photocell
Light source, V	12

Ambient temperature, ^{0}C	0-50
Power supply, V-AC	190-240

Table 4.4. Technical data of gas analyser



Measurement	Measurement range	Accuracy
Temperature Type K	-200° to 1370 °C	±0.4 °C (-100° to 200 °C
CO_2 (IR)	0 to 50 Vol.% CO_2	±0.3 Vol. % CO2 + 1% of mv
O_2	0 to 25 Vol.% O_2	±0.2% of vol. (0 to 25 Vol.% O_2)
CO	0 to 10000 ppm	±5 ppm CO (0 to 199 ppm CO) ±5% of mv
NO	0 to 4000 ppm NO	±5 ppm NO (0 to 99 ppm NO) ±5% of mv

4.4. Combustion Parameters

One technique to determine how combustion chamber behaviour affects diesel engine characteristics is to analyse the pressure in the combustion chamber, since this behaviour may be directly controlled by the pressure in the chamber. Analysis of combustion chamber cylinder characteristics such as cylinder pressure, heat unleashed, ignition holdup, maximum pressure rise, efficiency, and so on, as seen via a Kistler pressure transducer.

4.4.1. Pressure Transducer

Exact measurements of the pressure generated by combustion may be obtained by mounting a quartz piezoelectric pressure transducer (DIN M121, IP67 with 8 sensors pole male) developed by Kistler to the top of the cylinder head. The sensor and charging amplifier are connected with high-temperature, resilient Viton wire. The electric charge produced by a piezoelectric sensor may be translated to voltages and utilised with customary testing and monitoring equipment. The output range of the charge amplifier is between 0-100 bar (40mV/bar), and it has a time constant of 5 ms. Depending on the source, it can run on voltages of 7 to 32 volts DC. The pressure transducer body has fins that assist in dispersing heat and maintaining the device's performance. Various parts of a pressure transducer measurement system are shown in Fig. 4.7. The particular details for the Kistler piezo quartz pressure sensor are shown in Table 4.5.

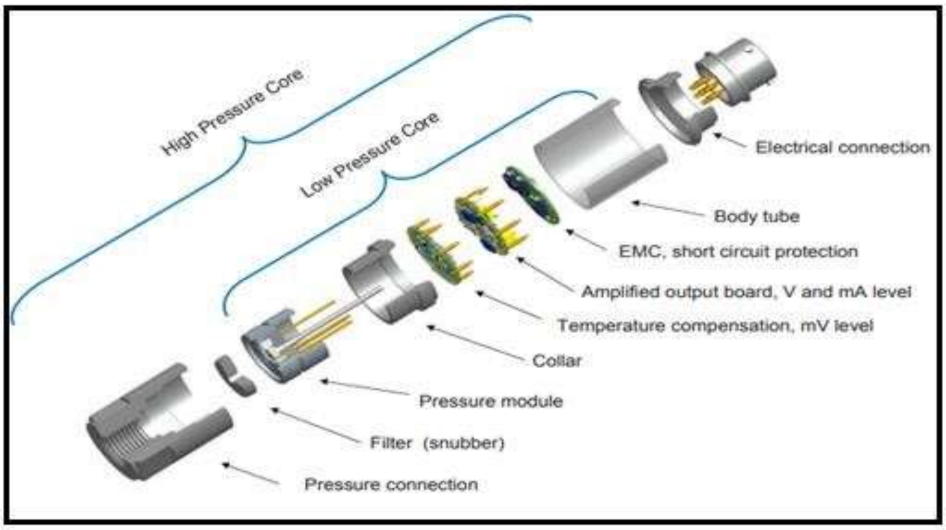


Fig.4.7.Pressure transducer

Table 4.5.Pressure sensor specification

Make and Model	**Kistler and 5395A**
Type	Piezoelectric
Material	Quartz
Pressure range, bar	0-100
Cooling	Air cooled
Operating temperature range, ^{0}C	50-350
Sensitivity, mV/bar	25
Supply voltage, V DC	7-32
Output impedance, Ω	100

4.4.2. Crank Angle Encoder

A 360-degree crank angle encoder is installed as far from the crankshaft as feasible to get the most precise reading possible. Torsional research on internal combustion engines is now possible thanks to an optical pickup device with a pulse count of 360 pulses per rotation (ICs). Data Acquisition Systems (DAS) are used to collect, analyse, and present sensor data. Through the different yield connections of the sensors, the board of control is tasked to DAS supplied with the unique link contribution. The DAS also has converters that take its raw material and turn it into digitally usable information. Using the information card helps to streamline and categorise the data. On a PC, in-house software analyses combustion chamber, start delay, heat release rate, mass division, and expected burning end. The average value of the variances between cycles is calculated by collecting data from the combustion chamber for 20 cycles in a row.

4.5. Mathematical Modelling

4.5.1. Brake Thermal Efficiency

The brake thermal efficiency (BTE) measures the engine competency in fuel energy metamorphosis into braking power. The effectiveness of the heat conversion into work will be measured by the BTE. The BTE is totally reliant on the engine construction, fuel, and use. Brake thermal efficiency (BTE) of a diesel engineis calculated using the following formula, with HV (heating value) in kJ/kg, fuel flow in kg/s, and braking power (kW).

$$BTE = \frac{BP}{\dot{m}_f \times HV} \times 100\% \tag{4.1}$$

4.5.2. Brake Power

The word "brake power" refers to the engine's actual, obtained power output, as WPO to the power required for things like fuelling, lubricating, heating, cooling, and operating after treatment equipment. BP is brake power (kW), T is torque (N-m), W_b is brake load (N), and R is dynamometer arm length (m), this formula is used to calculate the braking power of a diesel engine.

$$BP = T \times \omega = \frac{2\pi N W_b R}{60 \times 1000} \tag{4.2}$$

4.5.3. Mass Flow Rate of Intake Air

Mass Flow Rate is the volume of air flowing over a given period. The formula applied to adjudge flow rate of air intake is given below: C_d is the discharge coefficient of the orifice, A is its area, ρ_a is air density, and ΔP is its pressure difference.

$$\dot{m}_a = C_d A \sqrt{2\rho_a \Delta P} \tag{4.3}$$

4.5.4. Mass Flow Rate of Fuel

The fuel mass flow rate is measured in terms of mass per second. The mass flow rate of fuel is related to the total air flow rate of the engine by the fuel-to-air ratio. The formula for determining the mass flow rate of fuel is as follows: V_f and f may also be used to represent fuel density and volume, respectively.

$$\dot{m}_f = m_f = V_f \times \rho_f t_t \times 1000 \tag{4.4}$$

4.5.5. Brake Specific Fuel Consumption

Any internal combustion engine (ICE) that converts fuel into rotary or shaft power may have its Fuel efficiency, quantified as brake-specific fuel consumption (BSFC), assessed experimentally. Efficiency comparisons of internal combustion engines with shaft outputs are a common use of this metric. It's calculated by dividing fuel usage by output power. Below is the diesel engine's brake-specific fuel consumption (BSFC) formula.

$$\mathrm{BSFC} = \frac{\dot{\mathrm{m}}_{\mathrm{f}} \times 3600}{\mathrm{BP}}\ \mathrm{kg/kWh} \tag{4.5}$$

4.6. Uncertainty Analysis

Measurements of pressure, temperature, and engine speed, as well as measurements of BP, EGT, and BTE, are utilised as the foundation for mercurial analysis. Flow rates of biofuel and diesel is investigated by conducting three sets of experiments at chock-full load alongside 1500 rpm. The uncertainty is evaluated using the standard deviation and calculated using the mean from Ref. [57]. The average dispersion of the explanatory factors is 1.25%, whereas the average dispersion of the dependent variables is 2.12%. The exhaust gas analyser showed a paramount variation of 0.5% (NOx) and a minute deviation of 0.3% when subjected to a comparable measurement (CO). Table 4.6 lists the observable faults in the instruments under inspection.

$$\text{Uncertainty }\%\left(V_{\mathrm{R}}\right) = \sqrt{\left(\frac{\partial R}{\partial x_1} v_1\right)^2 + \left(\frac{\partial R}{\partial x_2} v_2\right)^2 + \left(\frac{\partial R}{\partial x_3} v_3\right)^2 + \ldots\ldots\ldots\ldots\left(\frac{\partial R}{\partial x_n} v_n\right)^2}$$

Table 4.6. Uncertainty of instruments

Name of instrument	Value of uncertainty
Encoder	±0.2%
CO	±0.3%
CO_2	±1.0%
Fuel sensor	±0.5%

HC	±0.1%
Load	±0.2%
NOx	±0.5%
O_2	±0.3%
Pressure	±0.5%
Speed	±1.0%
Smoke meter	±1.0%
Temperature	±0.15%

4.7. Economic Analysis

Most design decisions are based on economic factors. An economic system may demonstrate a sufficient return on investment. We would surely need to spend significantly on research and development efforts to design and create a highly dependable component or unit, and this would be reflected in large part in the overall cost. Like this, manufacturing facilities must be sufficiently advanced to permit the creation of precision components, which means that as dependability requirements rise, so do production costs. On the other side, a higher dependability factor would result in lower maintenance and replacement parts costs. Based on comparing lifetime cost, several techniques for economic analysis have been created, including:

- Annual cost method(ACM)
- Present worth method(PWM)
- Capitalized cost method(CCM)

Total yearly costs using the annual cost technique typically include capital expenditures, fuel expenses, and maintenance and operating costs. The best design has the lowest yearly cost. When yearly expenditures are added up to lifetime costs, the present worth technique may be thought of as an index method of comparison. The main difference between the capitalized cost technique and PWM is that, in order to account for lifetime fuel and O&M expenses, a hypothetical sum of money must be added directly to the capital cost.

4.7.1. Life Cycle Cost Assessment

It alludes to the whole cost from fuel generation to distribution. There are four stages that are considered when estimating the cost of WPO. The calculations are administered in Table 4.7, Table 4.8 and Table 4.9.

- Waste Plastics collection (from household and municipal waste plastic)
- Pre-treatment of Waste Plastics by using a Shredder.
- Pyrolysis and Hydro treatment process.
- Fuel delivery to the market.

Table 4.7. Cost Analysis for producing waste plastic oil

Sl. No.	Item	Cost in Rupees	Overall Cost	Expenditure/ Profit
1	Waste plastic collection. Considering the waste plastics from household and municipal waste plastic	25₹/kg	2500₹	Expenditure
2	For one tonne of WP	1000 x 25 = 25000₹/ton	25000 ₹	Expenditure
3	For transporting from local shop to Hydroxy power plant:	2000₹/ton	2000₹	Expenditure
4	For cleaning and segregating (Labour cost)	700₹/labour 20X700₹ = 14,000₹	14,000 ₹	Expenditure
5	Electricity consumed for running a5HP motor. Running cost. It takes 5 hrs/ton of waste plastic =746x5x5/1000 = of Shredder18.65units Bill of electricity=18.65x7.65 = 142.67₹		142.67 ₹	Expenditure
6	Running cost 1unit cost = 7.65₹ of the for 30 units/hr, Pyrolysis and Hydro treatment		(30x7.65= 229.5₹ 16hr = 16x229.5 =3762₹)	Expenditure
7	Overall Cost of electricity (Cost required for 1 ton of waste plastic based on time) It will take 16 hours for complete conversion of waste plastic to oil.		3762₹	Expenditure
8	Chemical cost for one litter of waste plastic oil, Natural Zeolite is used as a catalyst.100 kg of Zeolite is required for 1 ton of waste plastics. 1 kg of Zeolite=Rs.6.5/-100 kg of Zeolite = Rs.650/-		650₹	Expenditure

9	After experiment, left out mud is sold to farmers for agricultural purpose7₹/kg (150 kg/ton of waste mud is produced that is useful for agriculture purpose)	1050₹	Profit

Total Expenditure: 48054.67₹,

Profit on selling mud to farmers: 1050₹

Total Expenditure = Total invested amount-profit = 48054.67-1050

=47,004.67₹

Table 4.8.Comparative cost analysis for pure diesel and waste plastic oil

Sl. No	Waste plastic oil	Diesel
1.	For producing 45-55% of Waste plastic oil: 47,004.67₹ (for 450-550 litres)	For Diesel:109.66/litre
2.	For 450 litres of WPO 47,004.67₹	For 450 litres of Diesel: 109.66 x 450 = 49,347₹

Total cost 450 litres of diesel:49,347₹

Total cost for 450liters of WPO: 47,004.67₹

Formula for calculating Profit:

Profit=Revenue-Cost=2342.33₹

The formula for calculating the overall cost

Overall cost=∑Shredder+∑Cutting plant+∑Pyrolysis &hydrotreatment experiment setup

Cost of Shredder: 43500₹ (capacity of 500kg/hr)

Cost of cutting plant: 500000₹

Cost of pyrolysis and hydrotreatment experiment setup: 1050000₹

Overall cost =43500+500000+1050000=1593500₹

Table 4.9. Cost analysis of Shredder and pyrolysis and hydro treatment experiment setup

S No.	Type of Equipment	Capacity	Cost in Rupees
1.	Shredder	300kg/hr	34,600₹
2.	Shredder	500kg/hr	43,500₹
3.	Shredder	700kg/hr	53,200₹

4.	Pyrolysis Experiment setup	300kg/hr	820000₹
5.	Pyrolysis Experiment setup	500kg/hr	1050000₹
6.	Pyrolysis Experiment setup	700kg/hr	1783440₹

4.7.2. Capital Investment

Before an industrial facility can start running, it must buy and install a lot of expensive tools, services, and machinery. Land and service facilities must be bought, and the whole plant, including all pipes and instruments, must be built from scratch. Also, money is needed to cover the costs of running the plant. Overall capital investment is the total amount of money that has to be spent on building and running the place. The amount of money needed for the fixed capital investment refers to the sum required for the acquisition of equipment and the establishment of manufacturing and plant facilities. Investment in fixed capital can be broken down into.

4.7.2.1. Direct Cost

In addition to equipment costs, the cost that is directly applied to building a plant is referred to as a direct cost. Table 4.10 shows the direct cost of the plastic pyrolysis facility. The capacity of the Shredder and capacity of the Pyrolysis set is of 500 kg/hr.

Table 4.10.Direct cost of plastic pyrolysis plant

Sl. No.	Items	Range	%	Cost in Rupees
1	Building	15% of purchased equipment cost	15%	239025₹
2	Electricity	10-15% of bought equipment rate	10%	159350₹
3	Instrument and Control	6-30% of bought equipment rate	15%	239025₹
4	Insulation cost	8-9% of bought equipment rate	8%	127480₹
5	Installation	25-55% of bought equipment rate	25%	25,00,000₹
6	Land	4-8% of bought equipment rate	4%	63740₹
7	Purchased equipment	---	100%	1593500₹
8	Piping	40-80% of bought equipment Rate	50%	796750₹
9	Service facility	30-80% of bought equipment Rate	40%	637400₹

10	Yard Improvement	10-20% of bought equipment rate	10%	159350₹
	Total	---	---	65,15,620₹

4.7.2.2. Indirect Cost

Other than the cost of the equipment, a cost that is indirectly employed in a plant's construction is known as an indirect cost. Table 4.11 shows the plastic pyrolysis plant's indirect costs.

Table 4.11.Indirect cost of plastic pyrolysis plant

Sl. No.	Items	Range	%	Cost
1	Engineering & Supervision	8% of total direct cost	8%	35311960₹
2	Contractor fee	2-8% of direct plant cost	3%	132419.8₹
3	Construction Expenses	10% of Total direct plant cost	10%	441399₹
4	Contingences	Direct plant cost	8%	35311960₹
	Total	----	---	71197738.8₹

4.7.2.3. Variable Cost

Variable costs include the price of raw materials, other expenses, and utilities needed in the development of a facility. Table 4.12 shows the variable cost of the plastic pyrolysis facility.

Table 4.12.Variable Cost of Plastic Pyrolysis Plant

Sl. No.	Items	Cost
1	Raw material	25000₹
2	Miscellaneous	1500₹
3	Utilities	800₹
	Variable Cost	**27300₹**

4.7.2.4. Gross profit

Gross profit is the amount of money a business makes after all the costs of making and selling its goods or services are taken out.

$$Gross\ profit = \frac{Selling\ products}{Services} - Manufacturing\ cost$$

- Total Production cost of 450 litres of Diesel: 49347₹/day
- Total production cost of 450 litres of WPO: 47,004.67₹/day
- Profit = 2342.33₹/day/ton of WPO
- If income per day is 2342.33₹ per year we have 365 days, on average of 1 ton of production per day=2342.33₹ (per day/ton of WPO) x 365days=854950.45₹

- Total Income = 854950.45₹/year

Gross Profit = 854950.45₹-47,004.67

= 807945.78₹/year

WPO =807945.78₹/year

$$Net\ profit = Gross\ profit - Taxes\ (with\ 30\%\ tax)$$

$$= \frac{807945.78₹}{year} - 242383.73$$

=565562.04₹

4.7.2.5. Rate of Return

Gross profit is the amount of money a business makes after all the costs of making and selling its goods or services are taken out.

$$Gross\ profit = \frac{Selling\ products}{Services} - Manufacturing\ cost$$

- Total Production cost of 450 litres of Diesel: 49347₹/day
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= 807945.78₹/year

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= 807945.78₹/year – 242383.73
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Gross profit is the amount of money a business makes after all the costs of making and selling its goods or services are taken out.

- Gross Profit=selling products/services-Manufacturing cost
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= 807945.78₹/year
WPO =807945.78₹/year

$$Net\ profit = Gross\ profit - Taxes\ (with\ 30\%\ tax)$$

= 807945.78₹/year – 242383.73
=565562.04₹

4.7.2.6. Rate of Return

$$Rate\ of\ return = \frac{(Net\ profit)}{(Total\ capital\ investment)} \times 100\%$$

$$Rate\ of\ return = \frac{(565562.04)}{(65{,}15{,}620)} \times 100\%$$

= 8.6%

4.7.2.7. Payback Period

$$Payback\ period = \frac{1}{(Rate\ of\ return\ )}$$

$$\frac{1}{(0.128)}$$

= 11.52

4.8. Exergy and energy analysis

Energy analysis calculates energy efficiency by assessing the conversion of kinetic energy into electric energy. In contrast, exergy analysis considers other factors such as pressure, temperature, and speed to determine exergy efficiency. Exergy analysis is typically performed to quantify the quantity of valuable work obtained during a given process. Exergy analysis offers a framework for assessing qualitative measurements. The first law of thermodynamics establishes the fundamental principle of energy.

4.8.1. Energy Calculations

Energy and exergy analysis play a vital role in engine design by aiding in the minimization of losses during energy utilization, utilizing data from energy and exergy balances. This analytical approach applies the fundamental principles of the first and second laws of thermodynamics to internal combustion engines. The engine is considered as a control volume operating under steady-state conditions, as illustrated in Figure 4.8.

To facilitate thermodynamic calculations, certain assumptions were necessary due to constraints in the engine setup. These assumptions include:

- The air-fuel mixture used for combustion and the resulting exhaust gases were assumed to behave as ideal gases.
- The energy input to the control volume was determined as the total energy generated by the fuel-air combination. Nevertheless, a portion of this energy is expelled as exhaust and additional losses occur.
- The consideration of kinetic and potential energy was disregarded.

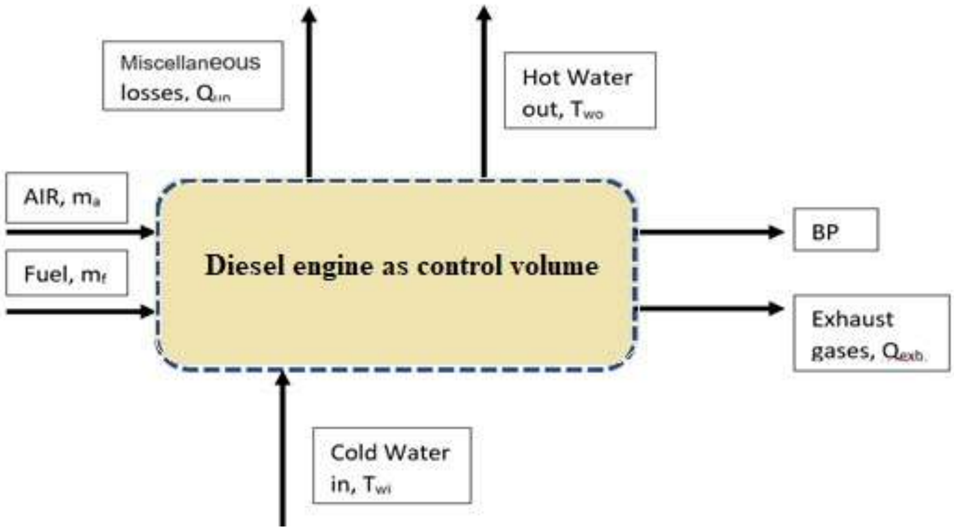


Fig.4.8. Control volume for energy–exergy analysis.

To conduct energy and exergy analysis, we utilized the chemical reaction described in Equation (4.8.1) to get data on the emission characteristics at the experimental setting.

$$aCHO_{xyz} + bO_2 + 3.76N_2 \longrightarrow cO_2 + dCO_2 + eCO + fNO_2 + gNO + hN_2 + jHO_2 \quad (4.8.1)$$

The current investigation involves doing an energy-exergy analysis to identify significant losses within the system, including water cooling losses (Q_w), exhaust gas losses (Q_{exh}) and other miscellaneous losses (Q_{un}). The analyses were conducted using the principles of the law of conservation of mass and energy, as depicted in Equations (4.8.2) and (4.8.3) respectively.

$$\sum m_{in} = \sum m_{out} \tag{4.8.2}$$

$$Q - W = \sum m_{out}\, h_{out} - \sum m_{in}\, h_{in} \tag{4.8.3}$$

Let (m_{in}) represent the mass flow rate at the intake and (m_{out}) represent the mass flow rate at the outlet . The symbol Q̇ represents the total heat input , while h represents the particular enthalpy. In accordance with the energy balancing theory, it is necessary to obtain the coolant input and outlet temperatures in order to determine the amount of heat lost from the engine to the cooling water and the heat carried by the exhaust gases. The water's flow rate was quantified utilizing a rotameter [115]. The net energy flow, (Q_{in}) was determined by calculating the power developed by the engine, BP, as well as the losses due to water cooling (Q_w), exhaust gas (Q_{exh}), and other miscellaneous factors ((Q_{un})). These calculations were performed accordingly.

$$Q_{in} = mCV_{in} \tag{4.8.4}$$

$$BP = \omega \times T \tag{4.8.5}$$

$$Q_w = m_w \times C_{pw} \times (T_{w2} - T_{w1}) \tag{4.8.6}$$

$$Q_{exh} = (m+m_a) \times C_{pg} \times (T_{exh} - T_{amb}) \tag{4.8.7}$$

$$Q_{un} = Q_{in} - (BP + Q_w + Q_{exh}) \tag{4.8.8}$$

Energy analysis relies on the principles of the second law of thermodynamics, along with mass conservation and energy conservation principles. Moving to the subsequent phase of the study, we commenced the exergy analysis of the internal combustion engine by formulating the exergy balance. The piston's thermal efficiency within the engine's control volume is quantified as the ratio of the work done (BP) generated at the output shaft to the input fuel energy (Qin), as expressed in Equation (4.8.9).

$$\eta_{th} = \frac{BP}{Q_{in}} \tag{4.8.9}$$

4.8.2. Exergy Calculations

The upper limit of the usable work that may be extracted from a process involving two thermal reservoirs is described by Equations (4.8.10) and (4.8.11), which represent the exergy balance for the chosen engine control volume.

$$Ex_{in} = Ex_{out} + Ex_{dest} \tag{4.8.10}$$

$$Ex_{air} + Ex_{fuel} = E(m_{out} \times \epsilon_{out}) + Ex_{heat} + Ex_{work} + Ex_{dest} \tag{4.8.11}$$

Ex_{air},E_{fuel} represent the exergy transfer rate for air intake and fuel, The termsEx_{heat},Ex_{work}andEx_{dest}. The exergy rate of heat transfer from the source to the control volume and subsequently to the environment, as well as the exergy rate developed by the shaft power, equivalent to the calculated brake power, and the exergy rate of destruction, which quantifies the exergy destroyed within the control volume, are influenced by factors such as friction and combustion [116]. These exergy terms were calculated using Equations (4.8.12)– (4.8.21).

$$Ex_{fuel} = m_f \times Q_{fuel} \text{x CV} \tag{4.8.12}$$

$$Ex_{air} = m_{air} \times m_{cp}\, air \times (T_{airi} - T_{amb}) - T_{amb} \ln\left(\frac{T_{airi}}{T_{amb}}\right) \tag{4.8.13}$$

$$Q_{fuel} = 1.0101 + 0.1728\left(\frac{H}{C}\right) + 0.0432\left(\frac{O}{C}\right) + 0.2169\left(\frac{S}{C}\right) \times \left(1 - 2.0628 - \frac{H}{C}\right) \tag{4.8.14}$$

$$Ex_{heat} = \sum\left(1 - \frac{T_{amb}}{T_{c\omega}}\right) \times Q_{loss} \tag{4.8.15}$$

$$Ex_{work} = BP \tag{4.8.16}$$

$$Ex_{out} = \sum m_i(\epsilon_{tm} + \epsilon_{chem}) \tag{4.8.17}$$

$$Ex_{work} = BP \tag{4.8.18}$$

$$\epsilon_{tm} = (h - h_0) - T_{amb}\,(S - S_0) \tag{4.8.19}$$

$$\epsilon_{chem} = RT_{amb}\, ln\left(\frac{y_i}{y_r}\right) \tag{4.8.20}$$

$$\eta_{ex} = \frac{Ex_{work}}{Ex_{in}} \tag{4.8.21}$$

η_{ex} the term used to describe this is exergetic efficiency. It is defined as the ratio of the exergetic work produced to the total exergy input to the system. This definition is based on the second law of thermodynamics and provides a more precise computation for the system's performance. The exergy efficiency as shown in Fig.4.9. The exergy efficiencies of pure diesel, WPO20D80, and WPO100D0 are approximately 33.9%, 33.0%, and 29.8%, representing the highest and lowest values, respectively. It has been seen that both BP and Q_w rise as the load increases, but Q_{exh} and Q_{un} exhibit a declining pattern. Furthermore, it was noted that when blending grows, the value of Q_w rises while the value of Q_{exh} declines. During the exergy analysis, it was noted that the rate of exergy efficiency reaches a maximum of 33.9% and 33.0% of the input exergy values for diesel and WPO20D80, respectively. As the load rises, combustion improves, irreversibility is reduced, and heat losses become less significant. This enhances the utilization of the fuel's potential energy, leading to higher exergy efficiency for the diesel-WPO blend.

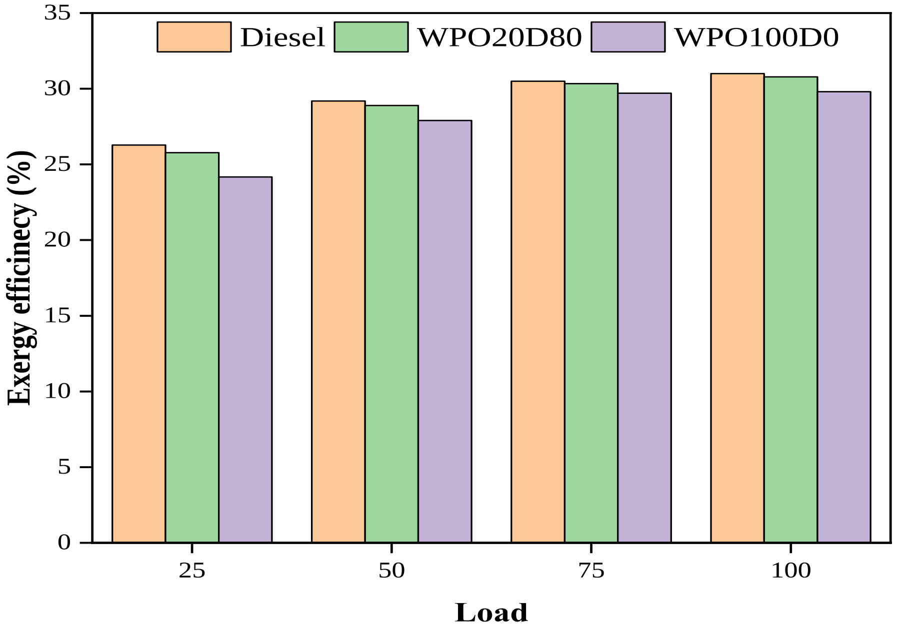


Fig.4.9.Exergy analysis with load.

Table 4.13 Energy analysis of a Diesel engine fuelled with fuel obtained from waste

Q in KW $mf * L.C.V$	Qbp W Shaft KW $2\pi NT/6000$	Q cooling KW $MWCPW(T2 - T1$	Q exhaust KW $megcpeg(T5 - Ta)$	Unaccounted $Q - Qs - (Qbp + Qcw + Qeg)$
6.259396	1.9254	1.98	1.92	0.43
6.8765812	1.984165266	2.01	2.13	1.05
9.061167308	2.3559035	2.57	2.95	1.18
11.57397338	3.159694733	3.16	3.87	1.39
14.26415673	3.580303339	4.19	4.88	1.61

CHAPTER 5

RESULTS AND DISCUSSION

Combustion in a Compressed Ignition engine is regulated by the air and fuel mix, which is affected by the delay time, spray characteristics, and airflow. Combustion processes are sensitive to variations in operational conditions. Engine performance and emissions are heavily influenced by combustion factors, including ignition delay, heat release, and rate of pressure increase, as well as the pressure histories of individual cylinders. All of these have been investigated experimentally in the current study by altering the compression ratio of a single-cylinder direct-injection diesel engine running on waste plastic oil. A thorough study has been conducted on the performance, combustion, and emission criteria of a DI diesel engine operating on Waste plastic oil (WPO). Bar graphs are presented in the report wherever comparison is required, and line/curve graphs are used wherever statistics are presented.

5.1. Performance Characteristics Vs CRs

5.1.1. Brake Thermal Efficiency

The brake thermal efficiency (BTE) variation for diesel and mixed fuels with respect to engine compression ratios is shown in Fig. 5.1. The BTE decreases as the allocation of alternative fuel augments in the blends. On the other hand, diesel fuel BTE increases as the compression ratio increases, indicating an excellent engine rendition configuration. Off the back of impecunious spray atomization and extended spray astuteness, which have a negative impact on air entrainment and ensuing air-fuel mixture formation, WPO combined with diesel unremittingly has a subsidiary BTE. The BTE produced by WPO40D60 and WPO20D80varies little from one another, but as the compression ratio increases, the BTE of all fuels also varies slightly. For instance, the BTE of WPO20D80 was 33.04 % at 19.5 and 28.1 % at 15.5 compression ratios. It is noteworthy that WPO100 consistently offers the lowest BTE, but diesel (D100) consistently delivers the dominant BTE for all compression ratios. Diesel fuel with a CR of 19.5 has the highest BTE (34.75%), whereas WPO100 with a CR of 15.5 has the lowest BTE (23.2%) at full load at 1500 rpm.

But when the CR is 18.5 or higher, the high pressures inside the cylinder cause problems like knocking, incomplete combustion, and higher thermal losses, which cause the BTE to drop. The BTE values for WPO40D60 and W100 are similar at all compression ratios because they have similar amounts of energy, burn similarly, and the effects of higher compression ratios, which lessen the problems caused by WPO's lower cetane number and higher viscosity.

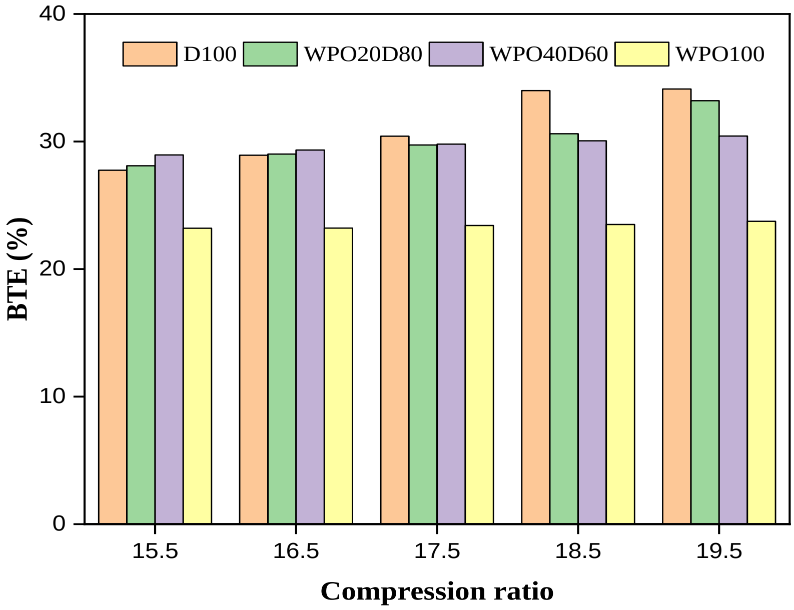


Fig.5.1. Engine brake thermal efficiency with CRs

5.1.2. Brake Specific Fuel Consumption

Brake-specific fuel consumption is used to evaluate an internal combustion engines fuel utilization by dividing the braking power generated (kW) by the fuel consumption rate (g/h), which results in a unit in g/kWh, the BSFC is calculated. The fuel consumption of the D100, WPO20D80, WPO40D60, and WPO100 is shown in Fig. 5.2 for compression ratios of 15.5, 16.5, 17.5, 18.5, and 19.5. There are no notable distinctions between D100 and WPO20D80. At maximum load with 1500 rpm, WPO100 consistently produces the greatest BSFC, whereas WPO20D80 consistently offers the lowest. The maximum BSFC (384.2 g/kWh) is provided by WPO100 at CR 16.5; the lowest BSFC (231.1 g/kWh) is provided by D100 at CR 19.5. The high cetane number of waste plastic oil, which led to a shorter ignition delay, made it harder for the fuel and air to mix, which likely contributed to WPO100's highest BSFC. Greater fuel consumption was observed because of adding WPO to diesel fuel.

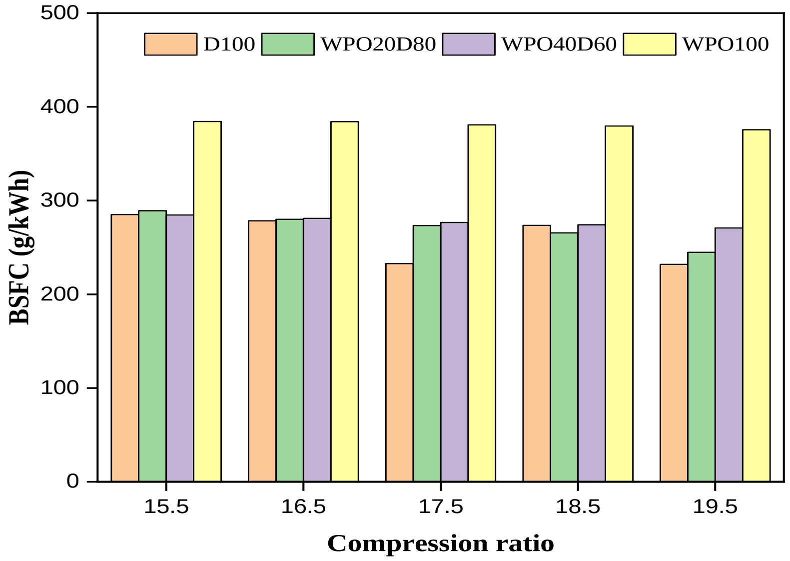


Fig.5.2. Brake Specific Fuel consumption variation with CRs

5.1.3. Exhaust Gas Temperature

At the exhaust manifold, the EGT is gauged. Due to its fluctuation with the air-fuel ratio, it may be employed to regulate the mixture of fuel and air entering the cylinder. The EGT from the four fuels that were investigated at five different compression ratios is shown in Fig. 5.3. None of the fuels exhibit significant variations throughout the whole range of compression ratios. The greatest EGT is constantly provided by D100, whilst the lowest is often provided by WPO100. The maximum EGT (469.84 °C) is produced by WPO20D80 at CR 18.5, whereas the lowest EGT is produced by WPO20D80 at CR 15.5 (444.2 °C). Therefore, at full load and 1500 rpm, the quantitative difference between the highest and lowest EGT is almost 5.4%.

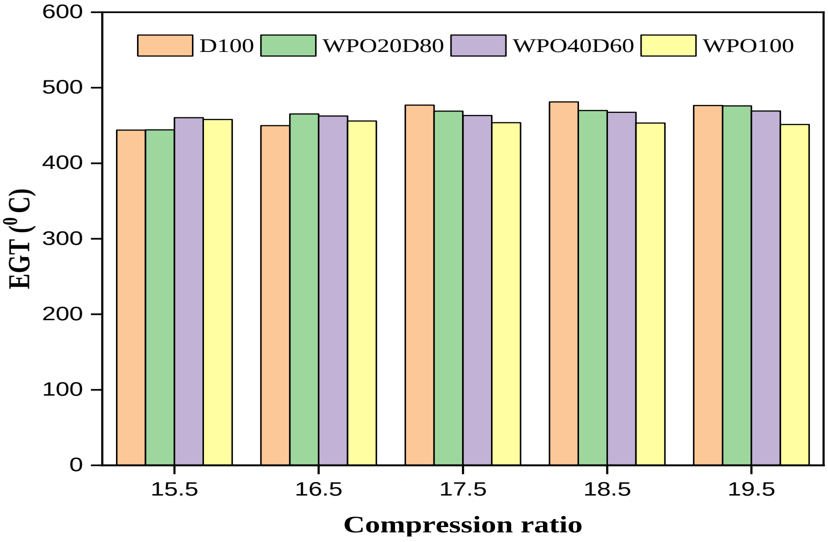
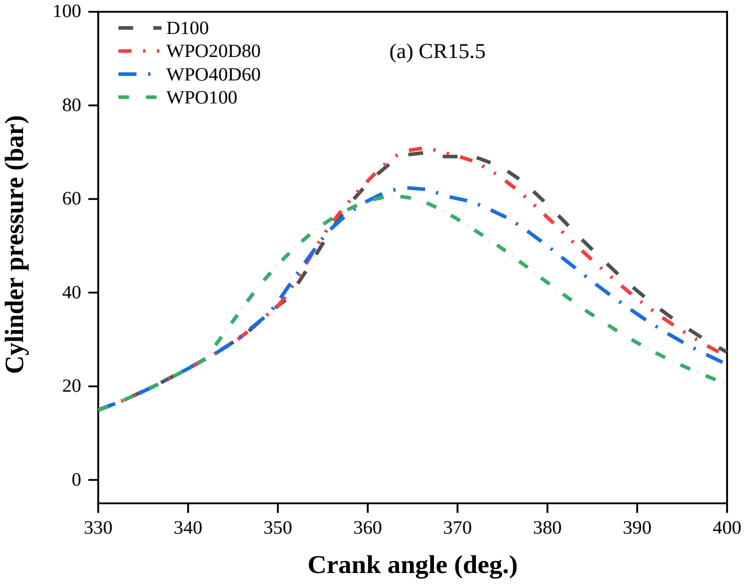


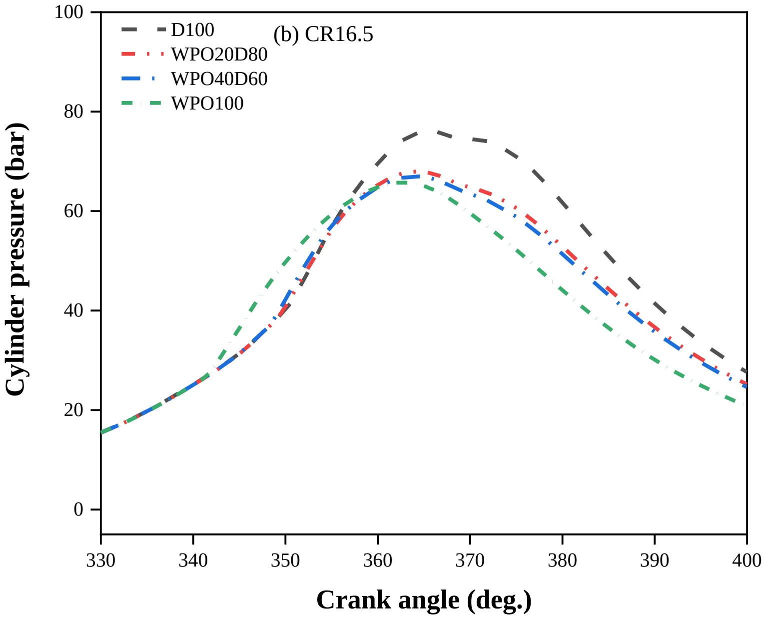
Fig.5.3. Exhaust gas temperature with CRs

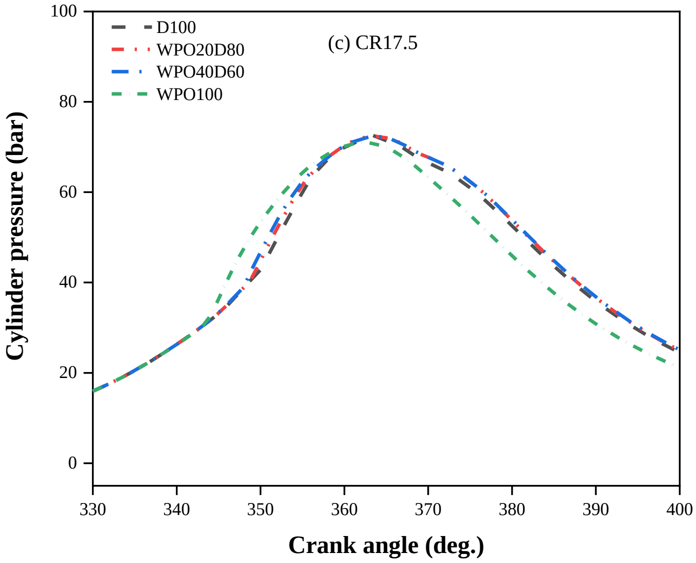
5.1.4. Cylinder Pressure

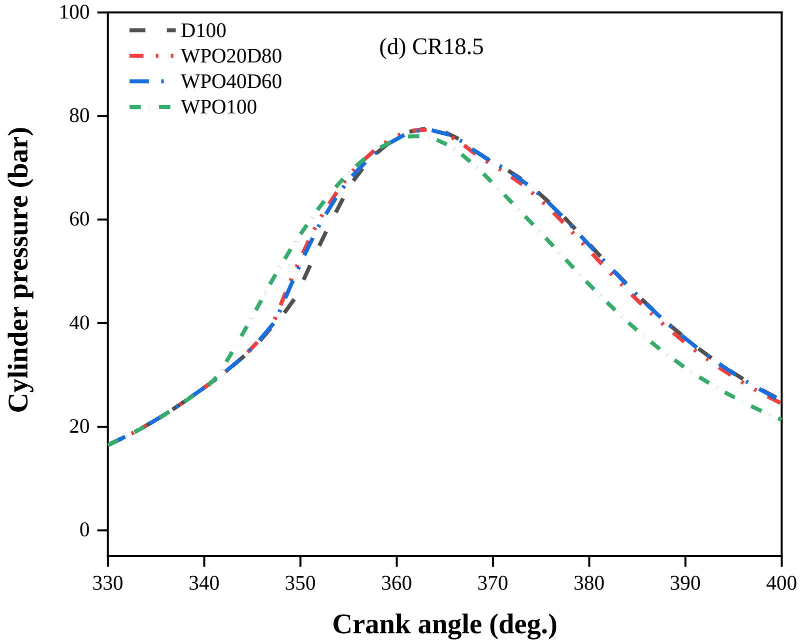
The cylinder pressure is measured during combustion in an IC engine. In-cylinder pressure peaks for the four types of fuel under investigation (D100, WPO20D80, WPO40D60, and WPO100) are shown in Fig. 5.4 at five different compression ratios: 15.5, 16.5, 17.5, 18.5 and 19.5. The figure demonstrates the patterns of all the tested blends. Peak cylinder pressure for all the investigated blends increases with increasing compression ratio, while WPO20D80 exhibits a similar behaviour except that peak cylinder pressure decreases and then increases again at a certain compression ratio. Entire fuels parade maximum cylinder pressure at the loftiest 19.5 compression ratio, with diesel pageant the uppermost value (82.99 bar).

This scenario had the greatest peak in-cylinder pressure of all the fuels examined (WPO20D80 at CR 19.5 of 82.4 bar). Instead, of all the models, WPO100 at CR 15.5 has the lowest peak in-cylinder pressure (60.57 bar). Therefore, there is a 0.71% difference between diesel fuel (82.99 bar) and WPO20D80 (82.4 bar). The lower peak in-cylinder pressure for waste plastic oil may be related to the cooling impact of WPO fuel owing to its relatively high latent heat of vaporisation, which decreases the in-cylinder temperature. Due to its greater clearance capacity, the low compression ratio is also known to have a low temperature. The peak cylinder pressure for WPO100 dropped the most at CR 15.5. This was because the WPO cooled the mixture, and the low compression ratio made the cooling effect even stronger. The lower peak latent heat of vaporisation of WPO is 200–230 kJ/kg. The higher cylinder pressure for WPO100 between 340°CA and 350°CA is due to its delayed and prolonged combustion, higher energy content, lower latent heat of vaporisation, and the fact that it burns effectively at higher temperatures, especially when compression ratios are high.


D100
WPO20D80
WPO40D60
WPO100
(a) CR15.5
Cylinder pressure (bar)
0
20
40
60
80
100
330
340
350
360
370
380
390
400
Crank angle (deg.)


D100
WPO20D80
WPO40D60
WPO100
(b) CR16.5
Cylinder pressure (bar)
0
20
40
60
80
100
330
340
350
360
370
380
390
400
Crank angle (deg.)


D100
WPO20D80
WPO40D60
WPO100
(c) CR17.5
Cylinder pressure (bar)
0
20
40
60
80
100
330
340
350
360
370
380
390
400
Crank angle (deg.)



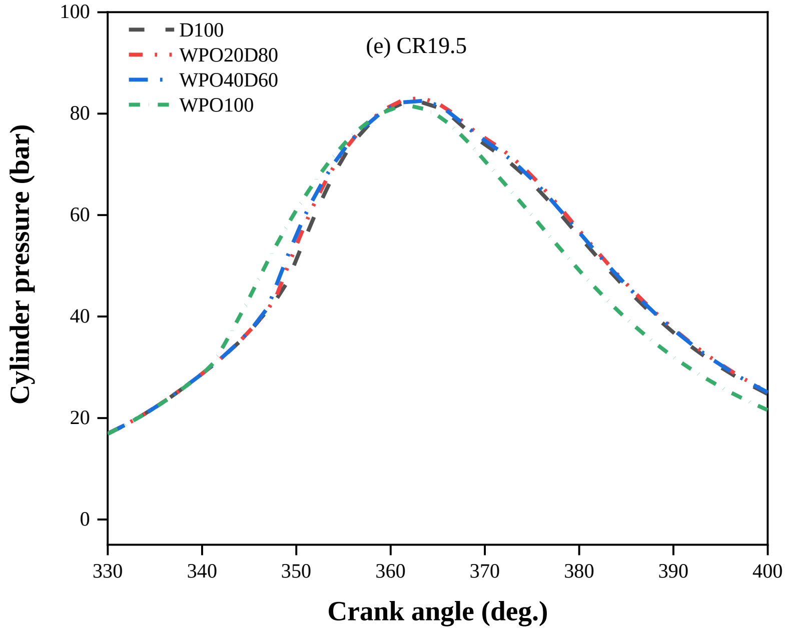


Fig.5.4. Cylinder pressure variation with crank angle and CRs

5.1.5. Ignition Delay

The ignition delay duration of the four fuels (D100, WPO20D80, WPO40D60, and WPO100) is shown in Fig. 5.5 for five different compression ratios: 15.5, 16.5, 17.5, 18.5, and 19.5. This is a crucial parameter that arbitrates the tone of the combustion. For high-grade and more even combustion in CI engines, a compact ignition delay is often preferable. Pure plastic oil has the shortest ignition delay, while diesel has the longest at low CRs.

Ignition delay reduces as load rises since the engine's temperatures rise as a result. WPO100 has the shortest ignition delay because it has the highest cetane, which is even greater than any other. A greater compression ratio is also known to raise the temperature inside the cylinder, which could further reduce ignition delay. As a consequence, at full load and 1500 rpm, WPO with the greatest cetane number (WPO100) at the highest compression ratio produced the shortest ignition delay (CR 19.5). Additionally, at CR 15.5, the difference in ignition delay between the fuels that generated the largest and shortest delays. Plastic oil's shorter ignition delay is due to its chemical makeup, enhanced vaporization rates, and the effects of temperature and pressure, all of which contribute to faster combustion when compared to certain conventional fuels. In general, a low cetane number causes a longer ignition delay. This effect is stronger at higher compression ratios, and it also makes it harder for fuel to mix and evaporate. In contrast, WPO40D60 might have better combustion characteristics at lower compression ratios, which would mean a shorter ignition delay compared to WPO20D80.

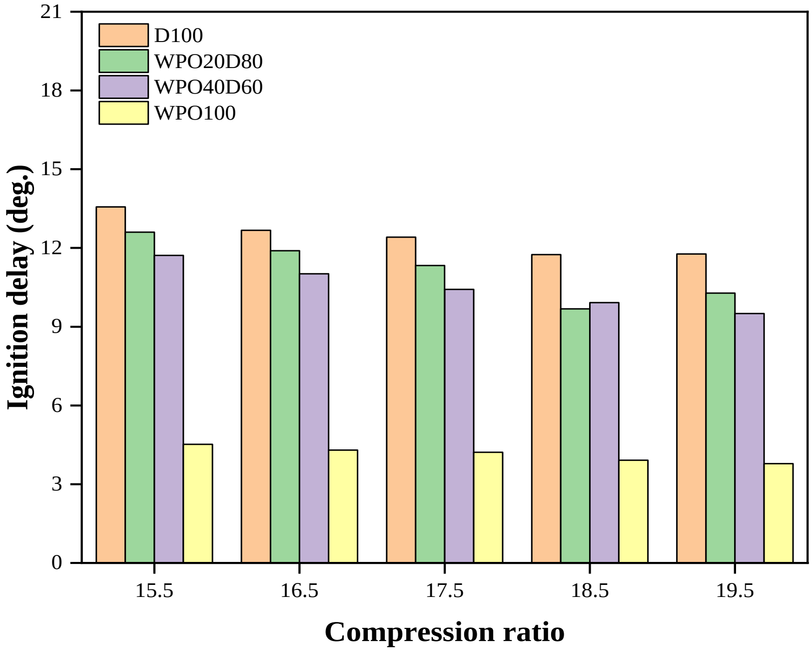


Fig.5.5. Ignition delay variation with CRs

5.1.6. Maximum Rate of Pressure Rise

The maximum pressure increase rate for the four blends under consideration (D100, WPO20D80, WPO40D60, and WPO100) at five different compression ratios 15.5, 16.5, 17.5, 18.5 and 19.5 is shown in Fig. 5.6. The highest rate of increase in pressure, concerning each crank angle revolution, represents an increase in combustion chamber pressure during the combustion stage. Regarding engine performance, this is quite significant. It is not advised to put pure plastic oil on an engine since it has the slowest rate of pressure build-up. Pure diesel has the fastest rate of pressure increase. Comparing WPO40D60 to WPO20D80, improved qualities are evident. At full load and 1500 rpm, all mixes and pure oils exhibit linear characteristics.

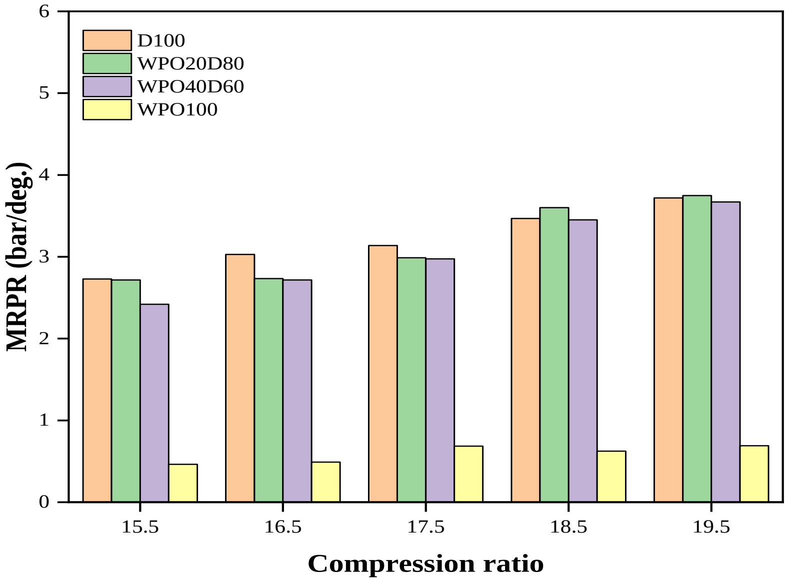


Fig.5.6. Maximum Rate of Pressure Rise variation with CRs

5.1.7. Smoke Discharge

The smoke discharge (%) of the four fuels under investigation (D100, WPO20D80, WPO40D60, and WPO100) is shown in Fig. 5.7 at five different compression ratios: 15.5, 16.5, 17.5, 18.5, and 19.5. Smoke emission in the diesel engines is significantly influenced by fuel atomization and oxygen deprivation. The smoke emissions of the four fuels under investigation at five different compression ratios are shown in the figure. All compression ratios of WPO20D80 and WPO40D60 exhibit a trend in smoke production, but WPO100 consistently generates a higher amount. The most smoke is produced by D100 (45.6%), while the highest is produced by WPO100 (51.1%); both were measured at CR 19.5. Therefore, for a full load situation with 1500 rpm at CR15.5, the difference between the highest (45.6%) and lowest (51.1%) smoke production is almost 5.5%. Only a combination of 40% and 60% waste plastic oil in diesel fuel exhibits a consistent small rise with increasing compression ratio (WPO20D80 and WPO40D60). This is because it has more oxygen and less carbon. It was also believed that a blend would increase air density and in-cylinder temperature, which would lead to improved fuel-air mixing and promote complete combustion while lowering smoke emissions. The steady smoke emissions of

WPO100 across all CRs result from ongoing challenges with incomplete combustion, inadequate air-fuel mixing, and the fuel's composition, which restricts the effect of compression ratio on lowering smoke levels.

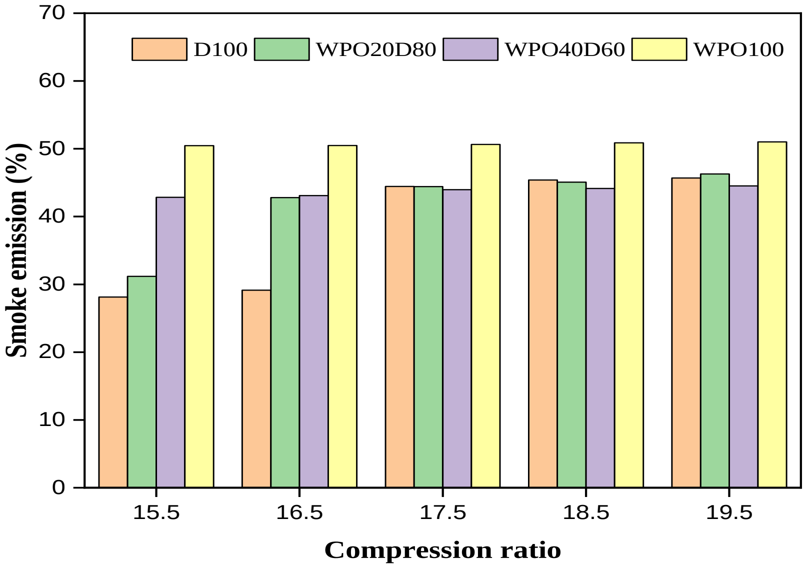


Fig.5.7. Smoke emission variation with CRs

5.1.8. CO_2 Emissions

Carbon oxidation results in the production of carbon dioxide (CO_2), a colourless, flammable, odourless gas. The greenhouse effect is increased due toCO_2 in the atmosphere, absorbed radiation, and the generation of ozone at elevated levels, which starves the planet of cooling. The CO_2 emission of four fuels under investigation (D100, WPO20D80, WPO40D60, and WPO100) at five different compression ratios: 15.5, 16.5, 17.5, 18.5, and 19.5is shown in Fig. 5.8. For all fuels across all compression ratios, there are no discernible changes. Whilst WPO20D80 at CR15.5 consistently provides the lowest CO_2 emissions. The lowest CO_2 (770.3 g/kWh) is produced by D100 at CR 15.5 at full load and 1500 rpm, while the greatest CO_2 (1100.4 g/kWh) is produced by WPO100 at CR19.5. Due to its greater calorific value and lower density when compared to WPO100 for achieving the same engine power output, D100 may have created the lowest amount of CO_2 emissions. This is because it releases less energy. The trajectory of CO_2 emissions is shown in the figure.

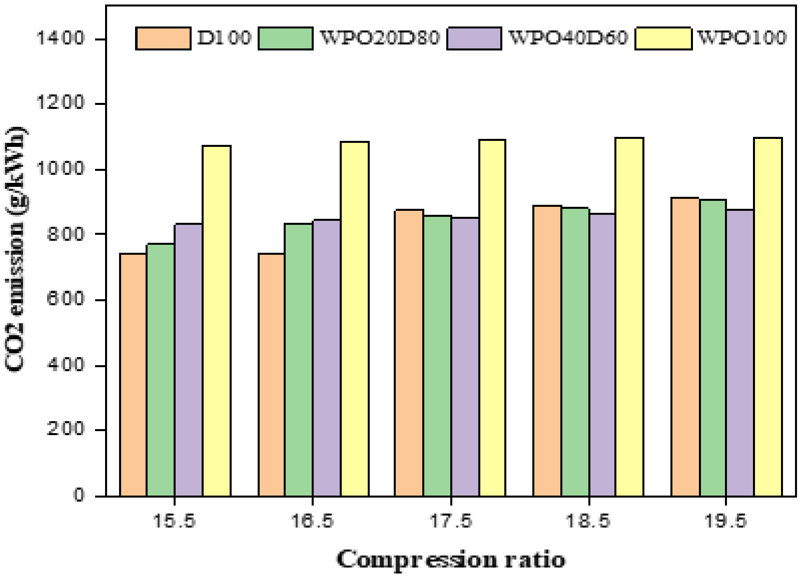


Fig.5.8. CO_2 emissions variation with CRs

5.1.9. NO_X Emission

NOx emissions are significantly influenced by the highest temperature of the gases within the combustion chamber, as well as the available reaction time. The NOx emissions of the four fuels under investigation (D100, WPO20D80, WPO40D60, and WPO100) are shown in Fig. 5.9 at five different compression ratios (15.5, 16.5, 17.5, 18.5, and 19.5). When the compression ratio increases from 15.5 to 19.5, the diesel oil combination under investigation exhibits the same pattern.

The technique is roughly the same for WPO made from waste plastics. D100 has a constant increase with the maximum NO_x level generated at CR 19.5, distant distinguishable fuels, which withhold the predominant NOx emissions at the highest compression ratio. The highest NOx emission is produced by D100 at CR 19.5(12.7 g/k-Wh), whereas the lowest is produced by WPO100 at CR 19.5 (8.7 g/k-Wh).Due to the decreased ignition delay, diesel fuel, as previously mentioned, has the maximum NOx emission at CR19.5. A shorter ignition delay results in combustion occurring at higher temperatures, which contributes to NOx formation. The primary reason for the NOx emissions increase is due to the decrease in residual gas and wall temperatures. In the way that the compression ratio went up, the cylinder pressure and temperature went up. This made up for the chilling effect of the WPO. This is due to the compression ratio going up and the clearance volume going down.

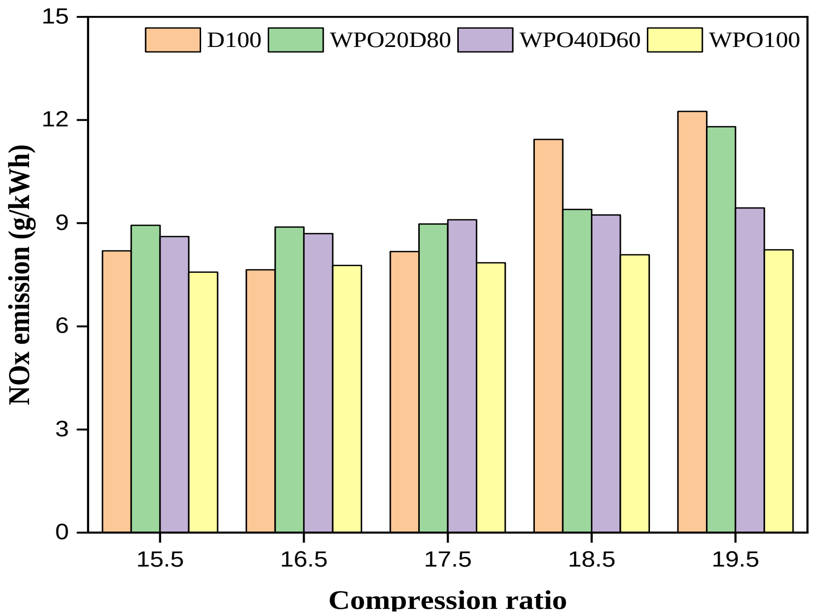


Fig.5.9. NO$_x$ emissions variation with CRs

5.2. Exergy analysis of a diesel engine fuelsed with fuel obtained from waste plastics:

Exergy analysis helps to find out the qualitative measurement. It is based on second law of thermodynamics. Rate of heat loss exergy, rate of exergy destroyed, amount of heat required for cooling. The main objective of the Morse test is to find out the power developed, IP etc. whereas exergy analysis involves in finding qualitative measurement as shown in Table 5.1.

Table 5.1. Exergy analysis of a diesel engine

Q Cooling						
Load	Q Cooling	Q Cooling	Q Cooling	Q Cooling	Q Cooling	Q Cooling
%	kW	kW	kW	kW	kW	kW
20	16.5D100	17.5D100	18.5D100	16.5B20	17.5B20	18.5B20
40	2.425	2.45655	2.425	2.01	2.014838292	2.205
60	3.21	3.00938	3.21	2.52	2.573371515	2.932
80	3.96	3.85435	4.01	3.27	3.159694733	3.96
100	4.21	4.14545	5.01	4.1	4.193662078	4.816
Rate of heat loss exergy						
Load	Rate of heat loss exergy	Rate of heat loss exergy	Rate of heat loss exergy	Rate of heat loss exergy	Rate of heat loss exergy	Rate of heat loss exergy
%	kW	kW	kW	kW	kW	kW
-	16.5D100	17.5D100	18.5D100	16.5B20	17.5B20	18.5B20
20	3.1	3.51	3.6	2.87	3.002	3.428
40	3.246	4.078	4.32	3.5	4.0124	4.164

60	3.748	4.49	5.4	4.2	5.245	5.38
80	4.364	5.254	6.3	5.11	5.72	5.85
100	5.1987	6.645	7.35	5.9	6.89	7.1
Rate of exergy destroyed						
Load	Rate of exergy destroyed	Rate of exergy destroyed	Rate of exergy destroyed	Rate of exergy destroyed	Rate of exergy destroyed	Rate of exergy destroyed
%	kW	kW	kW	kW	kW	kW
-	16.5D100	17.5D100	18.5D100	16.5B20	17.5B20	18.5B20
20	0.09	0.11	0.13	0.12	0.14	0.145
40	0.75	0.82	0.85	0.78	0.83	0.89
60	0.92	1.2	1.1	1.05	1.15	1.3
80	2.5	2.45	2.56	2.45	2.51	2.55
100	3.85	3.82	3.89	3.7	3.9	4.1

5.3. Performance Characteristics vs Loads

The results of using WPO mixed with waste plastic oil for varying loads, aiming to understand their performance and emissions characteristics. Waste plastic oil, obtained through pyrolysis of plastic waste, presents WPO opportunity to address both waste management and renewable energy production. By investigating the behaviour of these blends under different load conditions, we gain insights into their feasibility as a sustainable energy option for applications such as transportation and power generation. The research considers variables like the percentage of waste plastic oil amalgamated with prevailed diesel fuel and examines engine performance, fuel efficiency, and emission levels. These findings contribute to the knowledge of renewable energy sources and provide crucial data for promoting the WOP use blends as an environmentally friendly energy solution.

5.3.1. Brake Thermal Efficiency

Reduced brake thermal efficiency is caused by a rise in alternative fuels, such as waste plastic oil. With varying compression ratios, the BTE of the fuel also varies, which is the exact WPO site of what was expected. The thermal efficiency of the WPO20D80 brake is at 13% of BTE found at 20% of the load and 29.6% of BTE found at 100% of the load. We found that the WPO20D80 results were comparable to pure diesel, as shown in Fig. 5.10. The WPO20D80 brake's thermal efficiency goes up as the load goes up. This is because it burns more efficiently, loses less heat, and uses fuel more efficiently. It also has properties that work well together when the load is higher.

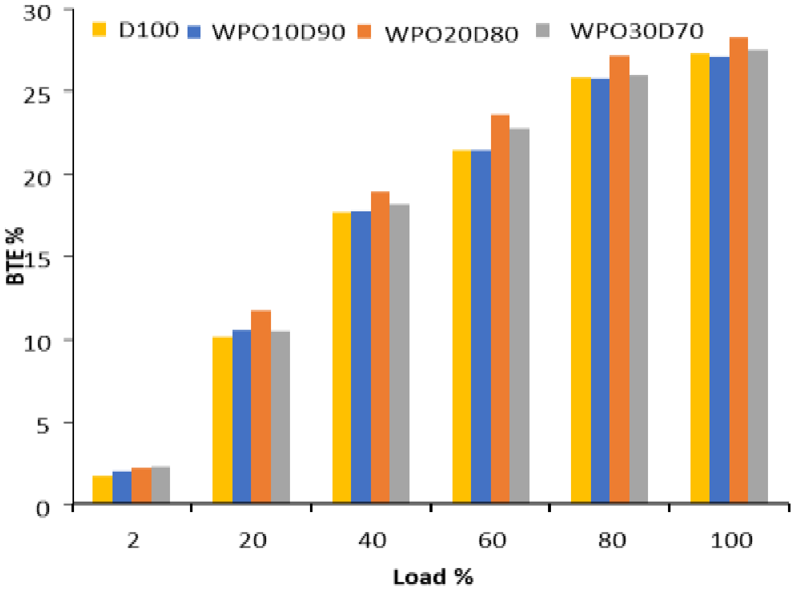


Fig.5.10. Brake thermal efficiency Vs. Load

5.3.2. Brake Specific Fuel Consumption

The performance of an engine is weighed by BSFC as shown in Fig. 5.11. In general, brake specific fuel consumption in other terms, is the fuel consumption to the brake power. BSFC of four different fuel compositions: diesel, WPO10D90, WPO20D80 and WPO30D70. BSFC is a measure of how much fuel is consumed per unit of power output. A lower BSFC means that less fuel is consumed, and more power is produced. It is seen that the BSFC of diesel is highest, followed by WPO10D90, WPO20D80 and WPO30D70. This means that diesel is the less fuel-efficient fuel, and WPO30D70 is the most fuel-efficient fuel. The difference in BSFC between the different fuels is due to the different properties of the fuels. WPO30D70 has a higher cetane number than the other fuels, which means that it ignites more easily and burns more completely. This results in a lower BSFC. The graph also shows that the BSFC of all four fuels decreases as the load increases. This is because the engines become less efficient as they heat up.

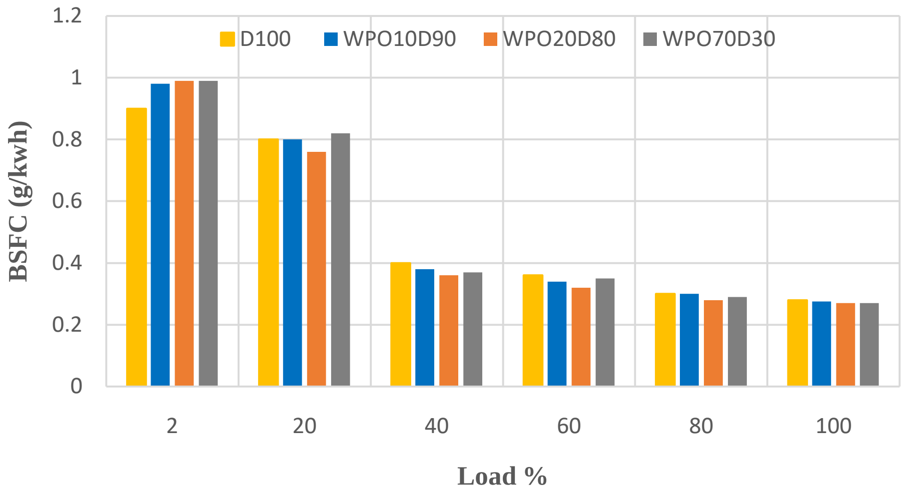


Fig.5.11. Brake specific fuel consumption Vs. Load

5.3.3. Exhaust Gas Temperature

At the exhaust manifold, exhaust gas temperature is measured usually. It is normally used to manage the air and fuel proportionate as shown in Fig. 5.12. The graph indicates the exhaust gas temperature (EGT) of four different fuel compositions: diesel, WPO10D90, WPO20D80 and WPO30D70. EGT is a measure of the temperature of the exhaust gases after they have passed through the engine. A higher EGT means that the exhaust gases are hotter, and this can be a sign of inefficient combustion or other problems. The graph shows that the EGT of the diesel is highest, followed by diesel, WPO10D90, WPO20D80 and WPO30D70. This means that diesel produces the hottest exhaust gases, and WPO10D90 produces the coolest exhaust gases. The difference in EGT between the different fuels is due to the different properties of the fuels. The graph also shows that the EGT of all four fuels increases as the load increases. This is because the engines become hotter as they work harder, and this heat is transferred to the exhaust gases.

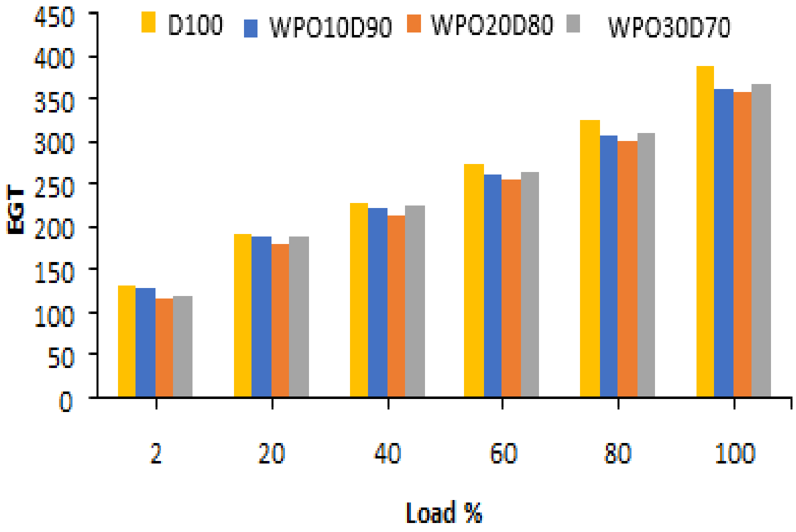


Fig.5.12. Exhaust gas temperature Vs. Load

5.4. Combustion Characteristics with Low, Medium and High Loads

5.4.1. Engine Torque

The bending force of an engine, measured in proportion to how quickly it is rotating, is referred to as the torque. Torque may be measured with the use of a device called a dynamometer. In today's engines, sensors are installed at the crank, and power is immediately measured help of the assistance of an Electronic Control Unit (ECU) that is connected to a data encoder. It is clear that pure diesel has the highest power as the load increases because of this. Figure 5.13 illustrates how the braking force of the engine varies depending on the load for both WOP mixtures and diesel.

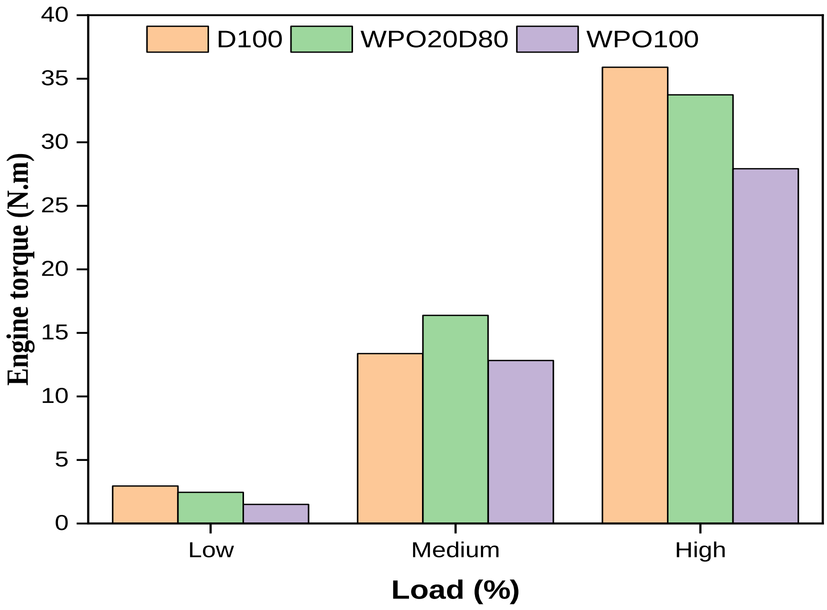


Fig.5.13 Engine torque with loads

5.4.2. Brake Mean Effective Pressure

Figure 5.14 illustrates how the average effective pressure of the brake changes depending on the load for both WPO mixes and pure diesel. The brake dynamometer is used to assess the average effective pressure, which is what this term refers to. Pure diesel has the greatest braking mean effective pressure, and this pressure increases with load.

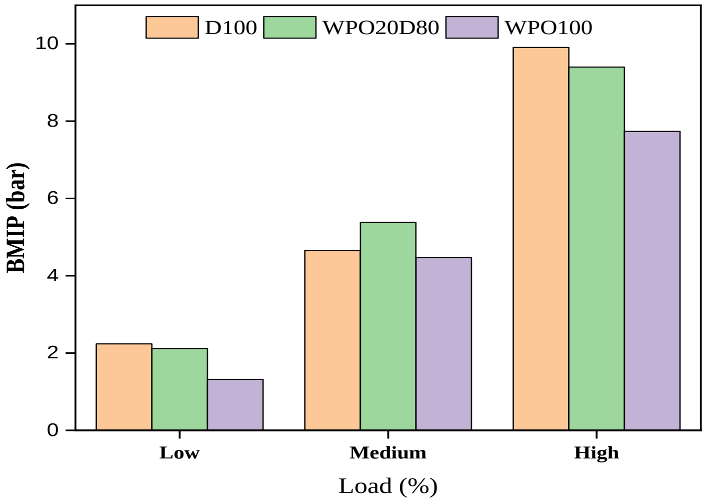


Fig.5.14 .brake mean effective pressure with loads

5.4.3. Volumetric Efficiency

Figure 5.15 illustrates how the volumetric efficiency varies with load for both the WOP blends and the pure diesel used in the experiment. The efficiency of the compressor cylinder to compressed gas is the definition of it. WPO offers the maximum volumetric efficiency regardless of the weight that is being carried. As can be seen in the figure, there was a correlation between an increase in engine load and a decline in volumetric efficiency.

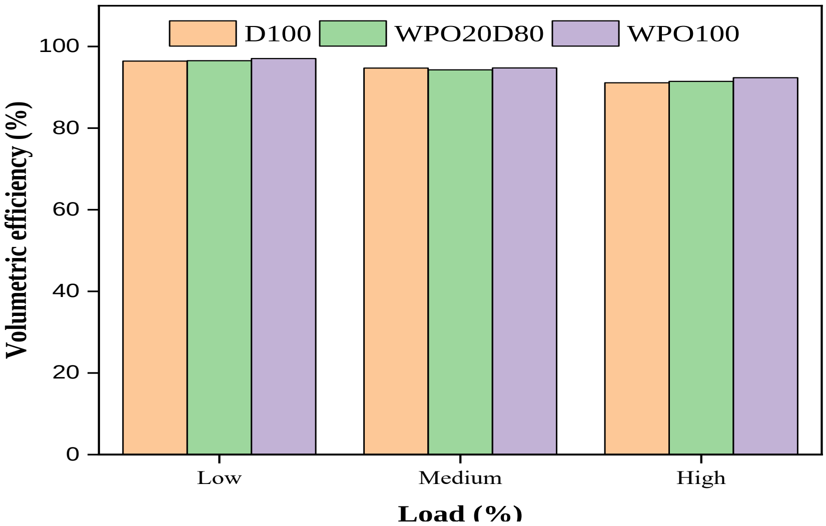


Fig.5.15.Volumetric efficiency with loads

5.4.4. Peak Cylinder Pressure

Figure 5.16 illustrates how the peak cylinder pressure varies with load for diesel fuel mixes including WPO as well as unadulterated diesel fuel. It refers to the pressure that is present during the suction, compression, expansion, and exhaust strokes of the engine. In comparison to pure plastic oil and blends, pure diesel exhibits the greatest peak cylinder pressure when the load is increased.

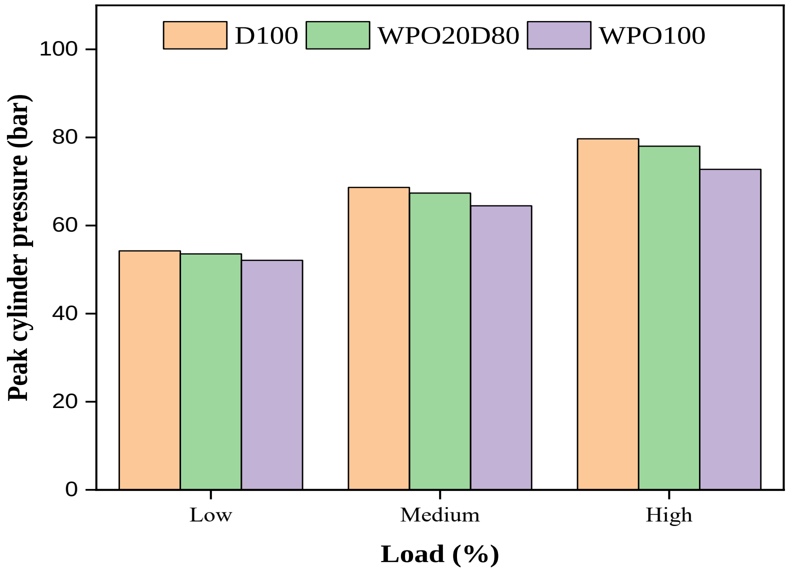


Fig.5.16.Peak cylinder pressure with loads

5.4.5. Smoke Emission

Figure 5.17 shows how the levels of smoke emissions change depending on the load for both the WPO blends and the pure diesel fuel. The combustion process in a diesel engine often releases smoke emissions into the atmosphere. Incomplete combustion, often due to low fuel quality, is the primary source of emissions. Due to its high viscosity, waste plastic oil contributes much more to overall emissions. Despite this, the results of this experimental research indicate that diesel fuel in its purest form produces the most smoke. Contaminants present in diesel fuel serve as the primary cause.

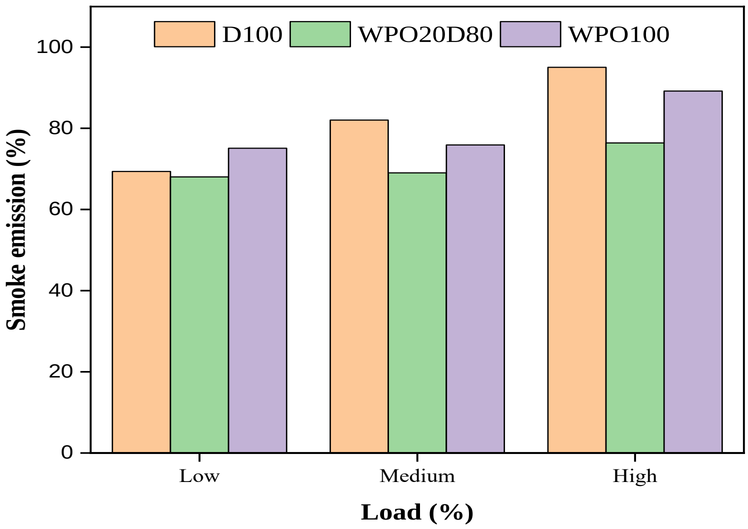


Fig.5.17. Smoke emissions with loads

5.4.6. NO_x Emissions

Figure 5.18 depicts how the levels of NO_x emissions change depending on the load for both WPO blends and diesel fuel. Combustion at the maximum possible temperature produces nitrogen oxides as a by-product of the process. WPO has the largest NO_x emissions and those emissions rise with the load.

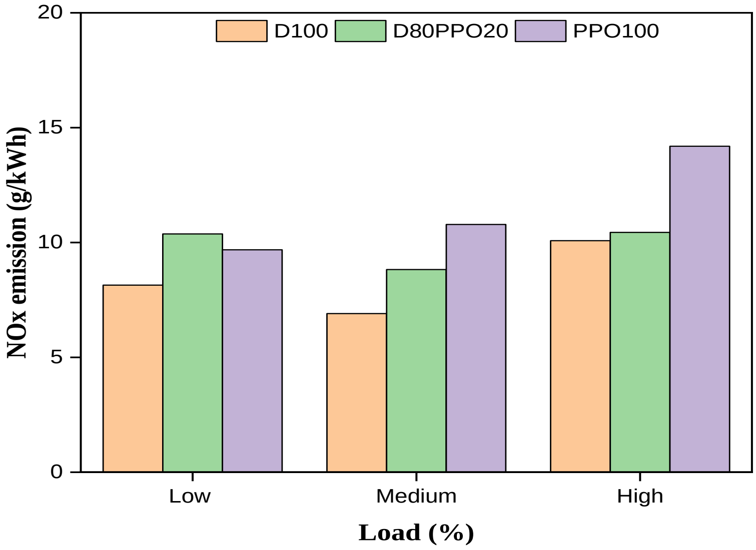


Fig.5.18.NO_x emission with loads

5.5. Economic Analysis

Economic analysis of a diesel engine fuelled with fuel obtained from waste plastics. Gross profit is the amount of money a business makes after all the costs of making and selling its goods or services are taken out, as shown in Table 5.1.

Table 5.2. Cost analysis

Gross Profit = Manufacturing cost- selling products/services	
Total production cost of 450 litres of diesel	49347₹/day
Total production cost of 450 litres of WPO	45554₹/day
Profit	3793₹/day/ton of WPO
Total Income	1384445₹/year
Gross Profit	1384445 - 45554.67 1338891₹/day/ton of WPO
Net Profit	401667₹/year (with 30% tax)
Net Profit	1338891 – 401667 937224₹

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1. Conclusion

- When the studies on the waste plastic oil (WPO) ratio are evaluated, it was concluded that the WPO ratio should be between 20% and 40% in the WPO-diesel blend mode. The reason why the WPO ratio cannot be increased to higher density and viscosity is that the WPO in the cylinder occupies more fuel consumption, reducing the engine performance.
- In the WPO diesel fuel mode, the specific fuel consumption increases in parallel with the increases in the WPO. The main reason for this is that WPO forms a non-homogeneous mixture with air and incomplete combustion. However, increasing the WPO ratio too much reduces the calorific value in the blend.
- The pressure patterns within the cylinder were identical, and each engine followed the same pumping procedure. Adding WPO shortened the engine ignition delay at a high engine load with CR7.5 due to its cetane number, and the blend fuels probably had a higher peak cylinder pressure. At high engine load and cetane number caused a shorter ignition delay and somewhat higher peak cylinder pressure for blend fuel.
- The addition of WPO fuel with diesel fuel decreases the cylinder pressure and temperature, resulting in decreased NOx emissions. The higher value of NOx emission was found to be 12.6 g/kWh for diesel (D100), and the lower value was 8.7 g/kWh for WPO100 at CR 19.5).

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6.2. Future Scope

It is possible to use WPO and mixes of it with regular diesel as an alternative fuel in Diesel engines. There are no changes that need to be made to the engines themselves. Because of the environment and the economy, their fame may grow soon. To find out if WPO materials are available and to build engines, though, more study and development are needed in the following areas:

- In the present research, a diesel engine was used to test several waste plastics oil WPO blends. These blends were evaluated using diesel engines. The production of these mixes included combining diesel and WPO in quantities that were equal in volume. It is possible that in the not-too-distant future, more studies will be carried out to maximize the different proportions of WPO that are present in the mixture to obtain higher performance while simultaneously reducing emissions.
- WPO quality varies from place to place, a variety of diesel engines can be used to test mixtures of waste plastics and WPO made in different places with waste plastics that are easy to get.
- During this inquiry, a combination of four different kinds of WPO that are produced from waste plastics WPO has been investigated. The scope of future study may be expanded if more than four various types of WPO are tested.

- To research, the impact that different operating circumstances have, it is feasible to perform tests with the engine functioning for lengthy periods while using a range of waste plastic WPO mixes. These experiments may be carried out to examine the effect that different operating conditions.

LIST OF PUBLICATIONS

1. Dunga Simhana Devi, Ravinder Kumar & Upendra Rajak. Experimental investigation of performance, emission and combustion characteristics of a CI engine fuelled by blends of waste plastic oil with diesel. Energy Sources, **Part A: Recovery, Utilization, and Environmental Effects**, 44:3, 7693-7708, https://doi.org/10.1080/15567036.2022.2115582
   (SCIE, IF:2.6)

2. Dunga Simhana Devi, Ravinder Kumar & Upendra Rajak. Investigation of Combustion and Performance Characteristics of Waste Plastic Oil. **Lecture Notes in Mechanical Engineering**.
   https://doi.org/10.1007/978-981-16-79094_80.(Scopus)

3. Dunga Simhana Devi, Ravinder Kumar &Upendra Rajak. Plastic waste as a biofuel feedstock-A conceptual study. **Materials Science and Engineering**.
   1116 012029.
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