Evaluation of Performance, Emission and Combustion Characteristics of Various Biodiesel of Indian Origin

A Thesis submitted to the Delhi Technological University, Delhi

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DOCTOR OF PHILOSOPHY

in

MECHANICAL ENGINEERING

by

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DECLARATION

I hereby declare that the PhD thesis entitled "**Evaluation of Performance, Emission and Combustion characteristics of various biodiesel of Indian origin**" is an original work carried out by me under the supervision of Dr. Naveen Kumar, Professor, and Dr. Rajiv Chaudhary, Professor, Mechanical Engineering Department, Delhi Technological University, Delhi. This thesis has been prepared in conformity with the rules and regulations of the Delhi Technological University, Delhi. The research work reported, and results presented in the thesis have not been submitted either in part or full to any other university or institute for the award of any other degree or diploma.

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CERTIFICATE

This is to certify that the work embodied in the thesis entitled "**Evaluation of Performance, Emission and Combustion characteristics of various biodiesel of Indian origin**" by **Khushbu Yadav**, (Roll No.-**2K17/PhD/ME/27**), in partial fulfillment of requirements for the award of Degree of **DOCTOR OF PHILOSOPHY** in Mechanical Engineering, is an authentic record of student's own work carried by her under our supervision.

This is also certified that this work has not been submitted to any other University or Institute for the award of any other diploma or degree.

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Dedicated to

My Father

Mr. Aneg Singh Yadav

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ABSTRACT

Diesel engines hold immense importance in India's transportation landscape, underpinning the nation's extensive mobility requirements. However, this heavy reliance on diesel engines also contributes to environmental concerns such as air pollution and greenhouse gas emissions. This emphasizes the need to explore and adopt sustainable alternatives, such as biodiesel, to reduce the environmental impact.

Biodiesel, a renewable substitute for traditional diesel fuel, has some issues that must be resolved before it can be widely used. One hindrance is oxidation stability, which is the resistance of biodiesel to deterioration when exposed to air, light, and heat. Subsequently, one more issue linked with biodiesel is increasing NOx emissions compared to other emissions. Antioxidant additives can be added to biodiesel compositions to improve its oxidation stability to help offset this issue. Antioxidants are needed for improving biodiesel's oxidation and mitigating NOx emission.

In the initial study of this work, waste cooking oil and neem oil were selected to produce biodiesel. Three synthetic antioxidants, pyrogallol (PY), tert-butyl-hydroxyquinone (TBHQ), and diphenylamine (DPA), and one natural antioxidant Tinospora cordifolia, were used. Later, the characterization of biodiesel was performed by Chromatography-Mass Spectroscopy for both biodiesels to identify the fatty acid composition of biodiesel or to determine the percentage availability of unsaturated fatty acid in biodiesel. Oxidation stability of waste cooking oil biodiesel and neem biodiesel evaluated by Rancimat as per ASTM and IS standards. Thereafter, 200 ppm, 500 ppm, and 1000 ppm of all four antioxidants mixed into biodiesel and oxidation stability were evaluated for all the antioxidants treated biodiesel. 200 ppm of antioxidants not meeting the specified standard. All 1000 ppm of antioxidant-treated biodiesel meet standards.

The prepared antioxidant-treated biodiesel with 500 ppm and 1000 ppm of antioxidants was used for further test analysis. 20% blend of biodiesel with diesel used for analysis. The physiochemical properties of diesel, diesel-biodiesel blend, and diesel-biodiesel with antioxidants for waste cooking and neem biodiesel were evaluated as per ASTM standard method. All the blends met the ASTM standard method and were comparable with baseline diesel.

At the end of the work, the Performance, emission, and combustion of tested fuel blends were analyzed on Kirloskar make, direct injection engine. Results obtained from engine trials were compared with antioxidant-treated biodiesel blends and biodiesel blends with baseline diesel. Brake thermal efficiency increases, and brake-specific energy consumption decreases for antioxidant-treated biodiesel blends compared to biodiesel. NOx emission for 80D20(WCB+1000DPA), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), 80D20(WCB+100TC), 80D20(NB+1000DPA), 80D20(NB+1000DPA), 80D20(NB+1000PY), 80D20(NB+100TC), blends decrease in comparison to without antioxidant blend at full load. HC, CO, Smoke, and EGT emissions for antioxidant-treated biodiesel blends slightly increased compared to biodiesel but were still found lower than diesel fuel. The results of the experiments were used for prediction and validation. The methodology used for the data that best fit linear regression analysis was the quasi-newton approach. R^2 values for BTE and BSEC are 0.989 and 0.996, respectively. The proposed ANN model's performance and accuracy met all requirements.

Therefore, the results of this study show antioxidants were found to be effective in oxidation stability, performance of biodiesel, and reducing exhaust emissions compared to diesel. Natural antioxidants were also found to be effective as antioxidants.

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NOMENCLATURE

ASTM	American Society for Testing and Materials
@	At the rate
AVL-437	AVL-437 Smoke Meter
B100	Biodiesel 100%
B.P	Brake Power
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BHA	Butylated Hydroxyl Anisole
BHT	Butylated Hydroxyl Toluene
CV	Calorific Value
CO_2	Carbon Dioxide
CO	Carbon Monoxide
cSt	Centistokes
CP	Cloud Point
CFPP	Cold Filter Plug Point
CI	Compression Ignition
°C	Degree Celsius
°C	Degree Celsius
°CA	Degree Crank Angle
EN	European Union Standards
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FAME	Fatty Acid Methyl Ester

FSSAI	Food Safety and Standards Authority of India
FTIR	Fourier Transform Infrared
FFA	Free Fatty Acids
GC-MS	Gas Chromatography Mass Spectrometry
g/kWhr	Gram per KiloWatt hour
HRR	Heat Release Rate
h	Hour
HC	Hydrocarbon
IS	Indian standard
IEA	International Energy Agency
J/kg	Joules/Kilogram
Kg	Kilogram
kW	Kilowatt
ltr	Litre
MJ/kg	Mega Joules / Kilogram
MMT	Million Metric Tonnes
MUFAs	Monounsaturated Fatty Acids
NB	Neem Biodiesel
NO	Neem Oil
NO	Nitrogen-oxide
OSI	oil Stability Index,
NOx	Oxides of Nitrogen
PM	Particulate Matter
ppm	Parts per million
PiVH	Pivalic Hydrazide
PUFAs	Polyunsaturated Fatty Acids

PP	Pour Point
P-ϴ	Pressure-Crank Angle
PG	Propyl-gallate
PY	Pyrogallol
RUCO	Repurpose Used Cooking Oil
RPM	Revolutions Per Minute
SFAs	Saturated Fatty Acids
SO_2	Sulphur-di-oxide
TBHQ	Tert-butylhydroxyquinone
UNFAs	Unsaturated Fatty Acids
VCR	Variable Compression Ratio
v/v	Volume by Volume
WCO	Waste Cooking Oil
WCB	Waste Cooking Oil Biodiesel
wt	Weight
w/w	Weight by Weight
WEO	World Energy Outlook

CHAPTER 1

INTRODUCTION

1.1 Motivation

India depends heavily upon imported crude oil to meet its energy needs. In order to enhance and bolster energy security, India must adopt measures of diversification in the field of energy sources with an emphasis on reducing dependence on fossil fuels, mainly imported oil. India faces significant environmental changes, ranging from air pollution, climate changes to emissions from greenhouse gases, etc. Burning fossil fuels increases air pollution and is one of the prominent reasons for greenhouse gas emissions, particularly in the transportation sector. Fossil fuels, particularly diesel, are associated with air pollution and significantly threaten public health. Diesel engines emit pollutants, which can contribute to respiratory hazards, cardiovascular diseases, and other associated and varied health problems.

India is an agrarian country with a vast agriculture sector. Agriculture residues, non-edible oil seeds, and waste can create additional income streams for farmers and rural communities which not only contribute towards the overall development of rural communities but also assist in measures of poverty alleviation and mitigating rural-urban migration. It is worthwhile to mention that India is also a signatory to several international conventions and initiatives focused on methods of sustainable development, mitigating the ill effects of climate change, and promoting renewable energy. Shifting to alternative fuels can help mitigate these environmental issues and bring forth the positives of improved air quality, leading to the betterment of public health and reducing vulnerability to global oil price fluctuations and geopolitical risk. Moreover, India has abundant renewable resources, which can be harnessed to produce alternative fuels, thereby reducing dependence on costly oil imports.

1.2 World Energy Scenario

The world's energy sector is at present going through a transition due to several factors. As nations strive to cater to escalating energy requirements of an ever-increasing population, there is an urgent need to address the pressing concerns of sustainable and clean energy sources. Environmental issues, technological growth, governmental changes, and changing market dynamics are the main forces behind this transition. Alternative fuels have shown considerable promise in mitigating carbon emissions, bolstering energy security, and promoting a more sustainable energy environment. This study aims to comprehensively examine the present condition of the primary energy situation, highlighting the significance of alternative fuels in pursuing a more environmentally friendly and sustainable energy future [1, 2].

1.3 Global Energy Consumption

There has been a notable rise in worldwide energy demand and consumption in recent decades due to fast industrialization, a growing population, and rising urbanization. As the world's population continues to rise and emerging economies seek to develop, it is more important than ever for policymakers, businesses, and stakeholders to fully understand the dynamics of energy demand and consumption. Figure 1.1 displays the top six countries' primary energy consumption in exajoules from 1995 to 2050. Energy consumption worldwide was 399 exajoules in 1995, scaled to 627 exajoules in 2019, and is predicted to increase by 666 exajoules by 2050. India's primary energy consumption has risen significantly over the years. Specifically, between 1995 and 2019, the consumption increased from 16 exajoules to 42 exajoules, representing a substantial growth of 162.5%. Projections indicate that this upward trend is predicted to continue, with an expected accelerated consumption rate of 109.52%, as stated in the World Energy Outlook 2023 [3].

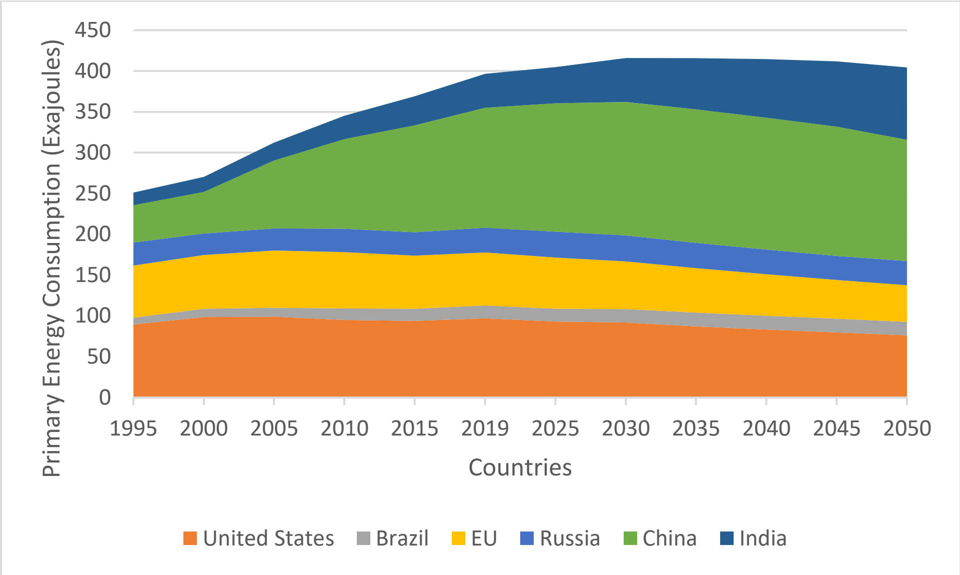


Figure 1.1: World's top energy consumers' primary energy consumption, 2023 (BP statistical evaluations of world energy, 2020)

The energy demand worldwide has been continuously upward, driven by various factors. The transportation sector, especially in emerging economies, has witnessed a substantial surge in energy recruitment. This surge can be attributed to the rising number of vehicles on the road. To address these increasing energy demands, alternative fuel options, such as biodiesel, must be explored, which can significantly reduce the dependence upon traditional fossil fuels.

Meeting the ever-increasing global demands for energy faces several challenges. First, a switch to cleaner and more sustainable sources of energy is necessary due to the finite reserves of fossil fuel as well as worries about climate changes and environmental deterioration. In this regard, there is an increasing focus on renewable energy sources and measures of improving energy efficiency to address the challenges associated with energy demand and consumption requirements. The declining cost of renewable technologies has made them more economically viable alternatives to fissile fuels. Governments and organizations worldwide implement policies and incentives to promote individual energy development.

1.4 Renewable Energy Growth

The world energy situation has been significantly improved by the rapid expansion of sources of renewable energy viz. solar, wind, hydro, biomass, etc. These renewable energy sources have witnessed remarkable advancements and cost reductions, thereby making them highly competitive and at par with fossil fuels. Notably, the reduced costs of renewable technologies, supporting government policies, and commitments by the international community to reduce emissions by greenhouse gases have made a significant impact in advancing the adoption of renewable energy sources. The transition towards sustainable energy has opened the path for the utilization and development of new sources of energy [2, 4]. Figure 1.2 makes a comparison between the total primary energy consumption of different fuels by the world in 2019 and 2020.

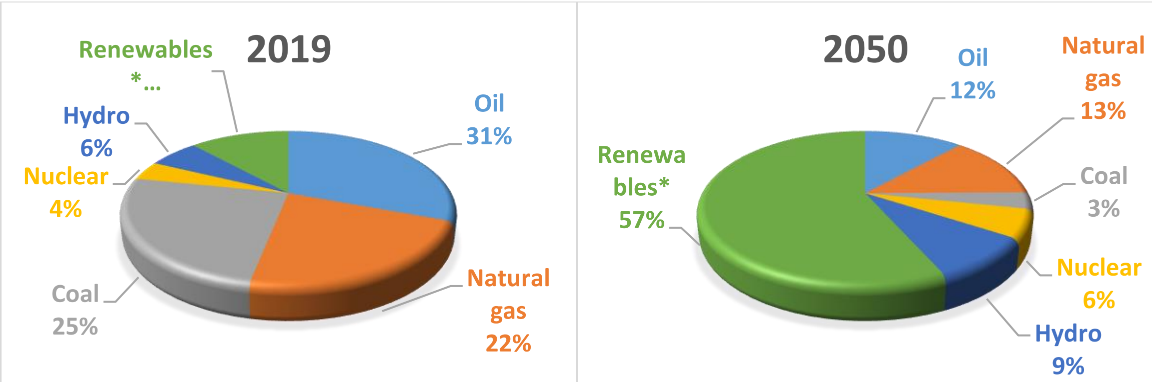


Figure 1.2: Total primary energy consumption of different fuels in 2019 and 2020 [B.P. stats review 2021]

The world energy consumption of renewable fuel in 2019 was 28.82 Exajoules which increased to 31.71 Exajoules in 2020 [1]. As per the estimates of World Energy Outlook

(WEO), the demand for Global energy is slated to grow by around 1% annually between 2019 and 2040, led by population and economic growth in developing nations. Oil and gas will remain the most prominent energy sources, accounting for around 55% of the global energy mix in 2040. However, the portion of oil in this combination is expected to decline from 33% in 2019 to 28% in 2040 as demand for transportation fuels shifts towards renewable energy proposed by International Energy Agency (IEA) [5].

1.5 India Energy Scenario

The energy scenario in India is of immense significance due to its rapidly growing economy, increasing population, and evolving energy needs. As the third-largest emitter of greenhouse gases and one among the top consumers of energy worldwide, India's energy sector is crucial in shaping the nation's development trajectory and addressing global climate change concerns. In recent years, India has been actively exploring alternative fuel options to slash down its dependency upon on fossil fuels by adopting procedures to allay the environmental effect of its energy intake [3, 6].

1.6 India's Energy Demand

In recent years, India's energy demand has witnessed remarkable growth. With our rapidly expanding middle class and increasing urbanization, there has been a surge in primary energy consumption for various purposes. Additionally, the transportation sector has experienced a sustainable rise in energy demand due to the growing number of vehicles on the road. The industrial sector, including manufacturing and industries, contributes to India’s energy consumption. Meeting this surging energy demand poses significant challenges [7]. Firstly, India heavily relies on fossil fuels; this dependence on non-renewable sources presents environmental challenges, including air pollution and greenhouse gas emission. India has embarked on an ambitious renewable energy development program to address this [3, 8, 9]. Figure 1.3 illustrates the energy demand of India measured in million tonnes of oil equivalent spanning the period from 2010 to 2040. The country's primary energy demand exhibits a significant rise, escalating from 700 Mtoe in the year 2010 to 1573 Mtoe in the year 2040. The energy demand from various sources, including oil, coal, natural gas, hydroelectric power, nuclear power, biomass, and other different sources of renewable energy, demonstrates varying increases over the same time frame. Energy demand from several sources, coal, oil, natural gas, nuclear, hydro, biomass, and other sources of renewable energy increased from 413, 242, 55, 10, 15, 182, 11 to 541, 411, 173, 58, 26, 204,160 in Mtoe respectively [3].

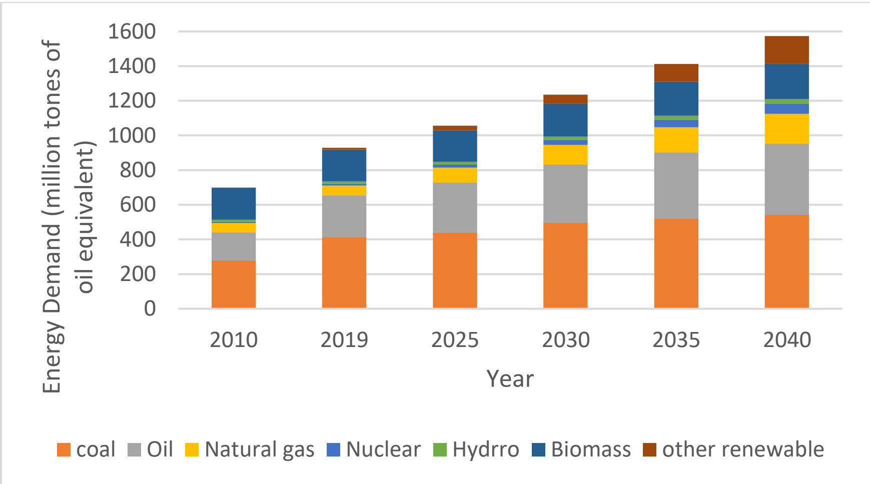


Figure 1.3: Energy Demand of various fuel sources in India

India's oil import dependency has been growing, and it is one of the biggest importers of crude oil globally. The oil is imported from various sources, including Middle East Africa and other oil-producing regions. India is not a major oil-producing country compared to other oil-rich nations. It has limited domestic oil reserves and relies heavily on imports for energy recruitment. Due to population growth, urbanization, and rising economic development, India's oil consumption has risen consistently throughout time. The transportation sector, including road, air, and rail, accounts for a substantial portion of oil consumption in India [2, 7]. Figure 1.4 depicts oil production capacity and consumption by various regions in terms of billion barrels per day. The industrial and commercial sectors also contribute to the country's oil ads. As mentioned earlier, the agriculture sector heavily relies on diesel fuel, which further to the overall oil consumption in India.

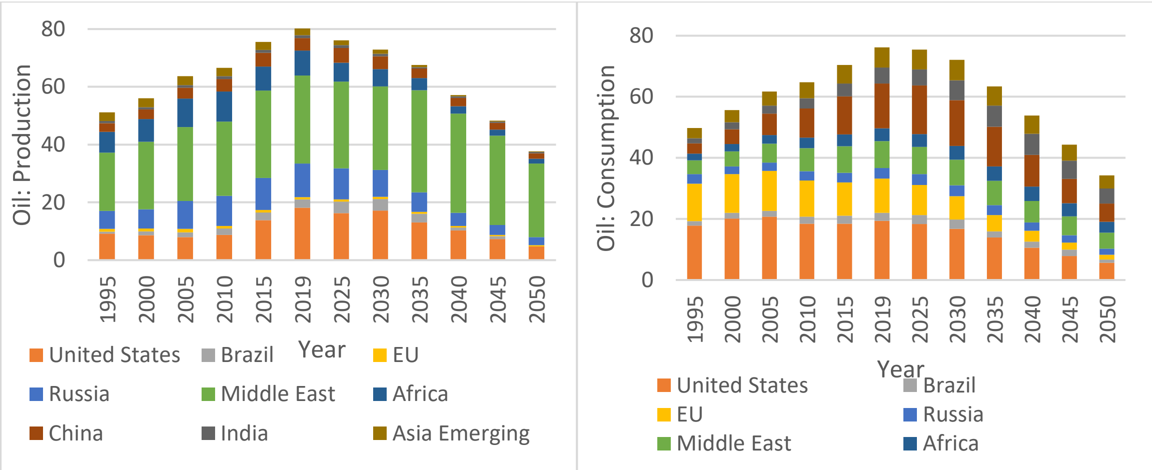


Figure 1.4: Oil production and consumption by various regions in a million barrels per day

In 2019, India's average oil production stood at 1 billion barrels per day, while its oil consumption reached 5 million barrels per day. Despite efforts to boost domestic production, India still relied heavily on foreign sources to bridge the gap. However, in the upcoming year 2050, India's oil production has declined to zero million barrels per day, while consumption has remained constant at 5 million barrels per day. This sudden drop in domestic prediction further exacerbates India's reliance on imported oil. By inducing the process of diversification in energy mix and reducing its dependency on imported oil, India gets to improve energy security, mitigate economic vulnerabilities, and facilitate the path for a balanced, suitable, sustainable, and self-reliant energy future.

Table 1.1: Comparison of oil production and combustion between 2019 to 2050 [2, 4]

Million barrels per day	2019		2040		2050	
	Production	Consumption	Production	Consumption	Production	Consumption
United States	18	19	10	11	5	6
Brazil	3	3	1	2	0	1
EU	1	11	1	4	0	2
Russia	12	3	5	3	3	2
Middle East	30	9	34	7	25	5
Africa	9	4	3	5	2	4
China	4	15	3	10	2	6
India	1	5	1	7	0	5

1.7 Diesel Engine Economy

India's economy heavily relies on diesel fuel, particularly in the agricultural, power, and transportation sectors. As the third-largest energy consumer globally, India has become dependent on importing diesel fuel due to its diesel-driven economy [10]. China and the United States hold the top two positions as energy consumers. Approximately two million compression-ignition (CI) engines, as per an estimate, are utilized in the sector agriculture alone, emphasizing the country's reliance on diesel fuel [8, 11].

However, relying heavily on fossil fuels presents numerous concerns for India. The depletion of its reserves has become a significant & urgent issue. The escalating diesel fuel costs compound the problem, resulting in heightened economic instability. In addition, burning fossil fuels contributes immensely to environmental degradation and climatic changes. This emphasizes the urgent need for a sustainable alternative fuel source in India [12].

India must look for practical diesel fuel substitutes to overcome these difficulties and foster economic resilience while taking environmental considerations. By implementing a strategy of energy source diversification, the nation can effectively mitigate its dependence on imported diesel fuel and develop a more sustainable and self-reliant energy sector. This transition would enable India to effectively address the consequences of diminishing fossil fuel reserves and positively contribute to environmental preservation [2, 11]. A diesel engine's economy refers to its overall effectiveness and cost-efficiency in fuel consumption and performance. Because of their excellent thermal efficiency, dependability, performance, and emissions, diesel engines are widely employed in various industries, including transportation, industrial uses, and power production.

1.8 Renewable Energy Growth in India

The expansion in the field of renewable energy in India has witnessed remarkable advancements in recent years, solidifying the nation's position as a leading contender in the international pursuit of environmentally friendly and sustainable energy alternatives. The Indian government has demonstrated a comprehensive awareness with regard to the importance of clean energy for attaining sustainable development over the long term. Consequently, it has implemented proactive measures to promote the widespread utilization of sources of renewable energy. The government has effectively facilitated the shift towards a more environmentally sustainable future by implementing several policies, initiatives, and targets. Additionally, the focus on alternative fuels such as biodiesel has played a crucial role in diversification of energy mix along with diminishing dependence on fossil fuels [8, 11, 13, 14]. Figure 1.5 shows renewable energy consumption worldwide for major contributor countries from 1995 to 2050 in exajoules. Every scenario shows a significant increase in renewable energy, with annual growth rates averaging 4–6%. So, in 2050, in the Accelerated and Net Zero scenarios and the New Momentum scenario, renewable energy will become the most significant primary energy source [3, 15].

To reduce emissions and protect the environment from hazardous pollutants, the automotive industry is changing considerably and moving away from conventional fuel-based vehicles. This transition will require updates for numerous cars powered by diesel engines. Biodiesel has emerged as a highly promising alternative, demonstrating a smooth transition due to its compatibility with regular diesel engines with no requirements of any modifications. Biodiesel serves as a source of fuel that is both renewable and biodegradable and has the additional characteristic of being non-toxic. Its major advantage exists in the point that it tends to produce fewer hydrocarbon emissions and carbon monoxide in huge contrast to traditional diesel fuel because of increased oxygen content [16–18].

India has abundant feedstock resources that can be effectively utilized for biodiesel production. Non-consumable oilseed crops, including jatropha, pongamia, mahua, neem, and waste cooking oil, have favorable characteristics for the generation of biodiesel and can be effectively grown on less fertile terrain. These crops have the distinction of not competing with the food crops for the purpose of acquiring agricultural land and offer a

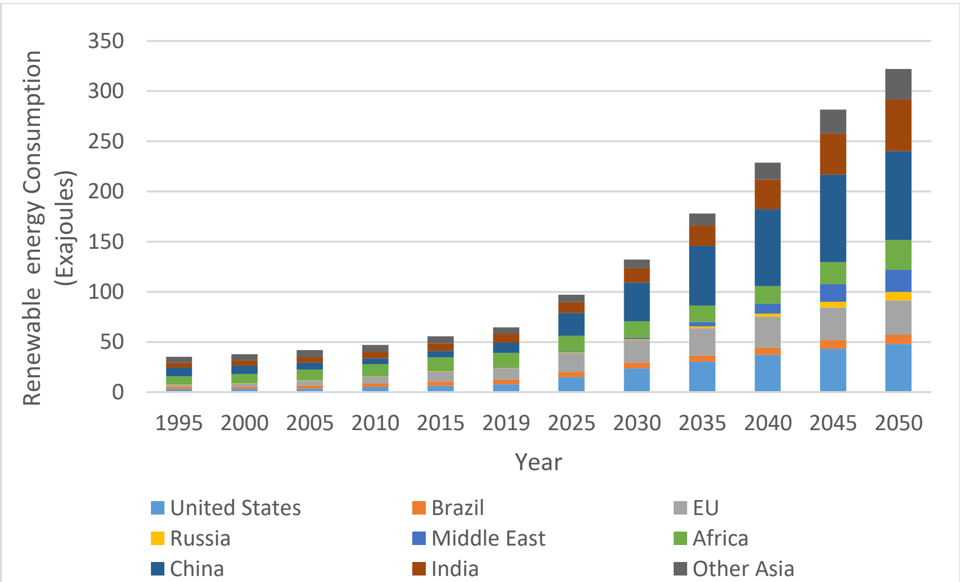


Figure 1.5: Leading countries consuming primary renewable energy in 2023 [BP statistical reviews of world energy, 2023]

sustainable feedstock option for the production of biodiesel. In addition, cultivating biodiesel feedstock crops can provide financial gains for agriculturalists and contribute to the advancement of rural areas [19, 20]. India is experiencing a consistent rise in its capability of producing biodiesel. Numerous entities from both the governmental and private sectors, as well as cooperative groups, have made substantial investments in establishing biodiesel manufacturing plants. State governments' establishment of biodiesel plants aims to boost domestic output and lessen reliance on imported fossil fuels. Biodiesel production has increased due to these initiatives, improving India's energy security and lowering its dependency on conventional fuel [21].

The commitment of the Government to promoting the usage of biodiesel as fuel is evident through the implementation of blending regulations. India has established a goal of incorporating 5% biodiesel into diesel fuel by 2030, as outlined in the biodiesel amendment of 2022. This development has substantial market potential for producers of biodiesel. Blending biodiesel has been shown to effectively decrease greenhouse gas emissions and bolster energy security by diminishing the nation's reliance on imported fossil fuels. Implementing this blending requirement has stimulated the allocation of resources toward the development of biodiesel infrastructure and facilitated the establishment of a viable market [8, 22].

1.9 Biodiesel Economy, Utilization, and Application

Biodiesel, a sustainable and renewable fuel made from organic feedstocks, has garnered considerable interest as it may serve as a substitution for traditional diesel fuel. Biodiesel has emerged as a possible alternative which may help in lessening the dependency on fossil fuels and reduction in emissions caused by greenhouse gases in response to worries about climate change, environmental sustainability, and energy security. Biodiesel economic viability relies upon the availability of feedstock that is used to produce biodiesel. Biodiesel production requires a specialized processing facility. To promote biodiesel production and consumption, many countries provide tax rebates, grant, and mandates. These policies play a pivotal role in maintaining the viability of biodiesel economics. Demand for biodiesel is affected by government policies, variations in fossil fuel prices, and customer preference towards sustainable fuel. Figure 1.6 depicts the global biodiesel production from 2010 to 2020, measured in thousands of oil barrels equivalent per day. The US, Europe, and the nations of the Asia Pacific area were predicted to contribute the most to the production of biodiesel in 2020. Between 2010 and 2020, the total amount of biodiesel produced increased from 300 thousand oil barrels equivalent per day to 716 thousand oil barrels equivalent per day [3, 4, 15].

Biodiesel presents a variety of economic benefits that contribute to its increasing use. This initiative offers the potential to broaden the range of energy sources and decrease reliance on imported fossil fuels, thereby increasing energy security and mitigating exposure to

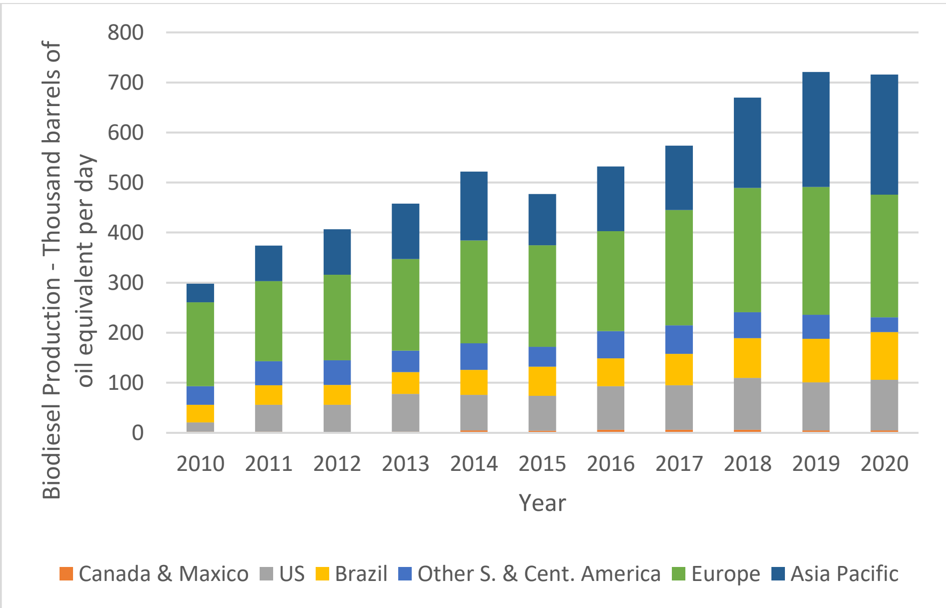


Figure 1.6: Represents the global production of biodiesel for major contributor countries

unpredictable oil prices on the international market. In addition, the production of biodiesel and its usage contribute to stimulating of local economies through the promotion of agricultural activities, the creation of employment possibilities, and the facilitation of rural development. Cultivating biodiesel feedstocks creates a value chain involving farmers, processors, and distributors, fostering economic expansion and enhancing the quality of life in rural regions. Furthermore, Figure 1.7 also presents biodiesel consumption in the leading countries. The top three biodiesel consumers in 2020 were Canada, Mexico, Europe, and the Asia Pacific [4, 15].

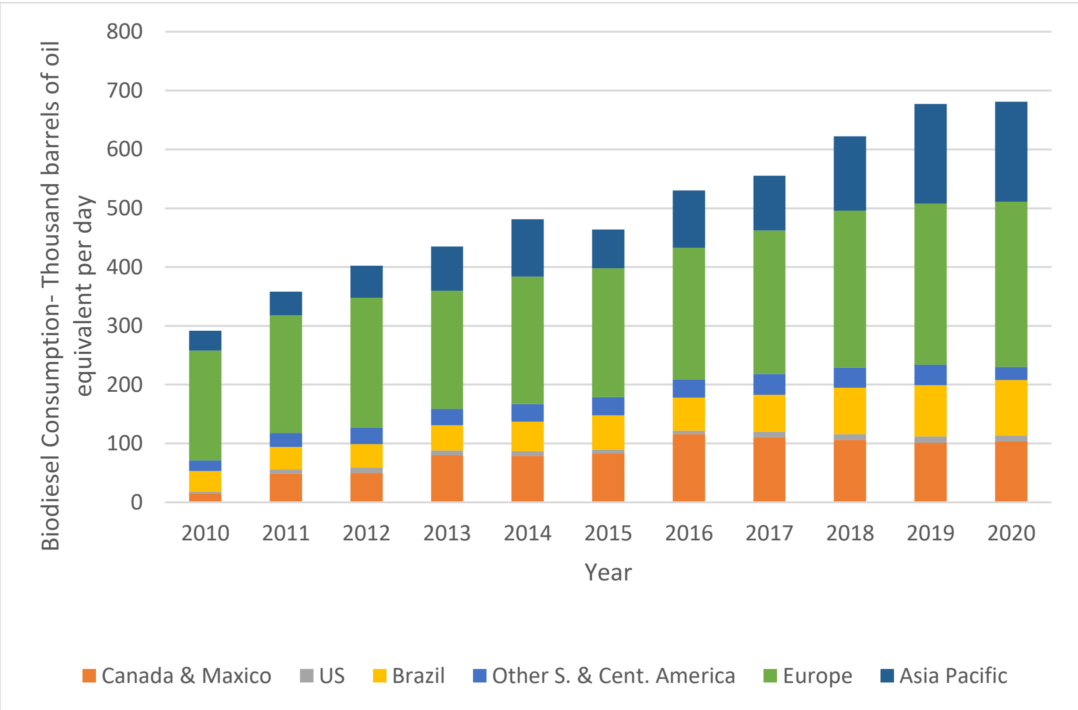


Figure 1.7: Represents the global consumption of biodiesel among the significant contributor countries

1.10 Biodiesel Economic Benefits

Energy Security: Biodiesel reduces dependence on fossil fuels, thereby improving energy security by diversifying the fuel supply. It reduces reliance on imported petroleum, mitigates geopolitical risks, and promotes domestic renewable energy production [11].

Job Creation: Employment possibilities are created all throughout the value chain as a result of the production and consumption of biodiesel. Biodiesel has the potential to create employment opportunities in both rural and urban areas across the whole value chain, from the production of feedstock to its processing, distribution, and retail sale [21].

Agricultural Sector Support: Biodiesel production requires the availability of feedstocks viz. animal fats, vegetable oils, and used cooking oil. This creates market opportunities for farmers, oilseed producers, and agricultural communities, providing additional revenue streams [10].

Economic Development: Biodiesel production facilities and associated industries contribute to regional economic development. Investments in biodiesel infrastructure, research and development, and manufacturing plants stimulate economic growth and attract capital inflows [8, 21].

Price Stability: Biodiesel offers price stability compared to petroleum diesel, as it is less susceptible to global oil price fluctuations. This stability can benefit consumers and industries by providing predictable fuel costs and reducing vulnerability to market volatility [8].

1.11 Problems Associated with Biodiesel

Biodiesel, characterised by serving as a substitute to Petro diesel offers twin advantages of being renewable and as well as environmentally friendly, possesses similar fuel quality parameters but is prone to deterioration when kept for an extended duration of time. The decline in the properties of biodiesel is primarily affected by several factors like oxidation, contaminants, temperature, and exposure to light. These factors contribute to various problems associated with biodiesel, particularly its oxidation stability which is regarded as the capacity of a fuel to withstand oxidation. This chemical reaction occurs as a result of the interaction of fuel with oxygen manifested in light or heat presence. The abundance of unsaturated fatty acid chains in biodiesel, resulting from its chemical composition, makes it more vulnerable to oxidation. Unsaturated bonds in biodiesel render it more vulnerable to oxidation than Petro diesel, primarily comprising saturated hydrocarbons [23–26]. The oxidation of biodiesel has several negative impacts that become obvious. Since biodiesel tends to darken over time due to the development of oxidation products, this color change is one noticeable change. In addition, the oxidation process can cause deposits to accumulate, clogging filters and other fuel system components. These deposits may harm engine performance and result in problems [27].

The loss of fuel clarity caused by biodiesel oxidation is another side effect. Byproducts of oxidation can make biodiesel cloudy or generate particulate matter, limiting fuel efficiency and increasing the risk of engine damage. Additionally, oxidation might produce acidic chemicals that may hasten the corrosion of fuel system parts and storage tanks, aggravating biodiesel degradation [28–31]. To address the challenges associated with biodiesel oxidation stability, researchers and industry experts have focused on various approaches. Antioxidants, such as synthetic additives or natural antioxidants derived from plants, can be incorporated into biodiesel formulations to enhance oxidation resistance. Additionally, improved storage and handling practices, including nitrogen blanketing and appropriate tank materials, can help in minimizing the oxidation of biodiesel and further its shelf life [32–34].

1.12 Antioxidants

Biodiesel is shielded from oxidation by antioxidant compounds, which work in various ways. By breaking the chains of events that free radicals started, they function as free radical scavengers. Antioxidants stop the spread of oxidation reactions and reduce the production of oxidative products by neutralizing these highly reactive molecules. To prevent oxidation, biodiesel has a variety of antioxidant components. Synthetic antioxidants like butylated hydroxy anisole (BHA) and butylated hydroxytoluene (BHT) are one popular type [33–38]. These compounds are potent antioxidants that work to stop the production of free radicals and peroxides. Synthetic antioxidants are frequently used because of their stability, cost-effectiveness, and compatibility with biodiesel. Natural or plant-based antioxidants are another type of antioxidant addition utilized in biodiesel. These include phenolic compounds, tocotrienols, tocopherols (vitamin E), and other natural extracts. Natural antioxidants are more environmentally friendly than synthetic antioxidants and are obtained from plant sources. They have excellent antioxidant properties and can raise biodiesel's oxidative stability [39].

Antioxidants also protect fuel quality while being transported and distributed, lowering the chance of clogged fuel systems and engine performance problems. Antioxidant additives are essential for ensuring dependable engine performance and reducing maintenance needs. Antioxidants assist in reducing fuel filter blockage, injector fouling, and engine deposits by inhibiting the growth of deposits and gums—this results in better fuel atomization, increased combustion effectiveness, and lower emissions. Additionally, antioxidants can aid in preventing oxidative reactions from causing fuel system components to corrode, extending the engine's life and reliability [32, 34].

1.13 Organization of the Thesis

The dissertation consists of five chapters. The framework and organization of these chapters is mentioned below:

Chapter 1: Introduction

It presents an outline of the research work carried out. It begins with the current energy scenario, diesel engine and their relevance, energy outlook, and motivation of this work. This chapter includes problems associated with biodiesel and their possible solutions. This chapter also provides a background of antioxidants, their types, and their uses. The thesis's introduction explains antioxidants' role in enhancing biodiesel's oxidation stability. Chapter 1 closes by introducing different antioxidants, their importance, and their utilization in biodiesel to evaluate their characteristics related with performance, emission, and combustion.

Chapter 2: Literature Review

This chapter discussed the detailed literature associated with the production of biodiesel, and its performance, and includes literature on the emission analysis of different biodiesels. The literature review also shows the impact on oxidation stability, physicochemical properties, performance, emission, and combustion after adding antioxidant with biodiesel. Challenges relating to biodiesel usage and antioxidant addition in biodiesel in CI engines are the focus of reviewing the literature. Available literature shows types of antioxidants, possible antioxidant dosage, and their impact.

Chapter 3: System Development and Methodology

The chapter gives a detailed process of production of biodiesel by means of esterification and transesterification from non-edible biodiesel. Here, the characterization of non-edible biodiesel is also discussed. Instruments for finding physicochemical properties and their prepared blend values are explained in detail. Preparation of antioxidants in biodiesel in different dosages, devices used for finding oxidation stability, and their principle described in detail. Also, the system development for evaluating performance, emission, and combustion are given therein.

Chapter 4: Result and Discussion

This chapter is dedicated with the deliberations on all experimental outcomes carried out by performance trials on diesel engines. All the performance characteristics, emission, and combustion results for different biodiesel with and without antioxidant addition (synthetic and natural antioxidant) were evaluated and compared with base-line diesel. Detailed discussion and analysis of their finding were reported with available literature review citations. Prediction analysis of performance and emission is also performed by the ANN method.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In earlier chapter, the crucial role played by diesel in global economy was highlighted. However, the increasing dependence on these engines and the resulting environmental degradation pose significant concerns for their sustainability. Integrating a biodiesel economy is a feasible solution to save millions of existing diesel engines. Enhancing the usability of biodiesel through the concept of antioxidants holds promise in augmenting the performance standards of engine and emission attributes portrayed by biodiesel and its blends in compressed ignition engines. This chapter gives an overview of Indian-origin-based biodiesel and potential feedstocks that can be utilized for biodiesel production. This chapter also enumerates biodiesel standards, limitations, antioxidants, oxidation stability, and the impact of antioxidants upon oxidation stability, performance, emission, and combustion. The outcome of the exhausted literature review, research gap, and objectives are also highlighted in this chapter.

In today's world, increased temperature, climate change, global warming, and pollution have become a matter of concern. Many researchers are working towards protecting the environment by dealing with these problems mainly caused by transportation pollution. Diesel fuel plays an essential role in our daily life in modern society by using it in the public and private transportation sectors. Diesel engines, on account of offering better fuel economy, delivering high efficiency and energy production, are the most widely employed gasoline engine in the transportation field. Although diesel engines adversely affect the environment, human health, and well-being [40]. Apart from many advantages of diesel fuel used in engines, it produces incomplete and undesirable by-products in the form of Nitrogen oxides (NOx), Hydrocarbons (HC), Carbon monoxide (CO), Sulfur Oxide (SOx), Particulates matter (PM) and Smoke [41]. Due to the enormous availability of diesel vehicles, massive pollution produces in the atmosphere. These problems come from diesel forced to find alternative energy resources such as Bioenergy. Renewable energy as bioenergy is considered beneficial for industrial and commercial applications because a clean energy source solves environmental issues [3, 4].

2.2 Biodiesel

Biodiesel (mono-alkyl ester) is a liquid biofuel made from multiple natural resources, ranging from vegetable oils, both edible & inedible, animal fats, residual cooking oil, etc. It has also been established that Different edible & non-edible vegetable oils are predominantly employed for biodiesel production [14, 43–45]. Biodiesel has several advantages over diesel fuel, like renewable, less toxic emission, higher combustion efficiency, higher lubricity, and being environmentally friendly. Most importantly, the use of biodiesel reduces dependency on imported petroleum fuel. Further, the properties showcased by biodiesel are comparable with those displayed by diesel thus facilitating its direct use in diesel engines with no modification required [46]. Apart from having lower energy content, a few problems associated with biodiesel are increased NOx emission, low engine speed, higher viscosity, high pour, and cloud point, and low stability, and low engine power [6,7]. These problems associated with biodiesel can be improved by combining additives to it. These additives are pivotal in enhancing the quality and improved performance in biodiesel properties [47]. Further biodiesel stability is characterized in terms of storage stability, thermal stability and oxidation stability. Oxidation stability is affected by double bonds existing within chains of fatty acid chain because of the formation of insoluble sediment and gum in biodiesel [48]. Oxidation stability can be improved by using antioxidants. Antioxidants are also known as free-radical scavengers as they prevent the development of radicals or unstable molecules [49]. Further, the oxidation stability exhibited by Tilapia oil biodiesel was improved by adding natural antioxidants (ethanolic extract of turmeric) and synthetic antioxidants like propyl gallate, butylated hydroxyl toluene, butylated hydroxyl anisole. Approximately similar results are obtained by Propyl gallate and natural antioxidants [50].

The structure of fatty acid profiles both physical and chemical, directly influences the qualities of oil utilized in the production of biodiesel. Fatty acids are further categorized into mainly two distinct types, saturated and unsaturated, as indicated by previous research [51]. The combination of polyunsaturated and monounsaturated fatty acids produces unsaturated fatty acids. Unsaturated acids with high levels of unsaturation exhibit a greater susceptibility to oxidative degradation. Conversely, including saturated fatty acids cause diminished low-temperature characteristics [52, 53]. Binary mixtures of different biodiesels like sunflower, corn, cottonseed, soybean, colza, and residual cooking oil improve low oxidation stability among these biodiesels [54–56]. The oxidation stability exhibited by sunflower biodiesel was enhanced by mixing 60% of soybean biodiesel to meet the standard. Colza found the most effective blender for biodiesel [57]. Citrullus colocynthis biodiesel and camelus dromedaries' fat biodiesel are blended in different proportions to improve oxidation stability [58].

Both methods can improve Oxidation stability by using antioxidants and altering the fatty acid profile by blending biodiesel. The usage of synthetic antioxidants is proposed by many researchers for improving biodiesel performance, and few have worked towards natural antioxidants to do the same.

2.2.1 Indian-origin feedstock for biodiesel production

Biodiesel is characterized as a sustainable fuel source derived from vegetable oils and animal fats. It is found to be a much better substitute for existing conventional petroleum diesel fuel and more environmentally friendly due to its better combustion properties [59–61]. Biodiesel can be categorized into two distinct types, namely conventional biodiesel, and advanced biodiesel, which are differentiated based on the particular raw materials utilized for their production [62–64]. The production process of conventional biodiesel by means of using vegetable oils and animal fats through a chemical process, known as transesterification. Advanced biodiesel is produced from several non-food sources like algae, waste grease, and other cellulosic materials [13, 44, 65]. Different generations of feedstocks are shown in Table 2.1. There are three generations of feedstocks meant to produce biodiesel.

Table 2.1: List of Indian-origin feedstocks for biodiesel production as per categories

First Generation (Edible Vegetable Oils)	Second Generation (Non-edible Sources and Animal Fats)	Third Generation (Biomass from Microalgae)	Non-Plant Sources
Sunflower	Jatropha	Microalgae and macroalgae	Waste Cooking Oils from restaurants and households
Soybean	Karanja		Used Engine Oils
Mustard	Mahua		
Palm	Neem		
Canola	Castor		
Coconut	Rubber Seed		
Corn	Animal fats		
Cottonseed			
Olive			
Peanut			
Rapeseed			

Edible oil is not a viable feedstock for the generation of biodiesel because it competes with meals supplied by edible oil sources. However, it is advisable to prefer using non-edible feedstocks as the primary resource for biodiesel synthesis owing to their significant availability. The primary feedstocks utilized for biodiesel manufacturing are non-edible and waste cooking oil. In India, land cultivation of plants like jatropha, Karanja, and mahua gained attention as they are non-edible plants that can be grown in semi-arid areas with minimum irrigation. These plants offer sustainable feedstock options for biodiesel production, particularly in rural areas. Tables 2.2 to 2.7 show Indian-origin feedstock used for biodiesel production with their plant details, including yield and oil content [16, 45, 66–68, 69]. WCO is regarded as an essential feedstock when it comes for producing biodiesel

Table 2.2: Detail representation of the Jatropha tree and seed

	Jatropha	Tree	Seed
Scientific Name	Jatropha curcas		
Tree Type	Tree		
Crop Type	Seed		
Yield per year	2500 kg/ha		
Oil content	40-50 %		

Table 2.3: Detail representation of the Karanja tree and seed

	Karanja	Tree	Seed
Scientific Name	Millettia pinata		
Tree Type	Tree		
Crop Type	Seed		
Yield per year	900-9000 kg/ha		
Oil content	30-50 %		

Table 2.4: Detail representation of the Mahua tree and seed

	Mahua	Tree	Seed
Scientific Name	Madhuca longifolia		
Tree Type	Tree		
Crop Type	Seed		
Yield per year	20-200 kg/ha		
Oil content	35-50 %		

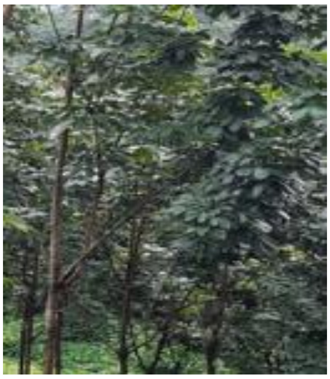
Table 2.5: Detail representation of Neem tree and seed

	Castor	Tree	Seed
Scientific Name	Azadirachta indica		
Tree Type	Tree		
Crop Type	Seed		
Yield per year	2670 kg/ha		
Oil content	25-45 %		

Table 2.6: Detail representation of Castor tree and seed

	Castor	Tree	Seed
Scientific Name	Ricinus communis		
Tree Type	Tree/shrub		
Crop Type	Seed		
Yield per year	450 kg/ha		
Oil content	45-50 %		

Table 2.7: Detail representation of Rubber tree and seed

	Rubber	Tree	Seed
Scientific Name	Hevea brasiliensis		
Tree Type	Tree		
Crop Type	Seed		
Yield per year	100-150 kg/ha		
Oil content	40-50 %		

in India. It is derived from repeated frying of food, which increases the content of free fatty acids (FFA) and makes it unsuitable for consumption [69–73]. Other waste oils and fats, such as animal fats, can also be used as feedstocks. It's worthwhile to mention that the choice of feedstocks used for producing biodiesel depend on multiple factors ranging from climatic and local soil conditions, percentage of oil content to yield percentage in a hectare.

Furthermore, the process of feedstock selection necessitates a thoughtful evaluation of factors such as sustainability, economic viability, and environmental impact. Opting for waste materials, such as used cooking oils, not only presents an economically sound feedstock choice but also serves as a valuable contribution to waste management and environmental conservation. India, as a nation, boasts a diverse range of feedstocks originating from various sources, encompassing both plant-based and residual waste materials, all of which can be efficiently harnessed for biodiesel production. The decision on which feedstocks to use hinges on several considerations, including their availability, cost-effectiveness, oil content, and overall sustainability.

2.2.2 Waste cooking oil: A Potential Feedstock

Waste cooking oil has always been a subject of considerable interest due to its environmental and economic benefits. Multiple salient aspects contribute to recognizing it a highly recognized and valuable resource.

Waste management: WCO, or waste cooking oil, is an organic waste product produced by homes, eateries, and food processing plants. Improper practices of disposing off the WCO lead to the obstruction of drainage systems. WCO may increase pollution levels and higher health hazards. India has the potential to effectively manage and recycle waste cooking oil by utilizing the same primary resource. This approach would result in significantly reducing the amount of WCO being released into aquatic ecosystems, decreasing environmental damage [9, 74].

Renewable Energy Sources: The method involving the transformation of waste cooking oil biodiesel into biodiesel is usually performed by a chemical procedure referred to as transesterification. Biodiesel, obtained as a derivative from waste cooking oil biodiesel, is observed to be an environmentally friendly energy alternative that has the potential to be utilized as a feasible substitution for conventional diesel fuel. Waste cooking oil biodiesel shows similar properties as diesel fuel, having benefit to utilize in same engine without modification. It may be regarded as a green choice in minimizing air pollution and fight climate change because it emits fewer hazardous pollutants and less carbon dioxide [74].

Energy security: India heavily depends on crude oil imports to fulfill its energy requirements. By employing WCO as a raw material for producing biodiesel, the nation could reduce its dependency upon fossil fuels which are usually imported, thus bolstering energy security and mitigating susceptibility arising from swings in global oil prices [69].

Economic benefits: Besides promoting a circular economy, using WCO as a feedstock generates revenue. It encourages the development of networks for WCO collection and recycling, which can provide employment and income for those engaged in biodiesel collection, processing, and manufacturing. Additionally, using biodiesel made from WCO can reduce the amount of money spent on importing crude oil [75].

Reduced carbon footprint: Biodiesel produced from WCO has a significantly lower carbon footprint than conventional diesel. The carbon emissions from burning biodiesel are offset by the carbon absorbed by the crops used to produce the feedstock. By adapting WCO as a feedstock, India can contribute to its commitments under the Paris Agreement and reduce greenhouse gas emissions.

Health and Environmental Benefits: Conventional diesel fuels emits pollutants such as sulfur oxides, nitrogen oxide, and particulate matter, which harm human health and the environment. Biodiesel produced from WCO has lower levels of these pollutants, resulting in improved air quality and reduced health risks for urban and rural populations [74].

Regulatory Initiatives: The Indian government has taken several regulatory initiatives to promote using WCO as feedstock. It has mandated the collection of WCO by licensed agencies and the use of a certain percentage of biodiesel in diesel blends. These policies create a favorable environment for WCO utilization and incentivize stakeholders to participate in WCO collection and recycling activities given by RUCO- an initiative by FSSAI.

The utilization of used cooking oil potential feedstock in India offers a range of benefits, including waste management, renewable energy production, energy security, economic growth, reduced carbon emissions, and improved health and environmental outcomes, by embarrassing WCO as a valuable resource, India can make significant progress towards sustainable development and contribute to a greener and cleaner future.

2.2.3 Waste cooking oil availability and consumption in India

The Food Safety and Standards Authority of India (FSSAI) introduced a novel program called Repurpose Used Cooking Oil (RUCO) on World Fuel Day in 2018. This effort aims to establish an effective system that facilitates the transformation of discarded cooking oil in biodiesel. According to the national biofuel policy, 2018, the utilization of biodiesel which is derived from non-edible feedstock and WCO is employed in various sectors such as transportation, stationary, portable, and other applications [74, 76–79]. The policy also establishes an indicative objective of incorporating a 5% biodiesel blend into diesel. The proposition is set to be implemented by the year 2030 [80]. India uses a significant quantity of 24660 ML yearly, making it the third-largest edible oil consumer globally. Among the total amount of edible oil, 40% is allocated for commercial use, specifically for the food and beverage industry, while the remaining 60% is intended for household consumption. During 2020-21, the import volume of edible oil amounted to 133.52 lakh tonnes, while the consumption volume reached 256.41 lakh tonnes.

Table 2.8: Total consumption and availability of edible oil along with biodiesel generation from waste edible oil (RUCO Booklet) [69]

	Consumption in liters	% of total consumption	Availability in liters crore	Potential Generation (Biodiesel)
Commercial	986.67	40%	148	15%
Household	1,480.00	60%	78	5%

A potential avenue for biodiesel production involves utilizing 15% of commercial and 5% of domestic edible oil. The Goods and Services Tax on biodiesel was reduced from 12% to 5% to encourage the use of WCO as a feedstock [69].

2.2.4 Neem oil: A Potential Feedstock

Neem oil is found to be possessing unique properties for protecting biodiesel and known as a potential feedstock due following reasons:

High Oil Content: Neem seeds contain a significant amount of oil, typically ranging from 30% to 45% of the seed's weight. This increased oil content makes neem oil an alternative feedstock for biodiesel production, as it ensures a good yield of biodiesel per unit of feedstock [66].

Non-Edible Feedstock: Neem oil is obtained from the seeds of neem trees, which are non-edible. Using non-edible feedstocks for biodiesel production helps prevent competition with food crops and supports sustainable agriculture practices [81].

Availability and Sustainability: Neem trees are widespread across India and may be found in various settings, including arid and semi-arid regions, which are often challenging environments for the growth of other oilseed crops. Neem seeds have a good content of oil availability from their seed. Neem plants can withstand periods of drought and can adjust to a variety of soil conditions; as a result, neem oil feedstock derived from these trees is a reliable and sustainable resource [13].

Environmental Benefit: Creating biodiesel from neem oil is associated with various benefits for the natural environment in its immediate vicinity. Neem trees canto successfully reduce back on emissions of greenhouse gases by absorbing carbon dioxide while they are in the process of growing. This occurs during the trees' life cycles. In addition, neem biodiesel has lower levels of sulfur and aromatics than regular diesel, which helps reduce air pollution and minimize emissions of dangerous pollutants. Neem biodiesel is produced from the seeds of the neem tree. Using neem oil for producing biodiesel reduces emissions coming out from the engine [82–84].

Blending and compatibility: neem biodiesel can blend in diesel in various proportions and be utilized for running diesel engines without any modification. Neem biodiesel can blend from 5% to 95% in conventional diesel, but as per available literature, B20 gives the best results. Due to this, neem biodiesel considers a versatile fuel used in diesel engines directly or by blending in existing diesel engines [82–84].

Renewable Carbon Neutral: Biodiesel produced from neem oil is considered renewable because it is derived from a plant source. Neem biodiesel is usually regarded as a carbon-neutral fuel. This same is attributed to the fact that CO_2 so released in the combustion process gets balanced by that carbon dioxide which neem trees absorb while growing [85, 86].

Beneficial By-products: biodiesel production from neem oil also left a valuable byproduct. Glycerol is produced as a byproduct during transesterification, followed by the esterification process. That can be utilized in various industrial products or converted into other valuable substances, contributing to the neem biodiesel industry's sustainability and economic viability [87, 88].

It is worth noting that while neem oil has several desirable characteristics for biodiesel production, it may require additional processing steps compared to some other feedstocks. Neem oil possesses considerably high free fatty acid (FFA) content, thereby affecting the biodiesel production process. Therefore, esterification or acid esterification may become necessary to be employed as pre-treatment to lower down the content of FFA before implementing transesterification process [85, 87, 89].

Neem oil possesses many attributes that bestow upon it unique characteristics to be regarded as potential feedstock employed for producing biodiesel in India. It possesses considerably high oil content, wide availability, non-edible nature, sustainability, environmental benefit, blending compatibility, and renewable nature which make neem oil an alternative option to produce biodiesel. However, further research and development efforts are required to optimize the production process and ensure the financial feasibility of neem-derived biodiesel as commercially viable alternative form of fuel.

2.2.5 Neem seed availability and collection in India

Neem tree has 25 to 45% of the potential availability of oil in its seed. Neem is a highly versatile crop with many uses in agriculture, medical treatment, cosmetics, and other fields. It is utilized as a natural insecticide in agriculture, insect deterrent, and fertilizer [83, 90, 91]. Neem oil is considered a non-edible feedstock as its having Azadirachtin, one of the poisonous components in the oil that has the pesticide characteristic and works as a powerful insecticide.

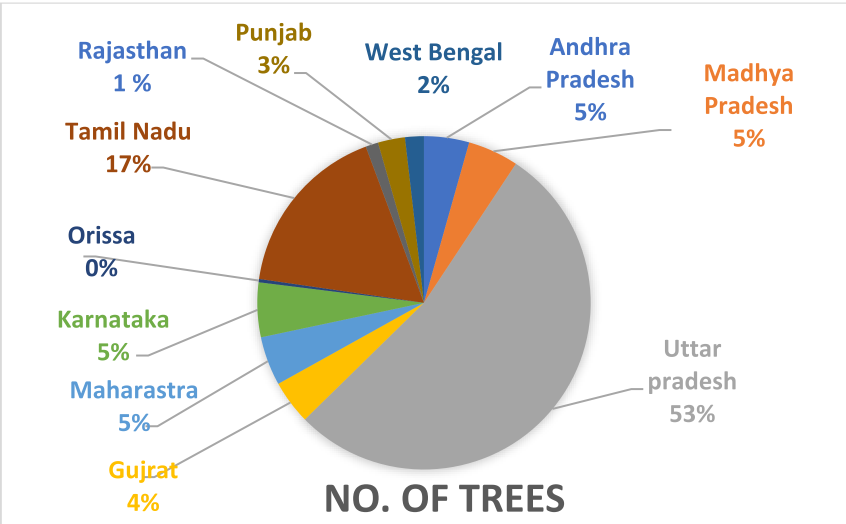


Figure 2.1: State-wise number of neem trees available [81]

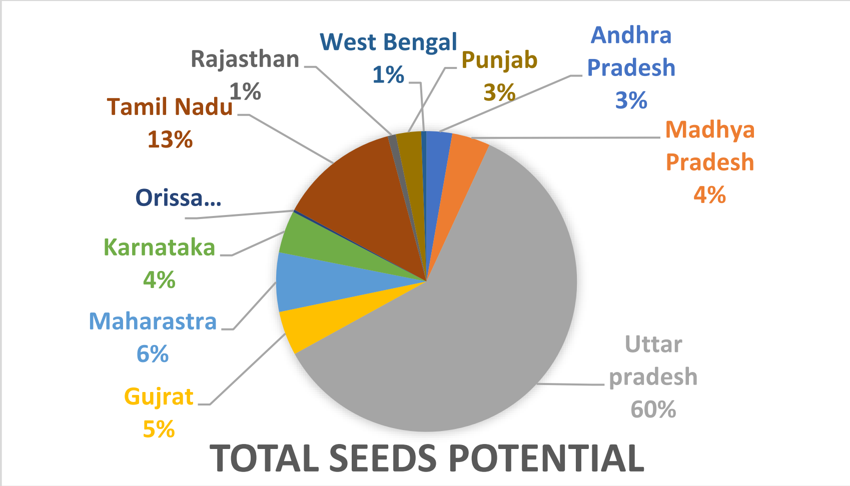


Figure 2.2: State-wise availability of neem seeds

The residual part of neem oil can be transformed into biodiesel using transesterification or esterification. In India, the majority of neem trees are found in Andhra Pradesh, Madhya Pradesh, Uttar Pradesh, Gujrat, Maharashtra, Karnataka, Tamandu, Rajasthan, Panjab, and West Bengal states [13, 81, 86, 88, 92]. Figures 2.1 and 2.2 show the potential availability of several neem trees and total seed in different states. Table 2.9 shows the entire annual collection of neem seeds state-wise. Out of all these states, Uttar Pradesh is one of the major producers of need seed, but, unfortunately, the collection of neem seed in Uttar Pradesh is zero [81].

Table 2.9: Distribution of actual collection of neem seed from different states [81]

S. No.	State	Total Oil Potential (1000 T)	Actual Collection (%)
1	Andhra Pradesh	2.5	27
2	Madhya Pradesh	3.6	2
3	Uttar Pradesh	53.2	NA
4	Gujrat	4.2	1
5	Maharastra	5.6	1.o
6	Karnataka	4	20

S. No.	State	Total Oil Potential (1000 T)	Actual Collection (%)
7	Orissa	2.4	NA
8	Tamil Nadu	11.4	29
9	Rajasthan	0.8	NA
10	Punjab	2.4	NA
11	West Bengal	0.5	27
	Total	90.6	107

2.2.6 Potential availability of different non-edible feedstock and waste cooking oil in India

As per RUCO (Repurpose Used Cooking Oil) initiative 2019, India is one of the leading consumers of vegetable oil. The total Potential availability of used cooking oil is 222 crore litters. Out of that household and commercial availability is 74 and 148 crore litres. India is the world's top producer of neem seeds, producing 4.4 lakh tonnes annually. This yields 88,400 tonnes of oil and 3.5 lakh tonnes of cake. However, only 10% of the 300,000 tonnes of neem seeds collected in the country are processed, yielding only 3,000 tonnes of neem oil. Non-edible feedstock used to produce biodiesel for 1000 metric tonnes of fuel is given in table. India consumed 88.2, 82.67, and 99 billion liters of diesel in 2020, 2021, and 2022 respectively.

Table 2.10: Biodiesel production from multiple feedstocks (Million Liters), Global Agriculture Information Network (Biofuels Annuals 2023)

Calendar Year	2020	2021	2022
Non-edible Industrial	140	95	105
Used cooking Oil	45	65	65

2.3 Biodiesel and Diesel Standards

The combustion properties possessed by biodiesel have to be comparable to the ones possessed by diesel fuel. Diesel and biodiesel both meet ASTM requirements for bearing both chemical and physical characteristics. Biodiesel such developed from various oil sources has physio-chemical characteristics with varying chemical compositions and values [44]. The physiochemical properties of alternative fuels comprise several characteristics viz. density, kinematic viscosity, pour point, flash point, cetane number, and oxidation stability, among various others. Standard specifications were established, laid down and developed in every nationality so as to enable engine manufacturers and as well as biodiesel producers to employ consistent criteria. Physio-chemical properties of biodiesel are different in different countries due to climate change [23]. All conventional diesel engines can run on biodiesel if the fuel complies with the required specifications. The American standards, namely ASTM D6751, and the European standards, known as EN14214, are two sets of regulations that apply to specifications [93, 94].

Table 2.11: Comparison of properties of Diesel and Biodiesel as fuels along with Testing methods [93, 94]

S. No.	Property specification (Unit)	Test Methods	Diesel	Biodiesel
			ASTM D975	ASTM D6751
			Limits	Limits
1	Kinematic Viscosity@40˚C	D445	1.3 mm^2/s - 4.1 mm^2/s	1.9 mm^2/s -6.0 mm^2/s
2	Density@15˚C	D4052	848 Kg/m^3	878 Kg/m^3 min
3	Flash Point	D93	60 ˚C to 80 ˚C	93.0 ˚C min
4	Pour Point (˚C)	D97	-35 ˚C to -15 ˚C	-15 ˚C to 10 ˚C
5	Cloud Point (˚C)	D2500	-15 ˚C to 5 ˚C	-3 ˚C to 12 ˚C
6	Cetane Number	D613	40 to 55	48 to 60
7	Acid Number	D664	-	0.50 mgKOH/g max

S. No.	Property specification (Unit)	Test Methods	Diesel	Biodiesel
			ASTM D975	ASTM D6751
			Limits	Limits
8	Total Glycerine	D6584	-	0.24 %m/m
9	Free Glycerine	D6584	-	0.02 %m/m
10	Carbon Residue	D4530	0.15	0.050 %m/m max
11	Water & Sediments	D2709	0.05 %Vol max	0.050 %Vol max
12	Specific Gravity@60˚C	D1250	0.85 Kg/l	0.88 Kg/l
13	Oxidation Stability	EN14112	-	6 hours

Table 2.3 presents the several parameters related to Biodiesel as fuel by ASTM D6751, along with a contrast to diesel fuel as specified by ASTM D975. Biodiesel produced from different feedstocks shows variation in their physical properties due to the biodiesel production processes, country climate condition, and their standards [18, 95]. Table 2.4 depicts various biodiesels and their physio-chemical properties. Given data shows that all biodiesels possess significantly high viscosity, flash point, and density while on the flip side, the oxidation stability and calorific value of biodiesel is low.

Table 2.12: Physio-chemical properties pertaining to diesel and their comparison with biodiesel

Feed-stock's	Density (Kg/m3)	Viscosity (mm2/s)	Acid Number	Oxidation Stability (hr)	Flash Point (°C)	Free Glycerin % m/m	Total Glycerin % m/m	Calorific Value (MJ/Kg)	References
ASTM D6761		D445	D664	-	D93	D6584	D6584	-	
Range		1.9-6.0	Max 0.80	-	Min 130	Max 0.02	Max 0.24	-	[96]
EN 14214	EN 12185	EN3104	EN14104	-	ISO3679	EN14105	EN14105	-	[96]
Range	860-900	3.5-5.0	Max 0.50	-	Min 120	Max 0.02	Max 0.25	-	[96]
Diesel	839	2.95	-	23.7	71.5	-	-	45.82	[97] [44]
Soybean biodiesel	884.5	4.12	0.15	4.97	176.5	-	-	-	[98]
Seasame Biodiesel	867	4.47		6.25	180	-	-	40.1	[99]

Feed-stock's	Density (Kg/m3)	Viscosity (mm2/s)	Acid Number	Oxidation Stability (hr)	Flash Point (℃)	Free Glycerin % m/m	Total Glycerin % m/m	Calorific Value (MJ/Kg)	References
Rubber Seed Biodiesel		5.45	0.1	6.1	179	0.004	0.129	-	[100]
Palm Biodiesel	843.963	4.92		13.37	259	-	-	-	[101]
linseed Biodiesel	-	3.3	0.2	2.2	184	0.02	0.25		[102]
Sunflower Biodiesel	882	4.719	-	0.9	183	-	-	42.02	[103][104]
Passion Fruit Biodiesel	-	4.1	0.3	3.1	172	0.01	0.21	-	[12]
Açaí Biodiesel	-	4.5	0.27	1.5	200	0.01	0.15	-	[102]
Croton Biodiesel	879	2.45	-	4.04	65.5	-	-	42.34	[105]
waste cooking Biodiesel	920	13.55	2	1.76	235	-	-	42.51	[106]
Methyl Jatropha Biodiesel	875.9	4.54	0.287	13.03	108.9	-	-	-	[107]
Ethyl Jatropha Biodiesel	874	4.913	0.278	13.51	110	-	-	-	[107]
Coconut Biodiesel	844.42	3.6757	-	29.4	241.5	-	-	-	[101]
Corn Biodiesel	865	4.363	-	2.2	170	-	-	39.12	[108]

2.4 Fatty Acid Composition of Potential Feedstock

Vegetable oils, evidently, possess a combination of saturated fatty acids (SFAs) and that unsaturated fatty acid (UNFAs), which can be further categorized into monounsaturated (MUFAs) and as well as polyunsaturated fatty acids (PUFAs) based on the quantity of unsaturated bonds present [66, 109–111]. Nevertheless, each of the examined vegetable oils has a unique fatty acid distribution based on the plants from which it was derived [53]. Saturated fatty can also be defined as short and medium SFAs if carbon atoms exceed 12. SFAs are Palmitic [C16:0], Stearic [C18:3], myristic [C14:0]. UFAs are linoleic acid

[C18:2], Oleic acid [C18:1], and linolenic [C18:3] [66, 111, 112]. Table 2.13 represents the majority of SFAs and UFAs percentages for various oil.

Table 2.13: Percentage of FFA content of various oil

Type of oil	[C16:0] (%)	[C18:0] (%)	[C18:1] (%)	[C18:2] (%)	[C18:3] (%)	References
Cotton seed	22.6, 13.32	2.9, 4.20	16.1, 26.47	57.9, 50.75	0.5, 4.25	[57] [113]
Linseed	6.6	4.4	18.5	17.3	53.2	[24]
Palm Kernel	12.2	1.3	10.8	-	-	[24]
Olive	13	3.7	39.1	35.4	-	[24]
Soybean	11.6, 11.67, 10.95, 11.03	4, 3.21, 4.31, 5.32	18.8, 23.47, 23.12, 24.15	56.1, 53.47, 53.27, 53.19	8.5, 6.45, 6.77, 6.07	[24] [114] [115] [113]
Sunflower seed	6.3, 6.3	3, 2.40	43.7, 30.4	47, 60.1	0.6	[24] [57]
Rapeseed	4.44	1.67	62.4	19.73	9.47	[115]
Canola	5.6	2.8	64.3	17.5	8.3	[57]
Sesame	8.5	5.4	38.8	46.3	-	[24]
Sal	3.69	47.07	43.98	1.2	-	[68]
Jatropha	14.2, 17.08, 15.13	7, 11.02, 8.89	44.7, 34.29, 43.01	32.8, 36.09, 32.05	0.2, 039	[24] [116] [113]
Palm seed Oil	42.6, 40.10, 42.63	3.8, 4.09, 4.75	41.2, 43.02, 41.18	10.4, 11.04, 10.08	0.2, 0.16	[24] [115] [116]
Sunflower	6.3	3	43.7	47	-	[24]
Pongamia/ Karanja	13.8	6.1	65.3	11.6	3.2	[48]

Type of oil	[C16:0] (%)	[C18:0] (%)	[C18:1] (%)	[C18:2] (%)	[C18:3] (%)	References
Corn	12	2.1	33.5	51	1.1	[57]
residual cooking oil	22.1	2.6	14.5	58.7	1.6	[57]
Castor	1, 1.09	1, 0.87	3, 3.34	4.2, 4.87	0.3, 0.44	[24] [116]

2.5 Biodiesel Challenges

Feedstock availability and competition: One of the biodiesel's foremost challenges is accessibility and rivalry for feedstock resources. Biodiesel has the potential to be derived from a diverse range of feedstock sources, encompassing vegetable oils viz. palm, soybean, rapeseed, and sunflower, along with animal fats and waste oils like the ones employed in cooking oil. The demand for these feedstocks utilized in biodiesel production may conflict with their usage as food sources or for other industrial applications, resulting in price fluctuations [13, 43].

Cold weather performance: Biodiesel showed a more excellent cloud point and gelation temperature than conventional diesel fuel, leading to potential challenges to using biodiesel in cold weather conditions. In regions with lower temperatures, using biodiesel blends may necessitate the incorporation of additives or implementing specific storage and handling protocols to mitigate issues related to gelling and performance [25, 117, 118].

Fuel quality and storage stability: The qualitative characteristics of biodiesel are significantly affected by parameters like feedstock and the process employed for producing biodiesel. Fuel characteristics and properties and their storage affect biodiesel stability and compatibility with fuel systems and exiting diesel engines. Storage stability leads to a change in the properties of biodiesel that can cause several causes to engine operations and affect engine efficiency [28, 54, 119].

Energy-intensive production process: The production of biodiesel encompasses various energy-intensive procedures, which consist of the cultivation of feedstock, the harvesting of said feedstock, the extraction of oil, and the process of transesterification. The energy inputs necessary for these processes, particularly in the context of large-scale production, have the potential to counterbalance the overall environmental advantages associated with biodiesel. Implementing energy-efficient technologies and optimizing production processes can reduce biodiesel production's energy intensity [43].

Technical compatibility and infrastructure: Regarding its technical compatibility with engines, fuel systems, and storage infrastructure, biodiesel has different features from regular diesel fuel. Biodiesel can clog fuel systems and cause some rubber and plastic parts to degrade because of its significantly high viscosity and low energy content. The efficient utilization depends on maintaining regular maintenance and infrastructure compatibility [11, 14] .

2.6 Oxidation Stability and their Mechanism

With a longstanding storing of biodiesel, fuel stability becomes a significant concern. Biodiesel has less strength than other fuels in terms of long-term storage. Biodiesel contains 6% to 12% weight of oxygen atoms in its molecular structure, which tends to react [120]. The process causes gums to develop and changes the color of the biodiesel fuel. To better comprehend the assessment of oxidation stability, a few elements must be investigated, including iodine value, peroxide value, induction time, oil stability index, viscosity, acid value, density, fatty acid methyl ester content, etc. The FAC of biodiesel is affected by several direct or indirect variables [24, 110]. A chain reaction involving fatty acids underlies the oxidation mechanism. Unsaturated fatty acids and molecules having double bonds in the chemical structure of biodiesel react with oxygen when they come into contact with air or water. The secondary product is created when the main products disintegrate and react. Formic acid, Aldehydes, format esters, short-chain fatty acids and higher-weight composition molecular materials are secondary products made after the formation of unstable allylic hydroperoxides, which are the primary product. The three stages of primary oxidation are initiation, propagation, and termination [27, 32, 121].

Initiation: in this stage, hydrogen is removed to develop a carbon-free radical (R·) from the carbon atom at a slow rate.

$$\mathbf{R\cdot + I \longrightarrow R\cdot + IH}$$

Propagation: in this oxidation stage, radicals quickly react with oxygen to give rise to peroxy radicals. Further, peroxy radicals carry out a reaction with hydrogen and give rise to hydroperoxide (ROOH).

$$\mathbf{R\cdot + O_2 \longrightarrow ROO\cdot}$$

$$\mathbf{ROO\cdot + RH \longrightarrow ROOH + R\cdot}$$

Termination: In this stage, stable products are produced when two radicals carry out the reaction amongst them.

$$\mathbf{ROO\cdot + ROO\cdot \longrightarrow \text{Stable product}}$$

The oxidation stability characteristic possessed by biodiesel produced by various feedstocks is evaluated by employing an induction period (in hours). It is further evaluated by using the Rancimat test method (EN 14112), which is utilized by American standards (ASTM D6751), European biodiesel standards (EN 14213 & EN 14214), and Indian biodiesel standards (IS 15607) [96, 97]. As per ASTM D6751 and IS 15607, the EN 15751 modified Rancimat Method and EN 590 are both used to evaluate the oxidation stability possessed by several biodiesel blends along with petro-diesel. EN14214 and ASTM D6751 indicate that the minimum induction period is 6 hours [98, 99]. There are several ways to increase biodiesel's oxidative stability and utilizing antioxidants is considered to be significantly prominent in this regard.

2.7 Additives and their Classification

Additives are chemicals mixed with biodiesel that bear advantages in multiple ways. Additives are used to augment biodiesel properties by advancing performance, emission, combustion, and cold flow characteristics [122]. There are several types of antioxidants like cetane number improver, cold flow improver, antioxidants, metal-based, lubricity enhancer, etc. additive selection depends on different blending characteristics of biodiesel such as density, viscosity, the solubility of additive, the toxicity of fuel blend, etc [39, 123–125]. Additives are added in a small proportion to the fuel. Nano additives are less than 100 nm particle size added for better mixing without any separation. The nanoparticles have the potential application to be utilized as fuel-added substances and move forward to improve the stability and combustion perspectives of biodiesel fuel [126]. Additives are categorized in different categories, as shown in Table-2.14. Further, some benefits of using additives are given as follows [39, 123, 127]:

- Protect the pipeline, petroleum tank, and massive corrosion.
- Cold flow properties enhanced and promoted biodiesel use.
- The emissions resulting from engine combustion have been effectively reduced.
- Encourages the enrichment of performance standards and combustion characteristics.
- Enhance the duration of storage stability under various operating conditions.

Table 2.14: Additives classification with their list and benefits [18, 8, 20].

Classification of Additives	Description	Benefits	List of additives
Metal Based Additives	Works as a combustion catalyst Improves engine performance	• Decline unburned hydrocarbon • Diminish exhaust gas emission	Aluminum, manganese, copper, iron, cerium, zinc, calcium, barium, platinum, etc.
Cetane Number Improver Additives	Works for the ignition delay period	• Shorter delay period • Reduces NOx emission to the environment	Nitrites, peroxides nitrates, Ethyl Hexyl Nitrates, Aldehydes, Alkyl Nitrates, Tetra-azole, Methyl Oleate, Di-Methyl Propane, Neopentane, etc.
Antioxidant Additives	Used to increase the stability of biodiesel	• Decline slug formation. • Enhance the tendency to deteriorate	Butylated hydroxyl anisole, Pyrogallol, Diphenylamine, Propyl-gallate, Tert-butylhydroxyquinone, Butylated hydroxyl toluene, etc.
Oxygenated Additives	Helps in combustion Positive Effects on Emission	• Affects Important properties of a fuel • Complete Combustion • Diminish pollution	Alcohol (Butanol, Methanol Propanol, Ethanol), Ether (diethyl ether, methyl-test-butyl ether, dimethyl ether, di-isopropyl ether), and Ester (acetoacetic ester, dimethyl carbonate ester, dicarboxylic acid esters), etc.
Lubricant Additives	Prevent mechanical wear in desulfurized fuel	• Increase engine lifetime • Protect from corrosion	Fatty acid esters, aliphatic amines, long-chain monocarboxylic acids, etc.
Cold flow improver additives	Used for cold start of the engine	• Support engine to run in cold weather conditions • Prevent from chocking of Fuel filter and feed lines	Ethylene Vinyl Acetate (EVA) amyl nitrate, hexyl nitrate, and octyl nitrate
Ignition Boost Additives	Works for Ignition delay Harmful emission	• Reduced ignition delay and emission • Noise level reduced	Amyl nitrate, octyl nitrate, and hexyl nitrate

2.7.1 Effect of synthetic antioxidants on oxidation

Antioxidants are used in biodiesel to enhance oxidation stability by seizing the peroxy radicals form during oxidation [129]. Antioxidants are again categorized into two types, synthetic and natural. Synthetic antioxidants belong to phenolic and aminic types [130]. Primarily used synthetic antioxidants are usually Tert-butylhydroxyquinone, Pyrogallol, Butylated hydroxyl toluene, Propyl-gallate, and Butylated hydroxyl anisole [130–132]. Synthetic antioxidants come from petroleum products, adding some cost to the production process and negatively impacting health. Figure 2.3 demonstrates the oxidation stability in the absence of antioxidants in biodiesel and also counts the impact of synthetic antioxidants on biodiesel's oxidation stability. TBHQ is added for increasing biodiesel's oxidation stability made from jatropha, olive, palm, and soybean [133].

African-origin croton oil methyl ester biodiesel has been produced by croton Megalosaurus oil. The oxidation stability demonstrated by croton oil methyl is apparently not lying in the range of EN 14214 specification. So, PY, PG, and BHA are antioxidants to increase oxidation stability. Out of these three antioxidants, PY is more effective than PG, and BHA is the least effective [105] Experiments have evaluated the performance of several antioxidants viz. TBHQ, PY, PG, BHT, and BHA in Karanja biodiesel. 500 ppm of PY antioxidant can enhance Karanja biodiesel's oxidation stability from 2.74 h to 21.12 h [134]. Tilapia biodiesel with synthetic antioxidants such as BHT, BHA, and PG is mixed to enhance oxidation stability from 1.98 h. BHT cannot increase the value up to the ASTM standard, but BHA and PG are effective as they increase value to 6.44 h and 10.18 h, respectively [50]. Chloroform Extract and Platymiscium floribundum ethanolic are antioxidants in soybean biodiesel.

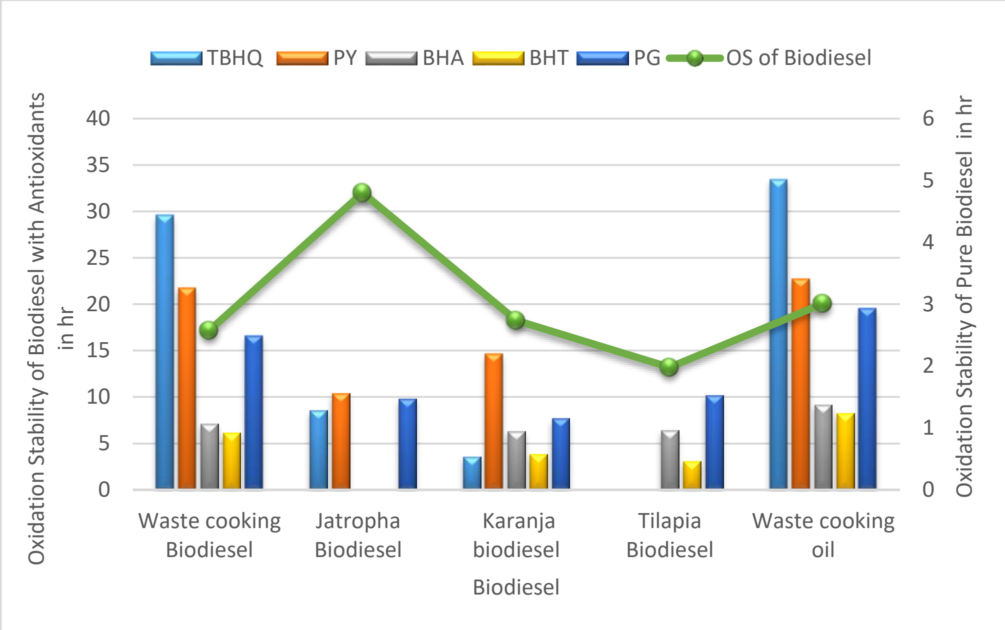


Figure 2.3: Improvement in IP by adding synthetic antioxidants (500 ppm) in biodiesel and oxidation stability without antioxidants [37, 134–137]

By adding Platymiscium floribundum to soybean biodiesel, the induction period significantly rises from 4.53 h to 18.09 h and 17.58 h by adding Chloroform extract, respectively [138]. N, N′-di-sec-butyl-pphenylenediamine was used by way of an antioxidant in the waste frying oil. This antioxidant increases the oxidation stability of waste frying oil from 0.17 h to 8.73 by mixing 500 ppm antioxidants via the rancimat test [139].

2.7.2 Effect of natural antioxidants on oxidation stability

Now a day's, researchers are focusing more on evaluating performance by using natural antioxidants. Natural antioxidants are taken out of plants and fruits. The phenolic compounds, tocopherols, flavonoids, carotenoids, and terpenes substances are generally found in different parts of the plants. Phenol is commonly used as a natural antioxidant to scavenge the free radical form during oxidation degradation [140]. The natural antioxidant is most attractive on account of it being renewable, eco-friendly nature and as well as being non-toxic [49]. Antioxidant compounds help slow oxidation by donating hydrogen atoms to free radicals [39]. Green tea extract is a natural antioxidant in waste cooking oil biodiesel. Without green tea extract, oxidation stability was 2.88 h, then oxidation stability increased to 7.11 h by adding 1000 ppm of green tea extract [49]. Cinnamon, Turmeric, black pepper, watermelon seed and red bell pepper are tested as natural antioxidants to check the effect on oxidation stability. These natural additives, as antioxidants, are added in a quantity of 2500 ppm to evaluate oxidation stability in waste cooking oil. All-natural additives are found effective, and turmeric is seen at its best effective as it increases oxidation stability by 18.61 h from 1.72 h [106]. The author used babassu oil to produce biodiesel, and their oxidation stability increased by adding three natural antioxidants camphor, isoamyl alcohol, and limonene. Adding these antioxidants improved oxidation stability by 52-92%, including improved viscosity and density of babassu biodiesel [141]. Synthetic antioxidant (propyl gallate) compared with natural antioxidant (pistachio hull extract) to check their oxidative properties in canola biodiesel. 250 ppm of propyl gallate improves oxidation stability from 1.53 h to 3 h; pistachio hull extract requires 2500 ppm quantity [50, 142]. Figure 2 gives the graphical representation of oxidation stability with natural antioxidants compared to base biodiesel. The Mesua ferrea L. biodiesel produced from Nahar oil contains extracts of potato peel, which serves as an antioxidant. To conform to ASTM standard, Biodiesel made from Mesua ferrea L. is combined with potato peel extract at 100, 150, 200, and 250 parts per million [143]. An increase in oxidation stability of 150 ppm can bring the value from 5.63 to 6.21 hours. Curcuma longa Linn., the natural ethanolic extract of turmeric, was combined with biodiesel made from tilapia oil to evaluate its resistance to oxidation. Applying this natural antioxidant could boost the sample's resistance to oxidation from 1.98 hours to 10.9 hours. In canola biodiesel, pistachio hull extract is being investigated as a potential antioxidant as an alternative to the synthetic antioxidant propyl gallate. 2500 ppm of this natural antioxidant enhances the induction duration of canola biodiesel from 1.53 h to 3 h to meet ASTM D6751 specifications [145].

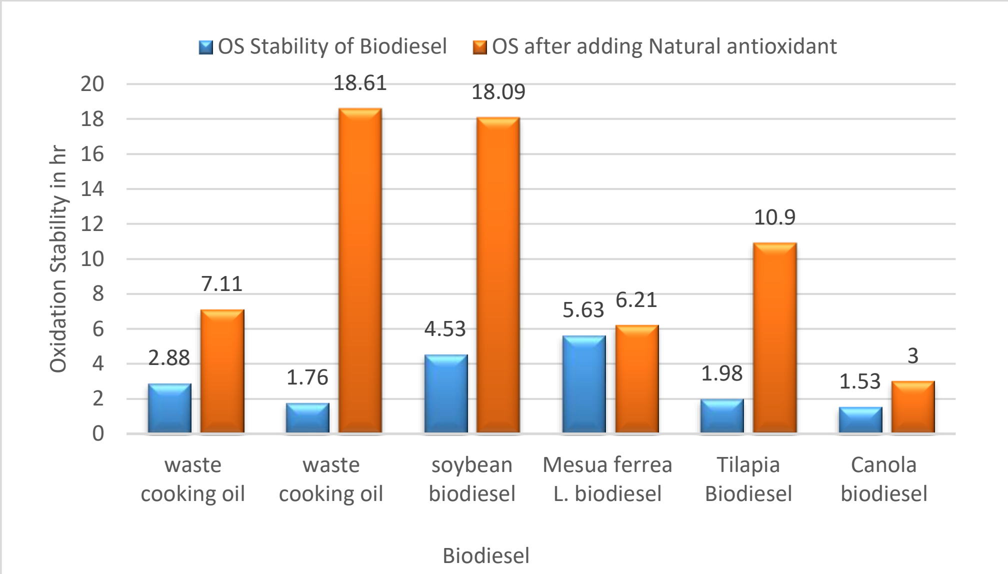


Figure 2.4: Improvement in IP by adding Natural antioxidants in biodiesel and oxidation stability without antioxidants [49, 50, 138, 140, 144]

Pomegranate hull and Extracts of green tea, such as chloroform and methanol, are used in rubber seed biodiesel as a natural antioxidant. Performance of these natural antioxidants compared with synthetic antioxidants, Butylated hydroxytoluene, 2,6-di-tert-butylphenol, gallic acid, and quercetin. Methanol extract is more effective in oxidation stability than other natural antioxidants. Pomegranate was the least effective at higher ppm than others [100]. TBHQ and BHT were used as synthetic antioxidants to evaluate oxidation stability compared with α-tocopherol, octylated butylated diphenylamine, and tert-butylated phenol derivative antioxidants. All these antioxidants are found to be effective [146].

2.8 Review of the Impact of Antioxidants on Performance, Emission, and Combustion

Numerous studies have investigated biodiesel from different sources, comparing its impacts on emissions and engine performance to those of fossil fuel in CI engines with or without modification.

Shahir et al. [147] A CRDI engine was used in a study for the assessment of several blends of biodiesel derived from animal fats to pure diesel fuel. An evaluation of the results of this investigation was conducted in comparison. The testing results showed that as the biodiesel percentage was raised, thermal efficiency significantly improved. In addition, significant variations were found between a blend of 70D30B (30% biodiesel). The mixture had reduced values of CO and O_2 but increased NO_X, CO_2, and HC.

Dutta et al. [148] In a study looking at the effects of adding alcohols, particularly ethanol and methanol, to palm stearin biodiesel, BTE was found to marginally increase. The maximum temperature within the cylinder was lowered when an alcohol blend was added to the biodiesel, which decreased the pressure increase rate during combustion. According to the data, therewere lower nitrogen oxide (NOx) emissions but higher levels of smoke and particle matter (PM).

Nabi et al. [149] For the engine assessment running on biodiesel made from frying cooking oil, a practical study was conducted. The 13-Mode European Stationary Cycle was used as the testing framework for the inquiry. The study's outcomes reveal notable improvements, including a 13% reduction in blow-by emissions, an 11-15% decrease in carbon monoxide (CO) emissions, a substantial 47-70% decrease in HC, a significant 84% drop in PM, and a significant increase in NOx when utilizing the reference fuel.

Nair et al. [92] A practical investigation was undertaken to assessment of diesel fuel as well as various blends of neem biodiesel. While brake power exhibited relative stability, recent discoveries highlight that using Neem biodiesel BTE increases compared to diesel. Emissions underwent reduction upon conducting a comparative analysis of the test fuel against reference values. Among alternative fuel blends, the B10 mix of neem biodiesel showcased enhanced performance and diminished emissions. Furthermore, the introduction of additives has been observed to lower levels of oxygen-based emissions commonly associated with biodiesel.

Bar et al. [150] In this study, the antioxidant butylated hydroxytoluene (BHT), along with benzoic hydrazide (BH) and pivalic hydrazide (PiVH), were investigated for their influence on nitrogen oxide. The evaluation of the effects of pivalic hydrazide and benzoic hydrazide at doses of 7.26 mmol/kg and 14.52 mmol/kg, respectively, did not reveal any appreciable change in NOx emissions.

Roy et al. [151] In this study, Wintron XC30 additives in combination with canola biodiesel used for experiments. Experimental inspections were made to analyze the performance of test various blends, including additives at 1800 rpm. Engine performance was evaluated and compared using measures of fuel blends engine output parameters and emissions. The results indicate a significant enhancement in operational efficiency and reduced emissions, contributing to a more environmentally friendly operation.

Madiwale et al. [152] The author investigates the amalgamation of Jatropha, Soybean, Palm, and Cotton seed biodiesel with diesel fuel, accompanied by a 5% concentration of ethanol as an additive. The blends, referred to as B20E5 (comprising 20% biodiesel, 75% diesel, and 5% ethanol), are under examination. The current study delves into the output parameters and emission attributes of diesel engines. Notably, the results reveal an inverse relationship between ethanol content and blend density. Ethanol augmentation enhances the combustion quality and cold flow properties of the spray.

Hosamani et al. [153] An investigation was conducted to assess the combustion attributes of a VCR engine operating at full load. The study involved the utilization of two biodiesel blends in conjunction with conventional fuel. Various combustion parameters were evaluated, including pressure rise rate, net heat, cylinder gas pressure, cumulative heat release, and mass fraction burned. The biodiesel employed in the study is derived from simaruba and jatropha sources. The results demonstrate the impact of both blend compositions and compression ratios on above mention parameters. Biodiesel application improves combustion due to presence of higher oxygen content in it.

2.9 Literature Review Findings

It may be concluded from the review of the existing literature that biodiesel presents itself as an acceptable substitute for CI engines with attributes such as renewability, environmental friendliness, and decreased toxicity. Many researchers worked around biodiesel to resolve different issues associated with it. Several antioxidants are used to enhance the performance of biodiesel. The following are the noteworthy points found from the above literature.

Both saturated & unsaturated fatty acids are present in biodiesel, which can contribute to its oxidation and subsequent degradation, thereby impacting fuel quality and stability. This instability can extend beyond acceptable specifications, potentially influencing engine performance when such fuel is utilized. To address these challenges, researchers are exploring the integration of antioxidant additives to counteract these issues.

1. The composition of fatty acids within vegetable oil plays a pivotal role in shaping fuel characteristics. Vegetable oils encompass a spectrum of all categories of fatty acids. The fuel is more vulnerable to oxidation and subsequent degradation when it contains unsaturated fatty acids in usually higher amounts. Conversely, Saturated fatty acids are included, which improves properties related to low temperatures. In order to improve both cold flow qualities and oxidation stability, some researchers investigate the use of a combination of vegetable oil methyl esters.
2. Conversely, biodiesel exhibits an elevation in NOx emissions attributed to its oxygen content, alongside diminished engine power. These challenges can be mitigated through the introduction of minor additives to biodiesel. Extensive literature underscores the amalgamation of various synthetic and natural additives into biodiesel formulations, effectively enhancing both engine performance and emission attributes. Many literature surveys have been done on edible oil-based biodiesel and some on non-edible. Most work has been done on rapeseed, palm, canola, soybean, Jatropha, Karanja, cotton seed oil, sunflower, waste cooking oil, mahua, neem, etc.
3. In accordance with existing literature, scholars have employed a range of antioxidant additives including pyrogallol (PY), propyl gallate (PG), tert-butyl hydroquinone (TBHQ), butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA) along with substances like L-ascorbic acid, ethanol, β-carotene, benzotriazole, caffeic acid, tert-butylamine, and benzotriazole, among others.
4. Several researchers have dedicated their efforts to optimizing biodiesel yield. Among the most effective techniques is the utilization of response surface

methodology, which proves instrumental in determining the utmost biodiesel yield. This methodology typically involves the manipulation of four key processing variables to ascertain the optimal yield potential.

5. The researcher decided on a solution by incorporating mixes of tire pyrolysis oil into the biodiesel formulation because adding antioxidants to the base biodiesel would increase the cost. The antioxidant demand is significantly reduced by 50% with this smart blending method.
6. A comprehensive review of existing literature reveals that phenolic compounds inherent in the oil hold the potential to serve as natural antioxidants within biodiesel. In pursuit of this concept, researchers have harnessed the ethanolic extract derived from Moringa Lam Leaf and Tinospora cordifolia stem to fulfill the role of antioxidants.
7. Numerous researchers underscore the storage stability challenges associated with biodiesel. Prolonged contact of biodiesel with metal surfaces can result in corrosive tendencies, rendering long-term storage problematic. To address this issue, various antioxidants have been examined as potential solutions.
8. Biodiesel oxidation stability measures by stability index methodologies. Among these methodologies are ASTM D2274 and EN14112. Additionally, the Rancimat and petrOXY methods serve to determine the induction period.
9. The improvement of oxidation stability was investigated for oils made from Karanja, mahua, and jatropha. Oxidation stability analysis performed by consider different doses of antioxidants ranging from 100 ppm to 1000 ppm. Induction period calculated by adding these different doses of antioxidants in biodiesel.

10. As per available research, it becomes evident that phenolic compounds present in various oils hold the potential to serve as natural antioxidants within biodiesel. Building upon this concept, scientists have harnessed the ethanolic extract derived from Moringa Lam Leaf and Tinospora cordifolia stem to fulfill the vital role of antioxidants.

2.10 Research Gap Analysis

1. Edible oils are a principal source of human food. Non-edible oils are the only viable solution for biofuel production in India. Neem oil, Kusum oil, Mahua oil, and Sal oil are yet to be explored. The disposal problem of waste cooking oil can be resolved by transforming it into biodiesel.

2. Most research on edible oil with or without additives has been done to enhance oxidation stability. Synthetic antioxidants are predominantly used antioxidants for improving oxidation stability.

3. Researchers use limited antioxidant additives to enhance oxidation stability. Many synthetic antioxidants, like DPA, L-ascorbic acid, etc., can be tested to intensify this stability. Natural antioxidants like banana peel, gooseberry, walnut shell, etc., can be explored.

4. Natural antioxidants can also be utilized in biodiesel to improve its oxidation stability and possible risk related with human health and the environment on account of direct exposure to the additives during their release into the atmosphere.

2.11 Research Objectives

1. Selection of non-edible feedstock for biodiesel production.
2. Selection of additives based on parameters needs to be enhanced.
3. Production of Biodiesel from selected saturated and unsaturated non-edible feedstock using a transesterification process.
4. Determination of various physio-chemical properties of different test fuels with and without additives.
5. To study the oxidation stability of test fuels with and without the additive effect.
6. Development of engine test rig for experimental trial.
7. Experimental investigation on performance, emission, and combustion with different test fuels on the engine and compare with baseline biodiesel.

CHAPTER 3

SYSTEM DEVELOPMENT AND METHODOLOGY

3.1 Introduction

In this chapter, each step used to do the study systematically and methodically from the selection of feedstock to performance of the engine to prediction and validation is given, as per mentioned problem statement in chapter two. Figure 3.1 represents the procedure followed in this study.

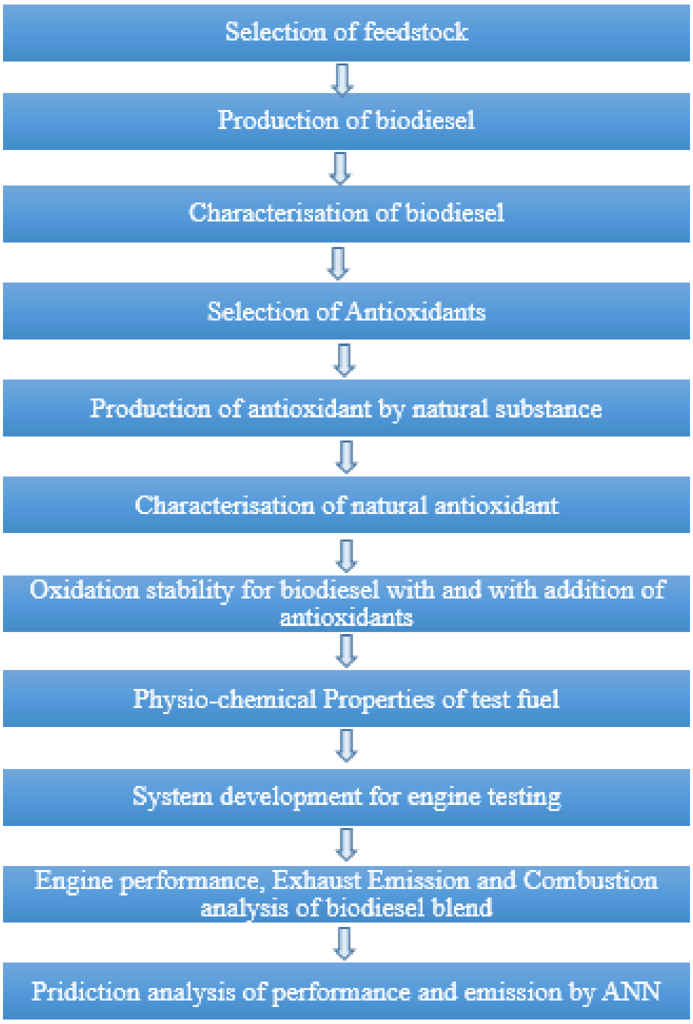


Figure 3.1: Research methodology process flow chart

Initial step in the research methodology is feedstock selection for biodiesel production. The selection of feedstock is influenced by availability, cost, and environmental impact. Based on the above-written parameter and literature survey, waste cooking and neem oil are utilized for biodiesel production in the present study. It is achieved through transesterification and the esterification process decided by the FFA content of oil. After production, gas chromatography-mass spectrometry (GC-MS) was used for biodiesel characterization which provides the percentage of available fatty acid compositions. The next step was to test the oxidation stability of the test sample. Oxidation stability was conducted under controlled temperature, pressure, and oxygen exposure time conditions. Antioxidants were added to enhance biodiesel's oxidation stability. Appropriate extraction methods were used for the production of antioxidant extract from natural sources after that characterization of antioxidants was performed to find the scavenging percentage for antioxidant extract. Moreover, Physicochemical properties of biodiesel like density, velocity, cold flow properties, calorific value, etc., were evaluated for test fuels with and without antioxidants as per ASTM methods. For experimental trials, an engine test rig was developed and described in detail. This chapter evaluates the emission, combustion and performance, analysis of the test fuels performed on an engine test rig and is described in detail. In the end, a description of the ANN approach's performance and emission prediction analysis is given.

3.2 Feedstock Selection for the Production of Biodiesel

Feedstock selection to produce biodiesel depends on several parameters, such as conversion process, sustainability, availability, and cost-effectiveness. Production of biodiesel can be done from a variety of feedstocks, edible and non-edible. Edible feedstocks are Canola oil, Soybean oil, Palm oil, Sunflower oil, peanut oil, Corn oil, Cottonseed oil, etc., and non-edible feedstocks are neem oil, Jatropha oil, Karanja oil. Residual cooking oil, Castor oil, animal fats, tallow, and algae, are name few examples [44, 66, 67]. It is significant to highlight that using edible feedstocks for biodiesel production has generated insecurity due to concern about potential effects on food security and the environment. As a result, non-edible feedstocks are being used more frequently as an environmentally friendly choice. Due to its sustainability, availability, and reduced production costs, used frying oil biodiesel has been found a superior alternative for producing biodiesel as it offers a solution for the disposal of wasted cooking oil as well as for the reduction of land and water pollution [72, 154, 155]. The absence of a well-defined strategy for procuring neem seeds for biodiesel production in India, particularly in areas such as Uttar Pradesh (UP), where the existing practice involves no collection of neem seeds. The lack of an organized neem seed collecting system in Uttar Pradesh (UP) leads to a considerable quantity of neem seeds being wasted or left unused. The neem trees exhibit a vast distribution within the region, their seeds are used for the production of biodiesel [13, 81]. This study used waste cooking and neem oil as a potential feedstock for the production of biodiesel and their investigations.

3.3 Biodiesel Production Process

Biodiesel production involves feedstock preparation, transesterification/esterification, separation, and purification. An explanation of each step is given below:

1. Feedstock Preparation:

The initial step in biodiesel production was the feedstock preparation. The most utilized feedstock is waste vegetable oil, such as used cooking oil and non-edible feedstock. To eliminate any impurities like leftover seed or water, it is necessary to expose the feedstock to oil filtration and then increase its temperature to above 100 degrees Celsius.

2. **Pre-Treatment:**

If the feedstock contains high levels, a pre-treatment step such as acid esterification or transesterification may be necessary. This helps reduce the FFAs to an acceptable level.

3. **Transesterification:**

The triglycerides present in the feedstock, are chemically transformed into biodiesel through transesterification. In the availability of a catalyst, triglycerides must be combined with alcohol to perform the fundamental transesterification process. The process takes many hours to complete, completion time depends on the types of feedstocks and amount of FFA content present in it, and occurs in a heated environment. Processes for transesterification typically fall into one of two categories [156].

a. **Transesterification**: For the transesterification process, Potassium hydroxide (KOH) or sodium hydroxide (NaOH) is commonly used strong base catalyst. If feedstocks have FFA content less than two (FFA<2) then base-catalyzed transesterifications (transesterification process) are performed. The catalyst is used to break down the triglycerides and converted them into fatty acid methyl esters, biodiesel, and glycerol by reacting with the alcohol to produce alkoxide ions [71].
b. **Acid-Catalyzed Transesterification**: In acid catalyzed transesterification process (also called esterification), sulfuric acid (H_2SO_4) or hydrochloric acid (HCl) is used as a powerful acid catalyst. Another name for this procedure is esterification. If there are more than two free fatty acids (FFA>2), the esterification procedure must be carried out. In this procedure, the acid catalyst changes the alcohol into an alkyl ester, which combines with the triglycerides to create biodiesel and glycerol [157].

4. Separation:

The mixture gets settled down in a separating tank after transesterification and contains biodiesel, glycerol, unreacted alcohol, catalyst, and other contaminants, where the different densities caused two distinct strata to emerge. Glycerol is found in the bottom layer, and biodiesel in the top layer. The leftover biodiesel layer underwent additional processing after draining the glycerol layer.

5. Purification:

Despite being separated, biodiesel still contains contaminants such as water, detergent, catalyst, and residual alcohol. Usually, the following actions are taken to purify the biodiesel:

a. **Washing**: Water-soluble contaminants, such as soap and leftover catalysts, were removed from the biodiesel by washing it. Up until the desired purity is reached, many washes may be conducted. For this process, Warm water is mixed with biodiesel and shaken well then left over a few hours for separation [158].

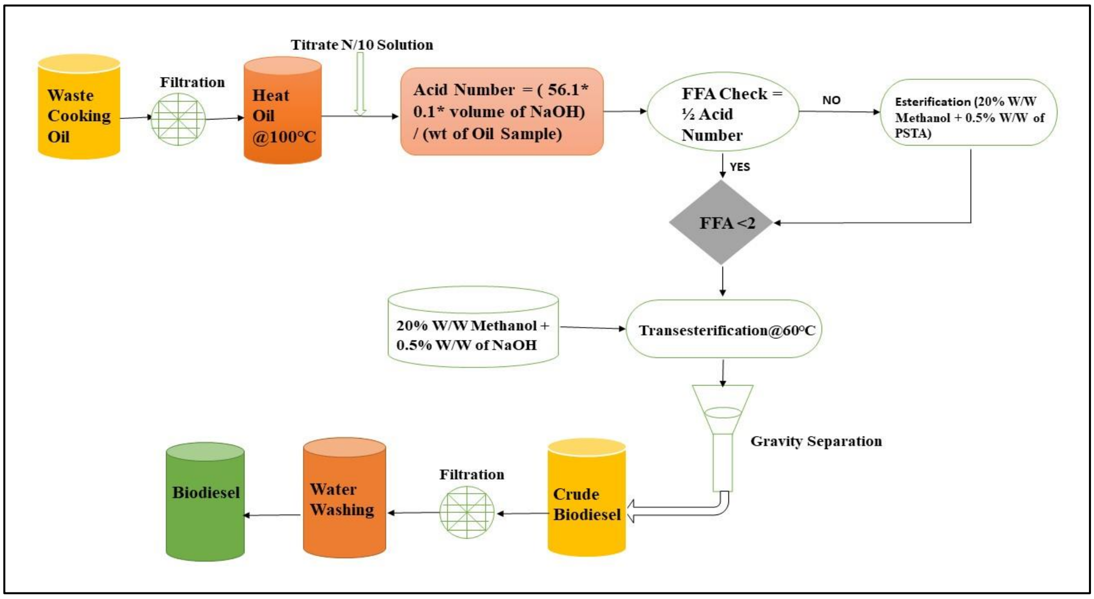


Figure 3.2: Biodiesel production process

b. **Drying**: After washing, the biodiesel was dried thoroughly to eliminate any lingering water. This step is critical as moisture can lead to complications when storing and burning the fuel.

c. **Filtration**: Biodiesel was passed through filters to remove any particulate matter or solid impurities that may affect its quality.

The glycerol obtained from the separation step can be further processed to remove impurities and used in various industries, such as pharmaceuticals, or as a feedstock for other applications.

Waste cooking oil was prepared as feedstock and checked FFA by titration with N/10 solution. Calculated FFA comes in the range of 1.122 – 1.402 for WCB. For FFA <1, single-step transesterification process performed for production of WCB.

Figure 3.3: Production of waste cooking oil biodiesel

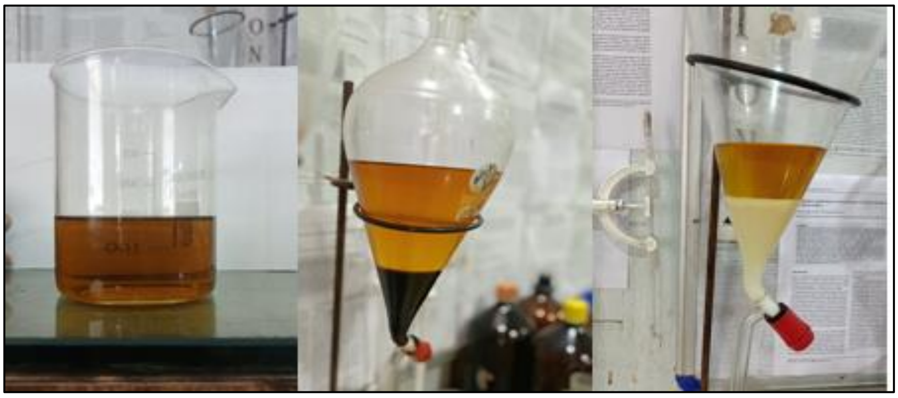


Figure 3.4: Production of neem biodiesel

First, neem oil was prepared by filtration and heating, then checking FFA. FFA of Neem oil was found to be in the range of 3.506-5.89, which was more than two. So, esterification followed by transesterification was performed for making biodiesel from neem oil.

3.4 Biodiesel Characterization by Gas Chromatography-Mass Spectrometry

Gas Chromatography-Mass Spectrometry is used for characterization of biodiesel, The working process of GC-MS involves several key steps. Here's an overview of the process, represented in Figure 3.5.

Sample Preparation: A representative sample of biodiesel is prepared for analysis. This typically involves dissolving the biodiesel in a suitable solvent and, if necessary, derivatizing the biodiesel to enhance the volatility and stability of the compounds to be analyzed.

Injection and Separation: The first step after sample preparation is, Inject the biodiesel sample into a capillary column of GC. The GC separates the individual compounds in the biodiesel based on such as boiling point, volatility, and polarity. The separated compounds are eluted from the GC column in a time-dependent manner.

Ionization: The components enter the instrument's mass spectrometer (MS) portion after discharge from the GC column. The chemicals are ionized in the chamber after being attacked by high-energy electrons. Electron ionization (EI) is the leading technique employed in GC-MS for biodiesel analysis.

Mass Analysis: After accelerated ionized substances, The ions are breakdown based on their mass-to-charge ratio (m/z) in the mass analyzer. Quadrupole and time-of-flight (TOF) mass analyzers are the most often utilized in GC-MS for biodiesel analysis. GC-MS commonly employs quadrupole and time-of-flight (TOF) mass analzsers for biodiesel analysis. The mass analyzer creates a mass spectrum for each compound based on the intensities and masses of the ions [159].

Compound Identification: The mass spectra recorded are matched with reference libraries or mass spectral databases to identify the specific components in the biodiesel sample. The comparison process involves comparing the analytes' mass spectra with the existing ranges of reference compounds. Using sophisticated software tools and algorithms plays an essential role in facilitating this procedure, hence enhancing the identification of compounds.

Quantification: The quantification of recognized substances depends on utilizing the intensities of ions in mass spectra. To achieve this, it is customarily necessary to compare the analyte's ion peak areas or powers to those of internal or external calibration standards with established concentrations.

Data Analysis and Reporting: The findings from the gas chromatography-mass spectrometry study, including the chromatograms, mass spectra, and quantification data, are carefully analyzed and summarized into a comprehensive report. The report contains data regarding the substances that have been identified, their respective concentrations, as well as the complete composition of the biodiesel sample [157, 160].

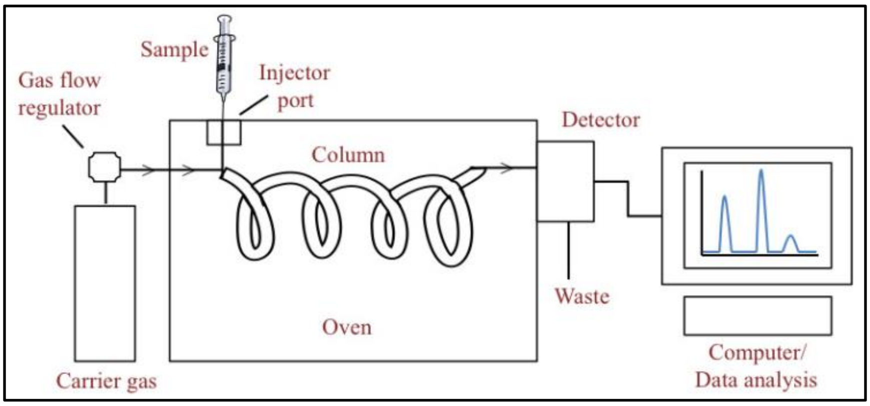


Figure 3.5: Working of gas-chromatography

3.5 Selection of Antioxidants

Antioxidant additives are compounds added to biodiesel to stop oxidation, increase fuel stability, and lengthen shelf life. They ensure fuel quality, lower engine deposits, and improve engine performance for a more sustainable and clean energy source by preventing the production of hazardous substances. Antioxidants can be categorized into two types [146, 161],

1) synthetic antioxidants, and
2) natural antioxidants.

Synthetic antioxidants are categorized into two types: phenolic antioxidants and aromatic antioxidants. Synthetic antioxidants with phenolic ring structures are referred to as phenolic antioxidants. They have an aromatic ring connected to a functional group called hydroxyl (-OH) and are frequently produced from hydrocarbons. Antioxidants of the amine type are synthetic substances that include an aromatic amine active group [146, 162]. These antioxidants are butylated hydroxytoluene (BHT), Pyrogallate (PG), butylated hydroxy anisole (BHA), Pyrogallol (PY), tertiary butylhydroquinone (TBHQ), etc. shown in figure 3.6.

Figure 3.6: Representation of synthetic antioxidants

Natural antioxidants comprise tocopherols (Vitamin E), ascorbic acid (vitamin C), Phenol compounds, and sterols. Natural antioxidants utilized in biodiesel are Potato peel extract, ginger, green tea, oregano, basil, turmeric, black pepper, Tinospora cordifolia stem extract, etc. [33, 154, 161].

Table 3.1 represents the use of some synthetic and natural antioxidants in biodiesel and their impact on the induction period. As per the literature available by researchers, the most utilized synthetic antioxidants are TBHQ, PG, BHA, PY, and BHT. Among these five antioxidants, TBHQ, PY, and PG give promising results regarding oxidation stability. In this present study, two synthetic antioxidants (TBHQ and PY), one aromatic amine antioxidant (Diphenylamine, DPA), and one natural antioxidant (Tinospora cordifolia stem extract, TC) were used to analyse the effect of these antioxidants on oxidation stability, and other performance parameters. A detailed description of antioxidants is given in Table 3.2.

Table 3.1: Natural and Synthetic antioxidants effects on biodiesel oxidation stability

Type of Biodiesel	Antioxidant	Antioxidant quantity	Test Methods	Oxidation stability without antioxidant	Increased value of oxidation stability by adding antioxidants in h	References
Pongamia Biodiesel	PY	200 ppm	Rancimat	1.83 h	6.5 h	[48]
Waste cooking Biodiesel	PG, PY, BHA, BHT, TBHQ	1000 ppm	Rancimat	2.58 h (Rancimat)	Rancimat @1000 ppm (BHA8.32, BHT8.95, TBHQ48.88, PG22.20, PY23.32) in h	[163]
Soybean Biodiesel	PrG, BHA, BHT, TBHQ, α-tocopherol	2000 ppm	Rancimat	1.36 h	α-tocopherol not showing any improvement in oxidation stability. BHT & BHA show improved valves with increased ppm. TBHQ is showing promising results.	[164]

Type of Biodiesel	Antioxidant	Antioxidant quantity	Test Methods	Oxidation stability without antioxidant	Increased value of oxidation stability by adding antioxidants in h	References
Crude Moringa oleifera	Aromatic Amine (DPPD, NPPD)	2000 ppm	Rancimat	3.05 h	@2000 ppm (DPPD34.5, NPPD18.4) in h, when mixed with 20% moringa biodiesel with 80% diesel blend	[165]
Karanja Biodiesel	BHT, Tinospora cordifolia stem extract	1000 ppm	Rancimat	2.49 h	@1000 ppm (BHT 15.32, stem extract 8.56) in h	[166]
Mesua ferrea L. Biodiesel	Potato peel extract (PPE) TBHQ	250 ppm	Rancimat	5.63 h	@250 ppm (PPE 7.02, TBHQ 7.0) in h	[143]
Calophyllum Inophyllum Biodiesel (CIB)	DPPD	1000 ppm	Rancimat	13.56 h (CIB20%)	1000 ppm DPPD shows Induction Period 22.7 h	[167]
Waste cooking Biodiesel	Camellia assamica	1000 ppm	Rancimat	2.88 h	1000 ppm of Camellia assamica shows an induction period of 7.11 h	[168]
Rapeseed Biodiesel	Ginger, Basil, Oregano and Moringa oleifera	500 1000 1500 2000	Rancimat	2.23 h	IP order: Ginger>Moringa Oleifera> Basil>Oregano Ginger: 11.5 h@500 ppm, 18.5 h@1000 ppm, 23 h@1500 ppm, 26.4 h@2000 ppm	[144]

Table 3.2: Detail of different categories of antioxidants

Type of antioxidant	Antioxidant name	Molecular weight	Molecular formula	Morphology	Solubility color	Color
Synthetic	TBHQ	166.22 (g/mol)	$C_{10}H_{14}O_2$	Powdered Crystal	Soluble	Light tan
Synthetic	PY	126.11 (g/mol)	$C_6H_6O_3$	Powder	Soluble	White
Aromatic amine	DPA	169.23 (g/mol)	$(C_6H_5)_2NH$	powdered Crystal	Soluble	Light yellow
Natural Antioxidant	Tinospora cordifolia stem extract	492.5 g/mol	$C_{25}H_{32}O_{10}$	Powder	Insoluble	Light Green

3.6 Production of Natural Antioxidants

Tinospora cordifolia, or "Giloy" or "Guduchi," is a medicinal herb frequently utilized in conventional Ayurvedic treatment. It has gained attention for its potential antioxidant properties. However, Tinospora cordifolia stem extract has the potential as a natural antioxidant.

The first step is to remove the Giloy plant’s stem and cut off the leaf. Giloy plant stems must dry in the sun for a few days before transforming into powder. One standard method is to create an extract using an appropriate solvent, like ethanol or methanol. Refluxing the plant material in the solvent for at least 6 to 8 hours is required for the procedure. By doing so, the active substances can dissolve into the solvent. A crude extract is produced after the mixture has been filtered to remove any remaining solid plant material after the extraction of active components in a solvent. Tinospora cordifolia stem conversion into Tinospora cordifolia stem extract is depicted in Figure 3.7.

The cordifolia Antioxidant Extraction is then produced by processing this extract in a rotary evaporator. A rotary evaporator, shown in Plate 3.1, is a device that effectively removes the solvent from the crude extract by vacuum and gentle heat. An ongoing rotation of the sample, dissolved in a flask, occurs as the pressure within apparatus is decreased by a vacuum system. This lowers the solvent's boiling point, evaporates in condenser at a lower temperature, after cooling it condensed back, and the solvent that has evaporated rises through the flask. The concentrated sample is separately collected. This concentrated extract is rich in active compounds, including potential natural antioxidants [106, 154, 169, 170].

Figure 3.7: T. cordifolia Antioxidant Extraction Process

Plate 3.1: Rotary Evaporator

3.7 Preparation of Test Fuel Blend with and without Antioxidants

For making blends, produced biodiesel from NO, and WCO was used to make diesel and biodiesel blends. For the preparation of the test fuel blend, 20% biodiesel was mixed with 80% diesel for making WCB and NB blends, 80D20WCB and 80D20NB, respectively. For the making of fuel blends, the splash method was used. To use this technique, one container must contain biodiesel and conventional diesel to create a homogeneous mixture by stirring for 5–10 minutes. Synthetic antioxidants TBHQ, DPA, and PY antioxidants, 500 ppm and 1000 ppm doses mixed with WCB and NB. 500 and 1000 ppm doses of Tinospora cordifolia, a natural antioxidant mixed with WCB and NB.

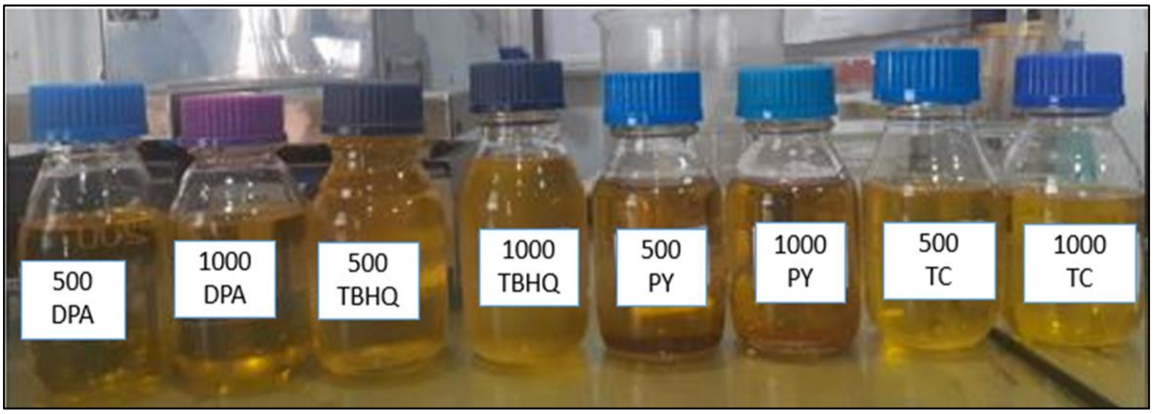


Figure 3.8: Waste cooking oil biodiesel with antioxidant

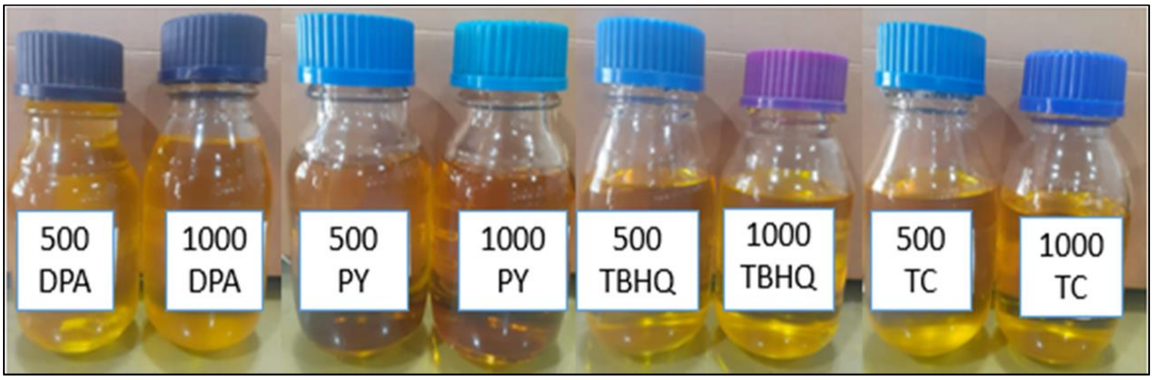


Figure 3.9: Neem biodiesel with antioxidant

Antioxidant dosages were added to biodiesel based on weight, and the antioxidant concentrations were converted from parts per million (ppm) to grams per liter (g/L) within the biodiesel. Specifically, 1000 ppm of antioxidants corresponded to 0.998859 g/L, while 500 ppm of antioxidants equated to 0.499429 g/L when incorporated into the biodiesel. Conversely, these concentrations were adjusted from grams per liter (g/L) to ppm as necessary. The physical representation of antioxidant-treated biodiesel in WCB and NB is shown in Figures 3.8 and 3.9. This study uses diesel, diesel-biodiesel (80-20%) blends, and diesel-biodiesel blends with synthetic and natural antioxidants to conduct engine test analysis, as represented in Table 3.3.

Table 3.3: Representation of various test fuel blends

Test Blends	Blend details
D100	Pure Diesel
80D20WCB	**80% Diesel 20% WCB Biodiesel in volume percentage**
80D20(WCB+500DPA)	80% Diesel 20% WCB Biodiesel with 500 ppm of DPA
80D20(WCB+500TBHQ)	80% Diesel 20% WCB Biodiesel with 500 ppm of TBHQ
80D20(WCB+500PY)	80% Diesel 20% WCB Biodiesel with 500 ppm of PY
80D20(WCB+1000DPA)	80% Diesel 20% WCB Biodiesel with 1000 ppm of DPA
80D20(WCB+1000TBHQ)	80% Diesel 20% WCB Biodiesel with 1000 ppm of TBHQ
80D20(WCB+1000PY)	80% Diesel 20% WCB Biodiesel with 1000 ppm of PY
80D20(WCB+500TC)	80% Diesel 20% WCB Biodiesel with 500 ppm of TC
80D20(WCB+1000TC)	80% Diesel 20% WCB Biodiesel with 1000 ppm of TC
80D20NB	**80% Diesel 20% Neem Biodiesel in volume percentage**
80D20(NB+500DPA)	80% Diesel 20% Neem Biodiesel with 500 ppm of DPA
80D20(NB+500TBHQ)	80% Diesel 20% Neem Biodiesel with 500 ppm of TBHQ
80D20(NB+500PY)	80% Diesel 20% Neem Biodiesel with 500 ppm of PY
80D20(NB+1000DPA)	80% Diesel 20% Neem Biodiesel with 1000 ppm of DPA
80D20(NB+1000TBHQ)	80% Diesel 20% Neem Biodiesel with 1000 ppm of TBHQ
80D20(NB+1000PY)	80% Diesel 20% WCB Biodiesel with 1000 ppm of PY
80D20(NB+500TC)	80% Diesel 20% NB Biodiesel with 500 ppm of TC
80D20(NB+1000TC)	80% Diesel 20% NB Biodiesel with 1000 ppm of TC

3.8 Physicochemical Properties Determination

The physicochemical characteristics of the fuels used in any experimentation significantly impacted the diesel engine's performance measurements. The enhancement in fuel quality enhanced the performance characteristics. To verify the diesel engine characteristics, measuring the physio-chemical parameters of the chosen fuel was essential. All required fuel properties and their various blends were determined experimentally using a variety of equipment in accordance with ASTM standards. The numerous methods, equipment, and procedures used to evaluate the properties of the fuel are thoroughly outlined in the following sections.

3.8.1 Kinematic viscosity

The fluid resistance measurement of a flow between adjacent layers is known as its viscosity. Low-viscosity fuel must be used in diesel engine applications to reduce pump effort and improve atomization. The fuel's volatility is significantly impacted by it. Less viscosity in the fuel means a faster evaporation rate, which produces a good mixture in an engine cylinder. Higher viscosity fuels result in improper combustion, which intern raises the accumulation of carbon deposits on the fuel injection system of diesel engines [171, 172].

According to ASTM D445 methods, the kinematic viscosity of the gasoline samples was evaluated at a temperature of 40 °C by "Petrotest Viscometer". Plate 3.2 shows the instruments used to determine the kinematic viscosity. It consists of an Ostwald-type capillary tube in a U-shape submerged in the viscometer reservoir, with the level bulb's upper and lower marks also submerged. Distilled water is poured into the reservoir. The fuel is then fed into the capillary tube bulb with a measured amount until it reaches the upper mark. Time was measured in seconds, and the capillary constant, as given in eq. 3.1 was multiplied to evaluate the kinematic viscosity value in mm^2/s, or cSt.

$$\nu = k*t \qquad [3.1$$

where,

ν = Biodiesel kinematic viscosity (mm2 /sec),

k = Capillary constant of tube (0.002935 mm2/sec2),

t = time consumed in traveling of fuel sample from upper to lower limit (sec).

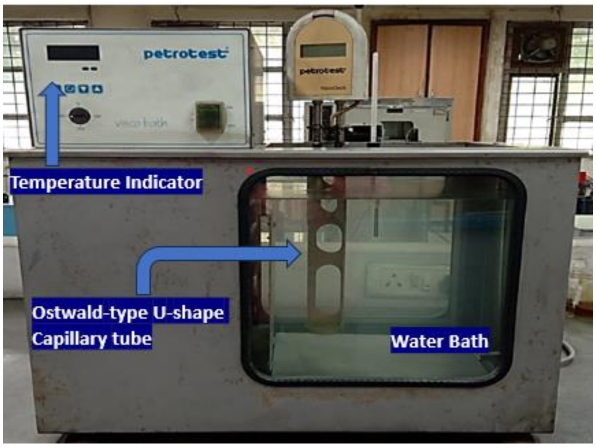


Plate 3.2: Viscometer

3.8.2 Density

Density, defined as the mass of fuel per unit volume, directly affects engine performance and efficiency. It affects the amount of gasoline injected into the engine and influences the fuel-air ratio. An optimal ratio ensures effective combustion, improving engine performance and fuel efficiency. Fuel energy content influences the Process of combustion and, subsequently the exhaust gas emissions [45, 173]. As diesel and biodiesel density affects combustion efficiency, fuel consumption, and emissions, accurate measurements of these substances are essential for testing engines.

The Density Meter, as shown in Plate 3.3, Model make DMA 4500 was employed in this analysis to determine the different fuel sample's density @ 15°C, as per ASTM D4052 method. This density meter uses the U-tube oscillating method as its measurement basis. The loaded sample oscillates inside the U-tube at a particular frequency set by the nature of the sample, and this frequency is used to calculate the density value. The procedure starts with injecting 10 ml of toluene into the U-tube pipeline to clean it thoroughly. After cleaning, the fuel sample is placed into the U-tube to determine its density. Each fuel sample was measured three times for accuracy and dependability, and the average of these measurements served as the final density reading.

Plate 3.3: Density Meter

3.8.3 Calorific Value

Calorific value also called the heating value or energy value quantifies the amount of energy generated for complete combustion of specified fuel in the presence of oxygen. It is often represented in energy per unit mass or fuel volume. The amount of energy a fuel may produce during combustion increases with its calorific value. The measurement process followed ASTM standard D240 [18, 120].

The Anton Parr 6100 Compensated Calorimeter, shown in Plate 3.4, was used to calculate the lower heating value also called calorific value, in this investigation. The oxygen bomb is charged using an automated and digitally controlled electric arc system in this calorimeter, ensuring controlled and precise oxygen filling. A known volume of the fuel sample is put within a sample holder that fits inside the bomb to calculate the calorific value. An electrode must be placed to ignite the mixture so that its middle is immersed in the fuel. The bomb is then loaded with oxygen.

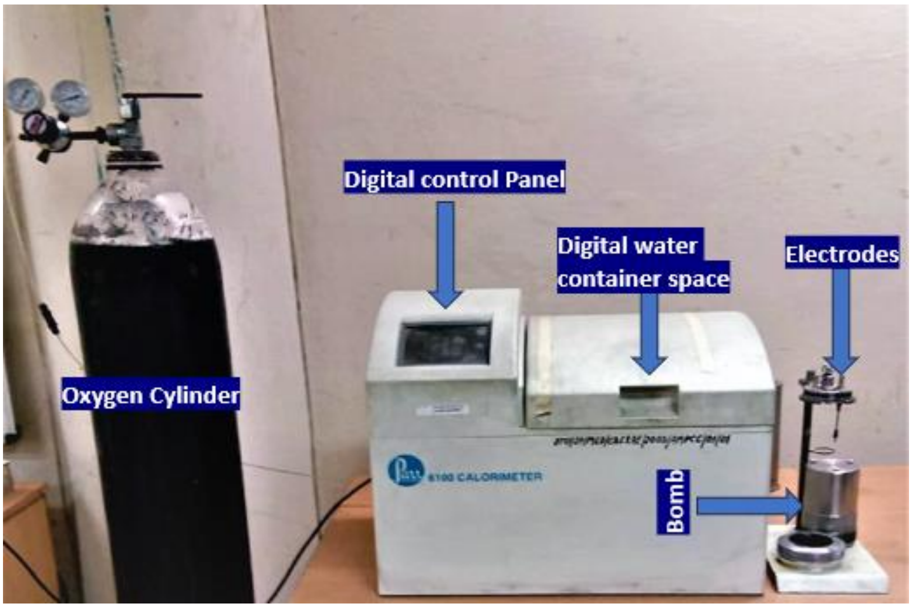


Plate 3.4: Bomb calorimeter setup

Then, the bomb is maintained in a calorimeter inside a jacket filled with water. when a current passes through the electrode, the fuel interacts with the compressed oxygen in the bomb to produce heat. On the panel of the bomb calorimeter system, the heat released is shown. After doing analysis, remove water, clean sample holder and electrode for further measurement.

3.8.4 Flash Point

The flash point, a fundamental property that gauges a fuel's flammability, is the minimum temperature at which gasoline vapor can ignite upon encountering ignition sources. According to the available literature, it has been noted that biodiesel generally exhibits a more excellent flash point compared to diesel fuel [18, 152].

Flash Point Apparatus, The Pensky Martens Automatic apparatus is used to calculate the test fuels' fire and flash points by considering the ASTM D 93 method, shown in Plate 3.5. During this process, a specific quantity of the fuel was placed into a container and tightly sealed with a cap. After that, the sample was heated intermittently, allowing oxygen to enter the cup briefly. Through these openings, the ignition source was mechanically placed within the cup to conduct the test.

Plate 3.5: Flash point apparatus

3.8.5 Cetane Index

The Cetane Index is a numerical measure to assess diesel fuel and biodiesel ignition characteristics. It represents the fuel's capacity for rapid ignition and effective CI engine combustion. Diesel fuel has the smoother engine running, higher ignition properties, quicker cold-start times, better cold-start performance, and higher fuel efficiency due to a higher cetane index. In addition, it causes a decrease in the emissions of particulate matter and unburned hydrocarbons, helping to improve air quality [45, 156, 171].

While an excessively high cetane index might result in a lean fuel-air mixture and operational problems, a reduced value of the cetane index increases the chance of engine banging. The cetane index must be calculated precisely, especially when contrasting various fuel samples. The cetane index was determined in this investigation using the ASTM D4737 standard. Equation 3.2 can be employed to calculate the cetane index.

Cetane index = 45.2 + (0.0892) *T10A + [0.131 + (0.901 * X) * T50A] + [0.0523 − (0.420 * X)* T90A] + [0.00049 * (T10A) 2 − (T90A) 2] * (107X + 60X2) (3.2)

X= [e-3.5 (D-0.85)] −1,

D = Measured sample fuel density at `15 °C,

T10A, 50A, 90A: Distillation temperature for obtaining 10%, 50%, and 90% vol. /vol. distilled fuel.

3.8.6 Clod flow properties

Fuel's "cold flow properties" refer to its capacity to function and flow at low temperatures, especially during cold weather. These characteristics are essential for many uses, including transportation fuels used in vehicles, aircraft, and other machinery working in colder areas or during the winter. Therefore, cold flow characteristics were determined by their cold filter plugging point and pour point [34, 122].

3.8.7 Cloud Point and Pour Point

The cloud point signifies the point at which the fuel’s paraffin and dissolved waxes commence crystallization, including a cloudy or hazy appearance. The gasoline can still exhibit gravitational flow at its minimum temperature, considered as the pour point. Below the pour point, the fuel becomes excessively viscous and may not flow properly, making it challenging to start engines or fuel systems [111, 116, 173]. The cloud-point and pour-point tests were performed using the specifications provided, respectively. Plate 3.6 displays the refrigerator used to calculate the cloud and pour points. A hole is provided on the refrigerator's top, and a test tube with a fuel sample provided with a rubber cork is inserted within it. A Resistance Temperature Detector (RTD) temperature sensor can be inserted into the cork's central orifice to measure the fuel's temperature. After every 3℃ reductions in temperature, the test tube is removed and examined to examine the cloud and pour point development.

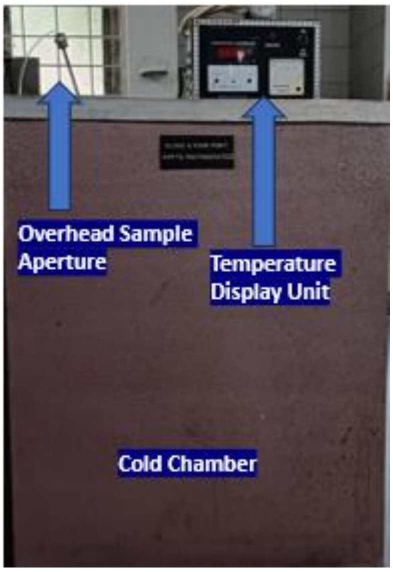


Plate 3.6: Cloud point and Pour point apparatus

3.8.8 Cold filter plugging point

The CFPP is the temperature at which diesel can no longer pass through a fuel filter, under specific conditions. This characteristic is crucial for diesel fuels because it predicts the risk of fuel filter clogging and consequent engine stoppage because of cold-induced wax crystallization [174]. The various fuel samples' CFPP were determined using the CFPP setup manufactured by Linetronic Technologies, as depicted in Plate 3.7. The device functions according to the ASTM D6371 standard to evaluate the CFPP of test fuel blends. The fuel is cooled to -34°C in the first step, and then a vacuum-assisted mechanism draws a metered amount into the capillary. The fuel's CFPP is determined when it does not pass through the specified 10-micron filter within a time restriction of 1 minute, as observed in the test setup.

Plate 3.7: Cold flow plugging point apparatus

3.9 Experimental Setup for Conducting Engine Trials

As previously discussed, the objectives are to identify the effect of antioxidant combustion, performance, and emissions. For making the same selection of appropriate Internal combustion is required. This section details engine selection, selection parameters, assembly of engine setup, and measurement of various parameters.

3.9.1 Selection of IC Engine

The current investigation employed a direct injection type engine (Kirloskar DAF8), 4-stroke, single-cylinder design. This engine is air-cooled, 3.5 KW power output, and operates at 1500 rpm. Table 3.4 represents the specifications of the compressed ignition engine. Figure 3.10 shows configuration of the engine used for testing.

Table 3.4: Specification of engine setup

Parameter	Specifications
Model	Kirloskar, DAF8
Type	Direct Injection Type, Four Stroke, Single Cylinder
Cooling	Air-cooled
Rated Wattage	3.5 KW
Rated speed	1500 rpm
Bore Diameter	95 mm
Length of the stroke	110 mm
Compression ratio	17.5:1
Fuel Injection Pressure and timing	200 bar and 23° bTDC (Before Top Dead Center)
Injector Type	Six-holed, Solenoid
Lubrication system type	Forced Feed

The cylinder block comprises cast iron, whereas the cylinder liner, known as the sleeve, is constructed from hardened high-phosphorous cast iron. It is inserted inside the cylinder block to give the piston a smooth surface to move up and down on. The camshaft is in the position of regulating the timing of valve opening and shutting in the engine. The fuel injection system of DAF8 direct injection engines comprises various components, such as the fuel pump, injectors, and high-pressure fuel lines. The configuration integrates cylinders and cylinder heads with fins to enhance the surface area, facilitating efficient heat dissipation. The engine block, pistons, and sometimes the crankcase have additional cooling fins. Engine oil plays a crucial role in an engine's functioning by providing lubrication to its moving parts and facilitating heat absorption, contributing to the cooling process. The engine has a thermostat that regulates airflow and ensures optimal operating temperatures. Plate 3.8 shows the test engine used to perform proposed analysis.

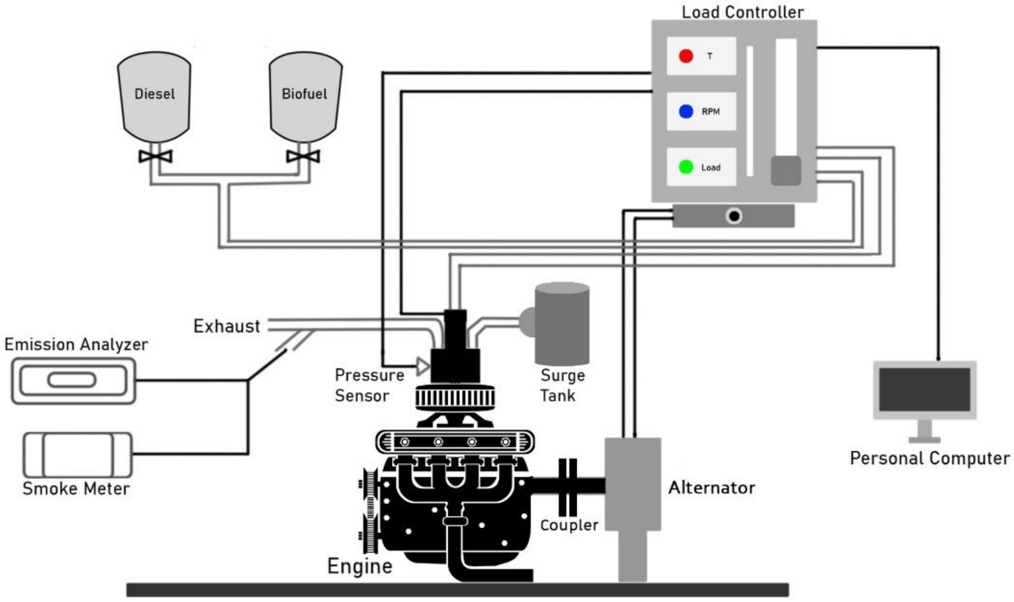


Figure 3.10: Configuration of engine setup

Alternators are commonly employed to apply electric load to air engines. A C generator, alternator having capacity of voltage, current, speed given as 230-volt, 21.7 amp, and 1500 rpm. The engine test setup connected to personal computer to take required data, shown in plate 3.9.

Plate 3.8: Engine Test Setup

Plate 3.9: Personal Computer system

3.9.2 Selection of engine test parameter

Some parameters must be observed during experimental trials, and some must be calculated per input conditions. These parameters are represented in Table 3.5.

Table 3.5: Observed and calculated parameters of the engine

1. Observed parameter	**2. Calculated Parameter**
• Engine load	• Brake Power (BP)
• Engine speed	• BTE
• Fuel consumption rate	• BSEC
• Temperature	• BMEP
• In-cylinder pressure	• HRR, Heat release rate
• Emissions CO, HC, and NOx, Smoke opacity	

3.10 Assessment of Observed and Calculated Engine Test Parameters

3.10.1 Engine load

Power generation depends on engine load. In general, the load opposes engine power. Engines are designed to operate at a specified speed for a rated or full load. A simple load calculation method is needed for the laboratory test, which uses varying loads. Engine test rigs employ dynamometers to measure engine power. This study used an air-cooled AC dynamometer. This allows faster load adjustment for rapid loading. The electrical dynamometer assembly has a rotor, shaft, bearings, shell, and bedplate.

Rotors are installed on shafts with bearings. The casing creates the magnetic field as a direct current passes through the air gaps on either side of the rotor to enable rotation into the magnetic field. The dynamometer had load resistance unit and AC generator, while control panel had an amp-meter, voltmeter, and switch fuse carrier. It is set up on the engine test equipment to calculate the power absorbed. Plate 3.10 displays the electric loading bulbs.

3.10.2 Engine speed measurement

For the measurement of speed RPM sensor (magnetic pick-up type) was used This sensor was placed next to a toothed gear and produced an AC voltage pulse for each tooth as it passed, creating a pulse for the entire gear. More pulses were produced in the coil as the gear's rotating speed accelerated.

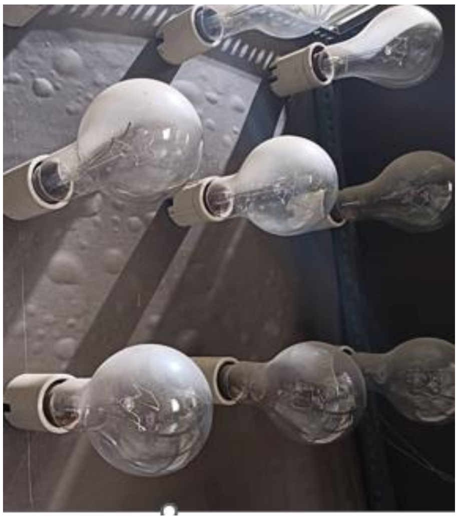


Plate 3.10 Electric loading bulbs

Plate 3.11 RPM sensor.

The data acquisition system received these impulse signals digitally, simplifying data collection and analysis. The control module of the data collecting system utilized the recently received pulses to compute the engine's revolutions per minute (RPM). The control panel displayed the final RPM value. Please refer to Plate 3.11 for an illustration of the RPM sensor.

3.10.3 Measurement of fuel consumption rate

The time it takes to consume a specific amount of fuel (10 cc) is measured using a timer to determine the mass flow rate of pilot fuel. The fuel consumption is then calculated using the following equation under different loading conditions given in equation 3.3:

Mass flow rate (kg/s) = (Mass of fuel consumed in kilograms) / (Time in seconds)

$$M_f \text{ (kg/s)} = M_f \text{ (kg)} / t \text{ (sec)} \qquad [3.3]$$

$$M_f \text{ (kg/s)} = (Ycc * \rho) / t$$

Where: M_f = mass flow rate in kg/sec, Ycc = 10 cc of volume consumed, ρ = density of fuel (kg/m3), t = time (sec).

3.10.4 Measurement of temperature

K-type thermocouples are frequently employed as temperature sensors in various applications, including temperature monitoring in diesel engines, represented in plate 3.12. K-type thermocouples are helpful in monitoring multiple engine components, including exhaust gases, cylinder walls temperature, and cooling systems temperature. They can measure temperatures between -200°C and +1350°C. They respond rather quickly, which enables real-time monitoring and control of the temperature, which is crucial for the efficient operation of diesel engines. A junction is made by joining two wires of different metals, especially nickel, and aluminum, at one end to form a thermocouple. A minor voltage is generated that is directly influenced by the temperature difference between the junction and the wires' opposing ends. The recorded voltage is used to ascertain the purpose of detecting the temperature at the connection.

Plate 3.12: K-type thermocouples

3.10.5 In-cylinder pressure measurement

A piezoelectric pressure transducer is used by a diesel engine to gauge the pressure inside its cylinders, fitted in the cylinder head as depicted in plate 3.13. It works using the piezoelectric phenomenon, in which mechanical stress brought on by pressure produces an electrical charge. The pressure transducer sends an electronic signal to a data acquisition system. This system analyses and stores the pressure data at various times during the engine's running cycle. It is perfect for real-time measurements of rapid pressure changes throughout the combustion cycle of an engine due to its quick response time and resistance to high temperatures and pressures.

Plate 3.13: Piezoelectric pressure sensor

3.10.6 Exhaust emissions measurement

The AVL Exhaust Gas Analyzer assesses and quantifies the different exhaust gas components emitted from an engine. This method is commonly used for measuring pollutants present in exhaust gases, including CO_2, NOx, HC, CO, and O_2. The exhaust gas analyser collects a sample of exhaust gas through a sampling probe. Depending on the gas being measured, the gas is then evaluated using various technologies, including infrared spectroscopy, non-dispersive infrared (NDIR) sensors, chemiluminescence, or electrochemical cells. The analyser monitors the intensity of the light traveling through the gas and uses that information to calculate the concentration of each gas component. Each component absorbs or emits light at particular wavelengths. The data is recordable for further analysis and adherence to emission standards. AVL 1000 gas analyser represented in plate 3.14.

An AVL smoke meter measures the visible smoke released from diesel engine exhaust. AVL smoke meter (DISMOKE 480 BT), shown in plate 3.15, was used in this study. The smoke meter uses a light source and a photodetector on either side of the exhaust gas stream. The cleaner the exhaust, the lower the smoke unit value. The filter paper is used to gather soot or

Plate 3.14: AVL Exhaust gas analyzer **Plate 3.15: Smoke meter**

unburned particles left over from the combustion process. The filter paper is exposed to the light beam as it continues to be filled with soot and black carbon particles. The photoelectric current between the main detectors and reference allows the photocell to detect soot particles' reflected light. The induced photoelectric current, therefore, measures the amount of soot or smoke.

3.10.7 Brake power

A term such as "brake power" (BP) describes the amount of power generated by the engine's crankshaft as measured at the flywheel or output shaft, excluding any power losses in the drivetrain or accessories. [48, 175]. The term "power output" refers to the helpful power that may be utilized for mechanical work, such as moving a vehicle or powering machinery.

Brake power can be calculated by given below equation 3.4.

$$BP = (2 * \pi * N * T) / 60 \text{ or } BP = (V * I) / \eta_G * 1000 \qquad [3.4]$$

Where:

BP = Brake Power (in watts, kilowatt, or horsepower)

π = Pi, approximately 3.14159, N = Engine speed or rotational speed (in revolutions per minute, RPM)

T = Torque produced by the engine (in Newton-meters, Nm), V – Voltage (Amp), I – Current (Volt), η_G = efficiency of the generator

3.10.8 Brake thermal efficiency

To determine how well an internal combustion engine transforms the available energy of fuel into meaningful mechanical work at the engine's output shaft, one important performance parameter called BTE is used [176].

The BTE is calculated by given equation 3.5.

$$BTE (\%) = BP (KW) * 100 / M_f * CV \quad [3.5]$$

Where:

M_f = Mass flow rate measured in kg/s

CV = Calorific value measured in kJ/kg

3.10.9 Brake-specific fuel consumption

Brake-specific fuel consumption considers an essential measurement. Fuel consumption of internal combustion engines calculated for produced power out. The BSFC can be stated in terms of the quantity of fuel consumed for every unit of electricity, such as grams per kWh (g/kWh) [45, 177, 178]. Similarly, brake-specific energy consumption refers to the quality of fuel energy utilized to generate a given amount of shaft power.

The formula for calculating brake-specific fuel consumption is given in equation 3.6:

$$BSEC (MJ/kWh) = [(M_f * CV) * 3600] / BP (kW) \quad [3.6]$$

M_f = Mass flow rate calculated in kg/s

CV = Calorific value calculated in kJ/ kg

3.10.10 Brake mean effective pressure

The average pressure placed on the piston of an internal combustion engine during the power stroke is measured by the BMEP, which is a crucial performance parameter. This reveals how well the energy supplied by fuel combustion into useful shaft work [155, 179].

The equation utilized for the computation of Brake Mean Effective Pressure is as follows (equation 3.7):

$$BMEP = [2*60* BP] / [L *A * N *101.325] \quad [3.7]$$

Where,

BP = Brake power measured in KW

L= Stroke length

N= number of power strokes per min, i.e., N/2 for 4-stroke and N for two-stroke engines

L= Stoke length of stroke in mete

A= cross-sectional area of the piston (m^2)

3.10.11 Heat release rate

The Heat Release Rate in a diesel engine refers to the speed at which energy is discharged throughout the combustion procedure. It is a measurement of the amount of heat an engine generates in a specific period of time when fuel is burned in its cylinders. When examining combustion characteristics, engine performance, and the evaluation of pollutants in compression ignition engines, a heat release rate (HRR) is essential [148, 176, 178]. One prevalent technique for estimating a diesel engine's heat release rate (HRR) involves examining cylinder pressure data acquired using in-cylinder pressure sensors. Pressure data is commonly gathered during the combustion cycle of the engine. Change in pressure to change in crank angle (dp/dθ) for a given time can be achieved by evaluating change in pressure rise at different crank angles. The first law of thermodynamics is employed for calculating the heat release rate.

According to the law

$$Q(cyl+wall) = U+W \qquad [3.8]$$

Where:

Q(cyl+wall) = Combined engine cylinder heat release and heat exchange across the walls;

U= Combust gases internal energy (J/kg)

W= System work done

The representation of the HRR is given by equation 3.9:

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1} * P * \frac{dV}{d\theta} + \frac{1}{\gamma-1} * V * \frac{dP}{d\theta} - \frac{dQ_w}{d\theta} \qquad [3.9]$$

Where:

$dQ/d\theta$ = Net rate of HRR (J/°CA)

$dQw/d\theta$ = Heat transfer rate executed from wall (J/°CA)

γ = Specific heat ratio

P = pressure inside the cylinder (bar)

V = Volume of the gases (m^3)

θ = Crank angle (°)

3.11 Engine Trials Methodology

The engine trial procedure involves several steps to ensure accurate and reliable data for testing different fuel blends' performance, combustion, and emission, Firstly, the engine test rig and all equipment are thoroughly inspected and calibrated to ensure optimal working conditions. Before starting the engine, initial checks are conducted to verify the fuel level and eliminate air bubbles in the fuel line. Initially, the engine started with diesel at no load for 20-30 minutes for stabilization. By doing so, the engine achieves equilibrium and stabilizes the exhaust temperature as per the specific load.

The engine test setup's data acquisition system (DAS) is turned on to collect signals from sensors and transmitters. In-cylinder pressure sensors capture the combustion data over 60 cycles to examine the data. Emission measurement equipment, such as exhaust gas analysers, evaluate pollutants, including other tailpipe emissions. In accordance with the calibrated specifications provided by the engine manufacturer and the IS:10000 requirements, engine testing is conducted at a rated power of 3.5 kW and a constant speed of 1500 rpm. Readings were taken at 20% loading intervals from no load to full load.

All engine output parameters were carefully analysed before starting testing for each fuel blend. To prevent any inconsistency in outcomes, the experiments were performed multiple times. As previously noted, a diesel tank was utilized for the baseline data, and after that, the fuel line was switched via a rotary valve to use a biodiesel tank to supply biodiesel blends in the combustion cylinder. Diesel was used to start the engine each time, and diesel was then stopped after at least 20 to 30 minutes.

3.12 Accuracies and Uncertainties of Measurements

Every work contains some level of uncertainty. The term "error analysis" refers to a detailed consideration of the uncertainties that result from physical measurements. These uncertainties impact test procedures, environmental circumstances, observations, sensors, and instrument calibrators. Accuracy and uncertainty for instruments are given in Appendix 1.

Overall uncertainty in this study = square root of uncertainty of [$(BSEC)^2$ + $(BTE)^2$ + $(\text{Brake power})^2$ + $(HC)^2$ + $(CO)^2$ + $(NOx)^2$ + $(\text{Smoke})^2$ + $(EGT)^2$].

Overall uncertainty = 2.9251.

3.13 Predicting Analysis of Performance and Emission Parameter using Artificial Neural Network

Currently, there is a growing interest among researchers in utilizing Artificial Neural Networks (ANN) within the automotive industry [180]. An ANN connects a system's inputs and outputs and has been effectively used to map nonlinear correlations between input and output across several disciplines. An ANN is made up of a number of hidden nodes that facilitate the connection between its input and output nodes, in addition to its input nodes. All three layers contain a distinct quantity of individual units called neurons. Neurons transmit their communication signals to neighboring neurons through a communication link characterized by a specific weight [158, 181]. In machine learning, the Artificial Neural Network technique consists of two primary steps: The process of training a neural network may be divided into two steps, as described by [158]. The first stage involves collecting data along with corresponding weights and biases. The data mentioned earlier is employed for the purpose of adjusting the parameters of the neural network. The subsequent phase is prediction when the neural network is trained using the provided input data.

3.13.1 ANN architecture

The focus of the present study is the application of artificial neural networks (ANN) in predicting the performance characteristics of blends consisting of waste cooking oil and neem biodiesel. The data set for the ANN model came from engine trials with various loads. The model's inputs included the engine load, percentage of blend, and antioxidant dose. The characteristics under investigation included the Input and output parameters of the engine as shown in architecture. The architectural layout of the ANN is depicted in Figure 3.11. In this ANN model, 70% of the available data was allocated for training, 15% was reserved for testing, and 15% was utilized as particular samples. The "quasi-Newton method" was employed in the training and optimization of data in the ANN modelling process [181, 182].

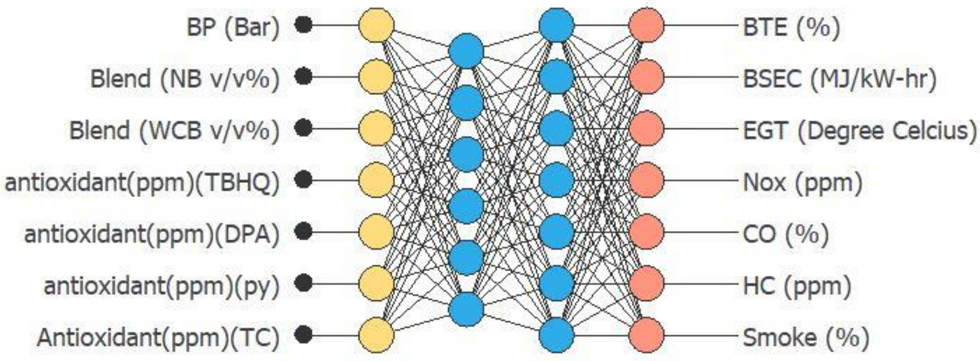


Figure 3.11: ANN architecture

3.14 Observed and Predicted Analysis

Linear regression analysis is commonly used as a standard way to assess the variation between the scaled output of a neural network and the corresponding targets. Three parameters are provided for each outcome variable in this analysis. These parameters measure the relationship between the scaled output and the target and include the correlation coefficient, slope, and y- intercept, The terms "slope" and "y-intercept" are typically represented in the context of this study as variables "a" and "b." For the best fit, the slop, y-intercept, and correlation all approach (R^2) to 1, while the y-intercept approaches zero. For a perfect fit, the slope between the output and the intended value should ideally be equal to one., and the flow chart illustrating the architecture of an ANN is depicted in Figure 3.12.

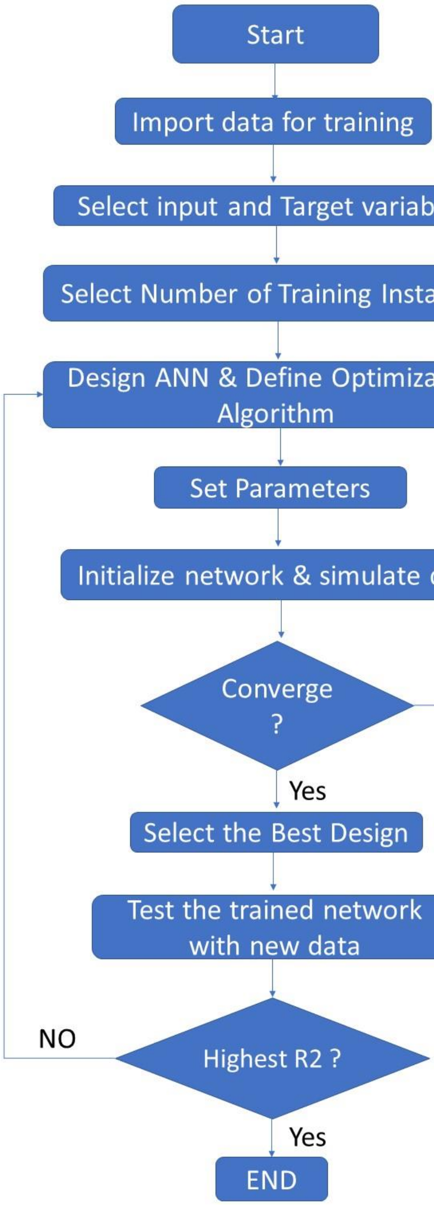


Figure 3.12: ANN flow chart

The fact that the y-intercept is zero indicates that the output and target are perfectly aligned. The correlation coefficient will be 1, when the targeted output and scaled output are perfectly correlated, the correlation coefficient will be 1.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter provides an extensive discussion of the finding achieved from this work. GC-MS analysis is explained to ensure biodiesel quality produced from different feedstocks, waste cooking oil, and neem biodiesel. The Chemical Structure for Fatty Acids in both biodiesels defines saturated and unsaturated fatty acids creating the need for antioxidants. This work uses two types of synthetic and natural antioxidants to identify their impact on biodiesel oxidation stability. The physicochemical properties of biodiesel treated with and without antioxidants are compared with regular diesel fuel. The testing protocol includes the use of two different kinds of antioxidants to increase the favorable ecological impact of producing biodiesel within its surroundings. The evaluation includes looking at how antioxidants affect the stability of biodiesel and comparing it to regular diesel. The results of this investigation are then examined and discussed.

Oxidation stability is evaluated for both the biodiesel. Later, different doses of antioxidants mixed in biodiesel and their effects on the induction period are calculated. This section also covers the use of a variety of blends. In a subsequent section, engine trials were carried out to ascertain the performance attributes of biodiesel. The engine's emissions, which include smoke opacity, Nitrogen Oxides, Hydrocarbons, and Carbon Monoxide generated during combustion, were also monitored, and examined. There are in-depth examinations of combustion properties, such as the HRR and the Pressure-Crank angle (P- Ɵ) curve. The results of these investigations are graphically depicted and explained.

The use of the ANN prediction model to estimate the diesel engine's output and emissions brings this part to a close. The ANN model was trained and tested using empirical data obtained from the CI engine. The model's effectiveness was proved by a comparison of experimental and ANN-predicted data.

4.2 GC –MS of Produced Biodiesel

Gas chromatography-mass spectrometry analysis is used to identify the distinct elements of essential oils, presenting them alongside the corresponding percentage composition of each element. This method amalgamates the strengths of gas chromatography and mass spectrometry to characterize various compounds or fatty acid profiles within a given sample.

Fatty acids (FAs) are primarily classified into two fundamental groups, determined by the presence or absence of double bonds. These groups encompass SFAs, which lack double bonds, and UFAs, characterized by the presence of double bonds. UFAs can be further divided into monounsaturated fatty acids (MUFAs), which have a single double bond, and polyunsaturated fatty acids (PUFAs), possessing two to six double bonds. Moreover, the categorization into cis or trans, forms is contingent upon the arrangement of these double bonds. Additionally, PUFAs can be subcategorized as n-3 or n-6, based on the position of the double bond [53, 112, 159].

4.2.1 GC-MS analysis of neem biodiesel

GC-MS proves to be a highly effective method for analysing the chemical composition of neem biodiesel. The information provided holds significant implications for assessing its quality and potential applications. Figure 4.1 illustrates the results of the GC-MS analysis conducted on neem biodiesel derived from Azadirachta indica. Additionally, Table 4.1

offers a detailed breakdown of the quantitative composition (%) of the components in neem biodiesel. Notably, neem biodiesel comprises 44.12% SFAs and 55.89% UFAs. The extent of unsaturation within biodiesel plays a pivotal role in determining its stability and shelf-life duration.

Among the prominent saturated constituents, Hexadecenoic acid methyl ester comprises 21.10%, followed by Methyl stearate at 17.45%. On the other hand, the unsaturated constituents consist mainly of 9-Octadecenoic acid methyl ester (E), accounting for 51.35%, and 9,12-Octadecadienoic acid (Z, Z) methyl ester contributing 3.47%.

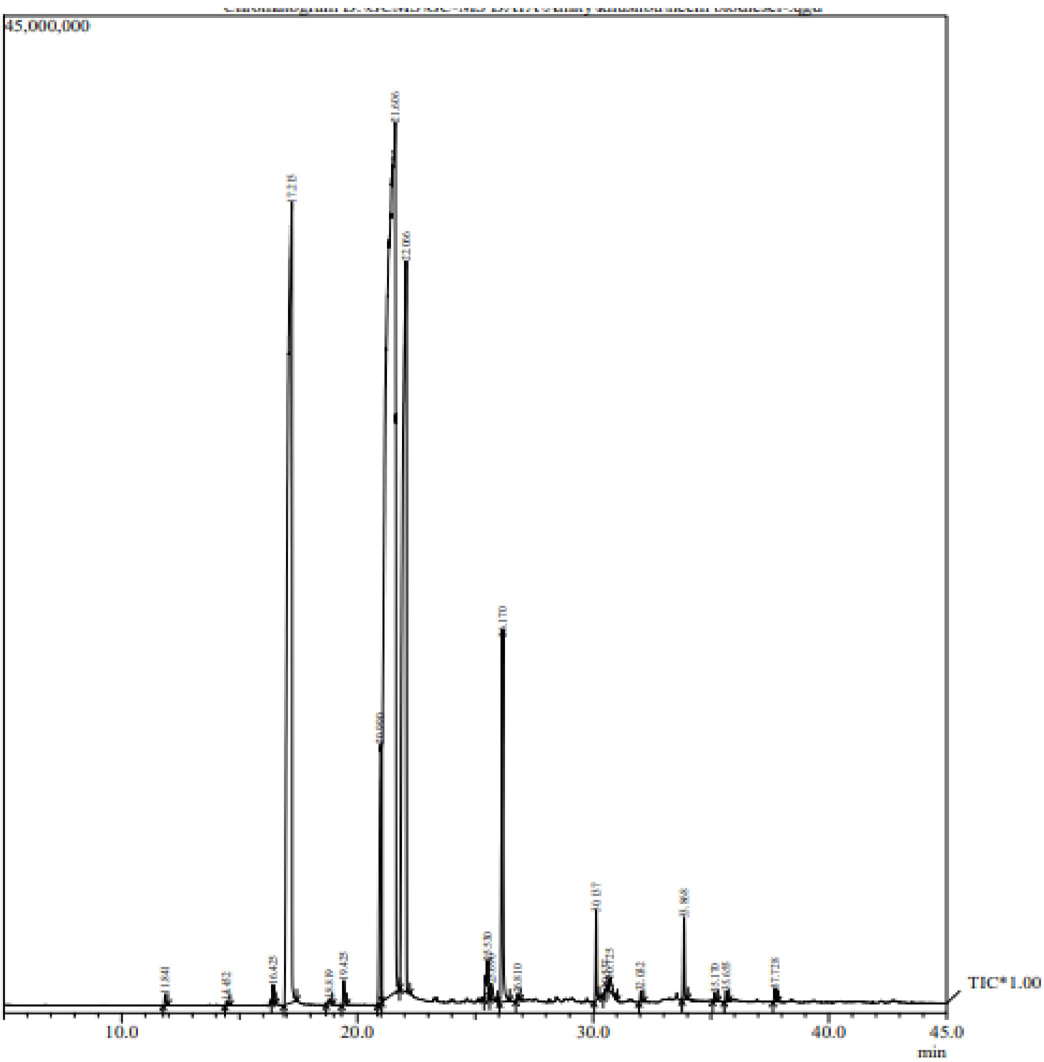


Figure 4.1: Represents a gas-chromatogram of neem biodiesel.

Table 4.1: List of saturated and unsaturated compounds present in neem biodiesel

Name	Compound type	Chemical formula	Area%
Methyl tetradecanoate	Saturated	C15H30O2	0.09
Pentadecanoic acid, methyl ester	Saturated	C16H32O2	0.04
Hexadecanoic acid, methyl ester	Saturated	C17H34O2	21.1
9-Hexadecenoic acid, methyl ester, (Z)-	Unsaturated	C17H32O2	0.18
cis-10-Heptadecenoic acid, methyl ester	Unsaturated	C18H34O2	0.08
Heptadecanoic acid, methyl ester	Saturated	C18H36O2	0.27
Methyl stearate	Saturated	C19H38O2	17.45
9,12-Octadecadienoic acid (Z, Z)-, methyl ester	Unsaturated	C19H34O2	3.47
9-Octadecenoic acid, methyl ester, (E)-	Unsaturated	C19H36O2	51.35
Eicosanoic acid, methyl ester	Saturated	C21H42O2	3.38
Cis-11-Eicosenoic acid, methyl ester	Unsaturated	C21H40O2	0.45
Octylcyclodecane	Saturated	C18H36	0.07
Octadecanoic acid, 10-oxo-, methyl ester	Saturated	C19H36O3	0.21
Tetracosanoic acid, methyl ester	Saturated	C25H50O2	0.58
Fumaric acid, cyclohexyl hexadecyl ester	Unsaturated	C26H46O4	0.29
Docosanoic acid, methyl ester	Saturated	C23H46O2	0.6
Tricosanoic acid, methyl ester	Saturated	C24H48O2	0.08
Silane, Trimethyl (1-Methylene-3-Phenyl-2-P	Saturated	C13H16Si	0.04
Hexacosanoic acid, methyl ester	Saturated	C27H54O2	0.13
Squalene	Unsaturated	C30H50	0.07
Pentacosanoic acid, methyl ester	Saturated	C26H52O2	0.08
Unsaturated fatty acid			55.89
Saturated fatty acid			44.12

4.2.2 GC-MS analysis of waste oil cooking biodiesel

Figure 4.2 illustrates the GC-MS profile of WCB, while Table 4.2 provides an overview of the distinct compositions of WCB, presenting the saturated and unsaturated compounds along with their corresponding % areas. The composition analysis reveals a saturated fatty acid content of 28.33% and an unsaturated content of 71.67%. It is important to note that the presence of UFAs in biodiesel is associated with the potential for oxidation degradation [183]. In a broader context, biodiesel with higher unsaturation levels is more susceptible to undergoing oxidative degradation, rendering it more prone to developing rancidity during its storage period. This degradation occurs due to the propensity of double bonds to react with oxygen, resulting in the formation of undesirable compounds that alter the texture, color, and purity [112, 183].

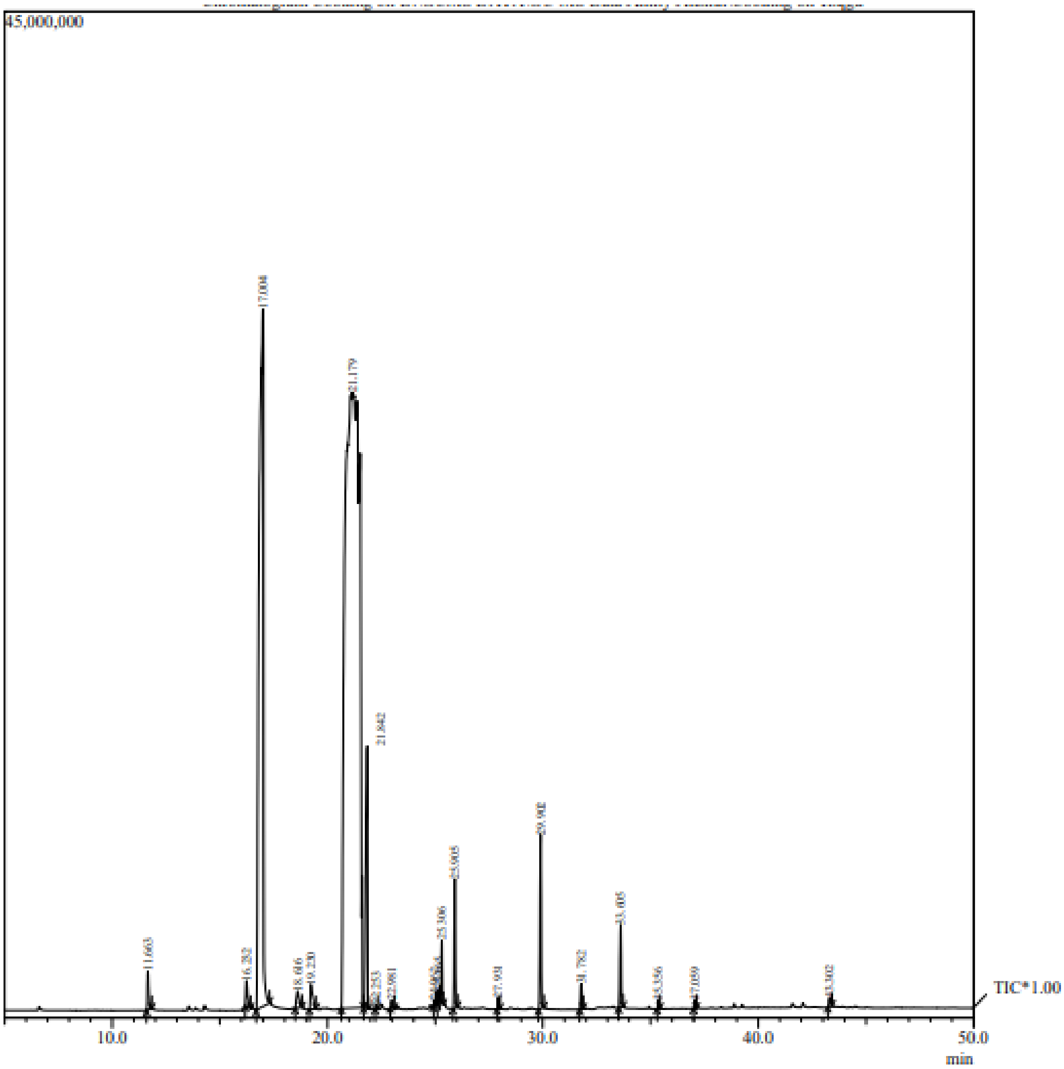


Figure 4.2: Represents a gas-chromatogram of waste cooking oil biodiesel

Table 4.2: List of saturated and unsaturated compounds present in WCB

Constituents type	Type	Chemical Formula	Amount (% area)
Docosanoic acid, methyl ester	Saturated	C23H46O2	1.63
Tricosanoic acid, methyl ester	Saturated	C24H48O2	0.22
9,12-Octadecadienoic chloride, (Z, Z)-	Unsaturated	C18H32O2	0.04
Hexacosanoic acid, methyl ester	Saturated	C27H54O2	0.07
Pentacosanoic acid, methyl ester	Saturated	C26H52O2	0.07
Hexadecatrienoic acid, methyl ester	Saturated	C17H28O2	0.03
Tetracosanoic acid, methyl ester	Saturated	C25H50O2	0.74
9,12-Octadecadienoic acid, methyl ester	Unsaturated	C19H34O2	0.09
Methyl Tetradecanoate	Saturated	C15H30O2	0.41
9,11-Octadecadienoic acid, methyl ester, (E, E)-	Unsaturated	C19H34O2	0.07
Eicosanoic acid, methyl ester	saturated	C21H42O2	1.17
(Z)-Methyl heptadec-9-enoate	Saturated	C18H34O2	0.35
Hexadecanoic acid, methyl ester	saturated	C16H32O2	22.1
gamma-Sitosterol	Saturated	C29H52O2	0.11
Heneicosanoic acid, methyl ester	Saturated	C22H44O2	0.1
Heptadecanoic acid, methyl ester	Saturated	C19H38O2	0.48
9-Hexadecenoic acid, mthyl ester, (Z)-	Saturated	C16H30O2	0.35
Cis-Methyl 11-eicosenoate	Saturated	C21H40O2	0.5
Methyl stearate	Unsaturated	C19H38O2	3.72
9,12-Octadecadienoic acid, methyl ester	Unsaturated	C19H34O2	67.72
Unsaturated fatty acid			71.67
Saturated fatty acid			28.33

4.3 DPPH Activity of Natural Antioxidant

Tinospora cordifolia stem extract is used as a natural antioxidant in biodiesel to assess its effect on oxidation stability. The antioxidant effectiveness of Tinospora cordifolia stem extract must be assessed prior to its use in biodiesel. The 2,2-Diphenyl-1-picrylhydrazyl (DPPH) assay is a widely used method for evaluating the antioxidant activity of natural compounds. [166]. In Figure 4.3, the methodology used in this study to assess a substance's ability to function as a hydrogen donor or a scavenger of free radicals (FRS) uses free radicals. The stabilized DPPH free radical is neutralized as part of the DPPH evaluation technique. The DPPH test is widely regarded for its dependability, accuracy, simplicity, and cost-effectiveness. It provides a reliable way to determine how well an antioxidant neutralizes free radicals. This is mostly attributable to the radical molecule's inherent stability, which eliminates the need for its creation throughout the testing procedure [170]. The DPPH method was used to mix an extract solution in ethanol (0.5 ml) at various concentrations (50-300 l/ml) with a 0.1 mM DPPH solution in ethanol (1.5 ml). The mixture was thoroughly combined and then permitted to rest for 30 minutes at room temperature. A spectrophotometer was then used to measure the absorbance at 517 nm (shown in Plate 4.1). A blank solution free of DPPH was utilized to offset the effects of the extracts' color, and an ethanolic DPPH solution served as the negative control. Ascorbic acid used as a reference. Each measurement was carried out three times. The resulting equation was used to determine the DPPH radical's scavenging capacity.

Table 4.3 displays the results of the scavenging activity of Tinospora cordifolia extracts at various dosages. Notably, as shown in Figure 4.3, the Tinospora cordifolia extracts displayed a peak scavenging capacity of 65.09% at 1000 g/ml. Comparable results are consistent with earlier published investigations. [169, 184]

Plate 4.1: UV Spectrometer

Table 4.3: Absorbance and percentage scavenging activity of developed Tinospora cordifolia (TC) extract at different concentrations using the DPPH method.

Concentration (µg/ml)	Absorbance of Control (Ao)	The absorbance of extract (As)	Percent scavenging activity = (A0 -As)/A0 x 100
100	0.974	0.79	18.89117043
200	0.974	0.71	27.10472279
300	0.974	0.66	32.23819302
400	0.974	0.59	39.42505133
500	0.974	0.54	44.55852156
600	0.974	0.49	49.69199179
700	0.974	0.41	57.90554415
800	0.974	0.35	64.06570842
900	0.974	0.34	65.09240246
1000	0.974	0.34	65.09240246

Percent scavenging activity = (A0 - As)/A0 x 100

Where, Ao = Absorbance of Control

As = The absorbance of extract

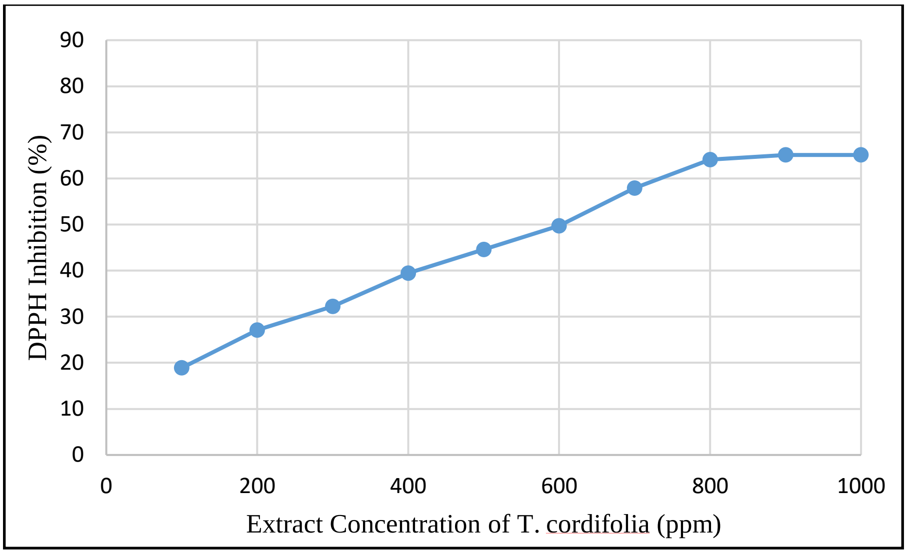


Figure 4.3: DPPH% scavenging activity of stem extract of Tinospora cordifolia

4.4 Oxidation Stability

Analysis of fatty acid constituents in both biodiesel shows saturation and unsaturation compound percentages. Both biodiesels having unsaturation compound in higher amount shows more susceptibility towards oxidation and need antioxidants to be added to them [26, 54, 56, 132]. Natural and synthetic antioxidants in various ppm are added in both biodiesels. Oxidation stability of pure biodiesels evaluated.

4.4.1 Oxidation stability of waste cooking oil biodiesel and neem biodiesel

The oxidation stability of each biodiesel was evaluated by the Rancimat method. Figure 4.4 and Figure 4.5 shows the induction period (hours) for waster cooking oil biodiesel and neem biodiesel, respectively. WCB biodiesel has 1.71 hours of induction period, and neem biodiesel has 2.49 hours. Based on the IS-15607, EN-14112, and ASTM D-6751 methods, it is stipulated

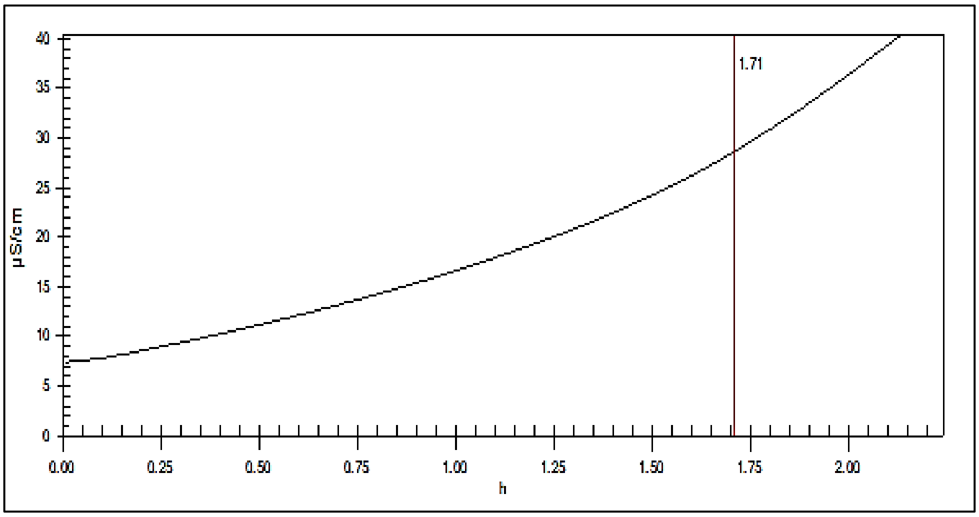


Figure 4.4: Oxidation stability of waste cooking oil biodiesel

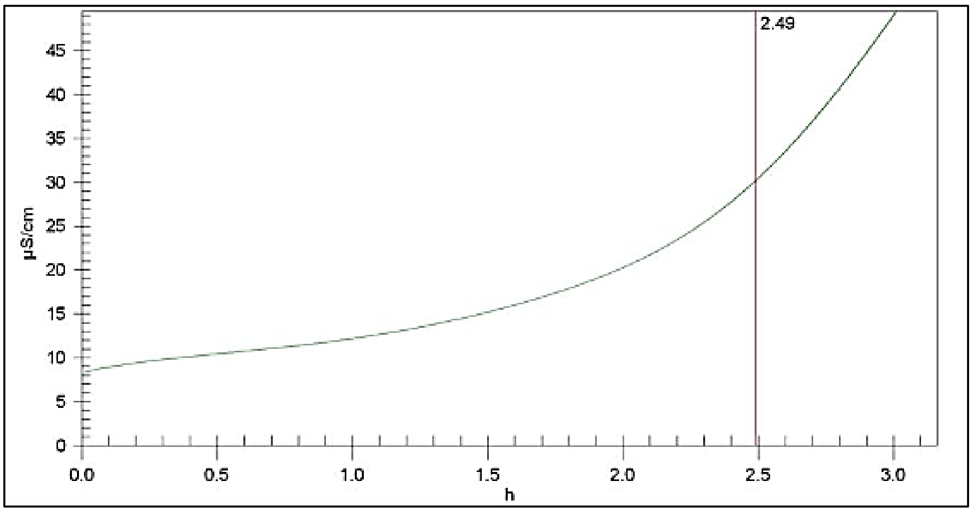


Figure 4.5: Oxidation stability of neem biodiesel

that the induction times must be a minimum of 6 hours, 6 hours, and 3 hours, respectively [119]. Both biodiesels fail to meet the standards outlined by ASTM, IS-15607, and EN, as a result of antioxidants inclusion in the biodiesel.

4.4.2 Oxidation stability of test fuels with and without the effect of antioxidants

The oxidation stability can be improved by adding antioxidants to biodiesel. TBHQ, PY, DPA (synthetic antioxidants), and TC (natural antioxidants) are added to waste cooking oil biodiesel and neem biodiesel in various quantities. 200, 500, and 1000 ppm doses of antioxidants mixed with both biodiesels to determine their effect on oxidation stability. The introduction of antioxidants to waste cooking oil biodiesel and neem biodiesel led to an extension in the oxidation period was increased for all the biodiesel samples having an antioxidant mix. 200 ppm doses of all antioxidants in both biodiesels did not meet standards except 200 ppm of PY in waste cooking oil biodiesel. 500 ppm doses of in both biodiesel meeting ASTM, EN and IS standards except 500 ppm of TC in neem biodiesel. 500 ppm of antioxidants in waste cooking increases the induction period for (WCB+TBHQ), (WCB+DPA), and (WCB+PY) are 6.38, 6.76, and 12.28 hours.

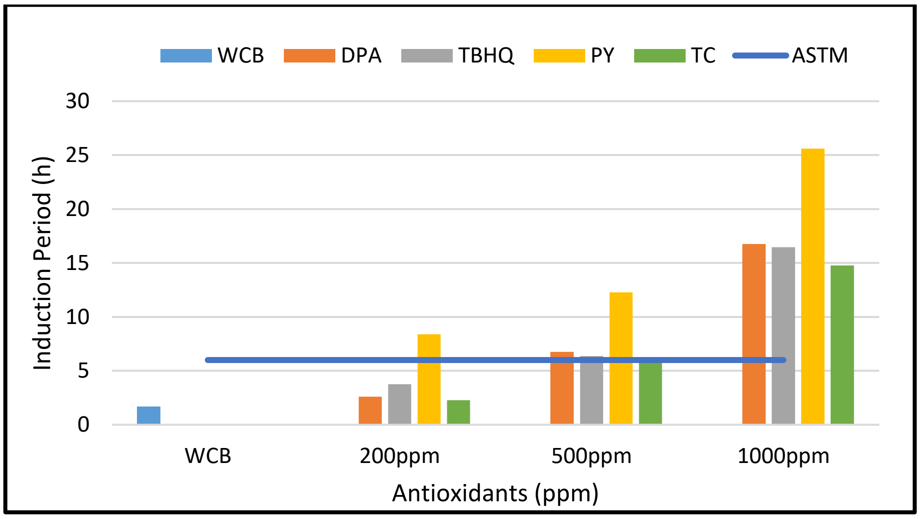


Figure 4.6: Oxidation stability of waste cooking oil biodiesel without and with antioxidants

For neem biodiesel, 500 ppm of antioxidants show an increase in induction period for (NB+TBHQ), (NB+DPA), and (NB+PY) are 6, 6.80, and 8.41 hours. TC antioxidant in WCB and NB increases the induction period of 5.98 and 4.47 hours for 500 ppm. 1000 ppm of antioxidants increases the induction period of WCB by adding TBHQ, DPA, PY, and TC are 16.47, 16.76, 25.60, and 14.77, respectively, from 1.71 hours of induction period of 100%WCB. The induction period of neem biodiesel increases by adding TBHQ, DPA, PY, and TC of 16.33, 15.17, 16.86, and 10.47 hours, respectively, from 1.71 hours of induction period of 100%WCB.1000 ppm dose of both synthetic and natural antioxidants meeting all three standards. 500 ppm and 1000 ppm of synthetic and natural antioxidant biodiesel blends were used for performance, emission, and combustion analysis.

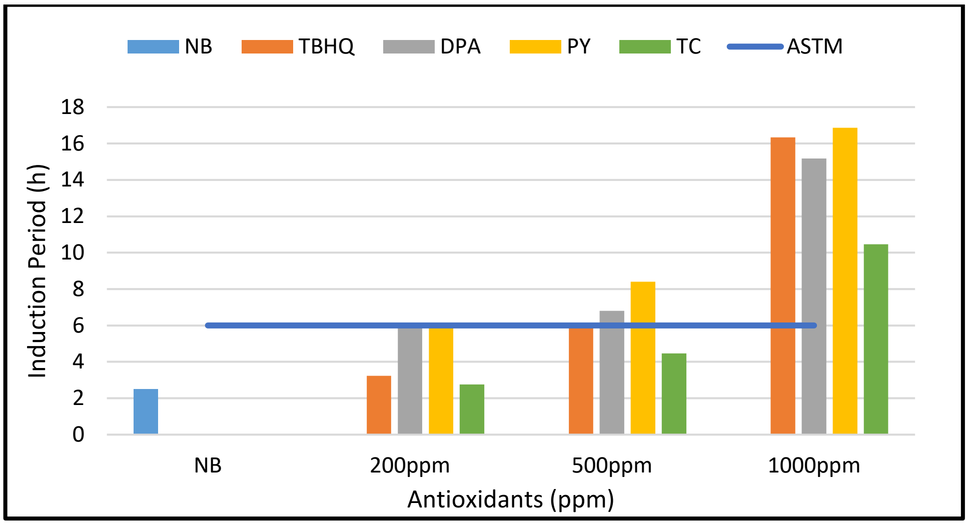


Figure 4.7: Oxidation stability of neem biodiesel without and with antioxidants

4.5 Physio-Chemical Characteristics of Biodiesel and their Blends

The evaluation of fuel quality and performance depends extensively on analysing physicochemical properties. Section 3 describes the equipment employed for the measurement of the physical and chemical characteristics of fuel blends. The measurements are performed in accordance with the ASTM D standards to ensure quality and accuracy. Estimating the chemical characteristics of fuels has been conducted with regard given to the ASTM D standards [93, 94]. This section elaborates on various physicochemical characteristics of all tested blends. Table 4.4 and Table 4.5 represents various physiochemical of diesel, pure biodiesel, and biodiesel blends with 500 and 1000 ppm concentration in synthetic and natural antioxidants in WCB and NB are given, respectively.

Table 4.4: Physiochemical characteristics test fuel blends with WCB

Fuel Properties	Kinematic Viscosity (cSt) @40 °C	Density @15 °C (Kg/m3)	Lower Heating Value (MJ/kg)	Flash Point (°C)	Cetane Index	CFPP (°C)	Pour Point (°C)
Diesel	2.93	832.4	42.145	63	47	-12	-11
Waste cooking oil biodiesel	5.97	896.8	39.0832	129	62.7	-4	-4.7
80D20WCB	3.09	849.2	41.8273	62	53.2	-7.4	-6.1
80D20(WCB+500 DPA)	3.17	849.7	41.4013	64.1	55.1	-8.8	-7.5
80D20(WCB+1000 DPA)	3.27	853.4	41.1478	67.2	55.9	-9.6	-8.5
80D20(WCB+500TBHQ)	3.16	849.8	41.3275	63.6	54.9	-8.5	-7.2
80D20(WCB+1000TBHQ)	3.21	851.2	41.1652	66.4	55.5	-9.7	-8.3
80D20(WCB+500PY)	3.2	849.9	41.4319	65	55.9	-9.3	-7.9
80D20(WCB+1000PY)	3.25	851.2	41.1284	67.8	56.4	-9.9	-8.7
80D20(WCB+500TC)	3.15	849.6	41.7642	63	54.5	-8.2	-6.9
80D20(WCB+1000 TC)	3.24	851.5	41.2943	65.6	56.1	-9.4	-8.1

Table 4.5: Physiochemical characteristics test fuel blends with NB

Fuel Properties	Kinematic Viscosity (cSt) @40 °C	Density @15 °C (Kg/m3)	Lower Heating Value (MJ/kg)	Flash point (°C)	Cetane Index	CFPP (°C)	Pour (Cloud) Point (°C)
Neem biodiesel	6.31467	886.2	38.3916	153	60	-6	-8
80D20NB	4.21356	853.2	40.6527	78	51	-8.2	-10
80D20(NB+500 DPA)	4.32	854.1	40.6742	80.4	53.9	-9.7	-11.9
80D20(NB+1000 DPA)	4.38	854.8	40.6885	81.3	54.9	-10.3	-12.8
80D20(NB+500TBHQ)	4.39	853.8	40.6715	80.1	53.5	-9.5	-11.5
80D20(NB+1000TBHQ)	4.43	854.9	40.68.92	81.5	54.6	-10.5	-13.3
80D20(NB+500PY)	4.35	854.4	40.6763	80.8	54.1	-9.9	-12.4
80D20(NB+1000PY)	4.4	855.1	40.6931	81.8	54.9	-10.6	-13.5
80D20(NB+500TC)	4.24	853.6	40.6412	78.9	51.9	-8.8	-10.7
80D20(NB+1000TC)	4.36	854.5	40.6223	80.9	54.4	-10.1	-12.6

4.5.1 Density of waste cooking oil biodiesel and neem biodiesel blends

Density is considered one of the most important parameters when discussing biodiesel. Density directly affects combustion parameters, injection period, mass flow rate, air-fuel ratio, etc. This factor significantly influences parameters such as cetane number, calorific value, and fuel atomization. Moreover, the density of biodiesel displays variations contingent on the purity and composition of its fatty acids. [62, 185]. Density is mass per unit volume, and the unit of density is kg/m^3. The density of biodiesel increases with time. Biodiesel having higher saturated fatty acid ester and small carbon chain hydrocarbon crystallized faster with time. Due to crystallization, volume decreases as density increases [22].

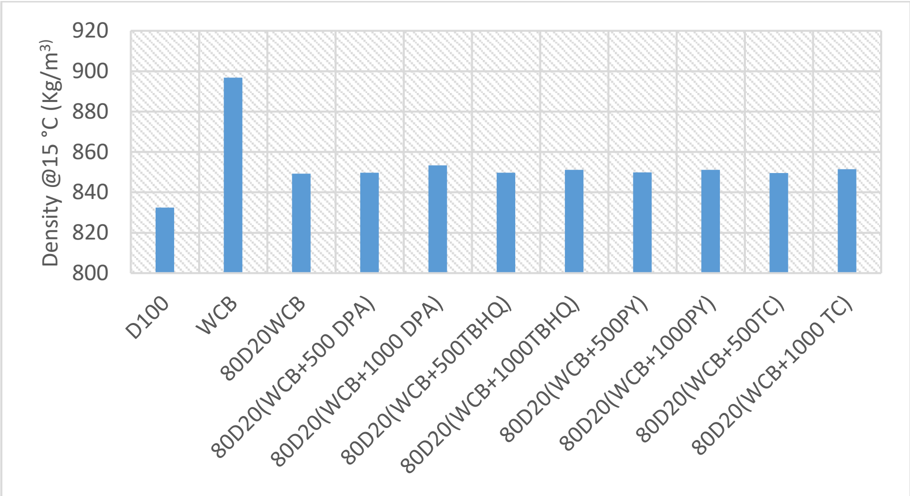


Figure 4.8: Density variation for WCB test fuel samples

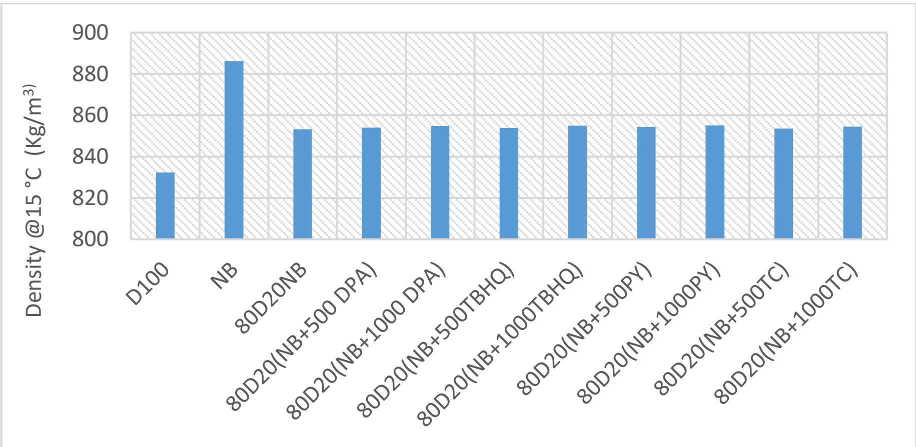


Figure 4.9: Density variation for NB test fuel samples

860-900 kg/m3 is the range specifies by EN14214 for biodiesel[186]. Figure 4.8 and 4.9 depicts the density of diesel, biodiesel, biodiesel blend, and biodiesel blend added antioxidants. Waste cooking oil biodiesel and neem biodiesel shows higher density than diesel and not meeting ASTM standards. Higher fuel density may cause higher fuel consumption, poor fuel atomization, and higher nitrogen oxides. Diesel-biodiesel blend shows lower density. Adding antioxidants into both biodiesel shows a slight increase in density, but it falls in the range described by ASTM standards.

4.5.2 Viscosity of waste cooking oil biodiesel and neem biodiesel blends

Biodiesel exhibits higher viscosity in comparison to diesel fuel. The performance and emission properties of an engine may be affected by this variation in kinematic viscosity [172]. With temperature increases kinematic viscosity of biodiesel decreases. The higher fuel viscosity leads to incomplete combustion and injector choking because of poor atomization during fuel spray injection into the cylinder. The lower viscosity of fuel cannot properly lubricate the injector pump [187, 188]. Biodiesel's kinematic viscosity is specified as 1.9 to 6.0 mm^2/s by the

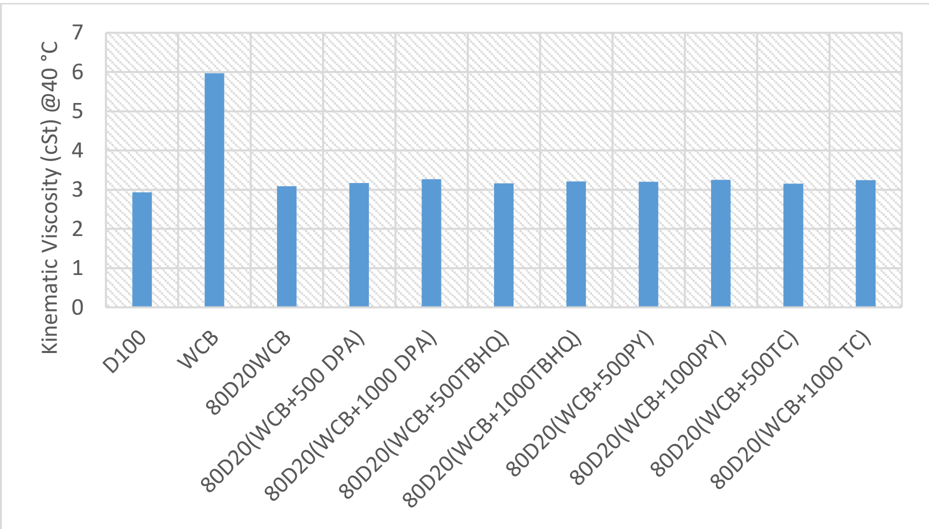


Figure 4.10: Kinematic viscosity variation for WCB test fuel samples

American Society for Testing and Materials standard (ASTM D6751), while petro-diesel is 1.9 to 4.1 mm^2/s by ASTM D975 method. European standard (EN 14214) has set kinematic viscosity values for biodiesel as 1.9 to 6.0 mm^2/s and petro-diesel as 1.9 to 4.1 mm^2/s given by ISO 3104 method [117, 187]. EN 14214 standard measures viscosity in the range of 3.50 to 5.00 mm^2/s [185]. Viscosity increases by increasing chain length, higher FFA, and saturation in biodiesel. The oxidation mechanism involves forming the double bond long-chain saturated compound and gum formation [162]. Figures 4.10 and 4.11 show variation in viscosity by adding antioxidants in it. The kinematic viscosity of neat waste cooking oil biodiesel and neem biodiesel is elevated. Neem biodiesel has higher fee fatty acid and shows higher value in viscosity.

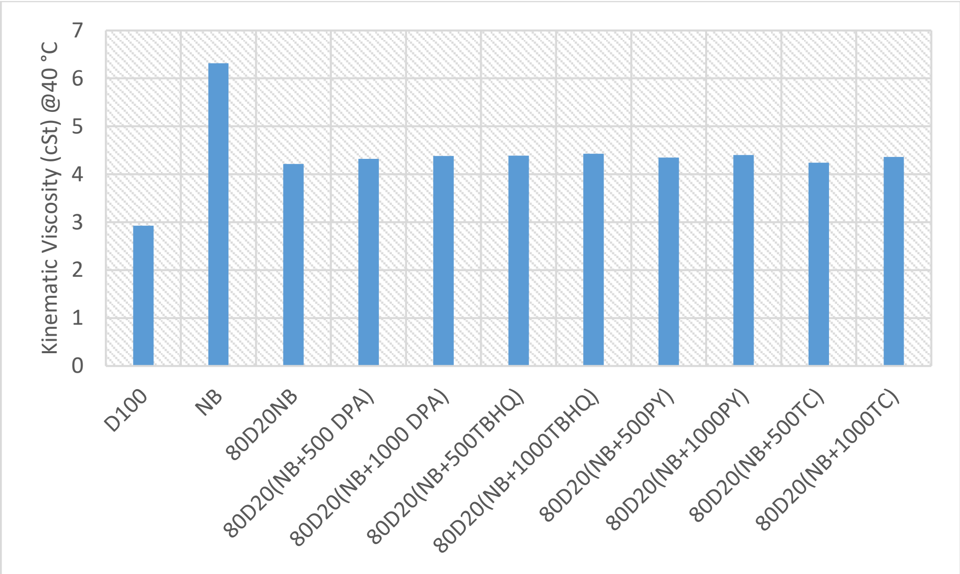


Figure 4.11: Kinematic viscosity variation for NB test fuel samples

Biodiesel blends added with antioxidants show a slight enhancement in viscosity value due to the prevention of oxidation by adding antioxidants [189, 190]. All blends of WCB show kinematics viscosity ranging from 3.09 to 3.27 cSt, and for neem, biodiesel blends 4.21 to 4.39 cSt as prescribed by ASTM and EN standards.

4.5.3 Calorific value of waste cooking oil biodiesel and neem biodiesel blends

The calorific value, also known as the lower heating value, quantifies the energy content within a fuel source. To achieve the engine's most effective performance, the fuel's heating value should not be lower than 35,000 kJ/kg, as specified by EN 14213 standards [191]. If the calorific value is higher, this suggests that the BTE is higher, leading to lower fuel consumption. Biodiesel commonly exhibits a lower calorific value compared to diesel due to its elevated oxygen content. The quantity of energy produced by the combustion of biodiesel is therefore less than that of diesel fuel when the same amount of biodiesel and diesel fuel is burned.

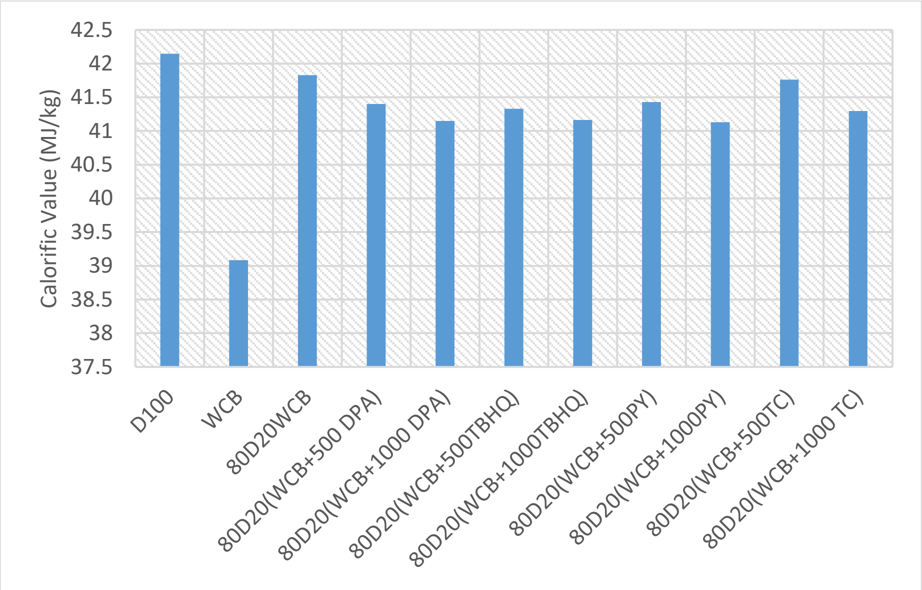


Figure 4.12: Calorific value variation for WCB test fuel samples

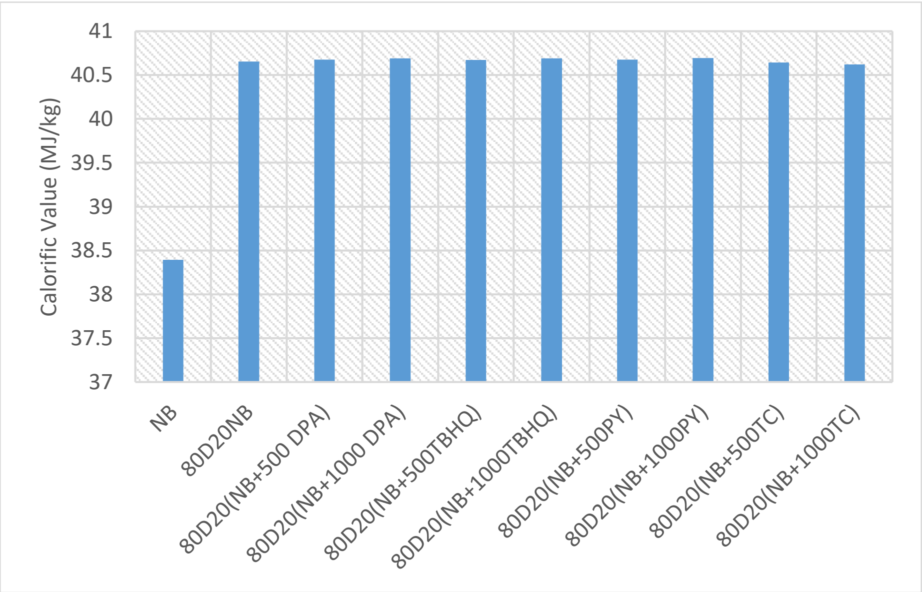


Figure 4.13: Calorific value variation for NB test fuel samples

The variation in total energy content for diesel and biodiesel can affect the efficiency and performance of the test engine. Figure 4.12 and 4.13 represents calorific values variation for diesel, addition with biodiesel, biodiesel blends, and antioxidant-treated biodiesel blend for fuel, waste cooking oil biodiesel, and neem biodiesel, respectively. The calorific value for diesel is higher at 42.145 MJ/kg [128, 192]. 80D20WCB and 80D20NB show an increase in calorific value than WCB and NB, respectively. Still, biodiesel blends that have been treated with antioxidants show a slight decrease in calorific value due to lower fuel consumption [128, 193].

4.5.4 Cetane Index of waste cooking oil biodiesel and neem biodiesel blends

The cetane index measures diesel fuel ignition quality that is connected to its combustion characteristics. A higher cetane index generally indicates improved ignition properties, resulting in smoother and more efficient combustion within diesel engines. WCB has more saturated fatty acids than NB and shows a higher cetane index (CN) [128, 144]. Figures 4.14 and 4.15 shows variation in the cetane index of diesel, biodiesel, biodiesel blends, and

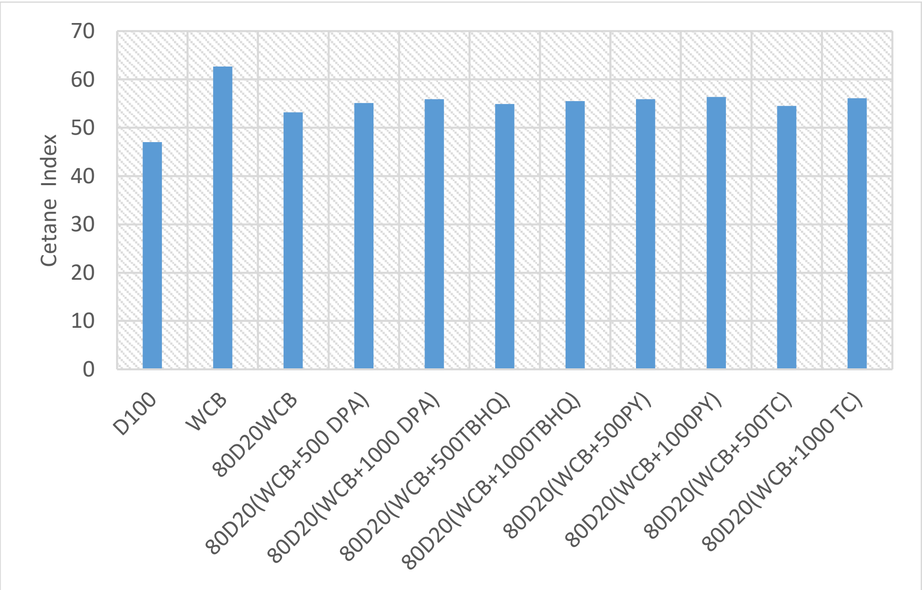


Figure 4.14: Cetane Index variation for WCB test fuel samples

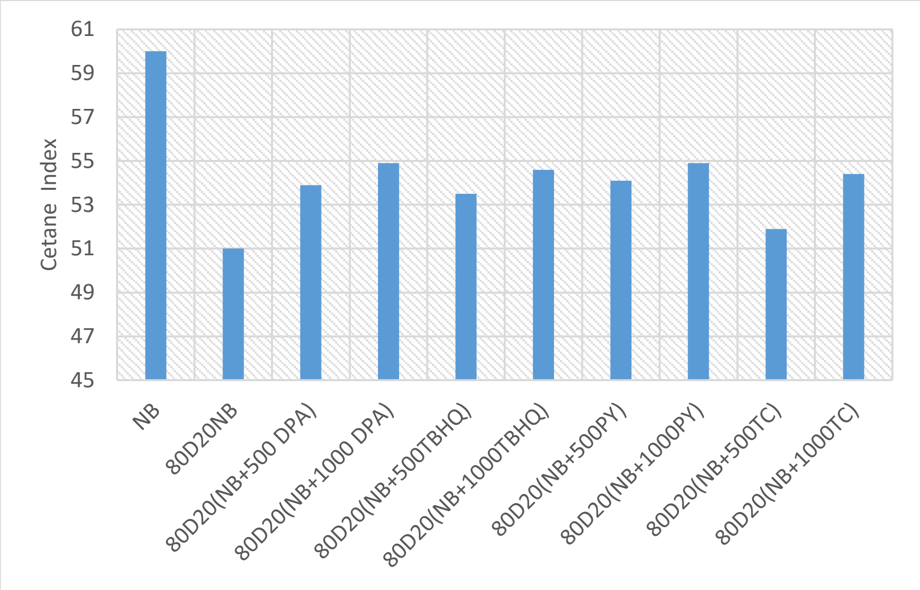


Figure 4.15: Cetane Index variation for NB test fuel samples

antioxidant-treated biodiesel blend. As per these figures and Tables 4.4 and 4.5, the cetane index of antioxidant-treated biodiesel blends increases as unsaturated acids are converted into saturated due to the presence of antioxidants [171].

4.5.5 Flashpoint of waste cooking oil biodiesel and neem biodiesel blends

The flash point of a fuel refers to the minimum temperature at which it releases sufficient vapor to create a combustible mixture with air in close proximity to its surface. The flash point is a critical safety criterion as it signifies the inherent fire risk connected with fuel when it is being transported, stored, and handled. Figure 4.16 and 4.17 represents variation in flash point with test fuel blends. Biodiesel flash point is frequently more significant than petroleum diesel, ranging from 120°C to 180°C. The elevated biodiesel's flash point can be ascribed to its molecular composition, which is frequently characterized by long-chain fatty acids. The increased length of these molecular chains leads to an elevation in the boiling temperatures of the fuel constituents, resulting in a rise in the flash point [171]. Biodiesel offers enhanced safety during storage and handling compared to conventional diesel due to its elevated flash point. The introduction of antioxidants to biodiesel blends leads to heightened flash points, which can be attributed to improved resistance to cold flow issues and reduced fuel volatility [191].

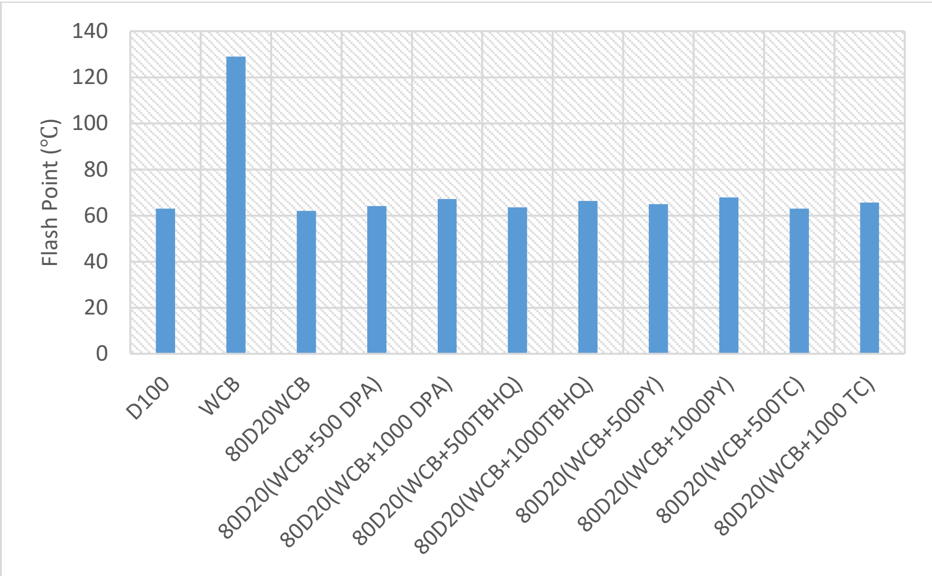


Figure 4.16: Flash point variation for WCB test fuel samples

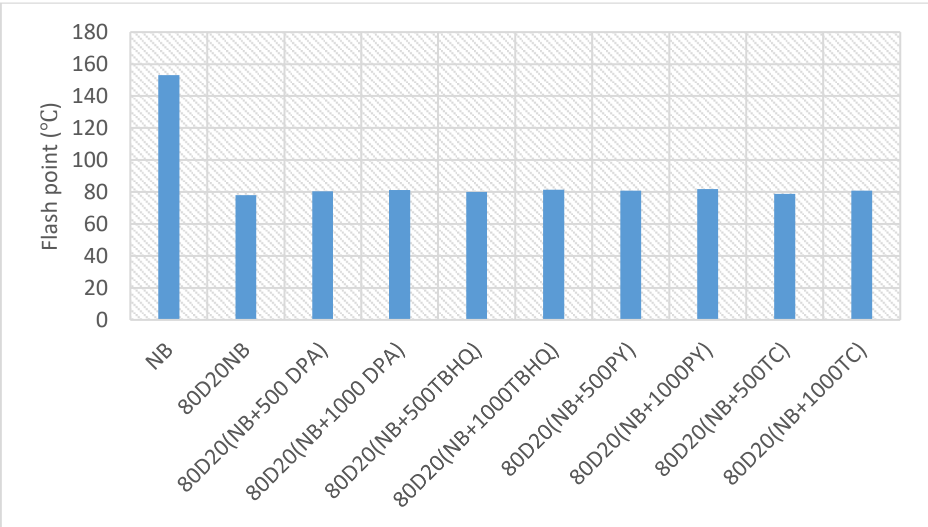


Figure 4.17: Flash point variation for NB test fuel samples

4.5.6 Cold flow characteristics of waste cooking oil biodiesel and neem biodiesel blends

The Cold Flow Plugging Point of diesel denotes the minimum temperature at which the fuel initiates the crystallization process and subsequent wax crystals formation, causing obstruction in fuel filters and fuel lines. This obstruction subsequently causes a decrease in the flow rate of fuel to the engine, potentially resulting in engine stalling. Biodiesel, exceptionally pure biodiesel (WCB and NB), exhibits a more excellent CFPP than conventional diesel due to the inclusion of saturated fatty acid chains within its molecular composition. A blend of biodiesel and petroleum diesel

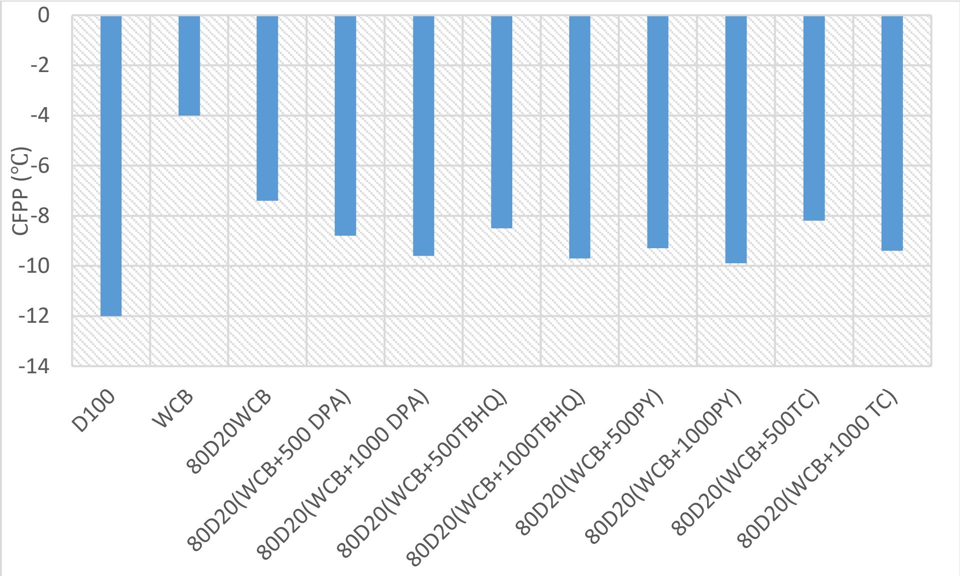


Figure 4.18: CFPP variation for WCB test fuel samples

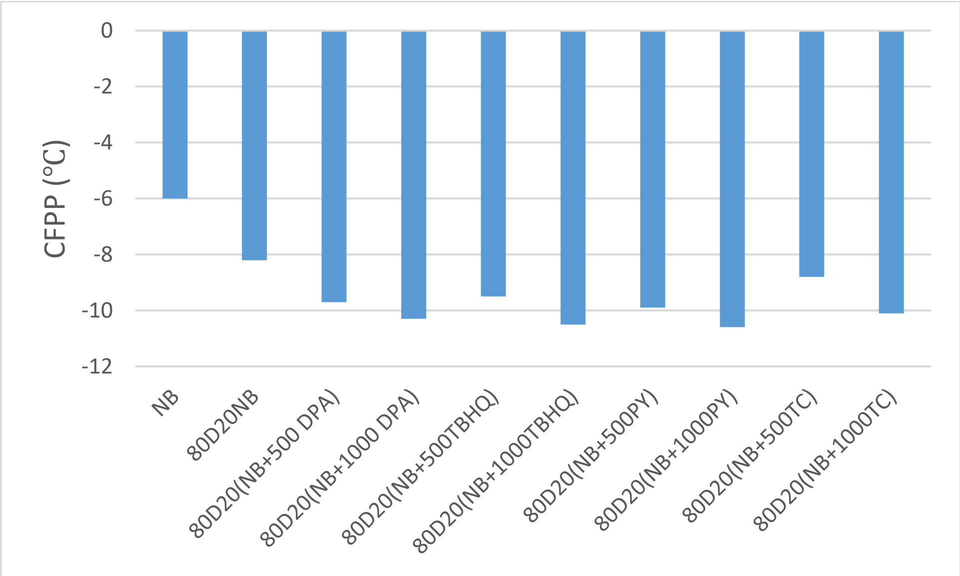


Figure 4.19: CFPP variation for NB test fuel samples

(80D20WCB and 80D20NB) It can reduce the overall CFPP and enhance its cold flow characteristics, making it more appropriate for utilization in colder geographical regions. Furthermore, previous research has demonstrated a correlation between oxidation stability and cold flow characteristics [25, 186]. An increased number of carbon double bonds of UFAs enhances the cold flow characteristics while reducing oxidation stability. Antioxidant-treated biodiesel blends can enhance oxidation stability and reduce cold flow characteristics as required.

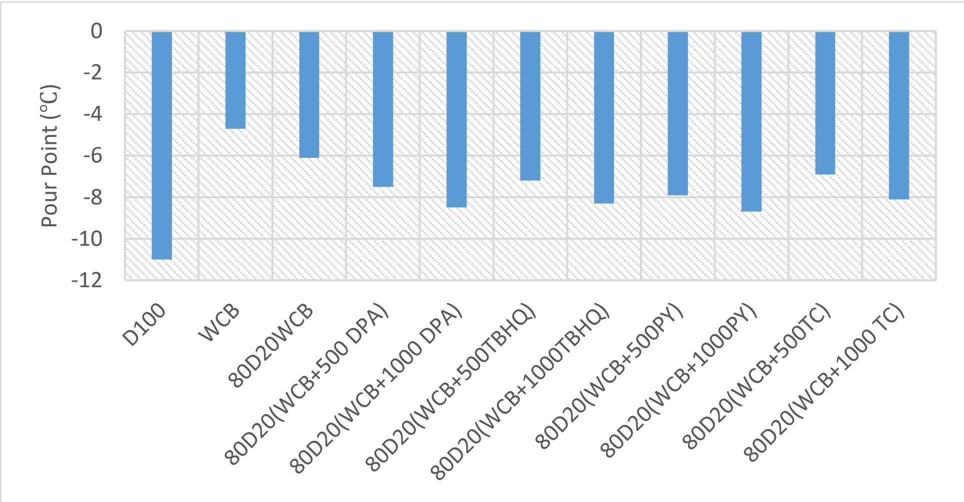


Figure 4.20: Pour point variation for WCB test fuel samples

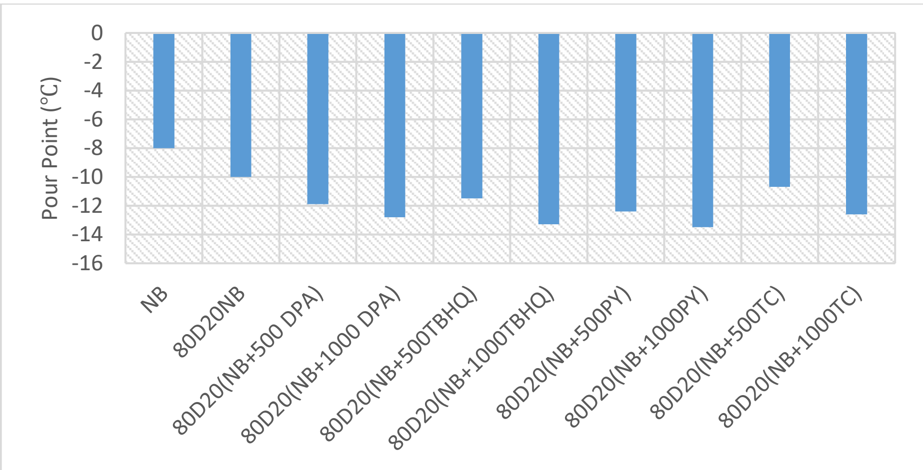


Figure 4.21: Pour point variation for NB test fuel samples

4.6 Engine Combustion Characteristics of WCB and NB Test Fuel Blends

The combustion process generates heat when fuel reacts with oxygen. In the occurrence of efficient combustion, emissions will be reduced. The calorific value and cetane index are essential factors that significantly influence the attainment of efficient combustion within a CI engine. Combustion unfolds through four distinct phases,

1) Physical delay and chemical delay (Ignition delay period),
2) Uncontrolled combustion (Premixed phase),
3) Controlled combustion (Diffusion phase),
4) After burning.

Understanding above mention phases during combustion is a complex phenomenon to understand [18, 95]. However, it can be explained by considering major influencing factors like Heat release rate (HRR), the Pressure-angle curve (P- Ɵ), and ignition delay, monitored during combustion. 80D20WCB and 80D20NB blends of biodiesel were considered to perform combustion analysis along with antioxidant (synthetic and natural antioxidants) treated WCB and NB biodiesel-diesel blends; these blends were compared with baseline diesel.

4.6.1 Heat release rate

The heat release rate holds significant importance in a compression ignition engine, given its considerable influences on the performance of the engine, efficiency, emissions, and durability. The HRR is also recognized for its role in optimizing engine design and control strategies. It contributes to heightened fuel efficiency and the reduction of harmful emissions such as nitrogen oxides (NOx) and particulate matter. Figure 4.22 and figure 4.23 shows variation between HRR with crank angle (J/^{o}CA) at full engine load for both

WCB and NB blends. Synthetic antioxidants (PY, DPA, TBHQ) were mixed in biodiesel, and both combinations were tested on the engine to find heat release variation with crank angle (Figures 4.22 & 4.23). From the depicted figure, among all fuel blends; it was noted that neat diesel (D100) exhibited the highest peak of heat release, measuring 72.56 J/°CA. It can be ascribed to the increased

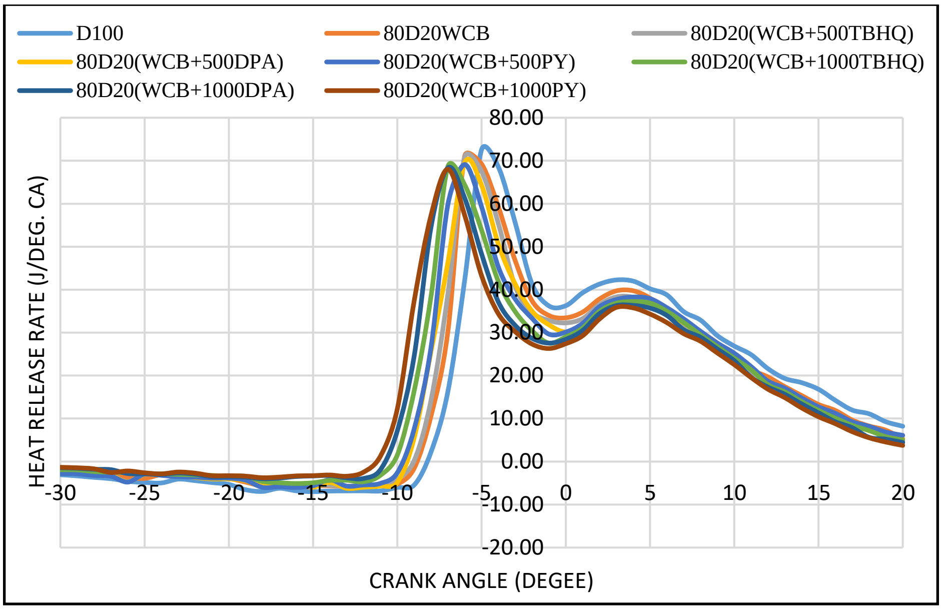


Figure 4.22: For synthetic antioxidants, HRR Vs crank angle for WCB

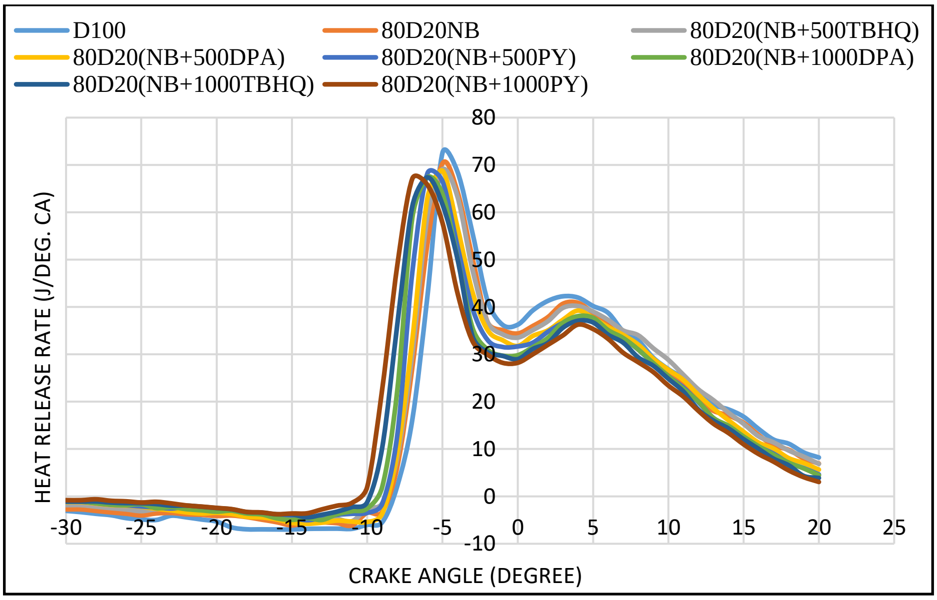


Figure 4.23: For synthetic antioxidants, HRR Vs crank angle for NB

calorific value and improved fuel atomization. The HRR for D80WCB20 and 80D20NB are 70.32 J/°CA and 71.11 J/°CA, respectively, which are lower than diesel due to their lower calorific value and flow characteristics. Compared to diesel-biodiesel blends, antioxidant-added biodiesel blends increase HRR with crank angle because of a longer ignition delay. In earlier studies, similar findings were made [190, 192].

Figure 4.24 and 4.25 represents variation in natural antioxidant (TC) treated biodiesel blend in 500 and 1000 ppm. Comparisons between diesel and biodiesel with and without antioxidants are also given. It is worth noting that the test fuel blends containing natural antioxidants [80D20(WCB+500TC), 80D20(WCB+1000TC), 80D20(NB+500TC), and 80D20(NB+1000TC)] exhibited a significant increase in HRR compared to 80D20WCB and 80D20NB. Increasing dossed of antioxidants reduces HRR because a higher cetane number reduces ignition delay, leading to less mixture availability. All the results are in line with available research.

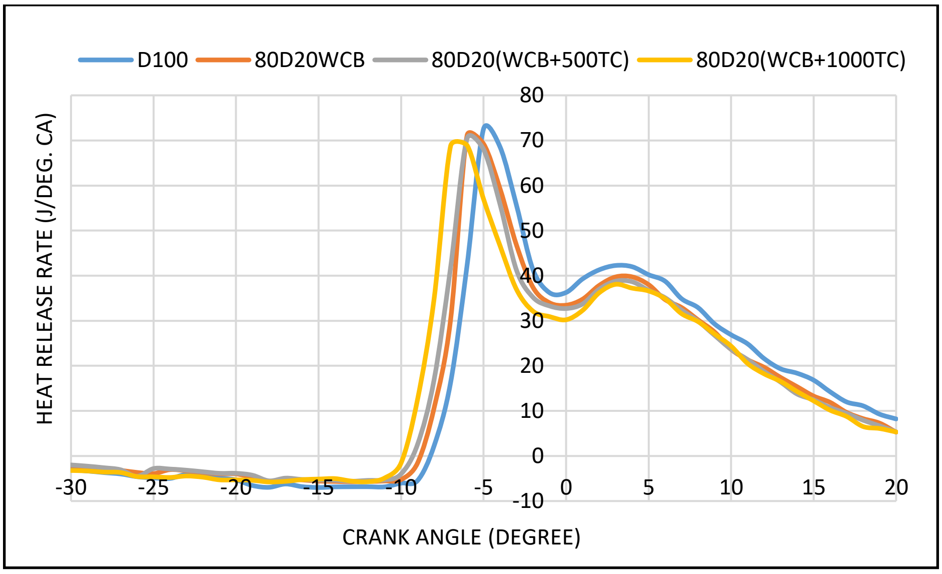


Figure 4.24: For natural antioxidants, HRR Vs crank angle for WCB

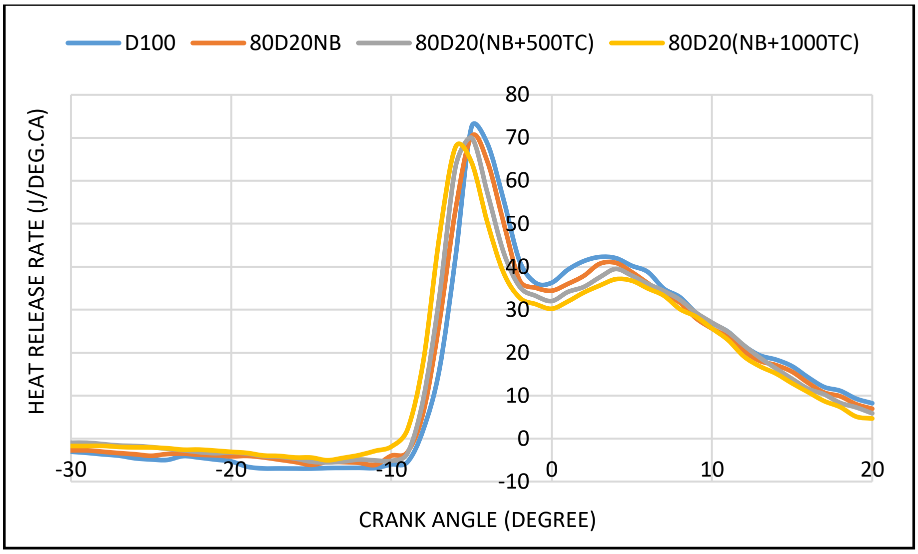


Figure 4.25: For natural antioxidants, HRR Vs crank angle for NB

4.6.2 In-cylinder pressure (P- Ɵ Diagram)

Analysing the pressure profile within the cylinder is of tremendous significance in understanding the engine's combustion process and overall performance. Typically, the measurement is conducted by employing pressure sensors mounted within the engine cylinder head or on the engine walls. By examining in-cylinder pressure data, engineers can acquire valuable insights into the combustion attributes, including the initiation of combustion,

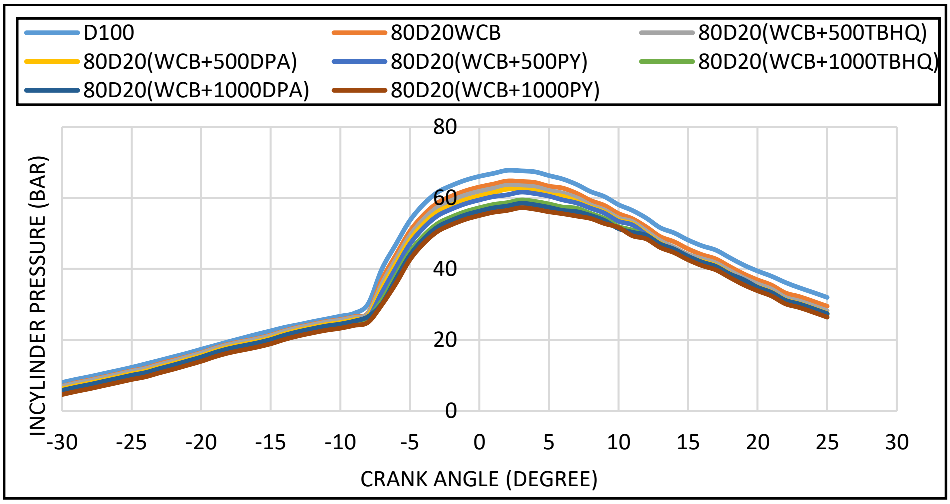


Figure 4.26: For synthetic antioxidants, CP Vs crank angle for WCB

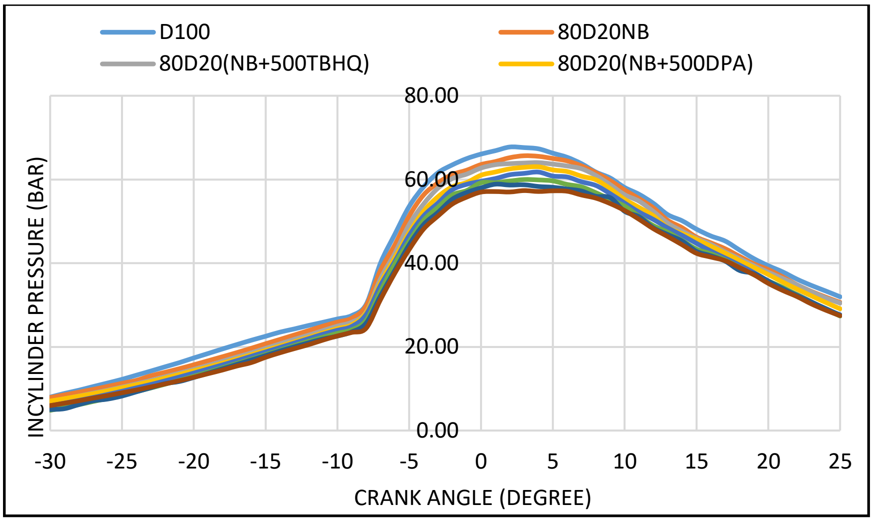


Figure 4.27: For synthetic antioxidants, CP Vs crank angle for NB

maximum pressure, and the rate at which heat is released. To improve the emission and performance characteristics of the compression ignition (CI) engine, it is essential to consider the pressure and temperature slope, which exhibit rapid fluctuations during different combustion stages. The pressure within the cylinder reaches its maximum value during the compression stroke's conclusion, namely when the piston is positioned at the top dead centre (TDC). At the bottom dead centre (BDC), the cylinder pressure reaches its lowest point during the expansion stroke, corresponding to the diffusion phase. Figure 4.26 and 4.27 illustrates the

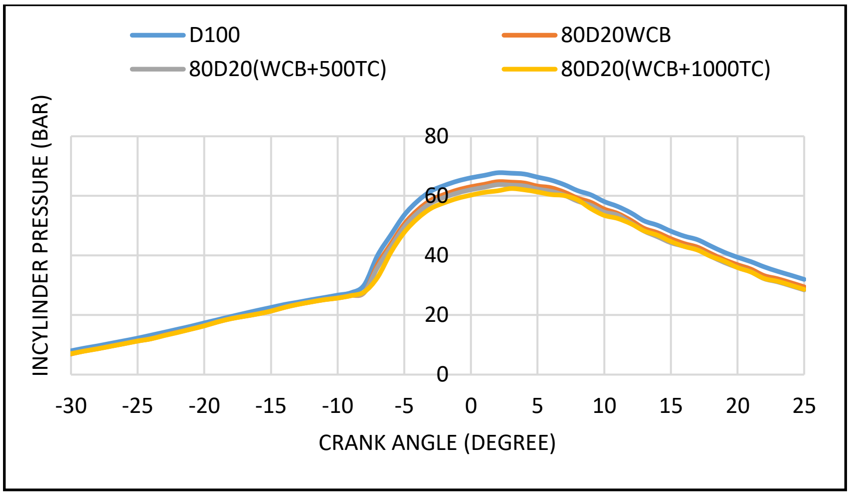


Figure 4.28: For natural antioxidants, CP Vs crank angle for WCB

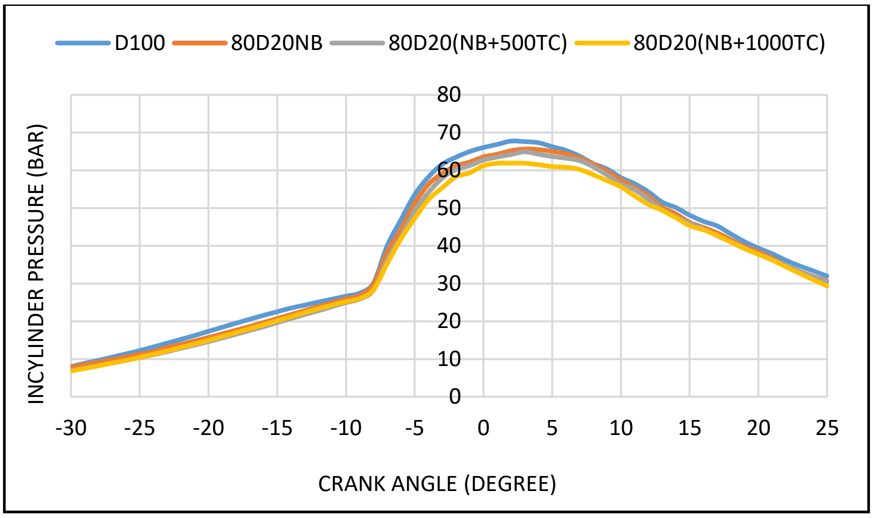


Figure 4.29: For natural antioxidants, CP Vs a crank angle for NB

fluctuation of in-cylinder pressure as a function of crank angle for synthetic antioxidant in WCB and NB blends and their comparison with those without antioxidant biodiesel blend and diesel. Among all the fuel blends, Diesel fuel (D100) exhibits the most prominent peak of in-cylinder pressure (67.75 bar) when compared to the other fuels because it has a higher calorific value, lower viscosity, smaller droplet size, volatility, and better fuel mixing. The peak pressure of 80D20WCB and 80D20Nb is 64.75 bar and 65.66 bar, respectively. Increasing doses of antioxidants in biodiesel reduces pressure rise in cylinders because of lesser HRR in the pre-mixed phase. Figure 4.28 and 4.29 represents the variation of natural antioxidants in biodiesel and their effects on pressure. Higher doses of antioxidants reduce pressure rise in comparison to all other blends.

4.7 Engine Performance Characteristics of WCB and NB Test Fuel Blends

4.7.1 Variation of brake-specific energy Consumption

Brake-specific energy consumption (BSEC) serves as a vital performance indicator, quantifying the amount of fuel consumption to generate per unit of power. The correlation between the BMEP and the BSEC for synthetic antioxidants for test fuel blends is shown in Figures 4.29 and 4.30. Among the multiple blends considered, it can be observed that D100 demonstrates a lower BSEC because of its higher volatility, lower viscosity, and more excellent CV (calorific value). Adding a 20% proportion of biodiesel into diesel fuel (80D20WCB and

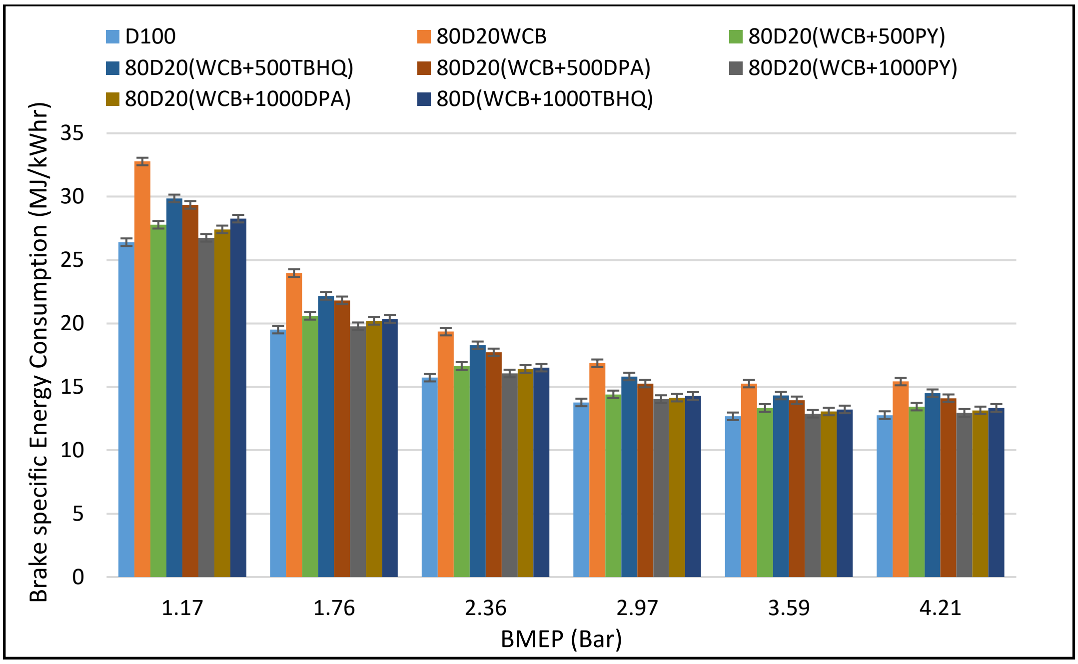


Figure 4.30: For synthetic antioxidants, BSEC Vs BMEP for WCB

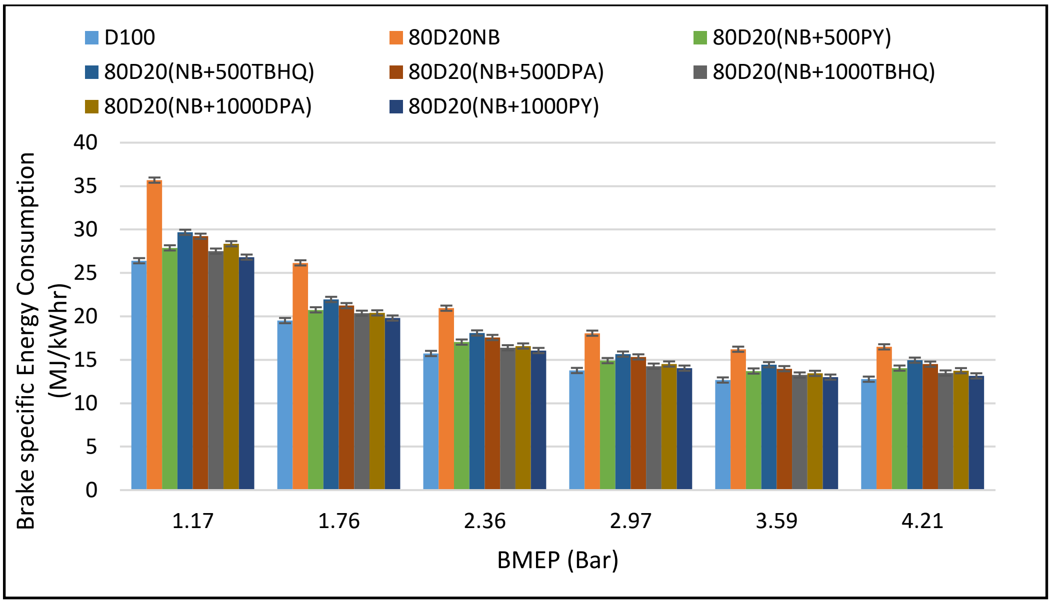


Figure 4.31: For synthetic antioxidants, BSEC Vs BMEP for NB

80D20NB) increases the BSEC. Antioxidant-treated waste cooking oil biodiesel blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows the decrease in BSEC in comparison to without antioxidant blend at full load by 13.50%, 14.76%, 16.03% and 16.67%, 18.31%, 20.31% respectively. By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) shows a reduction of 12.53%

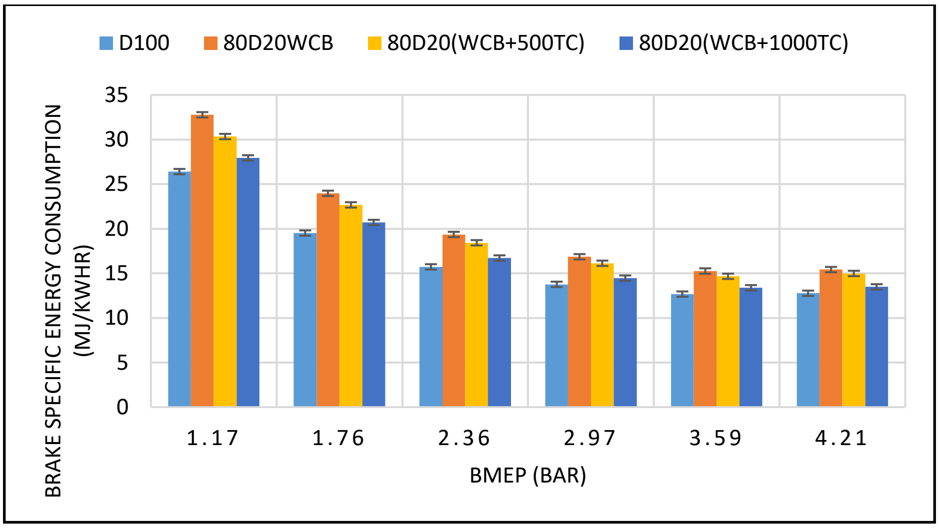


Figure 4.32: For natural antioxidants, BSEC Vs BMEP for WCB

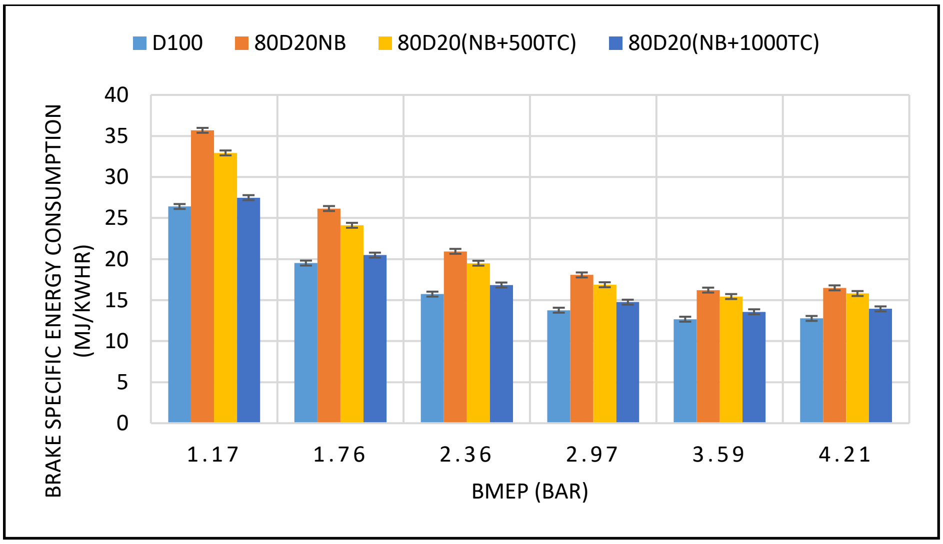


Figure 4.33: For natural antioxidants, BSEC Vs BMEP for NB

and 15.53 %, respectively. In comparison to blends that do not contain antioxidants, it is noteworthy to emphasize that the presence of antioxidants in biodiesel causes a decrease in BSEC. The features of amines that reduce friction and improve ignition quality may be responsible for the drop in BSEC [194]. Additionally, the presence of antioxidants impacts the blend's calorific value, which lowers BSEC [195]. Similar results were investigated by [190, 196].

4.7.2 Variation of brake thermal efficiency

Brake thermal efficiency (BTE) measures energy transformation from chemical to mechanical. A portion of the chemical energy is not entirely transformed into mechanical energy, as a fraction of it is dissipated through exhaust gases, cooling heat dissipation, and mechanical friction [157]. The relationship between BTE and BMEP for various fuel blends are depicted in Figure 4.34 to 4.37. Due to its lower density, higher calorific value, and lower viscosity, D100 exhibits higher BTE than all other fuel blends, resulting in lower fuel consumption [47]. But when the load increases, the air-fuel ratio drops, which causes a little reduction in BTE.

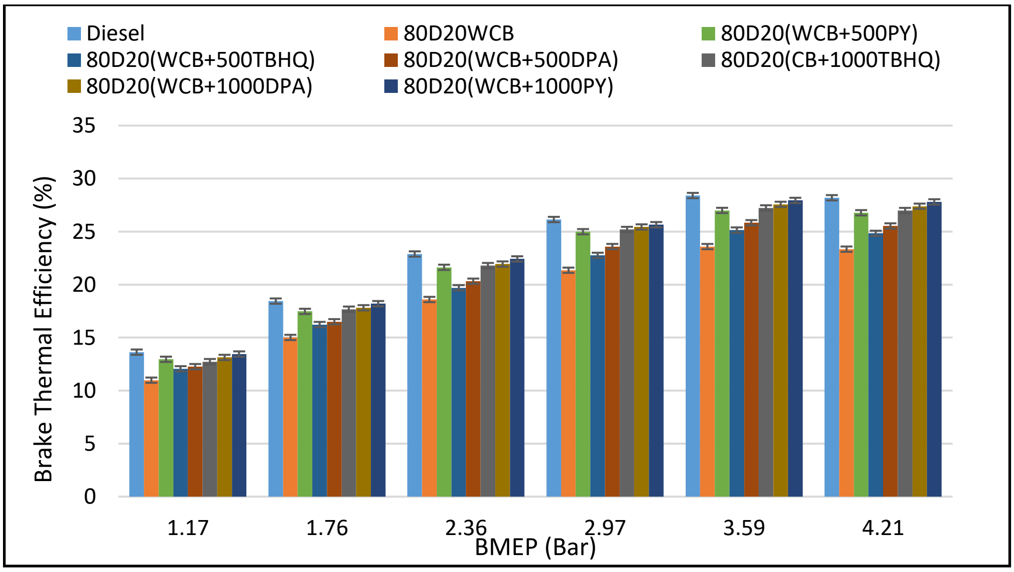


Figure 4.34: For synthetic antioxidants, BTE Vs BMEP for WCB

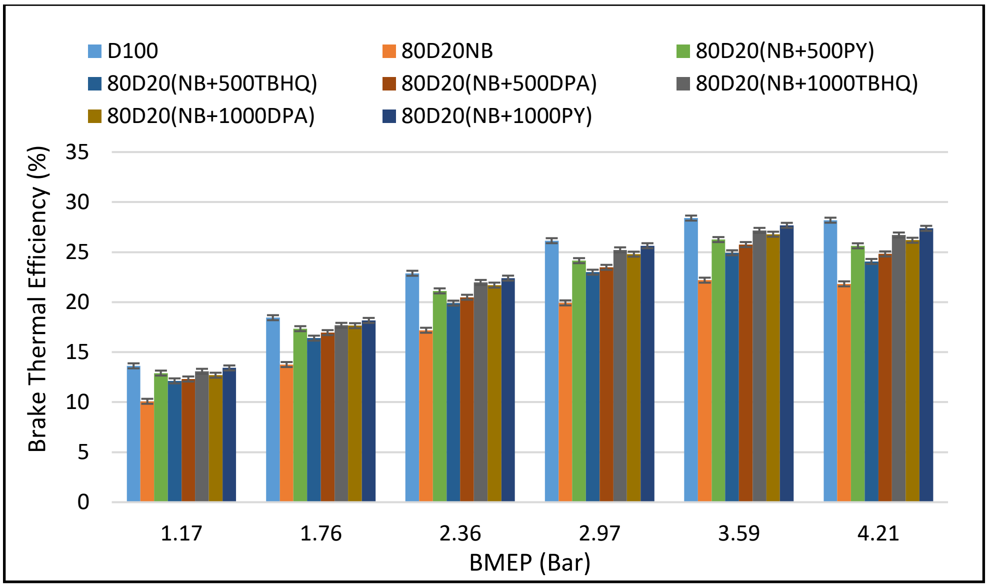


Figure 4.35: For synthetic antioxidants, BTE Vs BMEP for NB

Due to its low calorific value, higher viscosity, and poor spray properties, neem biodiesel and waste cooking oil biodiesel (80D20WCB and 80D20NB) exhibit lower BTE, resulting in increased fuel consumption [157]. However, using biodiesel-diesel fuel blends that have been treated with antioxidants causes an increase in BTE compared to blends that haven't been treated. Biodiesel blend with 1000 ppm dose, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows increase in BTE in comparison to without antioxidant blend at full load by 13.50%, 14.76%, 16.03% and 16.67%, 18.31%, 20.31% respectively given in figure 4.34 and 4.35. By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) shows an increase in BTE by 14.33% and 18.38 %, respectively. Specifically, the biodiesel sample treated with a 1000 ppm dose of antioxidants exhibits superior BTE compared to the biodiesel sample treated with a 500-ppm concentration of antioxidants. The enhancement in BTE can be attributed to the collaboration. impact of decreased BSEC and enhanced power output, as demonstrated in previously available research [197, 198].

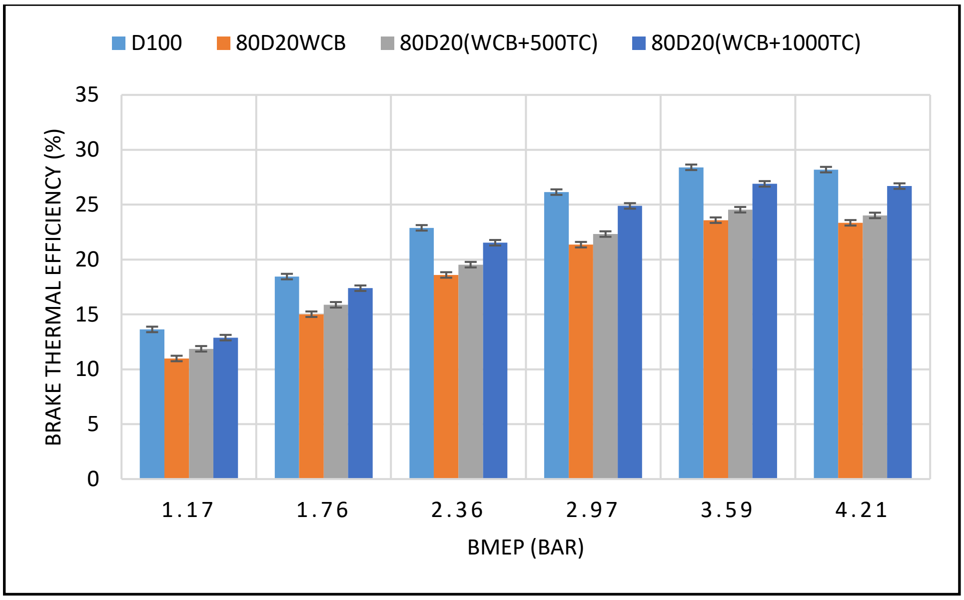


Figure 4.36: For natural antioxidants, BTE Vs BMEP for WCB

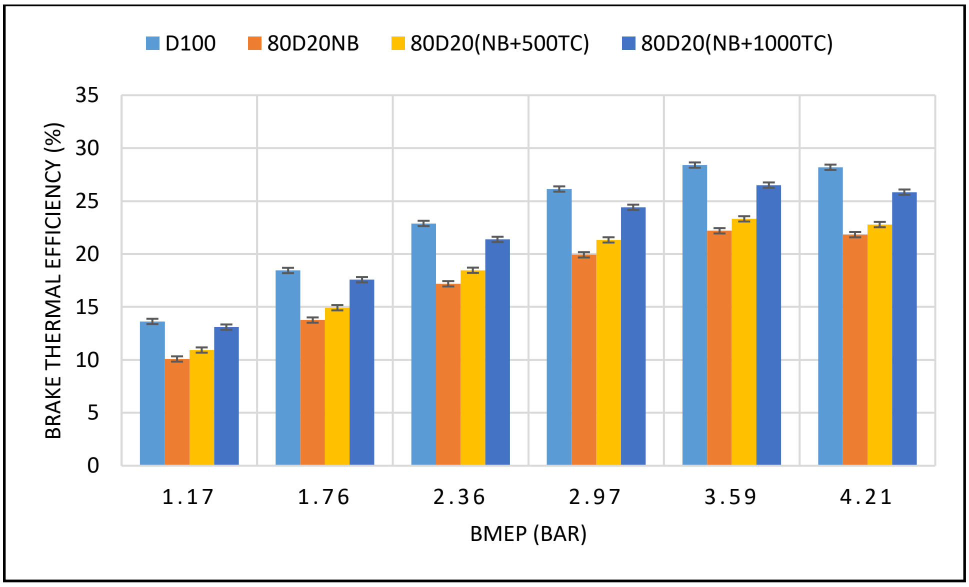


Figure 4.37: For natural antioxidants, BTE Vs BMEP for NB

4.7.3 Variation of NOx emission

The primary exhaust emissions from diesel engines predominantly comprise nitrogen oxides (NOx), nitrogen dioxide (NO_2), and notably nitric oxide (NO), which are generated by the Zeldovich mechanism during the process of combustion. NOx emissions rise throughout the combustion process for a variety of reasons. Numerous factors, including injection timing, ignition delay time, combustion chamber geometry, adiabatic flame temperature, physiochemical properties of the fuel, and equivalency ratio, have an impact on NOx emissions. [199]. Figure 4.38 to 4.421 represents the change in NOx with BMEP for test blends.

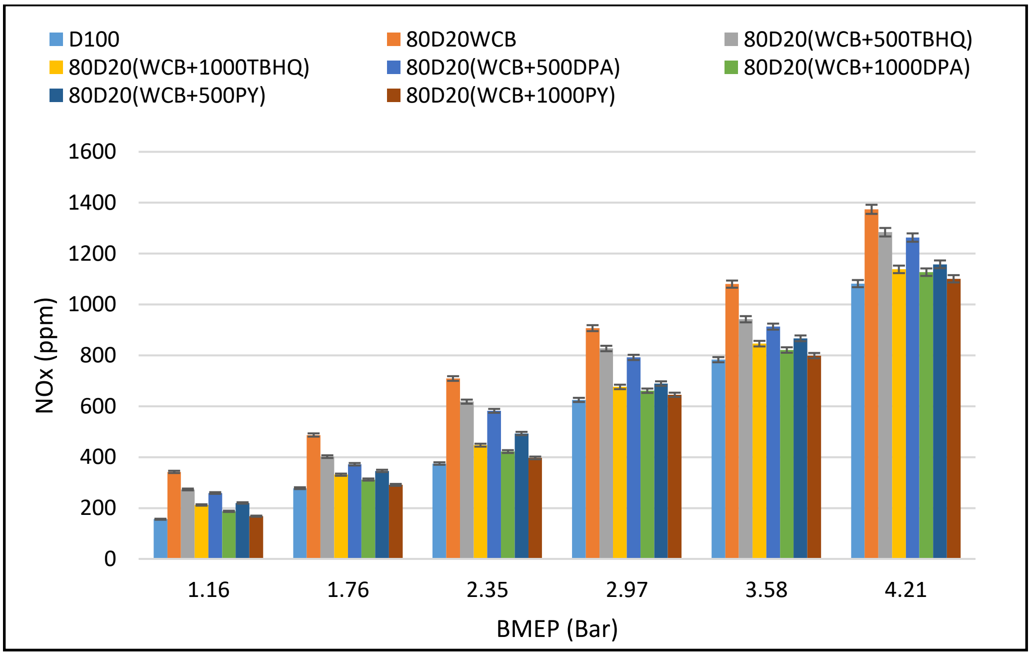


Figure 4.38: For synthetic antioxidants, NOx Vs BMEP For WCB

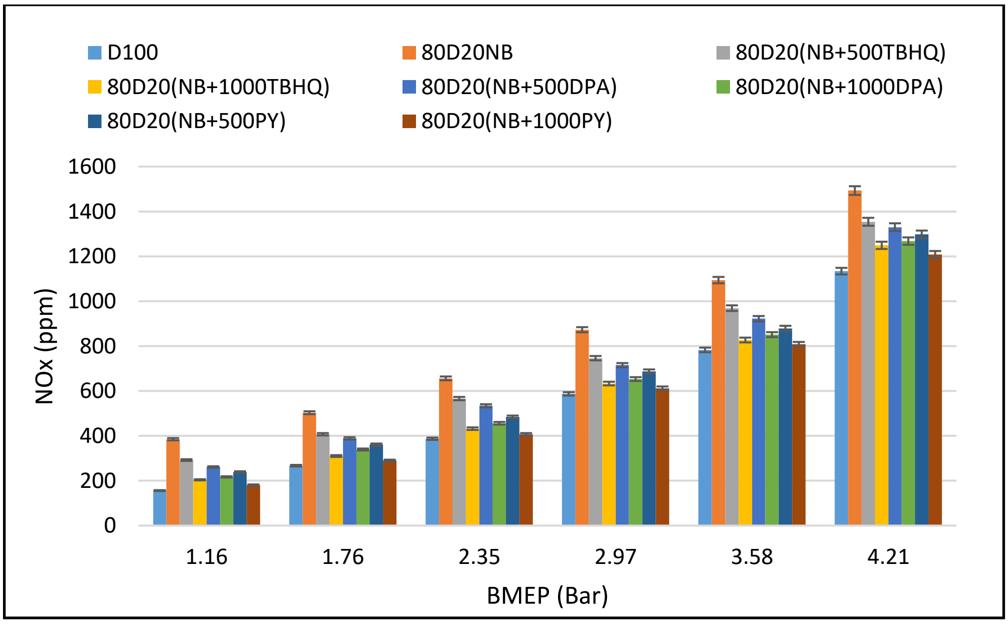


Figure 4.39: For synthetic antioxidants, NOx Vs BMEP For NB

D100 represents lower NOx, and biodiesel blends without antioxidants have higher NOx emissions. Because of the rising temperatures inside the combustion chamber under conditions of higher engine load, there is a corresponding rise in NOx emissions with an increase in engine load. NOx emission increased by the physical properties, presence of higher oxygen content, and molecular structure of biodiesel in the biodiesel blend, which increases combustion cylinder temperature. The constant production of peroxyl-free radicals during the oxidation of biodiesel results in the production of nitric oxide. The observed trend aligns with the results reported in prior research [195]. Antioxidant-treated blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows the decrease in NOx emission in comparison to without antioxidant blend at full load by 17%, 17.97%, 19.86% and 15.07%, 16.34%, 19.08% respectively. By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) shows reduction of 16.37% and 14.06 %, respectively. This decrease in the antioxidant-treated biodiesel blend results from free radicals and unsaturated chemicals in the fuel mixes being reduced by the

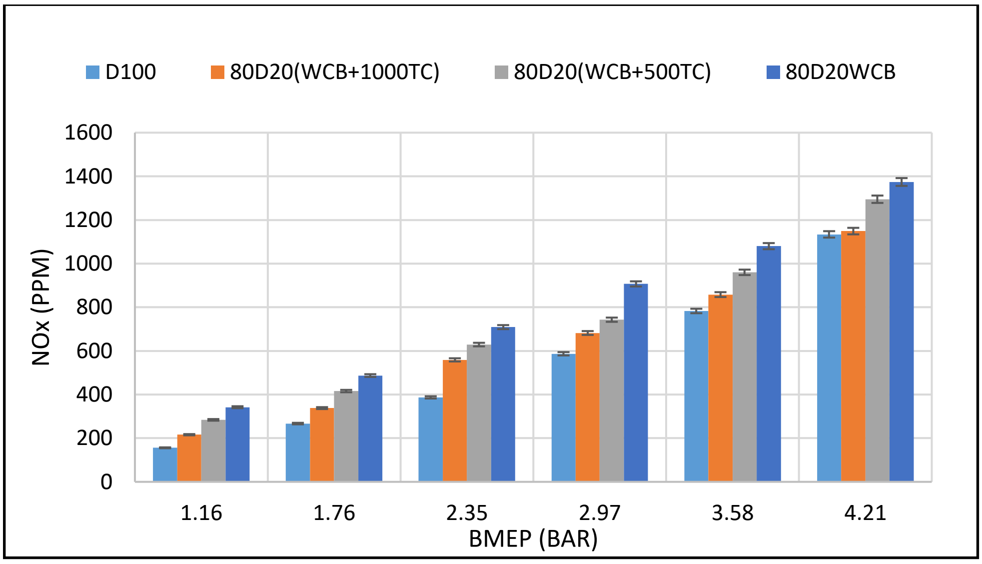


Figure 4.40: For natural antioxidants, NOx Vs BMEP for WCB

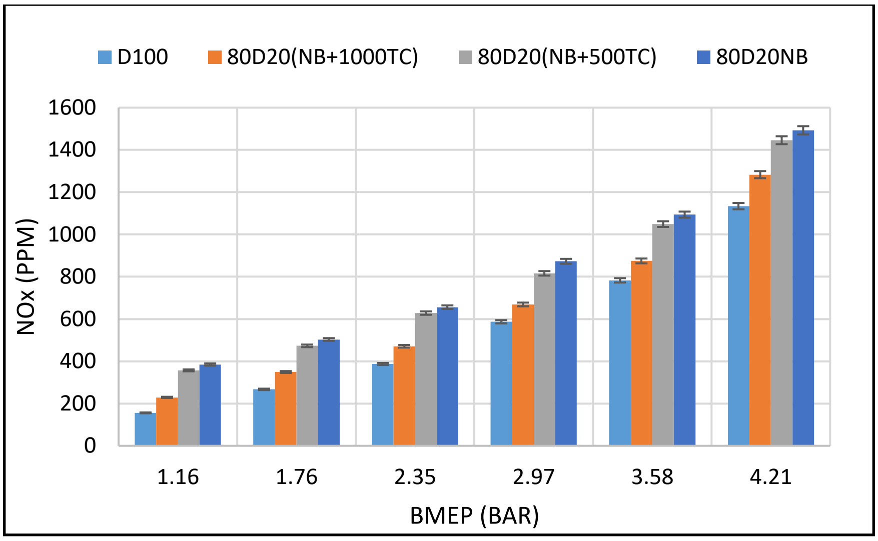


Figure 4.41: For natural antioxidants, NOx Vs BMEP for NB

antioxidants' reactivity with aromatic amines. Consequently, the oxidation procedure generates hydrogen peroxide and peroxyl radicals, which subsequently undergo conversion into hydroxyl radicals within the combustion chamber. This transformation process leads to temperature absorption and reduction in NOx[194].

The compound diphenylamine exhibits a rapid reaction with unpaired electrons, commonly referred to as free radicals, resulting in the formation of diphenyl nitric oxides, as explained in the given equations 4.1 and 4.2. Nitric oxides are considered effective scavenging agents due to their quick reactivity with nitrogen-cantered and carbon radicals (free radicals). antioxidants work as a quenching agent which helps to reduce NOx emission.

$$(C_6H_5)_2NH + RO_2 \cdot \longrightarrow (C_6H_5)_2N + RO_2H \qquad [4.1]$$

$$(C_6H_5)_2N + RO_2 \cdot \longrightarrow (C_6H_5)_2NO \cdot + RO \cdot \qquad [4.2]$$

4.7.4 Variation of CO emission

Carbon monoxide (CO) is a noticeable constituent of exhaust emissions produced from the incomplete combustion of fuel in CI engines. The variation in carbon monoxide emissions with varied BMEP for test blends is depicted in Figures 4.42 to 4.45. With the escalation in engine load, there is a corresponding increase in CO emissions. The rate of CO emissions exhibits a relatively slight increase during the initial half of the loading process. However, beyond this point, emissions experience a rapid rise due to increased fuel availability. This phenomenon results in incomplete combustion and high CO emissions during peak loading [160]. Due to the oxygen in the biodiesel component, which makes for more effective combustion, the

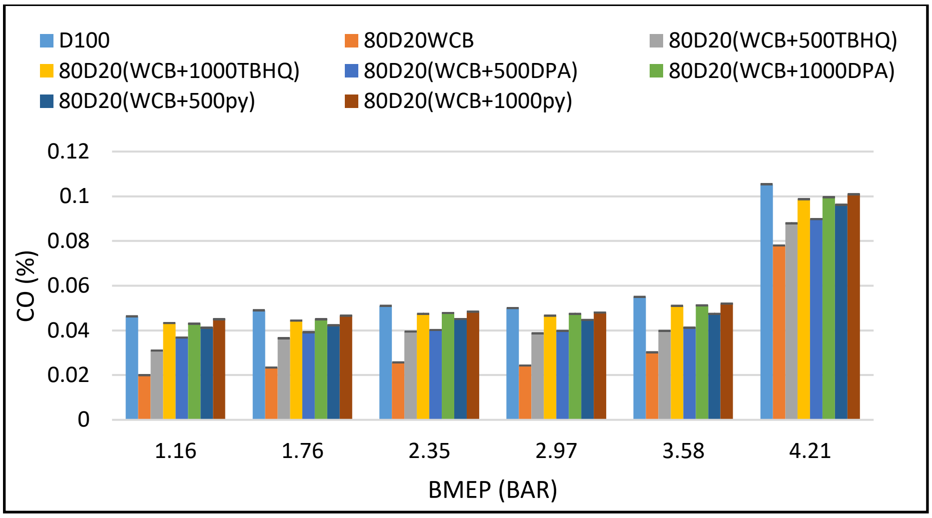


Figure 4.42: For synthetic antioxidants, CO Vs BMEP for WCB

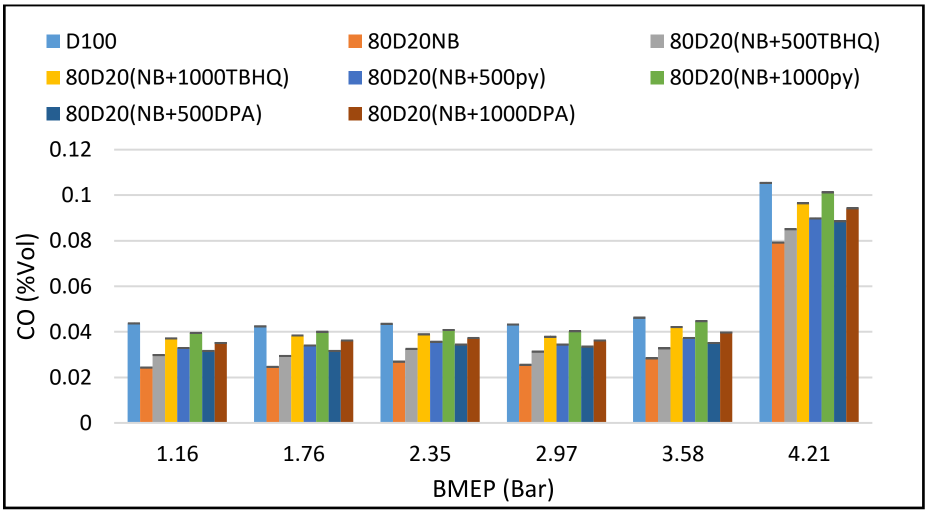


Figure 4.43: For synthetic antioxidants, CO Vs BMEP for NB

80D20(WCB) and 80D20NB blend emits less CO than pure diesel. However, it should be noted that pure diesel fuel has insufficient oxygen content., hence impeding the attainment of complete combustion and subsequently leading to elevated levels of CO emissions. The results of this study align with a previous investigation conducted by [196, 200]. Antioxidant-treated blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows the decrease in CO emission in comparison with diesel by 5.7%, 4.7%, 3.8%, and 9.2%, 7.6%, 3.8% at full load, respectively.

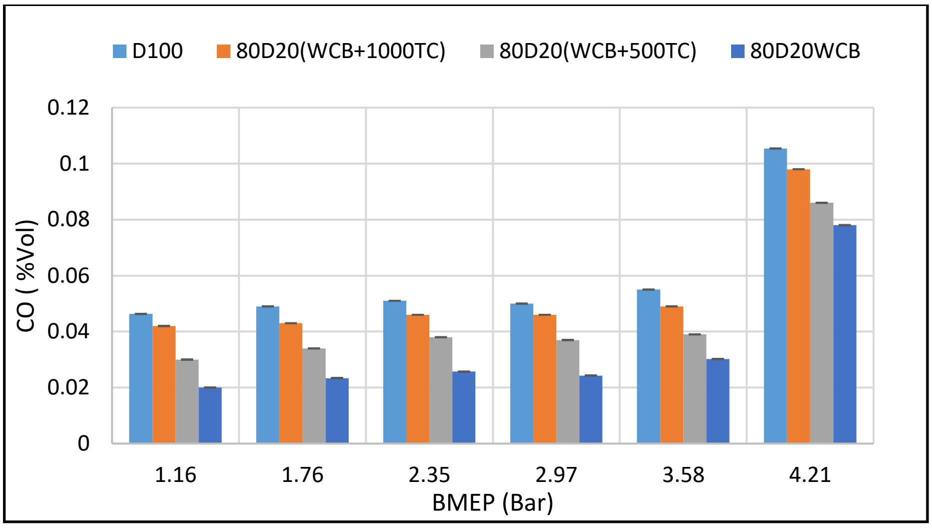


Figure 4.44: For natural antioxidants, CO Vs BMEP for WCB

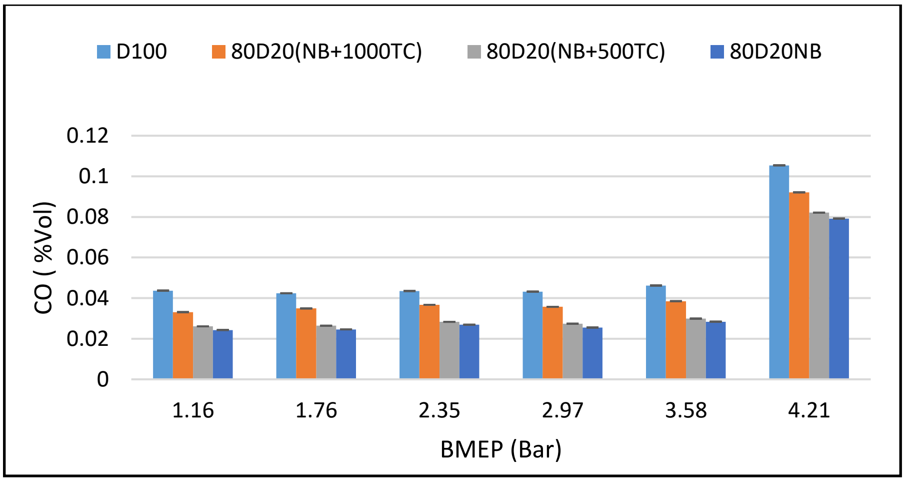


Figure 4.45: For natural antioxidants, CO Vs BMEP for NB

By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) shows reduction of 7.02% and 1fihure1%, respectively. However, using biodiesel-diesel fuel blends treated with antioxidants led to a considerable reduction in carbon monoxide (CO) emissions for all blends. variations in comparison with diesel. The reduction in emissions can be associated with generating OH (hydroxyl) radicals during combustion. These radicals are widely recognized for their high reactivity and contribute significantly to the oxidation of CO, which reduces CO emissions [177] Hydrogen peroxide (H_2O_2) and peroxyl radicals (HO_2) are continuously produced during the oxidation process. The radicals undergo conversion into hydroxyl radicals (OH) as a result of heat absorption, as depicted in Equations (4.3), (4.4), and (4.5). The presence and activity of hydroxyl (OH) radicals are necessary for the conversion of carbon monoxide (CO) to carbon dioxide (CO_2).

$$HO_2 \longrightarrow OH + O \qquad [4.3]$$

$$H_2O_2 \longrightarrow 2OH \qquad [4.4]$$

$$CO + OH \longrightarrow CO_2 + H \qquad [4.5]$$

The generation of hydroxyl radicals is also decreased as a result of a decrease in free radicals, which raises the levels of carbon monoxide (CO).

4.7.5 Variation of HC emission

Hydrocarbon emissions can originate from incomplete fuel combustion in the combustion chamber due to oxygen deficiency [20]. Hydrocarbon emissions fluctuate with BMEP for various test diesel blends, as seen in Figures 4.46 to 4.49. Due to more decadent fuel blends, all the blends produce slightly more hydrocarbon emissions at higher loads. 80D20WCB and 80D20NB, which contain more oxygen in biodiesel, lead to complete combustion and emit fewer hydrocarbons [199]. Antioxidant-treated blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows the decrease in HC emission compared to diesel by 9.5%, 6.3%, 4.7%, and 7.9%, 4.7%, 3.1% at full load, respectively.

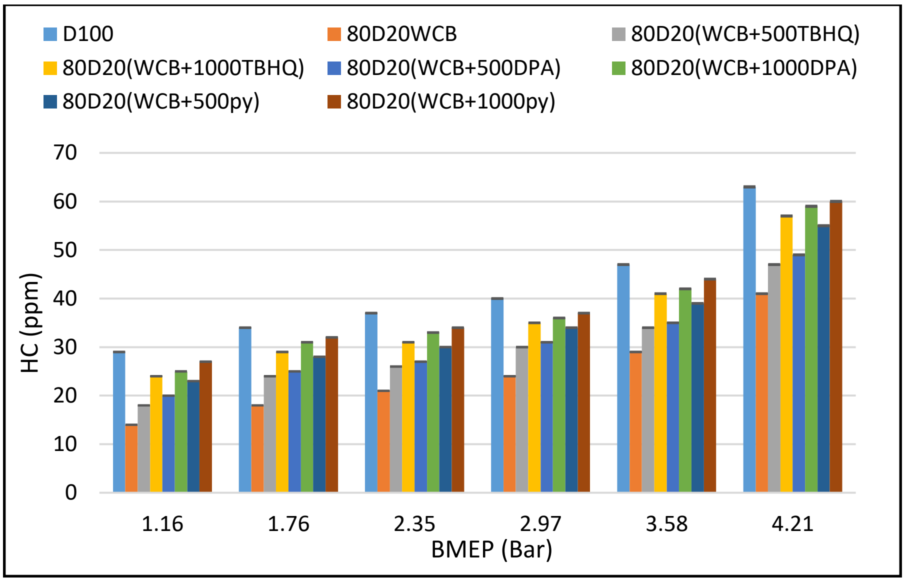


Figure 4.46: For synthetic antioxidants, HC Vs BMEP for WCB

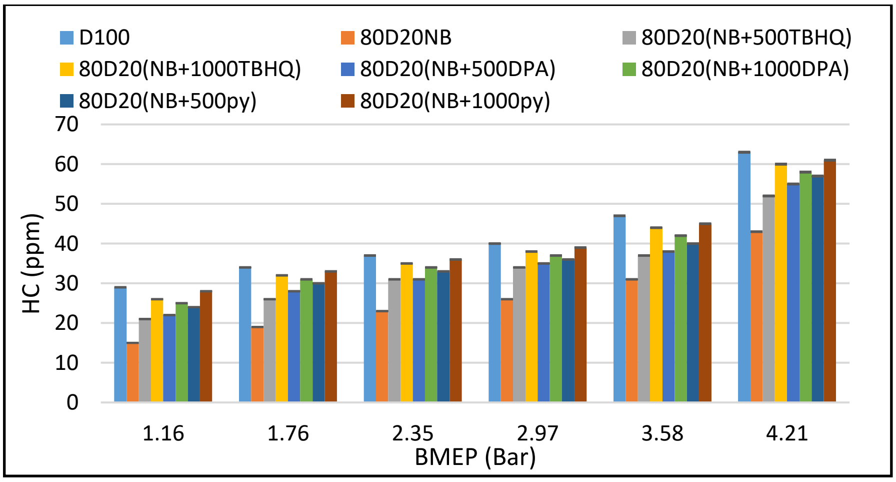


Figure 4.47: For synthetic antioxidants, HC Vs BMEP for NB

By adding TC antioxidants in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) show reductions of 11.11% and 9.73%, respectively. Antioxidant-treated fuel blends reduce hydrogen peroxide and peroxyl radicals, resulting in fewer free radicals for reactions and a slight increase in hydrocarbon emissions. HC emission found similar results as carbon monoxide emissions. This implies that antioxidants can affect hydrocarbon emissions. in less fuel mixtures [177, 197, 201]. Fuel blends that have been treated with antioxidants exhibit.

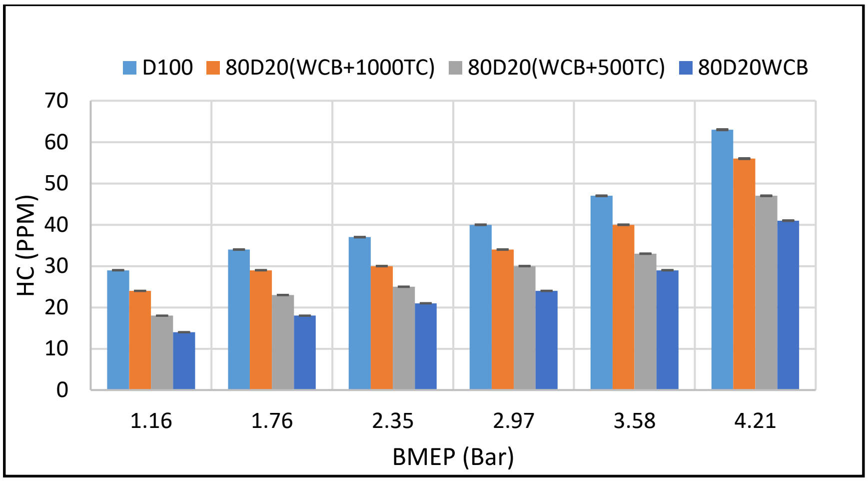


Figure 4.48: For natural antioxidants, HC Vs BMEP for WCB

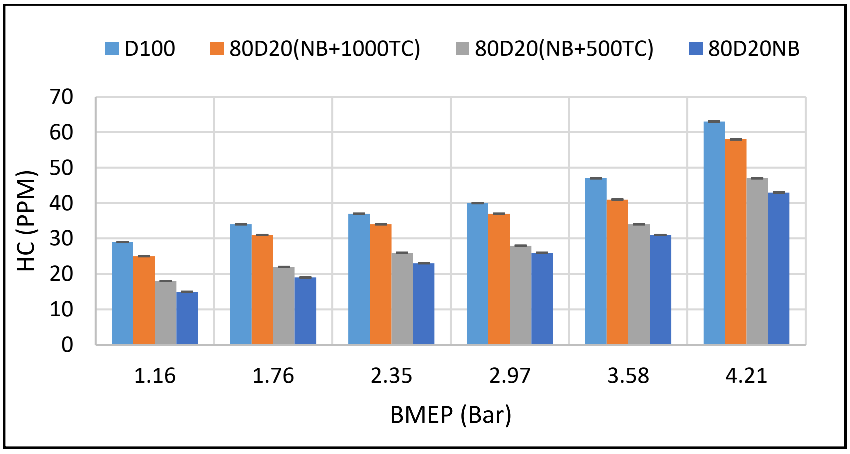


Figure 4.49: For natural antioxidants, HC Vs BMEP for NB

OH radicals that is necessary for the oxidation of hydrocarbons, as depicted in equations 4.6 and 4.7.

$$HC + OH \longrightarrow HCOH \quad [4.6]$$

$$HCOH + OH \longrightarrow H_2O + HCO \quad [4.7]$$

4.7.6 Variation of smoke emission

Smoke opacity is a quantitative indicator of the particulate matter emitted in exhaust emissions. A rich fuel-air mixture during the combustion process, insufficient oxygen supply, and incomplete combustion are all responsible for the smoke emissions. The variation between smoke opacity and different fuel blends at varying BMEP is given in Figures 4.50 to 4.54. Due to inadequate oxygen availability, pure diesel fuel demonstrates increased smoke opacity across all loads.

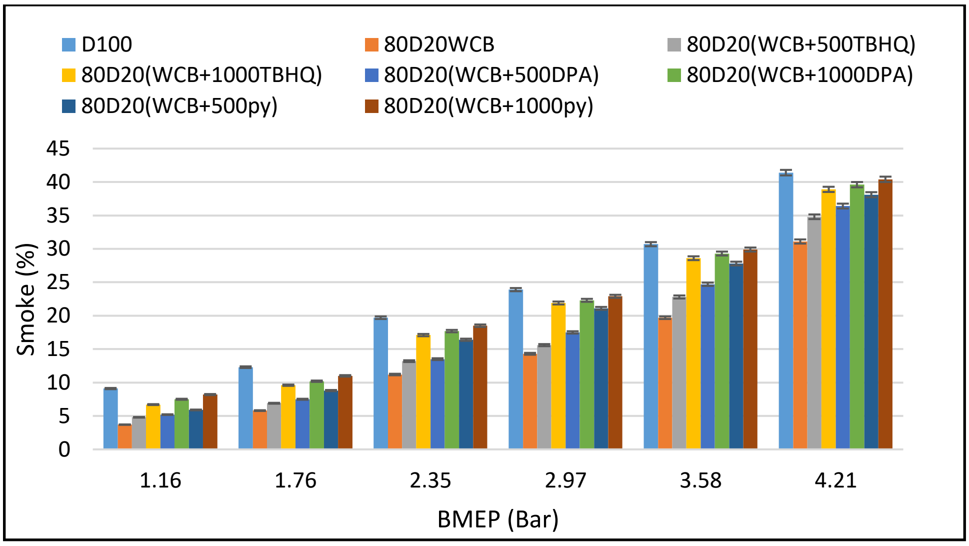


Figure 4.50: For synthetic antioxidants, Smoke Vs BMEP for WCB

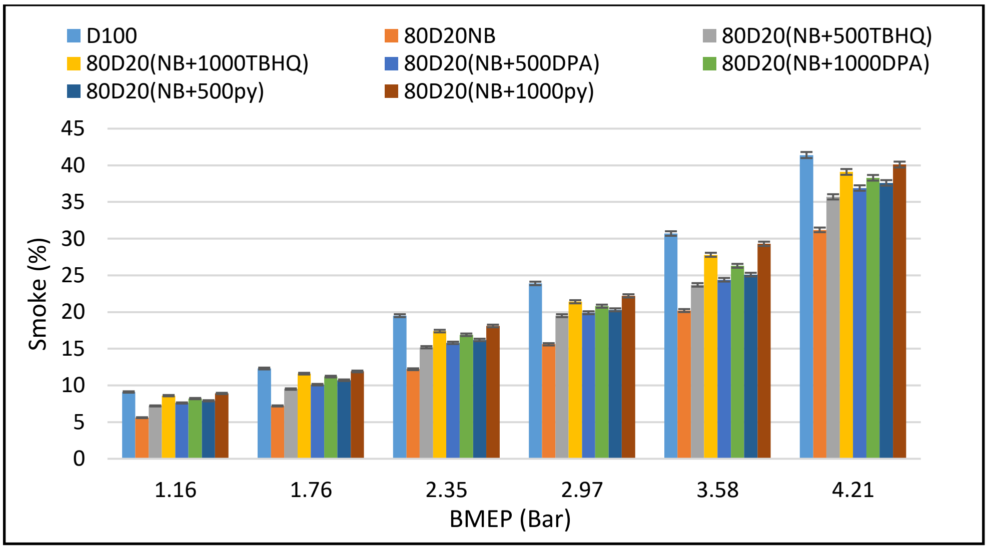


Figure 4.51: For synthetic antioxidants, Smoke Vs BMEP for NB

The smoke opacity tends to increase as the load. increases due to the enhanced fuel supply associated with higher loads. The investigations conducted by [156, 160] revealed comparable trends for all examined blends. However, the smoke opacity of the 20%

biodiesel blend, particularly the 80D20WCB and 80D20NB blend, exhibited a decrease in smoke opacity. Mixing biodiesel into diesel blends resulted in a rise in oxygen content, hence contributing to decreased emissions. This observation aligns with the findings reported by [192] in previous literature. Antioxidant treated blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows decrease in smoke opacity emission in comparison to diesel at full load by 6%, 4.34%, 2.4%, and 7.4%, 5.5%, 3.1% respectively.

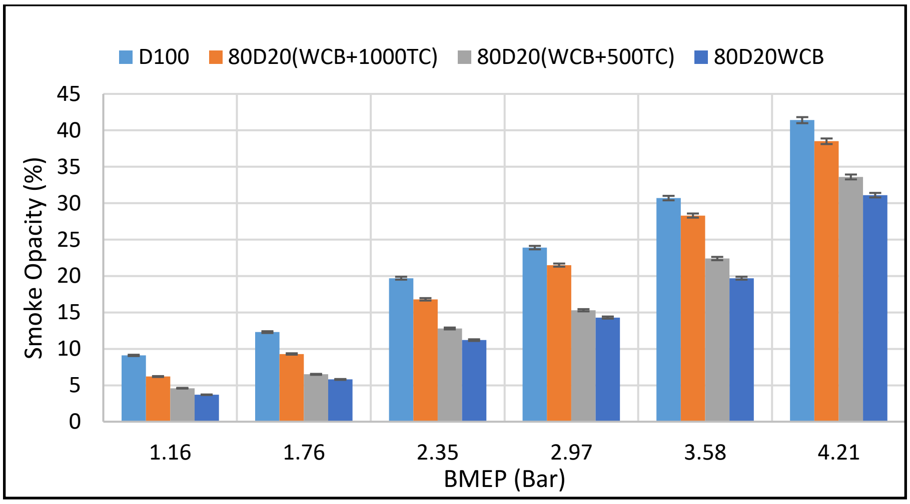


Figure 4.52: For natural antioxidants, Smoke Vs BMEP for WCB

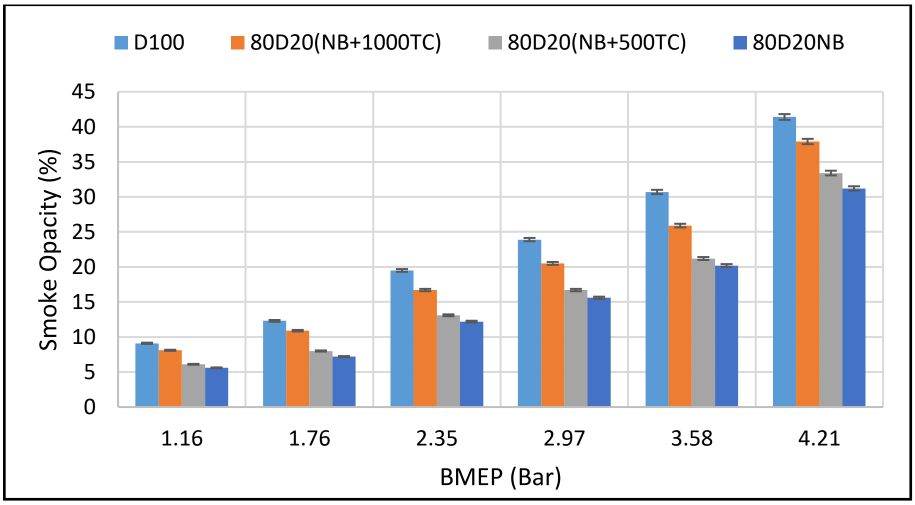


Figure 4.53: For natural antioxidants, Smoke Vs BMEP for NB

By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) shows reduction of 7% and 8.4%, respectively. Antioxidant-added biodiesel blends demonstrated a slight enhancement in smoke opacity compared to those without antioxidant blends. Antioxidants addition, which reduced oxygen availability, increased aromatic content, and increased the number of C-C bonds in the fuel mixture, all of which contributed to the observed increased smoke output. However, it should be emphasized that the study by [202] showed that these mixtures significantly reduced smoke opacity when compared to pure diesel.

4.7.7 Variation of exhaust gas temperature emission

Figures 4.54 to 4.57 display EGT variation with varied BMEP, corresponding to various fuel blends. According to a study conducted by [203], it has been observed that augmenting the engine's load is associated with increased EGT. The primary cause of this temperature increase is the dissipation of leftover heat from fuel combustion that was not later used. An increase in the temperature of combustion results in a corresponding elevation in the emission of waste heat, thereby impacting EGT (Velmurugan & Sathiyagnanam, 2016). The EGT is subject to the influence of the temperature within the combustion cylinder, which is connected to the generation of nitrogen oxides (NOx). Pure diesel has a lower EGT than a 20% biodiesel blend without antioxidants. Biodiesel blends have increased EGT due to enhanced combustion from oxygen delivery, air-fuel mixing, and ignition likelihood [160]. Antioxidant treated blends, 80D20(WCB+1000TBHQ), 80D20(WCB+1000DPA), 80D20(WCB+1000PY), and 80D20(NB+1000DPA), 80D20(NB+1000TBHQ), 80D20(NB+1000PY), shows the increase in

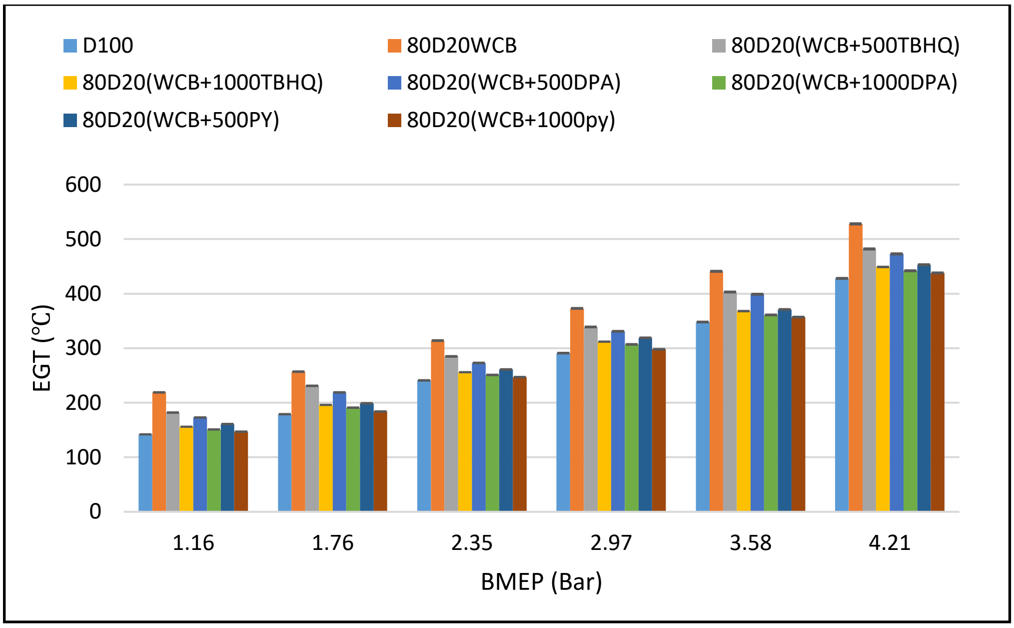


Figure 4.54: For synthetic antioxidants, EGT Vs BMEP for WCB

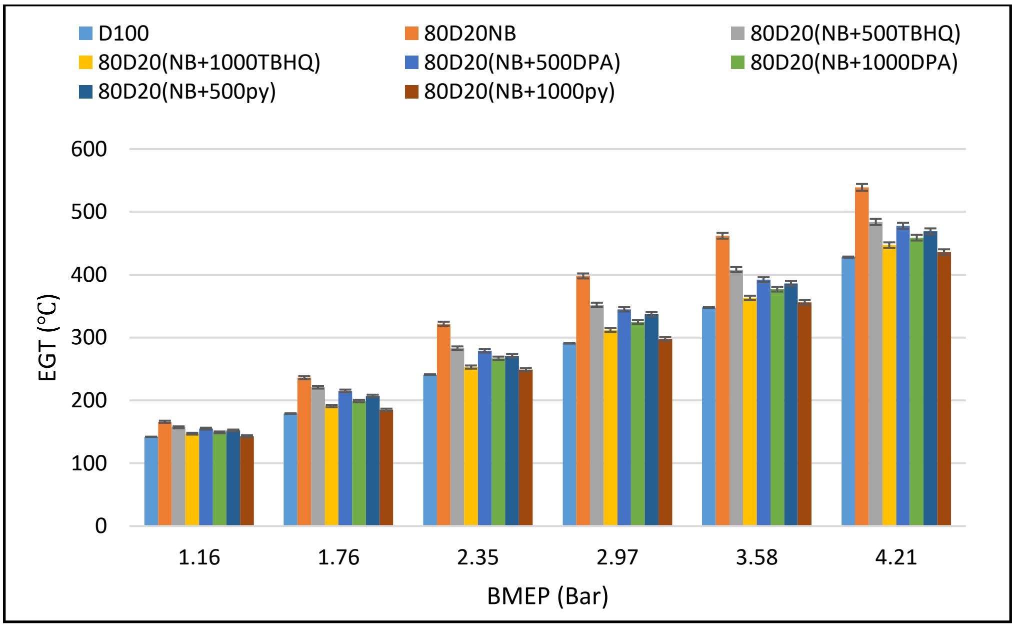


Figure 4.55: For synthetic antioxidants, EGT Vs BMEP for NB

EGT emission in comparison to without antioxidant blend at full load by 14.9%, 16.2%, 17.04%, and 14.84%, 17.06%, 19.10% respectively. By adding TC antioxidant in biodiesel, 80D20(WCB+1000TC) and 80D20(NB+1000TC) show reduction of 14.84% and 17.06%, respectively. Antioxidant-treated biodiesel-diesel blends have greater EGTs than diesel. In a previous study [201], Antioxidants hindered fuel conversion during combustion, causing this drop [200].

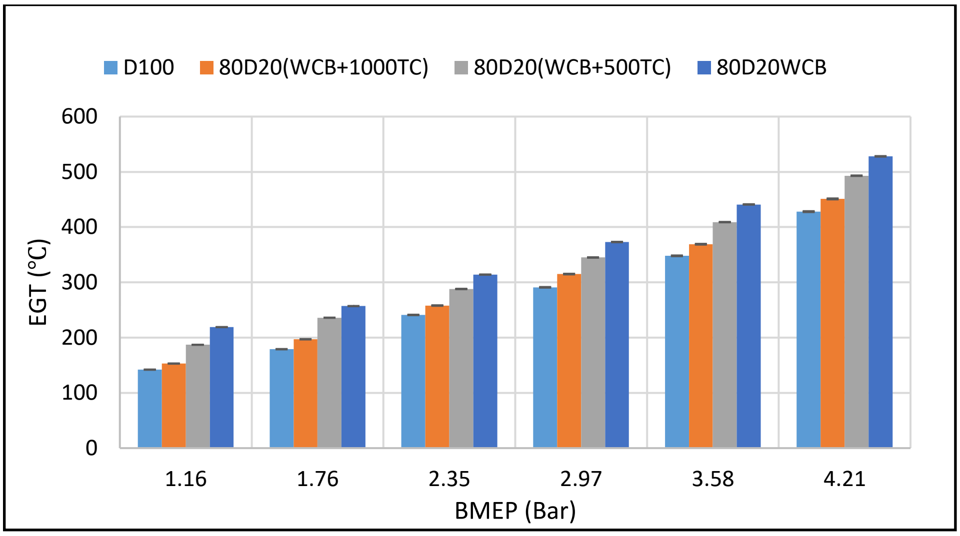


Figure 4.56: For natural antioxidants, EGT Vs BMEP for WCB

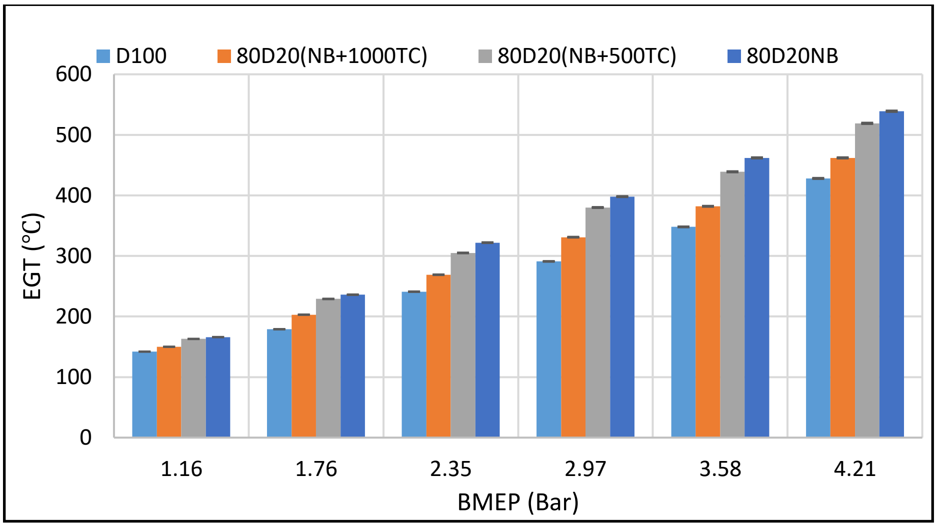


Figure 4.57: For natural antioxidants, EGT Vs BMEP for NB

4.8 Predictive Analysis using ANN vs. Real Analysis

Artificial Neural Networks (ANNs) are extremely powerful models in the field of machine learning, recognized for their ability to be trained in recognizing patterns and relationships within datasets. Predictive analysis activities, such as predicting characteristics or properties, performance, or behaviour based on input data, are tasks for which the ANN model is very suitable. Linear regression analysis is a commonly used technique for evaluating model performance. It involves comparing the scaled output of a neural network with corresponding target values to determine the extent of the model loss—the present study results in the determination of three parameters for each individual output variable. The parameters under consideration are the y-intercept, slope, and correlation coefficient, representing the relationship between the scaled output and the targets. The symbols 'a' and 'b' are used to describe the slope and y-intercept, respectively.

To achieve the best fit, the slope tends to approach unity, while the y-intercept tends to approach zero. This signifies a strong relationship between the output and desired target values. The correlation coefficient, denoted as 'R^2', tends to approach unity when there is a perfect fit, indicating a strong linear association between the scaled output and the target values. To get a perfect fit, the slope between the output and the target values should ideally be unity, and the y-intercept should ideally be 0, signifying no difference between the output and the target values. The correlation coefficient will also be one. When the targeted values and the scaled output are perfectly correlated, figure 4.58 to 4.65 shows a prediction analysis using ANN versus accurate estimation for the desired outcome, BTE, BSEC, NOx, HC, CO, Smoke opacity, and EGT. This paper presents an analysis of ANN through the application of simulation techniques and software interpretation, highlighting their application in research findings. Based on the analysis of artificial neural networks (ANN), it was determined that the R^2 values for BTE, HC, BSEC, CO. NOx, Smoke opacity, and EGT were observed to be 0.996, 0.989, 0.993, 0.995, 0.989, 0.992, 0.990. The present study reached the conclusion that Artificial Neural Networks (ANN) hold significant value as a technique for predicting the performance and emissions of internal combustion engines.

The linear regression parameters for the scaled output (BSEC, BTE, EGT, NOx, CO, HC, Smoke) with respect to input is given in Table 4.6.

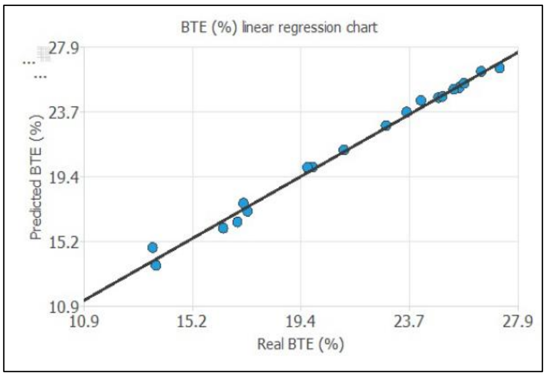


Figure 4.58: Predicted vs. real BTE (%)

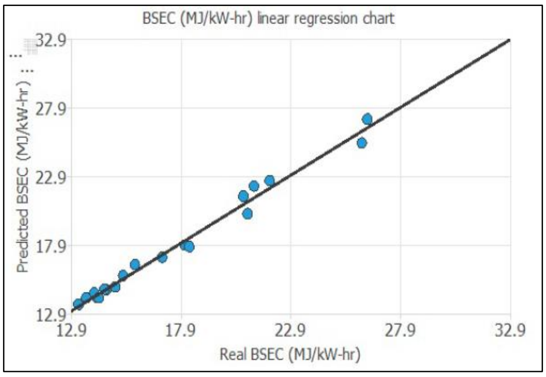


Figure 4.59: Predicted vs. real BSEC (%)

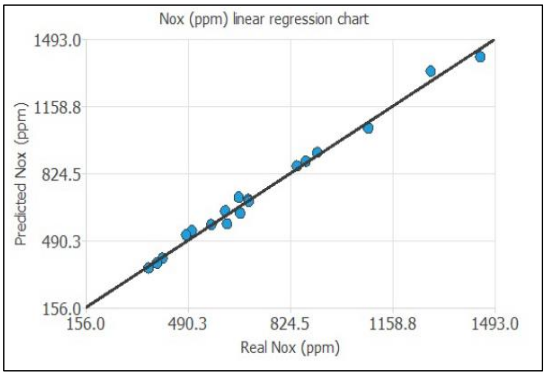


Figure 4.60: Predicted vs. real NOx (ppm)

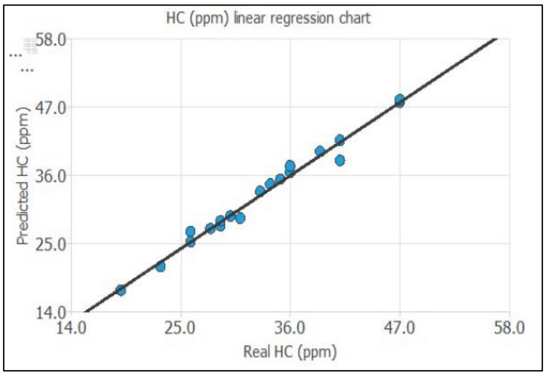


Figure 4.61: Predicted vs. real HC (ppm)

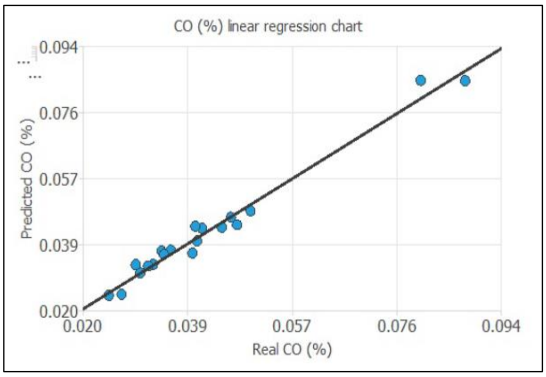


Figure 4.62: Predicted vs. real CO (%)

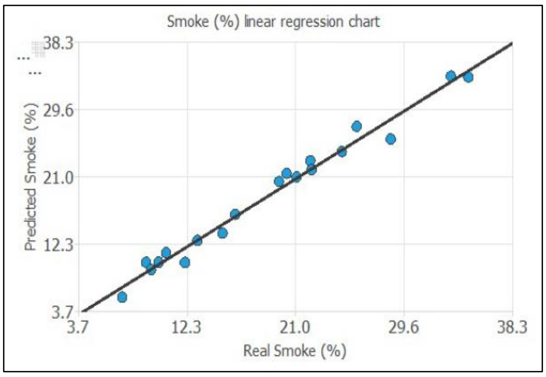


Figure 4.63: Predicted vs. real smoke opacity (%)

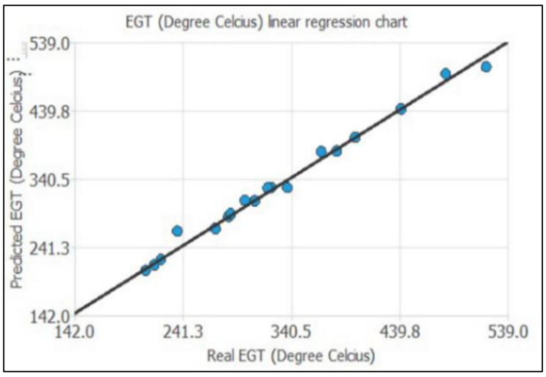


Figure 4.64: Predicted vs. real EGT (ppm)

Table 4.6: Linear regression parameters for the scaled output

S.No.	Parameter	Intercept	Slop	Correlation
1	BSEC (MJ/kW-hr)	0.352	0.989	0.993
2	BTE (%)	0.82	0.958	0.996
3	EGT (Degree Celsius)	3.88	0.995	0.995
4	NOx (ppm)	2.35	1	0.996
5	CO (%)	0.000682	0.987	0.989
6	HC (%)	-2.7	1.07	0.992
7	Smoke (%)	-0.484	1.01	0.99

4.9 Economic Analysis of the use of Additives

Cost analysis of antioxidants for 1000 ppm and 500 ppm is given in table 4.7.

Table 4.7: Cost analysis of antioxidants

Antioxidants	Cost of 500 grams (Rs)	Quantity required for 1000 ppm (gram)	Cost of 1000 ppm	Quantity required for 500 ppm (gram)	Cost of 500 ppm (Rs)
PY	7958 /-	0.9988	15.91 /-	0.4994	7.94 /-
TBHQ	1840 /-		3.67 /-		1.83 /-
DPA	920 /-		1.83 /-		0.918 /-
TC	436 /-		0.870 /-		0.435 /-

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusions

This research includes biodiesel (waste cooking and neem) using antioxidants to determine their impact on biodiesel properties, performance, emission, and combustion. TBHQ, PY, and DPA as synthetic antioxidants, and TC as a natural antioxidant mix in biodiesel dosages of 200, 500, and 1000 ppm. The induction period of biodiesel and antioxidant-treated biodiesel was analysed by the Rancimat test method. 20% of biodiesel mix with 80% diesel to blend waste cooking oil biodiesel and neem biodiesel without antioxidants and with antioxidants. Physiochemical properties of diesel, diesel-biodiesel, and diesel-biodiesel-antioxidant were estimated as per ASTM standards and used for engine testing.

Subsequently, combustion and performance characteristics for biodiesel with antioxidants blend were investigated and compared with D100, biodiesel blends (80D20WCB), (80D20NB). For performing prediction and validation of engine test analysis ANN prediction approach was used.

Outcome of extensive research work:

1. Waste oil has an FFA of less than two, and neem oil has more than two transesterification and esterification processes used for production, respectively.
2. GC-MS analysis of biodiesel characterizes SFAs and UFAs present within it. In the case of WCB and NB, the UFAs were determined to be 59.89% and 71.67%, respectively. A higher presence of unsaturated fatty acids indicates an increased vulnerability of the biodiesel to oxidation degradation.

3. The assessment of physiochemical attributes for biodiesel, diesel, and a blend of antioxidant-added biodiesel revealed that They meet ASTM test requirements and are within the permitted range. The introduction of antioxidants led to a minor elevation in viscosity and density compared to pure biodiesel, yet these increments remained lower than those observed in diesel. Notably, adding antioxidants had not much effect on the calorific content of the biodiesel.
4. Synthetic antioxidants are popularized in biodiesel to improve oxidation stability. The percentage scavenging capacity needs to be evaluated for natural antioxidants to identify its capability to use as an antioxidant in biodiesel. Natural antioxidant (Tinospora cordifolia) extract shows a maximum extraction capacity of 65.09% at 1000 g/ml.
5. 500 ppm of synthetic antioxidants in biodiesel meets standards, but 500 ppm doses of natural antioxidants is insufficient. By adding antioxidants of 1000 ppm doses meeting oxidation stability criteria for all blends and found most oxidation stable.
6. 500 ppm and 1000 ppm of antioxidant fuel blends used to evaluate performance. BTE enhances by adding antioxidants (both natural and synthetic) to biodiesel in comparison to the absence of antioxidants. D100 shows higher BTE.
7. Brake-specific energy consumption decreases by adding antioxidants to biodiesel compared to biodiesel not added with antioxidants. D100 shows lower BSEC.
8. D100 represents lower NOx, and biodiesel blends without antioxidants have higher NOx emissions. Adding antioxidants reduced NOx emissions significantly compared to those without antioxidants. Natural antioxidant, TC, reduces NOx by 16.37% for 80D20(WCB+1000TC) and 14.06% for 80D20(NB+1000TC), while

synthetic antioxidants can reduce NOx near 19% Waste cooking oil biodiesel and neem biodiesel.

9. However, compared to biodiesel without antioxidant treatment, there was a slight increase in the emissions of CO, smoke, and HC. It is noteworthy that all biodiesel blends containing added antioxidants exhibited emissions lower than those of diesel, which can be seen as a notable accomplishment attributed to the inclusion of antioxidants.
10. Among the fuels tested, diesel exhibits the most elevated HRR and CP. However, in WCB and NB supplemented with antioxidants, both HRR and CP experience a reduction in comparison to pure biodiesel. The increased cetane number associated with the biodiesel mixes can be responsible for this decrease. Specifically, diesel demonstrates a greater heat release rate and pressure ascent, specifically measuring 72.56 J/°CA and 67.75 bar.
11. To forecast performance and emission from engine test data, an ANN prediction algorithm was applied. According on the interpretation of the ANN results, the R^2 values ranged from 0.993 to 0.998, signifying a strong alignment between the projected outcomes and the intended values. This underscores the effectiveness of the ANN approach in achieving a robust correspondence between the anticipated and targeted values.
12. In conclusion, utilizing antioxidants, whether they are derived from natural sources or employed synthetically, has proven their efficiency in increasing the oxidation stability and overall performance of biodiesel.

13. Natural Antioxidants were shown to have a similar impact as synthetic antioxidants. For getting similar performance output, natural antioxidants will require in higher doses as compared to synthetic antioxidants.

5.2 Future Scope

- In the present work, the incorporation of biodiesel into diesel blends was restricted to a volume ratio of 20%. Nonetheless, to uncover novel avenues for investigation, it is worthwhile to extend research efforts toward exploring the feasibility of using biodiesel blends comprising up to 100% biodiesel content. This more thorough investigation may provide insightful information about the possible advantages and difficulties of using blends with larger proportions of biodiesel.
- Comprehensive risk assessments about the environmental release of antioxidants are viable considerations. Evaluation can be conducted to identify the potential impacts and consequences associated with introducing antioxidants into the environment.
- There is a compelling need for research endeavors to explore untapped sources of natural antioxidants, such as banana peels and gooseberries, renowned for their potential antioxidant applications. By exploring these unexplored avenues, we can uncover valuable insights into these natural sources' efficacy and potential application in providing antioxidant benefits.
- Life cycle assessment analysis of biodiesel can be performed. This entails a comprehensive evaluation of the entire life cycle of biodiesel, encompassing its production, distribution, utilization, and eventual disposal. This approach enables informed decision-making by considering biodiesel's broader implications and impacts throughout its entire exitance.

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APPENDICES

Appendix 1: Measured Parameters with their Accuracy

Measurements	Measurement principles with their limit	Uncertainty (%)	Accuracy
Cylinder pressure	Piezoelectric pressure Transducer (0-100 bar)	±0.1	±0.1 bar
Exhaust temperature	K-type thermocouple (0–1000 ^{o}C)	±0.2	±1 ^{o}C
Time	Digital stopwatch	±0.2	±0.2 s
Engine speed	Magnetic pickup type (0-2000 rpm)	±0.3	±10 rpm
Crank angle encoder (CAD)	Optical (0-720^{o})	±0.3	±1o
Engine load	Strain gauge type load Cell (0-25 kg)	±0.2	±0.1 kg
NOx	Electrochemical (0-5000 ppm)	±1.3	±50 ppm
HC	Non-dispersive infrared (NDIR) (0-30000 Ppm)	±0.2	±10 ppm
CO	Non-dispersive infrared (0-15% vol.)	±0.0.1	±0.03%
Smoke density	Photochemical (0-99%)	±1	±0.1%
B.P.	----	±0.05	----
BSEC	----	±0.3	----
BTE	----	±0.25	----

Appendix 2: AVL Dismoke 480 BT Smoke Meter Technical Specifications

Parameters	Specifications
Make and Model	AVL and AVL DITEST MDS 205 (Modular Diagnostic system)
Dimensions (WxHxD)	395 x 285 x 136
Weight	3.2 Kg
Interfaces	RS232 (Bluetooth Class1)
Humidity	max. < 90 %, non-condensing
Principle of measurement	Light Extinction
Length of Measurement	215 mm ± 2 mm
Emission Temperature (Max.)	200 °C
Power Consumption (Incl. heating)	approx. 78 VA
Heating Chamber temperature	100°C
Detector, (Dia 45mm)	Selenium Photocell
Source of light (12 V / 5W)	Halogen bulb
Accuracy	0.10%
Range	0-99%

Appendix 3: AVL Ditest 1000 Gas Analyzer Technical Specifications

Parameters	**Specifications**		
Make	AVL		
Gases measured	O_2 (Electro-chemical), CO, CO_2, HC (Infrared), NO (Electro-chemical)		
Dimensions (D*W*H), mm	85*270*320		
Weight	2.5 kg		
Humidity (non-condensing)	In between 10 to 90%		
Temperature	Operating @ 5°C to 40°C		
	Storage @0°C to 50°C		
Voltage, Volts	11 to 25, DC		
Power consumed, VA	20		
Measurement Range	**By Volume**		
Parameter	Measurement Range	Resolution	Precision
CO	0 to 15%	0.01%	± 0.03%
CO_2	0 to 20%	0.10%	± 0.2%
HC	0 to 30000 ppm	1ppm	± 10ppm
NO	0 to 5000 ppm	1ppm	± 50ppm
O_2	0 to 55%	0.01%	± 1%

LIST OF PUBLICATIONS

SCI JOURNALS

1. **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, 2022, **"Effect of synthetic and aromatic amine antioxidants on oxidation stability, performance, and emission analysis of waste cooking oil biodiesel",** *Environmental Science and Pollution Research*, vol-29, issue-19, pages-27939-27953. **Impact Factor- 5.19 (Q1).**
2. **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, 2022, **"ANN prediction approach analysis for performance, and emission of antioxidant treated waste cooking oil biodiesel",** Journal *of Environmental Science and Technology*. **Impact Factor- 3.519 (Q1).**

CONFERENCE PAPERS

1. **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, "**Comprehensive Study of Additives and Corrosion in Biodiesel**" **Proceedings of International Conference in Mechanical and Energy Technology, Pages1-11**. *International Conference on Mechanical and Energy Technologies (ICMET 2019)* organized by Department of Mechanical Engineering, Galgotias College of Engineering and Technology, Greater Noida, India from 07-08 November 2019.
2. **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, "**A review on cold flow properties of biodiesel and their improvement**" **IOP Conference Series: Materials Science and Engineering, Volume 804, Issue 1, Pages 012027**. *8th International Symposium on Fusion of Science & Technology (ISFT 2020)* held at J.C. Bose University of Science and Technology, YMCA, Faridabad, India from January 6-10, 2020.
3. **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, "**Effect of L-ascorbic acid antioxidant on oxidation stability of biodiesel**" **Emerging Trends in Mechanical and Industrial Engineering: Select Proceedings** (ICETMIE), 5 International Conference on Emerging Trends in Mechanical Industrial Engineering (ICETMIE-2022), 4 - 5 March 2022. Northcap University, India.

First Page of Publications

Environmental Science and Pollution Research (2022) 29:27939–27953
https://doi.org/10.1007/s11356-021-18086-x

RESEARCH ARTICLE

Check for updates

Effect of synthetic and aromatic amine antioxidants on oxidation stability, performance, and emission analysis of waste cooking oil biodiesel

Khushbu Yadav[1,2] · Naveen Kumar[2] · Rajiv Chaudhary[3]

Received: 28 June 2021 / Accepted: 9 December 2021 / Published online: 4 January 2022

Abstract
In the present study, an attempt was made to improve the oxidation stability of biodiesel by adding antioxidants to waste cooking oil biodiesel, and their impact on performance and emissions was analyzed. Two types of antioxidants were chosen for the analysis: an aromatic amine antioxidant, diphenylamine (DPA), and synthetic oxidants, tert-butylhydroxyquinone (TBHQ) and pyrogallol (PY). All the antioxidants were added to the biodiesel at doses of 200 ppm and 500 ppm to evaluate their effect. The oxidation stability was found as per the ASTM standard by mixing 500 ppm antioxidants for all three antioxidant-treated biodiesel blends. DPA yielded similar results as TBHQ, although PY had a better oxidation stability according to the Rancimat test. Gas chromatography and mass chromatography were also performed on the neat biodiesel. Performance and emission tests were performed on the antioxidant-treated biodiesel blends and diesel. The brake thermal efficiency of the tested fuel increased by 9.8%, 6.9%, and 15.88% when the DPA, TBHQ, and PY antioxidants were added to the test fuel compared to that of the test fuel without added antioxidant. The brake specific energy consumption of the test fuel decreased by 9.05% with DPA, 7.03% with TBHQ, and 14.08% with PY compared to that of the test fuel without antioxidant. The NOx emissions of the antioxidant-treated test fuels were reduced by 14.65% with DPA, 11.22% with TBHQ, and 23.10% with PY compared to those of the test fuel without antioxidants. Additionally, the aromatic amine antioxidant (DPA) was found to be effective in enhancing the performance and lowering the exhaust emissions compared to diesel for unmodified diesel engines.

Keywords Biodiesel · Additives · DPA antioxidant · Rancimat method · NO reduction · Induction time · Diesel engine

Nomenclature

TBHQ	tert-Butylhydroxyquinone
PY	pyrogallol
DPA	diphenylamine
PG	propyl gallate
BHT	tert-butylated
BHA	butyl-hydroxyanisole
DPPD	N,N′-diphenyl-p-phenylenediamine
NPPD	phenylenediamine
EN	European standard
WCB	waste cooking oil biodiesel
FFA	free fatty acid
GC–MS	gas chromatography and mass chromatography
BTE	brake thermal efficiency
BSEC	brake specific energy consumption
NOx	nitrogen oxide
HC	hydro carbon
CO	carbon mono oxide
EGT	exhaust gas temperature
% Vol	percentage volume

Responsible Editor: Ta Yeong Wu

Naveen Kumar and Rajiv Chaudhary contributed equally to this work.

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Springer

International Journal of Environmental Science and Technology
https://doi.org/10.1007/s13762-022-04660-4

ORIGINAL PAPER

ANN prediction approach analysis for performance and emission of antioxidant-treated waste cooking oil biodiesel

N. Kumar[1] · K. Yadav[1,2] · R. Chaudhary[3]

Received: 9 August 2022 / Revised: 11 October 2022 / Accepted: 7 November 2022

Abstract

For the purpose of lowering hazardous emissions and enhancing performance of diesel engine, waste cooking oil biodiesel has emerged as a feasible and promising biofuel. In this research paper, 300 and 400 ppm doses of tert-butylhydroquinone (TBHQ) and diphenylamine (DPA) antioxidants were added to waste cooking oil biodiesel of 20% volume to evaluate performance and emission parameters in unmodified diesel engine. An artificial neural network model was developed to predict brake thermal efficiency (BTE), brake specific energy consumption (BSEC), nitrogen oxide emission (NOx), carbon monoxide emission (CO), hydrocarbon emission (HC), and smoke opacity by considering load, blends, and type of antioxidant in different doses as input. Prediction and validation were carried out using the findings of the experiments. The quasi-Newton method algorithm was used to predict data that best fits with linear regression analysis. The result showed at full load, BTE and BSEC have R^2 values of 0.985 and 0.995, respectively. The recommended ANN model's accuracy and performance were acceptable. At full load, the brake thermal efficiency increased, and brake specific energy consumption was reduced for fuel blend with antioxidant in respect of without antioxidant blend. NOx emission was reduced by 2.32, 5.24, 7.35, and 12.44% for 300-doses DPA blend, 300-doses TBHQ blend, 400 doses TBHQ blend, and 400 doses DPA antioxidant blend, respectively, compared to without antioxidant blend. The adoption of ANN to predict performance and emission can speed up and lower the running cost of understanding output behavior.

Editorial responsibility: Shahid Hussain.

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Published online: 22 December 2022

Springer

First Page of Conference Papers

International Symposium on Fusion of Science and Technology (ISFT 2020) IOP Publishing
IOP Conf. Series: Materials Science and Engineering **804** (2020) 012027 doi:10.1088/1757-899X/804/1/012027

A review on cold flow properties of biodiesel and their improvement

Khushbu Yadav[a], Naveen Kumar[b], Rajiv Chaudhary[c]
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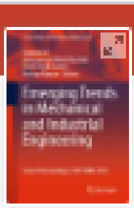
Abstract. The depletion of petroleum derivatives and expanded contamination caused by the consuming of fossil fuel is a driving component to consider the renewable source. Biodiesel is considered as most promising fuel to use in diesel engines. Biodiesel obtains from animal fats, Straight vegetable oils and waste by transesterification and esterification process. The properties of biodiesel oil meet the requirement of fuels and it can build a huge positive impact on pollution and make the fuel eco-friendly. Biodiesel with its points of interest undergoes a notable downside in the low-temperature properties. Due to inferior low-temperature properties of biodiesel, fuel crystallization and gum formation occur at low-temperature which leads to stopping of channels and tubes. It indicated higher pour point and cloud point, higher nitrogen oxide (NOx) which cuts down engine speed and power, injector coking. The present study review is done on low-temperature properties and Impact of different actions taken to improve these properties.
Keywords: Biodiesel, cold flow properties, additives.

Introduction
In many countries including India, researchers are focusing on an alternative fuel that is eco-friendly and renewable in nature. It is needed for the position of conserving the global environment and concern about long-term supplies of orthodox hydrocarbon based mineral diesel fuels. Biodiesel is derived from triglycerides using different sources vegetables and animal fats. With the help of transesterification chemical reaction biodiesel can be obtained, based on chemical reaction of fatty acid and alcohol catalyst and this biodiesel is known as methyl ester of fatty acid [1]. The main advantages of using this fuel these renewable properties such as good superiority exhaust gas emission and bio-degradability. The utilization of biodiesel gives significant decrease in emission of carbon monoxides, unburned hydrocarbon and particulates in conventional diesel engines [2].
Diesel fuel is essential in our country for transportation and agriculture. The chemical reaction to obtain fuel is transesterification. The lubricity effects of biodiesel are also better for engine then mineral diesel and prolong the engine life. [3] All vegetable oils have their own properties. Biofuel is enormously significant to preserve the engine from malfunction. With huge amount of mono, di, and triglycerides fuels are susceptible to coking and lead to the development of deposits in engine pistons, and other parts[4]. India imports 46% of edible oilseed and got fourth largest oil-producing country. India produces 9.3% of total world oilseed. Total world consumption is 3.1% while crude oil production in India is only 1%. [5].
Potential sources of production of biodiesel are Sal, Mahua, Pongamia, Jatropha and Neem. Bio-fuels not only help in stopping indiscriminate fossil fuel consumption but also are proven to be

 1



Emerging Trends in Mechanical and Industrial Engineering pp 419–429 | Cite as

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Effect of L-Ascorbic Acid Antioxidant on Oxidation Stability of Biodiesel

Khushbu Yadav, Naveen Kumar & Rajiv Chaudhary

Chapter | First Online: 01 January 2023

Part of the Lecture Notes in Mechanical Engineering book series (LNME)

Abstract

Researchers are exploring alternative fuels due to decreasing fossil fuel reserves, increased prices, and environmental concerns. Biodiesel is found one of the possible solutions to utilize. For instance, biodiesel contains no sulfur or aromatics that contribute to air pollution or acid rain but has poor oxidation stability. Antioxidant additives enhance the stability of a fuel blend against thermo-oxidative degradation during storage through inhibition of free radical chain reactions between unsaturated compounds found in biodiesel. In the present research work, waste cooking oil biodiesel is used, containing a highly unsaturated compound, to evaluate the performance of L-ascorbic acid antioxidant. The induction period of antioxidant-treated biodiesel has been evaluated at different ppm levels to maintain standard of biodiesel. 200 ppm of L-ascorbic acid antioxidant enhance oxidation stability and meeting EN standard.

Keywords

Biodiesel | Antioxidants | Oxidation stability | Induction time

Chapter 1
Comprehensive Study of Additives and Corrosion in Biodiesel

Khushbu Yadav, Naveen Kumar and Rajiv Chaudhary

Abstract India is a diesel-driven country with the extensive use of diesel engines in transportation, farming, and industrial sector. This is primarily due to high thermal efficiency and better fuel economy. However, diesel engines produce higher harmful emissions such as NOx, particulate matter (PM) as compared to diesel fuel, which is harmful to human health. Biodiesel is one of the attractive alternative fuels made from renewable resources and can be used in the existing CI engine without any major modification. Biodiesel has several drawbacks like high density, low heating value, and high fuel consumption. Additive plays an important role in alleviating problems of the use of biodiesel in diesel engine, and additives in biodiesel can result in improved engine performance, engine combustion, emissions, and physicochemical properties. Metal-based additives can result in improved emissions. The oxidation stability is also a major issue in the use of biodiesel. Oxidation stability leads to storage problem for a longer time period due to slush formation, and it also had their impact on stored metal and metal parts of the engine. Antioxidant additives provide protection against corrosion and enhance combustion process, and engine performance properties with the cleanliness of fuel lead to less wear. Antioxidants help to improve storage and stability characteristics. In the present study, a comprehensive review is done to study the different additives and their impact on engine performance, combustion, emission, and metal parts.

Keywords Biodiesel · Additives · Performance · Emission · Corrosion

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S. Yadav et al. (eds.), *Proceedings of International Conference in Mechanical and Energy Technology*, Smart Innovation, Systems and Technologies 174,
https://doi.org/10.1007/978-981-15-2647-3_1

A BRIEF BIOGRAPHICAL SKETCH

Khushbu Yadav is a dedicated professional in the field of Mechanical Engineering, with a strong academic background and extensive teaching experience. She earned her B.Tech in Mechanical Engineering from Maharana Pratap Engineering College, Kanpur, India in 2009. Building on her foundation, she pursued her M.Tech in mechanical engineering at Motilal Nehru National Institute of Technology, Allahabad, India in 2013. Continuing her academic journey, she enrolled in Ph.D. program at Delhi Technological University, where she joined the prestigious Centre for Advanced Studies and Research in Automotive Engineering (CASRAE) within the Mechanical Engineering Department. Her research pursuits have primarily revolved around alternative fuels, with a particular focus on Biodiesel.

With over a decade of teaching experience in mechanical engineering, she currently holds the position of Assistant Professor at the esteemed Amity School of Engineering and Technology, Amity University, Noida, U.P. Throughout her career, she has demonstrated her commitment to nurturing young minds and fostering academic growth. She guided many postgraduate and undergraduate students in their projects.

Her research endeavours have made a significant impact in her field. Her contributions have resulted in the publication of 2 research papers in SCI and Scopus-indexed journals, as well as 8 research papers in reputable peer-reviewed journals and conferences. She has been awarded by esteemed Research Excellence award for executing commendable research work in the year 2022.

In addition to her academic pursuits, she is an active member of the International Association of Engineers (IAENG), showcasing her commitment to staying engaged with her professional community. With her strong academic foundation, robust teaching experience, and notable research achievements, she continues to be a driving force in the field of Mechanical Engineering.

CURRICULUM VITAE

KHUSHBU YADAV

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Objective

To contribute the success and growth of the organization by undertaking assignment and delivering results on time by applying my knowledge and skills. I also look forward to work in a professional environment to enhance and sharpen my knowledge and teaching skills.

Professional Qualification

Degree	University	Year of Passing	C.P.I
Ph.D	Delhi Technological University, Delhi	2023	NA
M.Tech	MNNIT, Allahabad	2013	8.2
B.Tech	Uttar Pradesh Technical University, Lucknow	2009	71.3

Academic Qualification

Class	School	Year of Passing	Percentage
XII (UP Board)	G. G. I. C. Fatehgarh, Farrukhabad	2005	64
X(UP Board)	M. L. I. C. Amanpur, Etah	2003	60.16

Academic Project

- Evaluation of Performance, Emission and Combustion characteristics of various biodiesel of Indian origin.
- Air-Path Control of Turbocharged Diesel Engine
- Solar room heating system
- Production and characterization of biodiesel
- Oxidation stability analysis of biodiesel
- Production and characterization of natural antioxidants

Work Experience

- Working as Assistant Professor (AP-1) in **Amity School of Engineering, Amity University**, Noida.

  DURATION: - July 2014 – Till Date
- **1 year** of teaching experience as Assistant Professor in **MGM's College of Engineering and Technology**, Noida.

  DURATION: - July 2013 – July 2014
- **2 years** of teaching experience as a lecturer in United Institute of Technology, Naini, Allahabad.

  DURATION: - July 2009 – June 2011

International Journal Publication

- Khushbu Yadav, Naveen Kumar, Rajiv Chaudhary, 2022, **"ANN prediction approach analysis for performance, and emission of antioxidant treated waste cooking oil biodiesel",** Journal *of Environmental Science and Technology*. **Impact Factor- 3.519. (SCI-Q1 Rank)**
- Khushbu Yadav, Kumar N, Chaudhary R, 2022, **"Effect of synthetic and aromatic amine antioxidants on oxidation stability, performance, and emission analysis of waste cooking oil biodiesel",** *Environmental Science and Pollution Research*, vol-29, issue-19, pages-27939-27953. **Impact Factor- 5.19. (SCI-Q1 Rank)**
- Khushbu Yadav, Alam B, Chandra S. N, Khan S. A., Gupta A. "**Design and Manufacturing of Thermoelectric Waste Heat Recovery System**", *Journal of Material Science and Mechanical Engineering*, 2016, Vol. 03, No.04, PP.274-277.
- Khushbu Yadav, Choudhory R. Wakhle G. "**An Improved Bi-Functional Pen**", *International Journal of Engineering, Science, Technology and Management*, 2015, Vol. 01, No.01, PP.15-20.
- Khushbu Yadav, Jain. V, Shikha S. "**FRE: Functional Reverse Engineering for Mechanical Components**", *International Journal of Advanced Mechanical Engineering*, 2014, Volume 4, Number 2, pp. 139-144, ISSN 2250-3234.
- Khushbu Yadav, sraswati. S. "**Novel PI control strategy to control turbocharged diesel engine**", *International Journal of Engineering Research and Technology*, 2013, Vol.No.6, PP.282-286, ISSN 0974-3154.

Conference & other publication

- Bhandari M, Dubey A, Khushbu Yadav, 2022," Effect **of Anti-Oxidants on Oxidation Stability of Biodiesel**" *3rd Biennial International Conference on Future Learning Aspects of Mechanical Engineering* (FLAME - 2022), 3rd – 5th August 2022.
- Khushbu Yadav., Kumar N., Chaudhary R., 2022, "**Effect of L-ascorbic acid antioxidant on oxidation stability of biodiesel**" *5th International Conference on Emerging Trends in Mechanical Industrial Engineering* (ICETMIE-2022), 4 - 5 March 2022. Northcap University, India.

- Khushbu Yadav, Bisht A, Anwar S, Kharbanda C, 2022, "**Effect of anti-oxidant additive on oxidation stability of biodiesel**", *Journal of Physics: Conference Series*, vol-2178, pages-012028, IOP Publishing.
- Khushbu Yadav, Kumar N., Chaudhary N., 2020 "**A review on cold flow properties of biodiesel and their improvement**" *IOP Conference Series: Materials Science and Engineering*, Volume 804, Issue 1, Pages 012027.
- Khushbu Yadav, Kumar N., Chaudhary R., 2020 "**Comprehensive Study of Additives and Corrosion in Biodiesel**" *Proceedings of International Conference in Mechanical and Energy Technology*, Pages1-11.
- Khushbu Yadav, Rasal A., Saxena S, Nair N., Vikal M., Dwivedi G., 2019 "**Role of Additives in Enhancing the Performance Characteristics and Stability of Biodiesel – A Review**" *Advances in Interdisciplinary Engineering*, Pages 543-552.
- Kumar S., Khushbu Yadav, Dwivedi G., 2018 "**Impact analysis of Oxidation Stability for Biodiesel & its Blends**" *Materials Today: Proceedings*, 5 (2018) 19255–19261.
- Khushbu Yadav, Rhman Md. S., 2017 "**Effect of Rear Spoiler and Diffuser Angle on Aerodynamic Characteristics of a Sedan**" *International Journal of Research in Engineering*, IT and Social Sciences, ISSN 2250-0588, Impact Factor: 6.452, Volume 08, Special Issue, June 2018, Page 105-117.

Workshop Conduction

- Organized one day workshop on "**Robotics**" 8th Oct, 2015 organized through Amity Club of Mechanical engineering, Amity University.
- Conducted two weeks **ISTE Workshop** on **"Fluid Mechanics",** 20th -30th April, 2014 in MGM's CoET, Noida through **IIT Kharagpur** under the National Mission on Education through ICT (**MHRD**).

Conference participation

- **Khushbu Yadav**, Naveen Kumar, Rajiv Chaudhary, 2022, presented research paper on "Natural antioxidants and their implication in biodiesel" ***International Symposium on the Fusion of Science and Technologies (ISFT2022) & The 2nd Rajamangala University of Technology Suvarnabhumi International Conference (RUSiCON), Thailand,*** 16-19 August 2022 (online presentation)**.**
- **Khushbu Yadav**, presented research paper entitled "Effect of natural and synthetic antioxidant on oxidation stability of biodiesel" in the conference, **3rd Biennial International Conference on Future Learning Aspects of Mechanical Engineering (FLAME 2022)**, Amity University, Noida, 5th – 7th August 2020.
- **Khushbu Yadav**, presented research paper entitled "Additive and Blending Effects of Biodiesel on Engine Performance and Emission" in the conference **"Technology innovation in mechanical engineering (TIME 2021)**" Organised by Department of mechanical engineering, Sagar institute of science and technology, Gandhi Nagar Bhopal, 10-11 May 2021.

- **Khushbu Yadav,** worked as **joint organiser in 1st International Conference on New Frontiers in Engineering, Science, and Technology** (NFEST-2018), held in New Delhi, India, 8-12, 2018.
- Attended one-week **ISTE Coordinators Workshop** on **"Fluid Mechanics",** 11th -15th March 2014 conducted by **IIT Kharagpur** under the National Mission on Education through ICT (**MHRD**).

Workshop participation & other participation

- Attended a one-week online Faculty Development Programme on **"Machine Learning in Big Data Analytics, Principles, Techniques and Challenges"** organized by Department of Computer Science and Engineering, from 13th to 18th Feb 2023.
- Attended a one-week professional development programme on **"Recent Developments in Renewable Energy"** organized by Mechanical Department, Amity University, Noida, from 20th to 24th June 2022.
- Attended AICTE Training And Learning (ATAL) Academy online elementary FDP on **"Sustainable Transport Sources for Future Mobility Application"** organized at Maulana Azad National Institute of Technology, Bhopal, from 22nd to 26th Nov 2021.
- Attended a one-week professional development programme on **"Experimental Methods For Engineers"** organized by Mechanical Department, Amity University, Noida, from 21st to 25th Dec 2020.
- Attended Faculty Development program on "**Mentor-Mentee System**" organized by Amity University 27th -28th May, 2015.
- Attended Faculty Development program on "**Research: Optimization**" organized by Amity University 25th -29th May, 2015.
- Attended Faculty Development program on "**Amity Academic Structure & System**" organized by Amity University 8th -9th Oct, 2014.
- Attended Two week ISTE Workshop on "**Engineering Mechanics**", Nov 26th to Dec 06th, 2013 organized by IIT Bombay held at MGM's CoET, Noida.
- Attended Short Term Course on "**Applications of Artificial Intelligence Techniques in Engineering System**", 10th -14th June, 2013, MNNIT, Allahabad.
- Attended conference on "**World Congress on Frontiers of Mechanical, Aeronautical and Automobile Engineering**', 2nd -3rd Feb,2013, IITD, New Delhi.
- Attended One day Workshop on "**Human Values and Professional Ethics**" Program sponsored by UPTU held at UIT, 2010 Allahabad.
- Attended National Conference on "**Computer Science and Micro Electromechanical Systems"**, 20th -21th Feb, 2010, United Institute of Technology, Allahabad.
- Conduction of cultural programs in college as a Co-Convener of cultural committee held at UIT, Allahabad.
- Participated in the organization of International & National Seminars held at UIT, Allahabad.
- Participated in conducting sports in the campus of UIT, Allahabad.

Other Responsibilities:

- Admission Team Member 2015, 2016, 2017
- Placement coordinator Team Member
- Automobile Club Member
- ACME club coordinator 2014, 2015, 2016
- Faculty in-charge for Sangathan- Carrom Board
- Sangathan coordinator, 2014, 2015, 2016
- Conduct & Review of NTCC and GSSC
- Programme leader (PL), (Odd sem), 20016-2017
- Guiding Minor and Major Projects of students
- Convocation coordination team member
- AYF event coordinator 2014, 2015, 2016

Summer Training

- Organization : Electric Loco Shed
  Duration : One Month
  Topic : Mechanical AOH/IOH Unscheduled Inspection
- Organization : H.A.L.
  Duration : One Month
  Topic : Do-Aircraft

Personal Profile

Father's Name : Mr. Aneg Singh Yadav
Mother's Name : Mrs. Maloda yadav
Date of birth : 15th July, 1988
Gender : Female
Nationality : Indian
Marital status : Married
Language Known : Hindi & English

I hereby declare that all the above information is correct to the best of my knowledge.

KHUSHBU YADAV