PERFORMANCE OPTIMIZATION OF COMPRESSION IGNITION ENGINE FUELED BY TERNARY BLENDS OF DIESEL, BIODIESEL, AND PROPANOL

BY

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DECLARATION

Declaration by Candidate

I declare that this thesis is my original work and has not been presented for any degree in any other University. No part of this thesis may be reproduced without a prior written permission from the author and/or Moi University.

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DEDICATION

This thesis is lovingly dedicated to my family for their patience and tolerance in my absence during this study. I sincerely applaud my lovely parents for paying my early education under difficult circumstances, they constantly encouraged me to live to my full potential and to always trust in God.

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ABSTRACT

Compression ignition (CI) engines are widely used all over the world and are associated with higher fuel conversion efficiency, power output, torque output, durability, and reliability over spark ignition (SI) engines. However, there is the rapid depletion of fossil fuel reserves which has necessitated a search for alternative fuels for CI engines. Consequently, the main objective of this study was to optimize the performance of compression ignition engines fueled by ternary blends of diesel, biodiesel and propanol. The study's specific objectives included the production of ternary blends, investigation of engine performance under varying blend concentrations and determination of the optimal blend concentration that minimizes emissions of pollutant gases. In this study, biodiesel was produced from waste vegetable oil through trans-esterification process and was blended with commercial diesel and propanol in ratios of 0% to 25%, 75% to 100% and 0% to 5%, respectively. The physical parameters of the ternary blends, such as density and viscosity, were determined and blends were used to run a 16.8-kilowatt Petter's two-cylinder engine running at a constant engine speed of 2000 rpm and brake power of 10 kilowatts. The desirability technique was used to determine the optimal values, which included minimizing nitrogen oxide (NOx), hydrogen oxide (HC), and carbon monoxide (CO) emissions while maximizing brake thermal efficiency (BTE). Using design expert software, the experiment was carried out via the response surface method (RSM). Responses included brake thermal efficiency, brake specific fuel consumption (BSFC), emissions of nitrogen oxide, hydrogen oxide, and carbon monoxide, and the variables were blended from diesel, biodiesel, and propanol. Gas emissions from the optimal blend were measured using exhaust gas detectors. Five solutions with desirability ranging from 0.667% to 0.828% were discovered. They each had unique blend proportions and responses. The optimal combination with 0.828 desirability was deemed the best. The blend of 75.01%, 24.604%, and 0.386% was found to be optimal, with responses of BTE 63.001%, BSFC 0.153kg/kWh, and emissions of NOx 82.347 ppm, CO 436.013 ppm, and HC 4.877 ppm, and physical properties of 0.972 g/cm3 density and viscosity of 4.363 cP. BTE increased by 9% when compared to pure diesel with a density of 0.96 g/cm3 and a viscosity of 6 cP, while BSFC, NOx, CO, and HC decreased by 15%, 12.87%, 15.23%, and 75%, respectively. Different blends have different physical attributes, like density and viscosity, which affected engine performance. There was no direct relationship between the two properties. No phase separation was observed in the blends. Based on the results, the optimal ternary blend of diesel, biodiesel, and propanol is recommended for internal combustion engines due to notable improvements in engine performance and reduced emissions. Additionally, we recommend that future studies investigate the long-term effects of using ternary fuel blends on engine components. This could be done by conducting durability tests and monitoring emissions over extended periods of use. In addition, we recommend that future research also investigate the possibility of using other biofuels such as bioethanol or biogasoline in the ternary blend, to see if they could also improve engine performance, emissions, and fuel consumption. However, further research is required to establish the life span of the optimal blend and to determine if its efficiency decreases over time.

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ABBREVIATIONS

BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Cold Point
cP	centipoise
EGT	Exhaust Gas Temperature
FAC	Fatty Acid Composition
FFA	Free Fatty Acid
GC	Gas Chromatography
HC	Hydrocarbon
KV	Kinematic Viscosity
NOx	Nitrogen Oxide
PM	Particle per minute
Pro	Propanol
RSM	Response Surface Method
SI	Spark Ignition
WCO	Used cooking oil

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Compression ignition (CI) engines are used in public transportation, heavy-duty machinery, power generation and agricultural as well as industrial equipment. CI engine has high fuel-conversion efficiency, power output, torque output, durability, and reliability as compared to spark ignition (SI) engine. CI engines also have lesser emissions of carbon monoxide, hydrocarbons and carbon dioxide when compared to SI engines which use gasoline (Shahir et al., 2014).

There has been significant environmental degradation occurring around the world as a result of the rapid depletion of fossil fuel reserves due to rising energy demand. Fuel demand for transportation increased by 124 billion litters in 2015, and it is expected to rise by 200 billion litres by 2024, according to research (B. R. Kumar & Saravanan, 2016; Verma & Sharma, 2016). The high demand and depletion of fossil fuels have led to high oil-price fluctuations and more emissions of gasses. In response to the environmental impact, stricter emission regulations have been implemented, spurring the scientific community to seek out renewable biofuels that can be used in diesel engines instead of petroleum-based ones.

As a result, there has been a lot of focus on improving alternative fuel sources. Use of alternative fuels in diesel engines raises important issues that must be taken into account. Alternative fuels engine stability, emission control, fuel delivery reliability and engine stability are just a few of the many variables to consider. Aside from alternative fuel sources, the gases that contribute to the greenhouse effect and local pollution in the atmosphere need to be addressed as well (Shahir et al., 2014). Renewable fuels are frequently used as an alternative to fossil fuels. Biogas, Bio-alcohol, and biodiesel are all examples. In CI engines, biogas is not suitable because it requires high pressure to be utilized. It is also possible that it could be hazardous if it (Verma & Sharma, 2016) leaks. Direct use of biodiesel from edible vegetable oil can lead to food shortages. As a result, it cannot be used in diesel engines due to some of its properties that reduce the engine's efficiency performance.

Bio-alcohols like ethanol and methanol have lower calorific values compared to traditional fuels such as gasoline. This lower energy content translates to reduced energy released during combustion, potentially leading to decreased engine performance and power output when used as primary fuels.

Moreover, bio-alcohols often exhibit poor miscibility with lubricating oils, leading to challenges in achieving a proper blend within the engine. This poor compatibility can cause incomplete mixing or separation within the lubrication system, resulting in areas of insufficient lubrication. Inadequate lubrication can lead to increased friction and heat generation between engine components, potentially causing damage or accelerated wear.

Additionally, bio-alcohols typically possess lower inherent lubricating properties compared to conventional fuels. This deficiency in lubrication capability can further compound the issue by increasing friction between moving parts, potentially contributing to heightened wear and tear on engine components.

These combined factors of lower calorific values impacting engine performance and the challenges related to poor miscibility and inadequate lubricating properties underscore the potential drawbacks and complexities associated with the use of bio-alcohols in engines, necessitating careful consideration and potentially additional engineering solutions for effective integration.

This is why the use of bio-alcohols in CI engines is often limited or restricted. Alcohol fumigation, dual injections, alcohol-diesel blends, and alcohol-diesel emulsions have all been used to overcome these drawbacks (Ozsezen et al., 2011).

An ideal alternative to petrol or diesel would boast a combination of reduced emissions, enhanced fuel efficiency, and a decreased reliance on finite fossil oil resources. Such characteristics are fundamental in addressing environmental concerns, optimizing energy usage, and securing a sustainable energy future (Verma & Sharma, 2016). The quality of how a fuel performs in an engine, known as drivability, is crucial. This assessment considers diverse physical and chemical properties that fuels display from production through storage and eventual use. These properties influence how well the fuel functions in engines and throughout its lifecycle. Liquid fuels are subjected to a variety of tests to ensure that their properties remain consistent throughout the product's lifecycle. Ideally, the fuel should have the same drivability quality as the current conventional fuels. The CI engines must also be able to use it.

There has been a great deal of effort put into finding new sources of energy. For example, it has been discovered that the high viscosity of straight vegetable oils used directly in engines causes serious engine problems (Agarwal, 2007; Dwivedi & Sharma, 2014). A suitable catalyst is also needed for biodiesel production from vegetable oil, which has fuel properties that are similar to those of diesel, and the transesterification method can reduce the viscosity of the biodiesel (Verma & Sharma, 2016). Biodiesel made from vegetable oil can power a CI engine, according to Srivastava & Prasad (2000). Biodiesel appears to be a viable alternative to petroleum-based fuels based on the literature. It is both renewable and environmentally friendly. Using biodiesel as an alternative energy source has boosted the popularity of vegetable oils as a renewable, accessible, and more environmentally friendly fuel source than fossil fuels (Koçak et al., 2007).

Why go for biodiesel instead of using direct vegetable oil? The answer to this question lies in the properties of vegetable oil like viscosity, free fatty acids, calorific value, and flashpoint. These properties directly influence the combustion, efficiency, and overall performance of Compression Ignition (CI) engines when using vegetable oils as fuel. Vegetable fuel oils also have a high viscosity that has to be decreased to be more suitable for use when running a CI engine. Some vegetable fuel oils also contain a higher acid value/Free Fatty Acid (FFA) content. As a result, they need to undergo the step acid-based transesterification process for biodiesel production. Vegetable oil fuels also have a lower calorific value than petroleum diesel. In addition, the flashpoint of oils is superior compared to diesel, making biodiesel safer for storage. Due to the ability of the biodiesel and alcohol to have some good properties like oxygen, flash point, carbon content, and low heating value, which can improve diesel performance, therefore blends of the biodiesel, and alcohol have been carried out and shown good results in running the CI engine. The research conducted by other scholars has also ventured into ternary blends of diesel, biodiesel, and alcohol, yielding positive outcomes. While prior studies have predominantly emphasized widely used alcohols like ethanol and methanol, there's recognition that alcohols such as pentanol, butanol, and propanol can serve as effective alternatives for formulating biofuel blends (Laza & Bereczky, 2011). Better miscibility with biodiesel and diesel over a wide temperature range to form ternary blends, leading to improved engine performance, has been demonstrated for these alcohols in comparison to methanol and ethanol in terms of kinematic viscosity (KV), heating value (HV), flash point (FP), cetane number (CN), ignition quality (IQ), and flame speed (Atmanli, 2016; Yusri et al., 2017). Moreover, these alcohols have been reported to have a lesser affinity to water (Bencheikh et al., 2019; Muthaiyan & Gomathinayagam, 2016). Most ternary blends of different biodiesel, diesel and ethanol have been tested with varying amounts. Further research is needed to determine the best blend characteristics and ensure the long-term viability of engines powered by the fuel, according to the literature (Kumar and Saravanan, 2016). Using optimization blends in a diesel engine without modifying the engine's injector pressure, nozzle diameter, or injector duration is the main technical benefit of optimizing diesel fuel for a percentage of bio-origin components.

1.2 Problem Statement

Researchers are currently exploring biofuels derived from a ternary blend of diesel, biodiesel, and alcohol as an alternative energy source. Despite various studies on different blend percentages, there is a notable gap in research focusing on the ternary optimization of this biofuel. Understanding the distinct characteristics of this blend, which differs from fossil diesel, is crucial for efficient use. Additionally, the statement suggests the potential role of fuel additives in altering fuel properties, enhancing performance, and reducing emissions. However, there is a lack of clarity on how these additives specifically interact with the proposed diesel-propanol-biodiesel blend made from used cooking oil. Addressing these gaps is essential for a comprehensive investigation into the performance and emissions of the ternary blend and optimizing it as an alternative fuel source.

1.3 Justification

The optimization of the blend of diesel, biodiesel, and alcohol is necessary because it allows for the best possible combination of fuel properties that results in high engine performance, economical fuel consumption, and reduced environmental impact. By finding the optimal blend ratio, the engine can run efficiently without the need for engine modifications. The use of biofuels, including biodiesel, helps to reduce dependence on petroleum and provides potential benefits such as being renewable and carbon neutral. Alcohol is also a suitable fuel for engines, offering low emissions. The blend of diesel can mitigate against the corrosive nature of alcohol. The use of biodiesel made from used cooking oil is cost-effective and reduces environmental degradation. The optimization of the blend allows for the best use of the advantages of each fuel and reduces the shortcomings of using a single fuel. This results in a more efficient engine with less brake-specific fuel consumption and a smaller impact on the environment.

Advanced research is required to determine the optimal ternary blend at which the fuel will facilitate the engine's high performance with economical fuel consumption and less environmental impact. An optimal blend ratio of the diesel, biodiesel and alcohol is needed to acquire the best ratio at which the ternary blend can run a CI engine efficiently and without engine modification.

According to Dale (2008), biofuels are significant liquid fuels since they can be used in place of either gasoline or diesel. They have the potential to be renewable and carbon neutral, and they can be produced in enormous quantities. The fact that biofuels are practically the only petroleum substitutes with potential for broad-based economic, national security, and environmental benefits makes them crucial as well (Dale, 2008).

Alcohol has also been used to run engines, its major advantage being that it can be burned in existing engines with little modification (April et al., 2012). It is also associated with little emissions, thus lesser air pollution (April et al., 2012). Propanol's characteristics indicate that it contains more oxygen than diesel. Alcohols are employed as fuel blending ingredients to enhance the quality of the unleaded diesel because propanol's 26.6 (% weight) oxygen will aid in combustion while conventional ultra-low sulfur petroleum diesel fuel has negligible oxygen content. Alcohol increases the amount of oxygen in diesel fuel mixture. Additionally, the fuel's oxygen content lowers CO and PM emissions while raising NOx emissions (Board & City, 1907; Suhaimi et al., 2018).

Blends of alcohol with diesel fuel may enhance the density, viscosity, and flashpoint of the fuel. The enhancement of these characteristics results in better fuel atomization. The disadvantages of alcohol-diesel blends are less severe than those of diesel fuel in terms of characteristics like cetane number and calorific values. Low cetane number and calorific value typically exhibit protracted ignition delay and combustion delay. High flame temperature and greater NOx emission result from this (Suhaimi et al., 2018). The blend of diesel can mitigate against the disadvantage of the corrosive nature of alcohol.

There is enough proof to demonstrate that biodiesel may be utilized in existing diesel engines as an alternative, green fuel without major hardware modifications (Manjula et al., 2016). Vegetable oils are comparable to mineral diesel fuel in terms of energy density, cetane rating, heat of vaporization, and stoichiometric air/fuel ratio. According to published research, using virgin vegetable oil as the raw material resulted in the production of biodiesel with the fewest and smallest equipment units, but at a higher raw material cost than the other processes. As a result, using used cooking oil to make biodiesel resulted in a lower raw material cost of production. Additionally, in this comparison, used vegetable oils typically exhibit a more economically advantageous aspect, being notably more cost-effective than diesel fuel. The cost of using virgin vegetable oil may be higher, it is therefore preferable to use used cooking oil as a biodiesel feedstock.

The management of these used cooking oil and animal fats presents a substantial challenge due to their disposal issues such as pouring these substances down drains or discarding them in landfills, poses severe risks. and potential for contaminating water and land resources. Used cooking oil and animal fats are available around the world. Despite the fact that some of this leftover cooking oil is utilized to make soap, the majority of it is released into the environment. Thus, it may be inferred that one of the most cost-effective options for manufacturing biodiesel is the use of used cooking oil, which is otherwise wasted and improperly disposed of. Utilizing used cooking oil increases the economic viability of biodiesel production and also lessens environmental degradation, as the cost of feedstock is one of the main considerations in the manufacturing of biodiesel. It has been established by a large number of authors (Bencheikh et al., 2019; Elkady, Ahmed Zaatout, 2015; Manjula et al., 2016; Yang et al., 2007) that engines that run on diesel produce significantly higher levels of nitrogen oxide emissions than engines that run on biodiesel.

Several authors reported that a combination of 20% biodiesel and 80% diesel is the ideal concentration for enhancing performance (Das et al., 2018; Mohammed et al., 2020). Utilizing biodiesel mixes in conjunction with catalytic converters allows for a significant reduction in all of the regulated emissions. In order to adjust the qualities of the final fuel and reduce the shortcomings of a single fuel by utilizing the other fuels' advantages, all diesel, biodiesel and alcohol fuels must be blended together. A combination with the best qualities can be achieved at its optimum point. The engine will run more efficiently, using less brake-specific fuel, and will have a smaller impact on the environment.

At 2000 RPM and constant engine load, it will be simple to find the ideal blend of the diesel and biodiesel and propanol using the RSM. The RSM makes it simple to compare several mixes and choose the one that works best for a particular application.

1.4 Scope

The scope of this study is to experimentally obtain the optimal ternary blend of diesel, biodiesel, and propanol that would effectively run a CI engine. The biodiesel used was produced from used cooking oil by the transesterification method. The blending process involved the utilization of mass ratios for the fuels. The fuel properties studied were density, kinematic viscosity, sulphur content, calorific value, water content, and flashpoint. They were checked as per the Kenya fuel standards Appendix 24; Appendix 25. A response surface method (RSM) was used to generate the number of experimental blends under the central composite design by the use of design expert software. The RSM was used to analyze the data obtained, and the optimal blend was obtained from the analysis. The performance and emission of the ternary blends were carried out on a compression ignition engine Petters type of 2 cylinders and a maximum output of 16.8kw with a maximum speed engine of 2000rev/min connected to a dynamometer. The engine load was varied when using different fuel blends as per the experimental design. The engine was tested in terms of the engine's power output, brake specific fuel consumption, brake thermal efficiency, and concentration of CO, CO_2, SO_2, and NO_x on the exhaust.

1.5 Objectives

1.5.1 Research objective

To determine the optimum ternary blend ratio of diesel, biodiesel and propanol that will improve engine performance and lower emissions.

1.5.2 Specific objective

1. To characterise physical properties of a ternary blend of diesel, biodiesel and propanol produced at varying ratios.
2. To optimize the performance of an internal combustion engine running on different ternary fuel blends and concentrations.
3. To analyze the exhaust gas emissions composition of the optimal ternary fuel blend.

1.6 Significance of the Study

This study is significant for its exploration of an optimal ternary blend comprising diesel, biodiesel, and propanol, aiming to serve as an alternative fuel for compression ignition (CI) engines. The primary objective is to find a fuel that seamlessly powers CI engines without necessitating modifications to existing engine infrastructure. The potential adoption of this alternative fuel offers the prospect of reducing reliance on depleting fossil fuels, addressing concerns about fluctuating fuel prices, and mitigating the significant contribution of fossil fuels to global warming.

Going beyond its technical goals, the study has broader implications for real-world beneficiaries. The identified optimal ternary blend has the potential to bring about substantial benefits for waste cooking oil generators, the transport sector, and the environment. For waste cooking oil generators, the findings offer a sustainable solution for waste cooking oil disposal, a pressing environmental issue. Incorporating waste cooking oil into the ternary blend could reduce disposal challenges and contribute to a circular economy. Given that waste cooking oil constitutes a significant source for potential biodiesel production globally (with 36.8 million metric tons produced in 2020), repurposing this waste into a viable fuel source could notably mitigate against environmental impact.

The transport sector stands to gain from the development of an alternative fuel that enhances engine efficiency without requiring costly modifications. The positive outcomes of the project could result in reduced operational costs and increased fuel efficiency for vehicles utilizing the optimal ternary blend. Considering that the transport sector accounts for a substantial percentage of global energy consumption, any improvement in fuel efficiency holds the potential for significant environmental and economic benefits.

Moreover, the adoption of the optimal ternary blend carries the potential to reduce the environmental footprint associated with traditional fossil fuels. This shift could lead to decreased greenhouse gas emissions and a reduced dependence on rapidly depleting fossil fuel reserves. The transport sector, a significant contributor to air pollution and greenhouse gas emissions, could benefit from the positive outcomes of this study, contributing to broader environmental sustainability targets.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This literature review chapter examines a range of studies and articles pertaining to fuel blends, engine performance, gas emissions, and technical methods. The goal is to provide a comprehensive understanding of the current state of research in this field, including key discoveries and missing information in the literature. The review will investigate whether utilizing an optimal ternary fuel blend can lead to high engine performance, cost-efficient fuel consumption, and minimal environmental impact, and also if there is a specific ratio of diesel, biodiesel, and Propanol that leads to the best outcome when running a CI engine efficiently and without the need for engine modification.

2.1 Overview

When evaluating a new automobile fuel, the most important consideration is its ability to reduce pollutants, boost fuel efficiency, and reduce dependence on fossil fuels. The drivability of a new automobile fuel must match that of current conventional fuels. The most critical requirement is that the fuel can be used in standard engines.

Research into the use of biodiesel and alcohol in compression ignition engines is proving beneficial, according to the current studies and existing research. This is due to the high biofuel percentage of the blend, which gives it similar qualities as commercial diesel (Khond & Kriplani, 2016).

Research into qualities that can be altered fundamentally is needed, according to previous studies (Khond & Kriplani, 2016). Soot composition and cetane number are examples of qualities that can be lowered. Other properties include density, viscosity, lubricity and energy content as well as flashpoint and the calorific value of the fuel blend (Meher et al., 2006).

2.2 Vegetable Oil as Fuel

Using vegetable oils as substitutes for conventional fossil fuels is viable. Beyond refined oils, used cooking oil offers an alternative source, easily collected from diverse sources like residences and restaurants, rendering it a more cost-effective option. Biodiesel production costs can be reduced by using the WCO because the raw material is inexpensive. Biodiesel can be made at a lower cost and with less impact on the environment when used cooking oil is recycled. However, due to the expensive cost of disposal, many people simply dump their used cooking oils into the environment without any treatment (Foo et al., 2021). This is bad for the environment since it leads to pollution. It is therefore possible to minimize the cost of biodiesel production while keeping our environment clean by using used cooking oils (Arifin, 2009).

When used directly in diesel engines, vegetable oil causes numerous issues (especially in the direct-injection engines). Sticking, formation of solid residue when it undergoes severe oxidative and thermal breakdown and trumpet formation on injectors are only a few of the problems that might arise from the thickening or gelling of the fuel, as well as from the high viscosity (approximately 11–17 times higher than diesel fuel) and low volatilities of the fuel. These challenges arise due to the substantial molecular size of triglycerides, with a mean molar mass of 873.22 g·mol−1, and the elevated molecular weight of fatty acids, averaging at 277.41 g·mol−1 (Barbosa et al., 2022; Meher et al., 2006)

It is also difficult to use vegetable oil directly in engines since plant oils typically contain free fatty acids, phospholipids, sterols, water, smell, and other contaminants.

Kinematic viscosity, density, and other key qualities of WCO are significantly higher than those of mineral diesel, making them more critical for a fuel's ability to burn efficiently. Chemical processes such as emulsification, pyrolysis or transesterification must be performed on the oils before they may be used (Srivastava & Prasad, 2000). Transesterification is one of the greatest methods since it is relatively simple, can be done under normal conditions, and provides the best efficiency and quality of the converted fuel (Shahid et al., 2012).

2.3 Biodiesel

There is a need for biofuels since they could replace diesel and gasoline in the future. Also, biofuels may be generated in vast quantities, some of which are renewable and carbon neutral, and they are readily available. Their unique properties make them an excellent replacement for petroleum in terms of both economic and national security as well as environmental aspects (Dale, 2008).

Traditional Petro-diesel can be replaced with a non-toxic, sustainable kind of biodiesel that can be degraded naturally. This biodiesel is more oxygen-rich than petroleum diesel since it is made from short-chain alcoholic beverages such as methanol or ethanol and fatty acids from virgin or used vegetable or animal oils (both edible and non-edible) (Agarwal, 2007; Das et al., 2018). Its use in diesel engines has shown great reductions in the emission of particulate matter, carbon monoxide, sulphur, hydrocarbons, smoke and noise. The combustion of fuel derived from vegetable oil does not contribute to the overall levels of CO_2 in the atmosphere (Srivastava & Prasad, 2000) because the fuel itself is made from agricultural resources that are formed through the process of photosynthetic carbon fixation (Sukjit & Punsuvon, 2013). The viscosity of biodiesel affects controls of diesel injector injection. It is necessary to manage the viscosity of fatty acid methyl esters to avoid interfering with the functioning of the fuel injection system. Therefore, the desired viscosity resembles diesel fuel. Biodiesel has a higher flash point than petroleum diesel, making it transport-safe. Cetane measures the ease of ignition and combustion. Increasing the cetane number enhances ignition. Combustion, stability, drivability, white smoke, noise, and emissions of both carbon monoxide and hydrocarbons are all affected by the cetane level. The greater cetane number of biodiesels enhances combustion efficiency (Meher et al., 2006). Meher et al., 2006also shows that the density of biodiesel should be between 860 and 894 kg /m³ at 15^{o}C, and viscosity at 40^{o}C is between 3.3 and 5.2 mm²/s.

2.3.1 Production of biodiesel

To make biodiesel, fats and oils are chemically combined with alcohol, like methanol, and a catalyst, such as sodium or potassium hydroxide. An alkali catalyst with an optimal concentration of 1 percent by weight has been shown to work best when the reaction temperature is 50–60 °C and the molar ratio of alcohol to oil is 6–12:1 (Verma & Sharma, 2016). Transesterification is best performed at a reaction time of 120 minutes or longer (Verma & Sharma, 2016).

2.3.2 Process of Synthesizing Biodiesel

The production of biodiesel can be accomplished through the use of a variety of procedures, micro-emulsion process, thermal cracking process, and transesterification process, among others.

2.3.2.1 Transesterification

To produce biodiesel, triglycerides are subjected to a reaction with an appropriate alcohol (such as methyl, ethyl, or any of a number of other options) in the presence of a catalyst at a temperature that is kept constant for a predetermined amount of time. Fatty acid alkyl esters and glycerol are the end products of a catalysed chemical process involving vegetable oil and alcohol. There are situations in which a strong base can help speed up the reaction and increase the yield, like when a catalytic reaction is required. Since this reaction can be reversed, an excessive amount of alcohol is used to shift the balance in favour of the product. Methanol is commonly used as an alcohol because of its low price and several physical and chemical benefits. When mixed with vegetable oil, it reacts in presence of a catalyst to form biodiesel as shown in Equation 1 (Meher et al., 2006). The stoichiometric ratio of alcohol to triglycerides must be 3:1 for a complete transesterification reaction. In order to achieve the greatest ester yield, the equilibrium ratio must be increased to produce biodiesel (Gashaw & Teshita, 2014).

Glycerine and alkyl esters are the ultimate products. Glycerine is a by-product, but the main product is alkyl esters, which are good fuels for CI engines. The reaction of the triglyceride with methyl alcohol is depicted in Equation 2 (Meher et al., 2006). In the first step, the carbonyl carbon of the triglyceride is attacked by the alkoxide ion.

The general reaction with the presence of the catalyst is as in Equation 1.

$$\begin{array}{ccccccc} & \textit{Catalyst} & & & & & \\ RCOOR^1 & + & R^2 & \rightleftharpoons & RCOOR^2 & + & R^1OH \\ \textbf{\textit{Ester}} & & \textbf{\textit{Alcohol}} & & \textbf{\textit{Ester}} & & \textbf{\textit{Alcohol}} \end{array} \qquad \textbf{Equation 1}$$

The general chemical reaction of the tri-glyceride with methyl alcohol in the presence of the catalyst is shown in Equation 2.

$$\begin{array}{cccccc} \boldsymbol{CH_2-OCOR^1} & & \boldsymbol{catalyst} & \boldsymbol{CH_2OH} & & \boldsymbol{R^1COOCH^3} \\ \boldsymbol{CH-OCOR^2} & \boldsymbol{+\ 3CH_3OH} & \rightleftharpoons & \boldsymbol{CHOH} & + & \boldsymbol{R^2COOCH^3} \\ \boldsymbol{CH_2-OCOR^3} & & & \boldsymbol{CH_2OH} & & \boldsymbol{R^3COOCH^3} \\ \textit{Triglyceride} & \textit{Methanol} & & \textit{Glycerol} & & \textit{Methyl} \end{array} \qquad \textbf{Equation } 2$$

Where R^1, R^2 and R^3, represent various alkyl groups. From (Verma & Sharma, 2016).

2.3.2.2 Mixing of alcohol and catalyst

The process is done by mixing alkali hydroxide with alcohol. The alkali can be potassium hydroxide or sodium hydroxide, and the alcohols methanol or ethanol. The mixing is done by a stirrer to ensure complete mixing where the alkali dissolves in the alcohol (Meher et al., 2006).

2.3.2.3 Chemical reaction

In a sealed container, the alcohol and catalyst mixture are added to the oil. Due to the ease with which alcohol can be vaporized, the reaction system is sealed off from the atmosphere. To expedite the reaction, a temperature below the alcohol's boiling point is maintained. In order to assure the complete conversion of the oil to its esters, excess alcohol can be used, and the alcohol can be recycled for future use (Gashaw & Teshita, 2014; Sahar et al., 2018).

2.3.2.4 Separation

During the process of the reaction, glycerol, biodiesel, and alcohol all mixed. Setting up an open system with a condensation system is used to recover the alcohol. The alcohol evaporates out from mixer and then is reclaimed in a separate container. Biodiesel floats because the glycerol phase is denser than the biodiesel phase. As a result, sedimentation can be used to extract glycerol from biodiesel. It's a simple process: Glycerol and biodiesel are separated from each other in the settling tank. Centrifuges can separate two materials more quickly by screening both phases in the separation process (Gashaw & Teshita, 2014; Sahar et al., 2018).

2.3.2.5 Biodiesel washing

It is not safe to use biodiesel in engines because it contains unreacted methanol and catalyst, which may cause component corrosion, and glycerol, which can diminish lubricity and create coking with other deposits in the engine. They can all be easily removed from biodiesel by repeatedly washing the biodiesel in water heated to 40 to 50 degrees. The biodiesel is washed by sprinkling hot water over it, and care is made to prevent the production of soap. To prevent soap production during the washing of biodiesel, it is important to ensure that the reaction mixture is neutralized properly and that the pH is not too high. It is also important to use a sufficient amount of washing solution, to ensure that all soap is removed. Additionally, washing the biodiesel in several stages can also help to reduce soap production and increase the purity of the final product. To remove any remaining water impurities, the washed biodiesel must be dried. To eliminate any remaining water, the biodiesel is heated to over 110^{o}C (Gashaw & Teshita, 2014; Sahar et al., 2018).

2.3.3 Factors affecting biodiesel production

Parameters such as moisture, free fatty acids, reaction duration, reaction temperature, catalyst, and the molar ratio of alcohol to oil all have an impact on the biodiesel process as it goes through the transesterification step (Verma & Sharma, 2016).

2.3.4 Biodiesel properties

The parameters defining biodiesel quality can be split into two groups: general parameters and those specific to the chemical composition of fatty acid alkyl esters. Table 2.1 outlines these general parameters.

Among these parameters, viscosity significantly affects diesel injector performance. Control is crucial as fatty acid methyl esters can exhibit high viscosity, impacting injector systems. Hence, specifications closely resemble those of diesel fuel to maintain optimal performance.

Biodiesel's higher flash point, compared to petrodiesel, ensures safer transportation.

Cold filter plugging point (CFPP) indicates cold weather performance. CFPP better reflects filterability than cloud point for biodiesel and petrodiesel. Specifications often include either pour point or CFPP, with some biodiesel standards specifying pour point, while others specify CFPP.

Table 2.1: General Parameters of the Quality of Biodiesel (Meher et al., 2006)**.**

Parameters	Austria	Czech Republic	France	Germany	Italy	USA
Density at 15 ^{0}C g/cm^3	0.85- 0.89	0.87-0.89	0.87-0.89	0.875-0.89	0.86-0.90	-
Viscosity at 40 mm^2/s	3.5-5.0	3.5-5.0	3.5-5.0	3.5-5.0	3.5-5.0	1.9-6.0
Flashpoint (^{0}C)	100	110	100	110	100	130
CFPP (^{0}C)	0/-5	-5	-	0-10/-20	-	-
Pour point	-	-	-10	-	0/-5	-
Cetane number	≥49	≥48	≥49	≥49	-	≥47
Neutralization number (mgKOH/g)	≤0.8	≤0.5	≤0.5	≤0.5	≤0.5	≤0.8
Conradson carbon residue %	0.05	0.05	-	0.05	-	0.05

In addition, the high cetane number of biodiesels serves to idealize it as a fuel of choice. It enhances easy ignition of the fuel and results in a shorter delay time and complete combustion of the fuel. Besides its desirable lubricating properties, it is also a clean-burning fuel that is effectively used without having to make any adjustments in the engine or fuel injection systems. According to Agarwal (2007), who compared diesel to biodiesels noting that it has a higher viscosity which, upon increasing temperature, decreases exponentially. It is important to consider biodiesel's physical and chemical properties as these directly influence the performance and emission characteristics of the fuel. Also affected are the handling and storage of the same. The raw vegetable oil used, and the conversion process largely affects the properties of the resultant biodiesel.

The spray parameters of a biodiesel and diesel blend with 20 percent biodiesel and 80 percent diesel (B20) are generally similar to those of diesel (Das et al., 2018). Running the engine is heavily dependent on fuel atomization, which has a significant impact on how well the fuel-air mixture is mixed and thus the amount of smoke produced. Increasing the viscosity of the fuel also increases the amount of energy required by the fuel pump and affects the engine's overall output. According to Agarwal (2007) who demonstrated that transesterification reduces biodiesel's viscosity significantly from that of raw vegetable oil, this still remains higher than the viscosity of diesel. Engine manufacturers expressed concern about the increased viscosity of biodiesel on the performance of their engines, according to Gerpen et al (Tat & van Gerpen, 1999). In order to overcome the drawback, conventional diesel fuel and biodiesel are blended together before being used in compression ignition engines (Das et al., 2018).

2.3.5 Environment gains of biodiesel

In terms of environmental impact, biodiesel outperforms diesel significantly. Biodiesel exhibits lower emissions of particulate matter, sulfur dioxide, and nitrogen oxides, all of which are harmful to air quality and human health. (Atabani et al., 2018, 2019). It equally has significant economic gains (Atabani et al., 2019). The raw material used to produce biodiesel is from waste vegetable oil which instead could have been dumped into rivers or stuffed into landfills which then eventually pose serious environmental pollution concerns. Examples of such wastes include spent coffee grounds from industries, used cooking oil, slaughterhouse wastages, animal fats, and used cooking oils. For gas emissions, when using biodiesel, literature has shown that there is a reduction in NOx and smoke emissions (Yoshimoto et al., 2018).

Nitrogen oxide emissions from biodiesel-diesel blends are also a source of concern, resulting in the search for fuels with lower levels of nitric oxide emissions. Biodiesel, which is a monoalkyl ester of long-chain fatty acids generated from renewable feedstocks, could replace traditional diesel fuel in some situations. Fat-acid-methyl esters, which can be made from vegetable oils via transesterification with methanol as well, make up the rest of the product. The chemical composition and purity of fatty acid alkyl esters are two of the criteria that determine the quality of biodiesel (Meher et al., 2006).

2.4 Use of Alcohol

The interest in alcohol fuels stems from their notable advantages compared to other discussed fuels. Their lower kinematic viscosity and improved cold flow properties, along with lower density in contrast to biodiesel, are particularly advantageous. These characteristics positively impact fuel performance. Lower viscosity aids smooth fuel flow in engines, optimizing combustion and efficiency. Enhanced cold flow properties prevent fuel thickening in colder temperatures, ensuring smoother engine startup and operation. Despite having a lower density than biodiesel, this fuel type potentially offers higher energy yield per unit volume, impacting fuel volume and energy content. (S. Kumar et al., 2013; Zaharin et al., 2017). Additionally, greenhouse gas emissions are reduced in alcohol fuels making this an ideal fuel environment-friendly alternative. If the alcohol is a straight-chain alcohol such as methanol or ethanol, engine modifications may be necessary to ensure proper combustion. Methanol and ethanol have a lower energy content and require higher compression ratios to ignite, so engine modifications such as higher compression pistons, stronger valve springs, and higher fuel injector flow rates may be necessary. Alcohol fuels, such as methanol, ethanol, propanol, and butanol, possess desirable properties that make them attractive as alternative fuels. These include lower emissions compared to gasoline and diesel fuels, as well as the ability to be produced from renewable resources like corn and sugarcane, making them more sustainable than fossil fuels. Additionally, these alcohol fuels have a higher-octane number, allowing for improved engine performance due to a higher compression ratio. These fuels are compatible with both SI and IC engines, although some engine modifications may be necessary. Alcohol fuels also have a higher heating value compared to diesel, leading to improved engine performance and efficiency. However, alcohol fuels have a lower energy content than diesel, meaning more fuel is needed to produce the same amount of energy. Butanol has a higher boiling point compared to other alcohol fuels, making it more resistant to evaporation. Propanol and butanol are acceptable for use in compression ignition engines, where its higher heating value improves engine performance (S. Kumar et al., 2013). Compared to butanol, methanol and ethanol have a higher heat of vaporization, which results in a longer ignition delay during burning (Shahir et al., 2014). Unlike methanol and ethanol, propanol and butanol have a higher flash point, making them significantly safer to carry in a storage or tank (Giakoumis et al., 2013). Butanol's autoignition temperature is the lowest of any alcohol, making it the most prone to spontaneous combustion in the air. Using methanol, ethanol, propanol, or butanol in a vehicle's fuel system can reduce dangerous exhaust emissions; however, this comes at the cost of diminished engine performance (Yusri et al., 2017).

Compared to diesel, simple alcohols (ethanol and methanol) have a number of advantages when it comes to fuel blends in the automotive industry. This is due to the fact that mix components derived from renewable energy sources will be used in diesel engines. Many of these blends are made from sugar cane, molasses, sugar beet, corn and barley as well as other biomass materials. They're made with technologies that have already been enhanced and proven. However, the use of simple alcohol in diesel engines presents a number of challenges. In diesel fuel, these include a lack of solubility, phase separation, and water tolerance (Çetin et al., 2009; Tutak et al., 2015; Yusri et al., 2017).

Based on numerous studies on the alcohol-diesel blends in CI engines, the most optimum way to use alcohol fuel is as part of a blend. These studies have also been used to explore the performance of the aforementioned engines and the emissions produced (Kumar et al., 2013).

Higher alcohols, on the other hand, have significant advantages. They can be used with vegetable oils without the use of a surfactant or emulsifier. They can also be created through the indirect hydration of glucose or the distillation of carbon-hydrogen. Because they have lower viscosities, they can be utilized to lessen the viscosity of blends. Furthermore, because their oxygen concentrations are higher, they have the potential to reduce particle emissions. As a result, mixing vegetable oil with various higher alcohols is expected to improve the qualities of the fuel mixes, such as combustion characteristics (Laza & Bereczky, 2011). Diesel fuel blends using high alcohol as a cosolvent to recover the potential of lower alcohol are a possible alternative fuel for the future (Atmanli et al., 2015). Propanol's impact on CI engines' performance and emissions has yet to be studied in depth. Predominant attention is paid on developing ternary alternative fuels using propanol as a solvent for diesel (Haigh et al., 2014).

Table 2.2 shows the results of comparing the majority of the attributes of gasoline and alcohol.

Table 2.2: Properties Comparison of the Gasoline and Alcohol

Property	Gasoline	Alcohol
Sources	Natural	Both natural and man-made
Octane Number	Comparatively low	High
Overall emissions	High	Low
Volumetric efficiency	Low	High
Sulphur Content	High	Low
Calorific value	High	Low
Corrosive in nature	Low	High
Cold weather starting	Good	Poor
Ignition Characteristics	Good	Poor

2.5 Propanol

Propanol is a primary alcohol with 3 carbons and a molecular formula of 32.04. It is a straight-chain alcohol, C_3H_8O. There are two isomers: 1-propanol, and 2-propanol. It is a colourless liquid that is flammable and volatile at room temperature. To cut costs, propanol is produced from petrochemicals using the oxo-synthesis process. Other less economical methods of production include fermentation of cellulose-derived sugars from biomass or municipal wastes.

Propanol's high production costs are a key deterrent to its widespread use as a fuel in internal combustion engines. It has more desirable properties than ethanol and methanol, making it a better choice for industrial applications. Higher CN, higher density, and higher KV are just a few of the many benefits to consider. In addition, it has a lower auto-ignition temperature and a higher flash point. In addition to these factors, the reduced latent heat of evaporation of propanol has prompted more research into its application in CI engines (Banugopan et al., 2010).

Among the many components of crude oil, you'll also find propanol. Fusel alcohol includes about 5% ethyl alcohol, 12.5% n-propanol, 15% isobutyl alcohol, 62.5 % amyl and iso-amyl alcohol, and 5% residual as its main components. Propionaldehyde and propane are the raw materials used to make commercial quantities of propanol.

Combustion efficiency is greatly improved due to propane's high oxygen content of 26.6%. Because of its higher vaporization heat, propane may produce less NOx than diesel. A potential advantage of propanol over ethanol and methanol is its lower self-ignition temperature, which equates more closely to that of diesel fuel. In comparison to ethanol and methanol, its flash point is much greater. In terms of energy density, propane is superior to ethanol and methanol. An increase in the combustible mixture's oxygen level reduces the time it takes for the mixture to ignite (Muthaiyan & Gomathinayagam, 2016). Propanol promotes adequate lubrication as it increases the mixture's viscosity and stabilizes it by ensuring fuel homogeneity in the event of increased water content due to its miscibility characteristics.

The properties of high alcohols were compared to those of diesel, and the results are as in Table 2.3. Propanol notably exhibits distinct advantages: it showcases a higher oxygen content of 26.62%wt compared to diesel. This heightened oxygen content is crucial for efficient fuel combustion, aiding in more complete and cleaner burning processes.

Moreover, propanol displays lower viscosity, a key factor contributing to smoother fuel flow within engine systems. This lower viscosity is beneficial for optimizing combustion and enhancing overall engine efficiency.

Additionally, propanol showcases lower density of 1.74 mm/s^2, offering potential advantages in terms of fuel volume and energy content. Its lower flash point ensures safer handling. Furthermore, propanol's lower carbon weight of 59.96%wt indicates a potentially lower environmental impact compared to diesel. These combined characteristics position propanol as a promising alternative fuel option with favorable combustion properties and reduced environmental implications compared to diesel.

Table 2.3: Comparison of diesel and alcohols Properties

Properties	Diesel	Propanol	Butanol	Pentanol
Molecular weight (Kg/kmol)	190–211.7	60.09	74.12	88.15
C (%wt.)	86.13	59.96	64.82	68.13
H (%wt.)	13.87	13.31	13.49	13.61
O (%wt.)	0	26.62	21.59	18.15
Solubility (g/L)	Immiscible	Miscible	77	22
Lubricity (μm corrected wear scar)	315	922	591	670.5
Cetane number	52	12	17	18.2-20
Self-ignition temperature (°C)	254-300	350	345	300
Density (kg/m3) at 15°C	835	803.7	809.7	814.8
Viscosity at 40 °C (mm/s2)	2.72	1.74	2.22	2.89
Lower heating value (MJ/Kg)	42.49	30.63	33.09	34.65
Latent heat of evaporation (kJ/kg)	270-375	727.88	581.4	308.05
Vapor pressure (mmHg)	0.4	20	7	6
Boiling point (°C)	180-360	97.1	117.5	137.9
Flashpoint (°C)	>55	11.7	35-37	49

Sources: (Al-Samaraae et al., 2017; Bencheikh et al., 2019; Muthaiyan & Gomathinayagam, 2016; Örs et al., 2020; Tutak et al., 2017).

2.6 Blending of Biofuel

The properties of biodiesel fuel are close to those of gas oil, and it is expected that biodiesel fuels would not pose problems in practical applications due to the higher viscosity of the original oil. In other countries, practical use of biodiesel fuel in automobiles and CI engines has been conducted with blended fuels of gas oil and small amounts of biodiesel fuels (Yoshimoto et al., 2018).

Biodiesel is miscible with alcohols and diesel fuel, according to the scientific literature. In order to find the performance of various blends, such as a diesel with biodiesel, alcohol with diesel and diesel and biodiesel and alcohol, experiments have been carried out. Such as biodiesel-methanol (Cheung et al., 2009; Venkata Subbaiah & Raja Gopal, 2011; Yilmaz, 2012; Zhu et al., 2010) biodiesel–ethanol (Banapurmath & Tewari, 2010; Venkata Subbaiah & Raja Gopal, 2011; Zhu et al., 2011) and comparisons of biodiesel–methanol and biodiesel–ethanol fuels have been studied as an alternative method of utilizing alcohols and biodiesel fuels to enhance engine emissions and performance.

According to Barabás et al. (2011), the diesel–biodiesel– ethanol blend is a great option as an alternative to diesel fuel for CI engines. This is based on research that shows that blending biodiesel and ethanol/bioethanol with diesel fuel generates fuel qualities that are nearly identical to those of diesel fuel alone. Some of the important fuel attributes that are modified when alcohol is added to diesel fuel include stability, density, viscosity, lubricity, energy content, the cetane number of the blend, compatibility, and corrosiveness of the materials employed. Surface tension, cold filter plugging point, flashpoint, carbon content, hydrogen content, heating value, and fuel biodegradability are additional critical considerations (Shahir et al., 2014). The solubility of vegetable oil in diesel fuel is dependent on the chemical structure of diesel fuel and the temperature within. Because of the combination of straight and branched hydrocarbons in vegetable oil and diesel, waxes can develop at milder temperatures. The micro-emulsion method is used to avoid this. Fuel characteristics are improved when large amounts of alcohol are added to the mixture, preventing phase separation of vegetable oil and diesel fuel (Atmanli et al., 2015). Past studies show that 20% biodiesel is the optimum concentration for biodiesel–diesel fuel blends to improve performance (Atmanli et al., 2015).

According to Yilmaz et al., (2018) on quaternary blends of diesel, biodiesel, higher alcohols, and vegetable oil in a compression ignition engine showed that the addition of propanol and pentanol to ternary blends decreased the density and kinematic viscosity of vegetable oil. As a result, diesel engines with biodiesel, diesel, and vegetable oil ran smoothly and safely (Yilmaz et al., 2018a). Therefore, from the literature, it can be concluded that blending of the fuels improves some properties of the other fuel, and each blend has its effect, which can lead to better results for the end product.

From (Yilmaz et al., 2018) result, biodiesel, diesel, vegetable oil, and a higher alcohol concentration (pentanol) — ranging from 10% to 40% — were tested in engines with quaternary fuel operation (concentration by volume). Quaternary blends were compared to the operation of B50 D50 and raw diesel. The engine ran smoothly without any subtle engine modifications after the above fuel modification. As a result, they were able to compare the findings to those of other studies using B50 D50 and D100 blends. The typical problems associated with raw biodiesel's physical and chemical qualities can be mitigated by using pentanol as a blending source for ternary blends of diesel, biodiesel, and vegetable oil (Appavu et al., 2019).

When compared to commercial grades of diesel fuel, biodiesel, which can be made from any type of vegetable oil or animal fat, typically possesses better densities, viscosities, cloud points, and cetane numbers while exhibiting lower levels of volatility and heating value.

Based on the methyl esters profile, blending rules to estimate biodiesel's density, heating value, viscosity, cetane number, and cloud point. It was observed that the typical average mistake was less than 2%, except for viscosity, where the average error was 10%. Other studies have estimated the parameters of biodiesel-diesel blends using blending methods similar to these for computing methyl ester blends (Benjumea & Agudelo, 2008)

In the analysis of ternary blends, literature is limited to biodiesel–diesel–bioethanol (Boulal et al., 2019), biodiesel–diesel–butanol (Al-Samaraae et al., 2017; Atabani et al., 2018) and biodiesel–diesel–diethyl ether fuels (Mohammed et al., 2020) . There is an undeniable need for further research on such ternary blends with different alcohols, as they each exhibit different characteristics due to the variations in their molecular structures. Generally speaking, higher alcohols such as propanol are considered ideal as compared to lower alcohols like methanol and ethanol. They have improved characteristics such as a lower KV, higher cetane number, flash point, and heating value. In addition, they are more miscible with diesel and biodiesel and less miscible with water (Muthaiyan & Gomathinayagam, 2016). They also have a lowered heat of vaporization and decreased corrosion paired with the high flame velocity. Unfortunately, there is very limited information regarding the use of propanol in the CI engine as part of a ternary blend (Yusri et al., 2017). A few studies have explored its use as a solvent, however, and reports regarding biodiesel– diesel–propanol blend.

Performance trials conducted by other researchers also demonstrated that the mixed fuels with 1-propanol or 1-butanol in rapeseed oil achieve steady combustion similar to gas oil operation with up to 40% alcohol addiction. Smoke emissions from fuels including alcohol blends were lower than those from gas oil, although the BSFC was higher when using alcohols (Yoshimoto et al., 2018).

When propanol is blended with biodiesel, it improves cold flow characteristics and lowers density, according to a study on ternary used cooking oil biodiesel, diesel, and propanol blends. Propanol was also found to increase brake specific energy consumption and brake specific fuel consumption while decreasing carbon monoxide exhaust gas temperature, nitrogen oxides, and smoke emissions. As a result of his research, ternary mixes were shown to have improved cold flow properties as well as densities (Bencheikh et al., 2019).

2.7 Fuel Blending Techniques

2.7.1 Splash blending

It's called "splash blending" because the fluid is poured into a container first, and then another fluid is added. Any fluid can be added, regardless of the order. In either case, unless a static mixer is utilized after the ingredients are loaded, splash-blended materials may stratify and fail to mix fully. It's a huge problem if the mixture doesn't get adequately mixed. Sequential or ratio blending may be better, but in-line or sequential blending is the preferred way of mixing (Enweremadu et al., 2011; R. M. Joshi & Pegg, 2007).

2.7.2 Sequential blending

Is a process in which a single meter and control valve are used to load numerous substances one at a time. For products with equal viscosity and density, this is a standard strategy. Sequential blending of biodiesel has the drawback of causing stratification in the fuel when different components have various properties because of insufficient mixing.

2.7.3 Ratio blending

It is possible to achieve ratio mixing with the simultaneous addition of several different ingredients to a single container. Ratio blending utilizes a common header with a meter and control valve for each product, resulting in a better blend and more complete integration.

2.7.4 Hybrid blending

The process of hybrid blending is essentially a combination of sequential blending and ratio blending, and it is intended for the purpose of ratio blending B100 into diesel oil sequential blenders that are already in use.

2.7.5 Sidestream blending

Sidestream blending is the process of combining a stream of fluid or gas (the sidestream) with a mainstream to achieve a particular combination or component ratio. In industrial contexts, this procedure is widely used to mix different types of fuels or chemicals, such as in the production of gasoline, diesel fuel, or other petrochemical products. Depending on the application and the desired outcome, the sidestream may be blended into the mainstream at various times during the process. Sidestream blending can be accomplished manually or automatically and may need the use of specialized equipment such as mixing tanks, pumps, or valves.

2.8 Physical Properties of Fuels

2.8.1 Density

The working principle of diesel engine design relies on density as a crucial fuel attribute in order to achieve volumetric fuel economy and maximum output. Changing the density of diesel fuel influences how much fuel is burned in a combustion chamber and what is discharged into the atmosphere as by-products. A range of 820 to 845 kg/m^3 has been established in national diesel fuel regulations to ensure the quality of the fuel.

2.8.2 Viscosity

Viscosity is critical since it impacts fuel flow and engine performance. The density and pour point are likewise strongly linked. The international standard for diesel fuel is 2.00 to 5.3 mm^2/s ISO 3104, ASTM D445, ASTM D7042 and IP 71, which is the range of the fuel's specification. Fuel flow via pipelines, injector nozzles, and orifices is dependent on the viscosity of the fuel. In order to avoid excessive pumping pressures, the fuel must have a specified range of viscosity.

2.8.3 Flashpoint

The fuel's flashpoint gives an indication of how ease fuel burn. For diesel fuels, however, it has no bearing on engine performance or ignition quality, it serves as a fire risk index for the safe handling, transportation, and storage of fuels. Diesel fuel must have a flashpoint temperature greater than 55°C to meet national standards, making it safer for transportation.

2.8.4 Sulfur content

The amount of sulfur in a gasoline is determined by several factors, including the type of crude oil used in its production, the refining process, and any additions. The national diesel standard (0.001%) specifies this value. It is regulated to avoid corrosion which leads to wear and strain. The presence of sulfur in diesel and other fuels can contribute to the formation of deposits in the engine, which can reduce its efficiency and cause excessive wear on moving parts. Sulfur can also corrode metal components in the fuel system, leading to leaks and other issues.

In addition, sulfur can cause problems with emissions control systems, as it can interfere with the operation of catalytic converters and other components that are designed to reduce the release of harmful pollutants into the environment.

2.8.5 Corrosiveness

The corrosiveness test evaluates the corrosive nature of petroleum products by employing copper strips and assigning them a rating of 1 based on the observed level of corrosion. This test serves to determine whether these products possess an acceptable degree of corrosiveness, gauging their potential impact on materials they come in contact with.

2.8.6 Colour

It is common practice to consider a fuel's colour as an indicator of its quality, and any shift in colour may indicate either deterioration of the fuel or contamination with other substances.

2.8.7 Water content

Improper storage and treatment of diesel fuel can result in a small amount of water in the fuel, either as free water or dissolved water. The total water content of diesel is limited to less than 200 ppm in the national diesel standard because removing water or moisture from the fuel might be difficult. Equipment corrosion and engine combustion issues can result from the presence of water in the fuel

2.8.8 Pourpoint

The Pourpoint is the lowest temperature at which a petroleum product can flow and is also used to measure diesel fuel's cold-weather performance. Diesel fuels are supplemented with chemicals to prevent gelling in moderate or severe weather conditions.

2.8.9 Cetane number

Cetane number determines the combustibility of the fuel. In general, greater molecular weight fuels have higher cetane numbers, which can have an effect on both gaseous and particle emissions by reducing the ignition delay. The cetane index, which is extremely close to the cetane number, is determined based on distillation temperatures of 10, 50, and 90 percent and the specific gravity of the crude oil. Flammable fuels have a higher auto-ignition temperature.

2.8.10 Distillation range

Distillation is a technique for separating chemical compounds based on their vapor pressures. Starting and warming up an engine rely on the distillation range because it impacts fuel performance and safety. Solid combustion deposits are affected by the presence of high-boiling components. The cetane index is based on the distillation range.

2.8.11 Heat of combustion

Is a measure of the energy released when a substance is burned. It is expressed as the amount of heat energy released per unit of mass of the substance being burned. The heat of combustion is an important property of fuels, as it determines the amount of energy that can be obtained from burning a given fuel.

2.8.12 Carbon residue

The number of carbonaceous deposits in the combustion chamber is directly proportional to the amount of carbon residue left over. When there is a higher value of carbon residue, one should anticipate finding greater carbon deposits.

2.8.13 Particulate matter

The presence of particle matter is indicative of the possibility of emissions of particulate matter. Particulate matter comprises carbon particles principally. Soot particles, which are carbonaceous particulates created by gas-phase processes, can have a negative impact on human health as a result of their ability to absorb and transfer carcinogenic elements into the environment as emissions. Excessive particles of soot have the potential to clog the exhaust valves.

2.9 Response Surface Methodology

Using response surface methodology (RSM) is a way to optimize a process that includes complex computations. Experimentation design that incorporates all the independent variables and leverages data input from the experiment to finally arrive at a set of equations that can give the theoretical value of an output is developed using this approach. Using the controlled values of the independent variables, a well-designed regression analysis produces the results. As a result, the dependent variable can be forecasted based on updated values of the independent factors (Anwar et al., 2015).

Based on the specific factorial designs created by Box and Behenkin, RSM is a statistical tool for optimizing data sets. Using unique experimental designs and Taylor's first and second-order equations, this scientific approach to discovering optimal circumstances is used. The Taylor expansion curve's reaction surface is determined by the RSM process (yield, impurity level, etc.)

The Taylor equation, which is the heart of the RSM method, has the form shown in Equation 3.

$$\text{Response} = A+B.X1+C.X2+\ldots H.X1^2+I.X2^2+\ldots M.X1.X2+N.X1.X3 \ +\ldots \qquad \textbf{Equation } 3$$

Where A, B, C . . . are the coefficients of the terms of the equation, and
$X1$ = linear term for variable 1
$X2$ = linear term for variable 2
$X1^2$ = nonlinear squared term for variable 1
$X2^2$ = nonlinear squared term for variable 2
$X1.X2$ = interaction term for variable 1 and variable 2
$X1.X3$ = interaction term for variable 1 and variable 3

A power series can be used to approximate any continuous function, as demonstrated by the Taylor equation. A wide range of continuous functions can be approximated using this technique. For this reason, the RSM methodology uses a combination of a

Taylor equation to approximate nature's response function, and a specific experimental design to determine its coefficients (Geiger, 2014).

The RSM is a statistical technique used to optimize a process or product by studying the relationship between multiple variables and the response of interest. However, before an application of RSM can be considered, certain conditions must be met. These conditions include identifying the important components of the process, ensuring that the factors being studied fluctuate within a specific range, and being able to link the response to the variables using a mathematical function. Additionally, the number of trials required for RSM increases as the number of variables increases, so it is important to keep in mind the limitations of the program when determining the number of variables to include in the study.

The RSM application has three steps. First, Box Behnken and Central Composite Design are classic examples of experimental design (CCD). Second, regression and statistical analysis are used to generate model equations that describe response surface modelling, and the final step is to optimize parameters or variables by using model equations (Anwar et al., 2015).

Response surface methods are known for providing the most information with the least effort. Second, the findings might be received fast because all experiments can be done at the same time. It's in this way that reaction surface technique comes into its own. Due to the use of partial factorial designs, such as central composite or star designs, the number of experimental points required is minimal, making RSM a relatively efficient process.

If n is the number of variables to be optimized, a full factorial three-level design would necessitate n3 experiments while a full factorial five-level design would necessitate n5.

Less experiments are needed when using response surface procedures because they are partial factorial designs. A full factorial design technique would necessitate 3125 experiments to test five variables at five distinct levels, for example. However, Response Surface Methodology requires only 48 tests a significant time and financial reduction.

2.9.1 Advantages of RSM

When doing experiments, using RSM can help one obtain the most amount of information possible, and the process itself requires one to plan ahead and be aware of how long the project will take. Due to the fact that it works with several responses at the same time, it is also helpful in providing information regarding the interaction that occurs between the variables. The most important benefit is that it provides information that is essential for the planning and improvement of a process (Anwar et al., 2015).

2.9.2 Disadvantages of RSM

Unlike other models, the RSM is famously bad at making predictions that aren't within the scope of the research. RSM is based on the premise that a series of designed trials can be used to get the best possible response. The RSM, utilizing a good design of experiments (DoE), is now widely employed for formulation optimization. Experiments in extraction, food preservation, fermentation, and other engineering fields have all utilized RSM (Anwar et al., 2015). An understanding of the response surface topography is the primary goal of RSM, which aims to discover the best possible response.

2.9.3 Optimization using a central composite design

Central Composite Design is one of numerous strategies for designing experimental procedures in response surface methodology (CCD). Optimizing with CCD allows for the screening of a wide variety of parameters and the role each factor plays in the process (Liu et al., 2013). As a result, CCD may also examine the impact of a single variable, as well as the cumulative effect of multiple variables. This ability is shared with other experimental designs, such as complete and partial factorial approaches, but it differs in that the number of experimental runs is reduced in this design. With just four variables, the full factorial technique will call for at least 81 experimental runs and replications, for instance (Box & Wilson, 1951). Only 31 experimental points are needed when utilizing the CCD approach (16 factorial points, 8 axial points, and 7 centre points). Both complete and fractional factorial designs can be used in CCD, which has two levels or several design points. Axially and centrally located factorial and axial points make up this pattern. CCD can be used to measure all possible regression parameters based on the combined findings of design points.

2.9.4 Regression

The regression method, which involves fitting the response into a polynomial model and using both first- and second-order response surface models, is used to assess all of the data collected following various experimental procedures. The first-order model can be used to approximate a response-based function based on a linear function of independent variables.

Equation 4 is the simplest form that may be used to express the first-order model.

First–Order Model

$$y = \beta_\circ + \beta_1 x_1 + \beta_1 x_2 + e \qquad \textbf{Equation } 4$$

Where y is the response of interest and depends on “x_1 and x_2” independent variables and “e” is experimental error where $\beta_{0,}$ β_1 and β_2 represent the regression coefficient.

In contrast, the second-order model typically uses two variables to express the approximated function. In addition to taking into account the terms of the first-order interaction model, it also takes into account all quadratic and cross-product terms.

A second-order model can mathematically be described in Equation 5.

Second-Order Model

$$y = \beta_{\circ} + \beta_1 x_1 + \beta_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + e$$ **Equation** 5

Where β_0, β_1, and β_2 represent the regression coefficient (Geiger, 2014; Mumtaz et al., 2017).

2.9.5 Application of RSM

RSM has been utilized by a multitude of researchers in order to optimize the reaction parameters that are a part of the process of producing biodiesel. For instance, RSM was utilized in order to optimize the methanolysis of B. carinata oil in order to produce biodiesel (Vicente et al., 2005). (H. C. Joshi et al., 2008)revealed how to make cottonseed oil into biodiesel using an improved process; CCD was used to determine the best temperature for the reaction as well as ethanol/oil mole ratios. The CCD had eight factorial points, six axial points and six duplicated centers. With these reaction circumstances (catalyst concentration of 1.07 %, oil molar ratio of 20:1) and reaction temperature of 250^{o}C, the authors obtained biodiesel with a 98% yield. Resonance surface approach was used to study the two-phase aqueous (ATPE) method for extracting anthocyanins from purple sweet potatoes (RSM). The best conditions for anthocyanin extraction were found to be a 45:1 (mL/g) liquid-solid ratio, 25% (W/W) ethanol concentration, 22% (W/W) ammonium sulphate concentration, and a pH of 3.3. The optimal conditions yielded an anthocyanin yield of 90.02 % and a partition coefficient of 19.62 % (Liu et al., 2013). Injection system parameters such as injection pressure, injection time, and nozzle tip protrusion were shown to influence the performance and emission characteristics of a twin-cylinder water-cooled naturally aspirated engine. The study's fuel was biodiesel, which was made from Pongamia seeds and combined with diesel through the transesterification process. The response surface methodology was used to make predictions about response parameters like BSEC, BTE, CO, hydrocarbons, smoke opacity, and NOx, as well as to identify significant interactions between the input components and the responses they elicited. The data showed that the highest levels of BTE and NOx were achieved with a 2.5 mm tip protrusion, 225 bar injection pressure, and 30 BTDC injection timing. The response surface methodology's desirability approach was utilized to fine-tune the injection system's settings for maximum efficiency and minimum NOx emission. Pongamia biodiesel blended diesel fuel performed best in a test engine developing 7.5 kW at 1500 rpm when injected at 225 bar, timed at 21 degrees before top dead center, and with a 2.5 mm nozzle tip protrusion (Pandian et al., 2011).

In order to optimize the performance parameters and exhaust emissions of a spark ignition engine running on ethanol-gasoline blends of 5%, 7.5%, 10%, 12.5%, and 15%, researchers used response surface methodology (Najafi et al., 2015a). There were 45 different conditions tested, each including different engine speeds and test fuels. By substituting ethanol blends for gasoline, both brake power and engine torque were improved, while brake-specific fuel consumption was reduced. In addition, the use of ethanol blends has decreased exhaust pipe CO and HC levels while raising CO_2 and NOx emissions. To minimize emissions and enhance performance, the RSM desirability approach was used to optimize independent variables. The experiments, which are derived from RSM, were designed using DoE. Optimizing engine operating parameters was accomplished through the application of RSM's Desirability approach.

Several biofuel gasoline mixes were discovered to have similar performance parameters to gasoline and significantly improved engine emission characteristics. The optimal % was 10% bioethanol and 90% gasoline, with the engine revving to 3000 rpm (E10). This research found that the optimum input parameters for brake power, Torque, BSFC, CO, CO_2, HC, and NOx resulted in values of 35.26 kW, 103.66 Nm, 0.25 kg/kW.h, 3.5 %Vol., 12.8 %Vol., 136.6 ppm, and 1300 ppm, respectively (Najafi et al., 2015a).

Both the response surface approach and artificial neural network applications were shown to accurately predict engine performance and exhaust emissions characteristics in the reviewed literature on alternative fuel (Yusri et al., 2018). Engine characteristics such as load, speed, and static injection timing for gasoline- and diesel-fueled spark- and compression-ignition engines have been the subject of various engine optimization studies by RSM, with the goal of improving engine efficiency and reducing exhaust emissions. (Najafi et al., 2015a; Win et al., 2005) optimizing a diesel-fuelled CI engine's load, speed and static injection timing to reduce noise, fuel consumption and exhaust emissions using RSM.

2.10 Exhaust Gases

Concerns about pollution from fossil fuels are motivating search for more environmentally friendly alternatives. Using alcohol fuels has been demonstrated to substantially lower the amount of nitrogen oxides and particulate matter emissions from internal combustion engines (Imran et al., 2013; Surisetty et al., 2011; Tutak et al., 2015). Due to the reduction in harmful emissions, the combination of an alcohol-diesel blend and a CN improver is viewed as a very promising alternative (S. Kumar et al., 2013). In a compression ignition engine, CO_2 is created as a result of the addition of alcohol to the diesel fuel, whilst particles containing carbon are formed as a result of combustion. Pollution with particulates is greatly reduced as a result of this (Choi & Reitz, 1999; S. Kumar et al., 2013; Yusri et al., 2018).

As a result of using biodiesel, fewer emissions of smoke, carbon monoxide particulate matter, and unburned hydrocarbons are produced, whereas NOx emissions are increased (Agarwal, 2007; Lin & Huang, 2003). Adding alcohols like methanol, ethanol, and butanol to diesel fuels has also been proven to have a major impact on the fuel characteristics, combustion, and emissions. Emissions-wise, these blends are practically on par with those of ethers, esters, and other oxygenates (Kumar et al., 2013). Alcohol blends have been shown in studies to improve some exhaust pollutants while having no negative impact on diesel engine performance (S. Kumar et al., 2013). Finally, the use of alcohol–diesel fuel blends reduce engine emissions without affecting engine performance significantly. Enhancing the characteristics and stability of gasoline mixes with fuel additives and CN improvers was proven to be beneficial (Kumar et al., 2013).

Alcohol fuels, such as methanol, ethanol, propanol and butanol, were found to lower hazardous emissions in the study of fuels' environmental impact. Nitrogen oxide emissions were found to increase as a result of an increase in the proportion of propanol. Particulate matter emissions were greatly reduced overall (Banugopan et al., 2010; Laza & Bereczky, 2009). There is, however, a worry that needs to be addressed because their use has been observed to impair the engine performance features (Yusri et al., 2018). Propanol enhanced brake thermal efficiency and reduced exhaust pollutants when combined with diesel and biodiesel.

2.10.1 Exhaust smoke

This is a visual sign of the engine's internal combustion. Blue and black smoke are separated by a dividing line in the middle. Droplets of lubricating oil from worn piston rings and cylinder liners enter the combustion chamber and burn, resulting in the blue smoke. Unburned fuel droplets produce white smoke, which is a sign that the engine is operating at a lower temperature than it should. It is common to see black smoke, which is composed of burned carbon particles as well as other solid products from combustion, at high working loads and high speeds.

2.10.2 Diesel engine emission

This emission contains elements such as nitrogen oxide, carbon oxide, organic molecules that are either unburned or partially burned, as well as partially burned hydrocarbons, visible smoke, and soot.

2.10.3 Nitrogen emissions

If a chemical reaction involving nitrogen and oxygen doesn't reach equilibrium, a mixture of nitrogen and oxygen compounds like nitric oxide (NO), nitrogen dioxide (NO_2), or dinitrogen trioxide (N_2O_3). Depending on the conditions of the reaction, these compounds can form other compounds like nitrogen monoxide (NO) or nitrogen dioxide (NO_2). By blending the presence of oxygen in propanol and biodiesel can promote more complete combustion of the fuel, which can lead to reduced emissions of particulate matter (PM). The reduction in PM emissions can also lead to a reduction in NOx emissions, as PM can act as a catalyst for the formation of NOx.

2.10.4 Carbon monoxide emissions

It is a hazardous byproduct that results from the burning of hydrocarbons and is also poisonous. The incomplete combustion that took place is the source of its emission. The amount of CO released into the atmosphere is directly proportional to the air-to-fuel ratio in comparison to the stoichiometric proportions. When there is a significant variation from the stoichiometric ratio, rich combustion will invariably result in an increase in the CO product as well as emission levels. The diesel engine runs with an overall lean mixture when it is in operation.

2.10.5 Hydrocarbon emissions

In areas where the flame is extinguished by walls and where the combustion process is hindered by severe dilution with air, they are formed. Fuel-air mixtures can either be too lean or too rich, depending on the vehicle's specifications. Slower thermal oxidation reactions might then consume this previously burnt fuel while additional air is included into the expansion process. Due to incomplete mixing, the hydrocarbons stay unconsumed.

2.11 Diesel Engine

Internal combustion engines with compression ignition, often known as CI engines, use hot compressed air to ignite the fuel. Compressed air becomes hotter, and this heat is utilized to ignite the fuel and burn it. Compression and suction strokes are performed in a similar manner in this engine. Fuel is fed into the cylinder at the end of the compression stroke, and the combustion process begins as a result of the heat of the compressed air. The diesel fuel that powers this engine is what makes it go. It is based on the Diesel Cycle idea. This engine's compression ratio typically falls between 14:1 to 22:1, buses, lorries and ships all make use of this technology the compression ratio of the engine presents opportunities and challenges when employing the ternary blend. Aligning the fuel characteristics with the engine's compression ratio is crucial to leverage its potential benefits in terms of efficiency, performance, and emissions.

The component of the engine and the assembly of the CI engine are as shown in Figure 2.1.

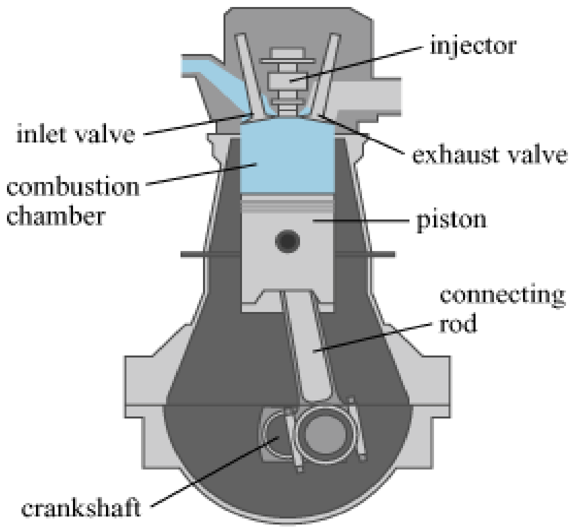


Figure 2.1: Components of Compression Ignition Engine

The main components of a compression ignition (CI) engine are:

1. **Injector:** During the process of compressing the air, it is utilized to inject the fuel into the cylinder.
2. **Inlet valve:** When the suction stroke is being performed, the air that is contained within the cylinder is drawn in through the inlet valve.
3. **Exhaust Valve:** Through the exhaust valve, the entirety of the spent fuel or exhaust produced by the cylinder is expelled.
4. **Combustion chamber:** It is a space within the engine in which the burning of gasoline takes place.
5. **Piston**: It is a portion of the CI engine that moves in a reciprocating motion, and it is responsible for producing that motion within the cylinder. The primary purpose of this component is to connect the crankshaft to the connecting rod in order to transmit the force of thrust that is created during the power stroke.

6. **Connecting rod:** It is a connection between the crankshaft and the piston.
7. **Crankshaft:** It is utilized to convert the reciprocating action of the piston into a rotating motion so that the mechanism can be utilized more effectively.

Figure 2.2 shows a representation of the strokes that the CI engine goes through, along with the varied positions of the piston and valves.

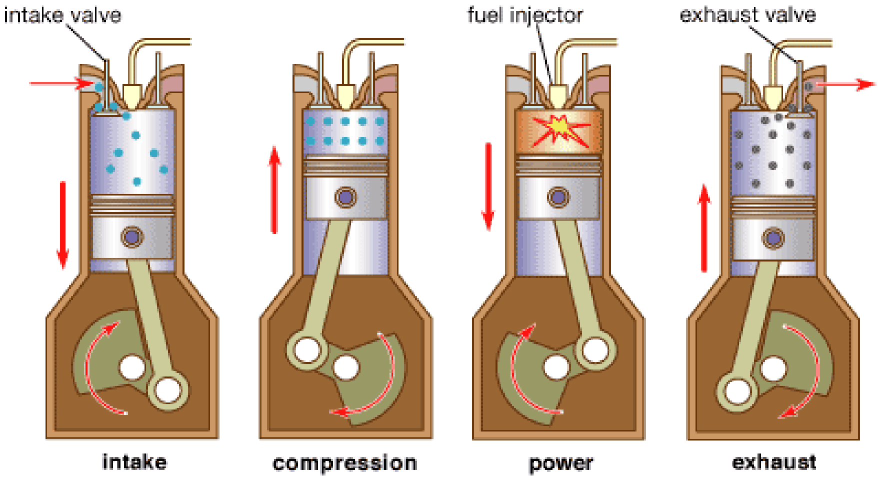


Figure 2.2: Image of CI engine cylinder at different stokes

How the CI engine works

1. **Suction Stroke** During this phase, the piston will go from TDC to BDC, which means it will descend downward. At the same time, the inlet valve will be responsible for sucking in air.
2. **Compression Stroke** The air that was sucked into the cylinder in the previous stroke is squeezed more tightly during this stroke. When air is compressed, its temperature rises, and eventually reaches the point at which diesel fuel can be burned. This is the point at which combustion may take place.
3. **Power Stroke**. The fuel is injected into the cylinder by the injector at the precise moment right before the end of the compression stroke. The ignition

of the fuel, which is followed by combustion, is triggered by the heat that is provided by the surrounding air. As a result of the fuel being burned, hot exhaust gases are created, which in turn place a very strong thrust force on the piston, causing it to travel downward in the cylinder. Through the assistance of the connecting rod, the piston will rotate the crankshaft. It is known as a power stroke due to the fact that power is generated during this stroke.

4. **Exhaust Stroke.** During this portion of the power stroke, the piston travels higher (from its BDC position to its TDC position), which forces the exhaust gases to exit the cylinder through the exhaust valve.

All of the strokes are repeated after the exhaust stroke. We obtain one power stroke every crankshaft revolution in a two-stroke engine. A power stroke occurs every second rotation of crankshaft in a four-stroke engine, on the other hand.

Diesel fuel is atomized and combined with hot compressed air during the power stroke. The result is a cylinder with several ignition sites. Early and uniform igniting are made possible by this method. As a result, a fuel's hydrocarbon content affects its ability to ignite. According to paraffinic content, cetane number measures the fuel's ability to ignite at a later time (Oil et al., 2015).

The diesel engine's power and fuel usage have an effect on the density coefficient. Diesel fuel is heavier in the summer months than in the winter. As a result of the fact that more substances have a direct impact on energy efficiency, the winter fuel has a higher efficiency percentage than usual. A more dynamic motor results in lower fuel consumption as a result. To put it another way, diesel fuel is more efficient in the winter because of the lower density. Temperature, density, and viscosity are all intertwined notions in physics (Oil et al., 2015).

2.12 Theoretical Perspectives and Gaps

From the reviewed literature, it was noted that many ternary blends of different biodiesel, diesel, and alcohol have been done with varying percentages, but more work is needed in specifying optimum blend characteristics and ensuring the long-term durability of the engines using the fuel, an essential area requiring clarification involves identifying the optimal blend ratios for diesel, biodiesel, and propanol within the ternary combination. Additionally, the search for the optimal blend of diesel, propanol, and waste vegetable biodiesel crucial for enhancing fuel conversion efficiency, remains inconclusive, prompting the need for additional research, and to understand the roles of various additives in improving the potential for alcohol–diesel fuel blends. The fuel properties, characterizations, and engine and emission performance analyses of ternary used cooking oil biodiesel–diesel–propanol blends revealed that more research on the application of these ternary blends should be conducted.

CHAPTER THREE

RESEARCH METHODOLOGY

3.0 Introduction

In this chapter, various ternary blends were created by mixing varying amounts of propane, used cooking oil, and pure diesel. Using RSM, the optimum factor levels were established, allowing the CI engine to provide great power with low fuel consumption and minimal pollution. The ternary blends manufactured were used to drive a two-cylinder diesel engine. The ultimate aim of the study was to mitigate against the release of detrimental gases while concurrently enhancing the performance metrics of Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE). Mathematical equations were used in forecasting and optimization. The models' connections between the variables and the consequent responses were simulated using RSM.

3.1 Research Materials

The required research materials used included:

3.1.1 Diesel

Diesel was purchased from local petrol station at Nakuru and its properties tested at Kenya Industrial Research and Development Institute. These properties included calorific value, sulphur content, flashpoint, kinematic viscosity, ash content, and water.

3.1.2 Propanol

Commercial propanol was used in this study and its properties are in given Table 3.1 based on manufacturer specifications.

Table 3.1: Manufacturer specification of propanol used in the study

Properties	Range
MF	C_3H_3O
MW	60.10
Assay	Min 99.5%
Identity (acc.to pharmacopoeias)	Passes test
Weight/ ml at 20°c	0.785-0.787
Refractive index (20°c; 589 nm)	1.376-1.378
Water (H_2O)	Max 0.1%
Acidity (as C_2H_5COOH)	Max 0.001%
Non-volatile matter	Max 0.002%
Benzene (C_6H_6)	Max 0.0002%
Ethanol (G.C.) (v/v)	Max 0.05%
Peroxide (as H_2O_2)	Passes test

3.1.3 Biodiesel

Bio-diesel was produced from waste vegetable cooking oil at Moi University Chemical and Processing Laboratory. The used cooking oil was obtained from KIVU restaurant Nakuru. The production of biodiesel was through a transesterification process. The transesterification reaction of the oil was carried out in a 2000 ml conical flask. A ratio of 1000g, 250g, and 7.5 g of WCO, methanol, and sodium hydroxide respectively was used (Verma & Sharma, 2016). A weighing balance was used to measure the weight as per the requirement. The production process is summarised in Figure 3.1

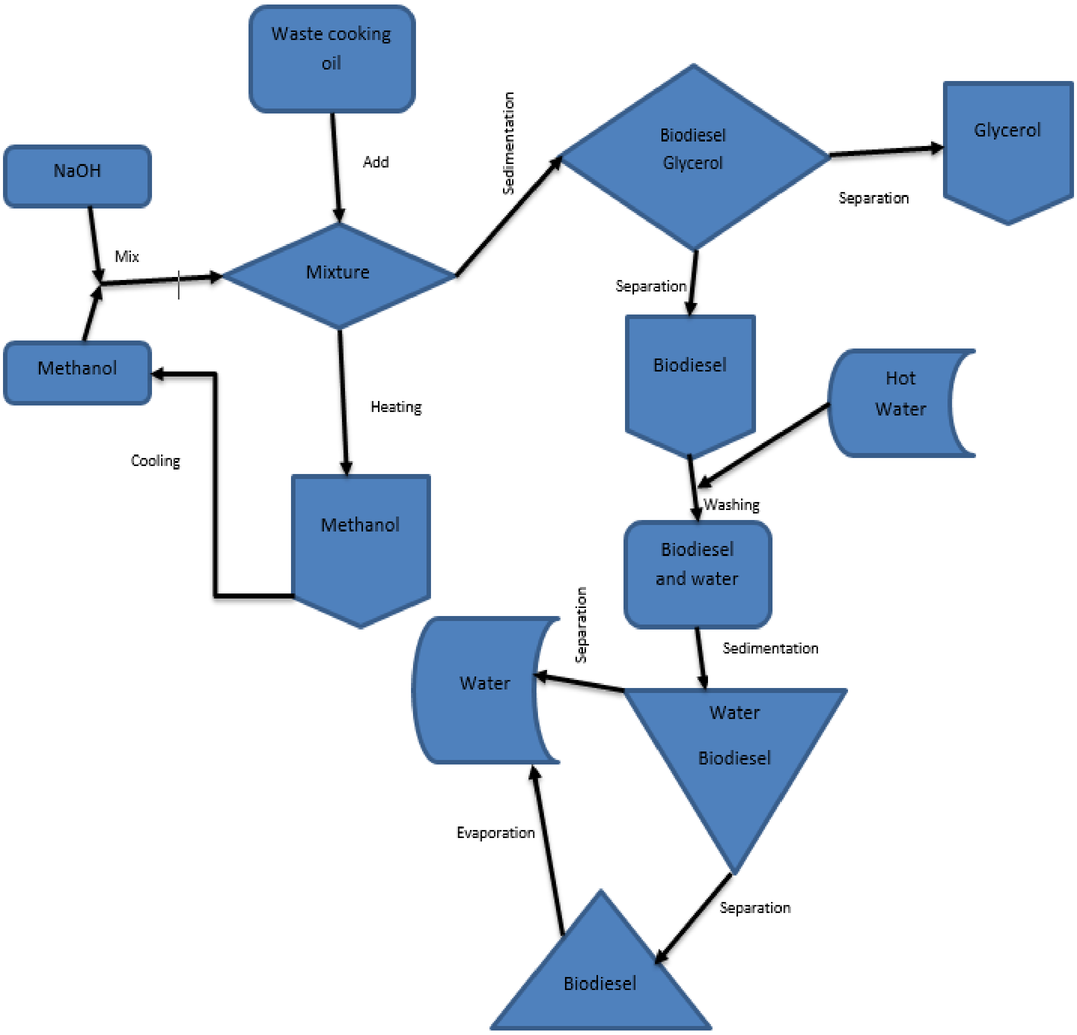


Figure 3.1: Flow chart of the production of biodiesel from used cooking oil

The process started with the mixing of NaOH pellets with methanol. NaOH is used as a catalyst. Total solubility was obtained, and the mixing was done using a magnetic stirrer hot plate. The specification of the sodium hydroxide was as follows SAP code 21620SG500, CASR: 1310-73-2, Batch no: 810510328HR, MFG: AUG 2018, EXP: JUL 2023.

The waste cooking oil was heated to a temperature of 110°C for 20 mins to remove any water present, before cooling it to 60°C. 1000g of used cooking oil at 60 °C was weighed and mixed with NaOH and methanol while stirring using an experimental set up shown in Figure 3.2. The reaction was carried out at 60°C for 90 minutes while stirring continuously. This was followed by extraction of methanol using experimental set up shown in Figure 3.3.

Figure 3.2: WCO, methanol, and NaOH are heated and stirred, with evaporating methanol condensed back into liquid.

Figure 3.3 Recovering methanol from WCO, methane, and NaOH involves heating, stirring, and collecting condensed vapor.

The extraction ran for 25 minutes to ensure maximum removal of methanol which was then followed by the cooling. The cooling process was to allow the sedimentation process to occur. To ensure the sedimentation process was complete, it was given 24 hrs to allow maximum separation of biodiesel from glycerol. The outcome is as shown in Figure 3.4 and Figure 3.5.

Figure 3.4: After 12 hours of cooling, glycerol and biodiesel undergo sedimentation, revealing insights into their separation behavior.

Figure 3.5: Reveals insights into the characteristics and properties of glycerol formed during sedimentation.

Biodiesel made from waste cooking oil can vary in color from yellow to dark brown, depending on the quality and condition of the oil used. Waste cooking oil, collected from restaurants and other food service establishments, can lead to a higher degree of impurities such as food particles, water and other contaminants, that can affect the color of the biodiesel produced. Additionally, the type of food that was cooked in the oil can also affect the color of the biodiesel. For example, deep-fried foods can leave behind more carbonized material, which can darken the color of the biodiesel. The color of biodiesel made from waste cooking oil was yellowish as shown in Figure 3.6.

Figure 3.6: Decanted biodiesel displays a distinctive yellowish color, offering key insights into its quality for further biodiesel synthesis analysis.

The bio-diesel produced was purified through washing with hot water where the catalyst (NaOH), residual glycerol and methanol were removed. It was done repeatedly until the bio-diesel was free of the impurities (Gashaw & Teshita, 2014). This was done using experimental set-up shown in Figure 3.7. The cleaned biodiesel was heated to a temperature of 120 °C for the total eradication of water present in the setup shown in Figure 3.8. The colour of the final product was bright yellow. The biodiesel was left to cool down and was stored, ready for characterization.

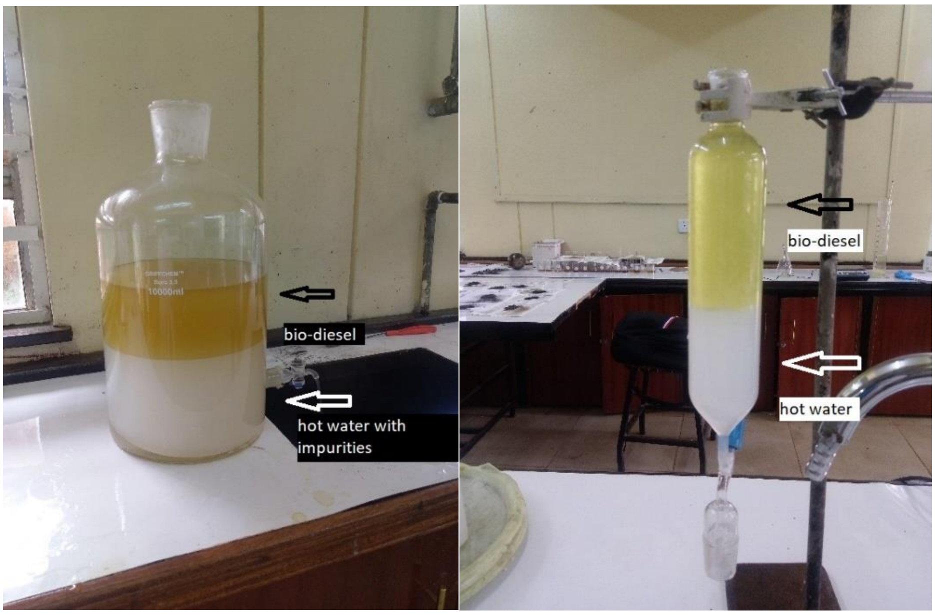


Figure 3.7: Washing biodiesel in hot water results in a purer end product, highlighting its importance in improving overall synthesis quality.

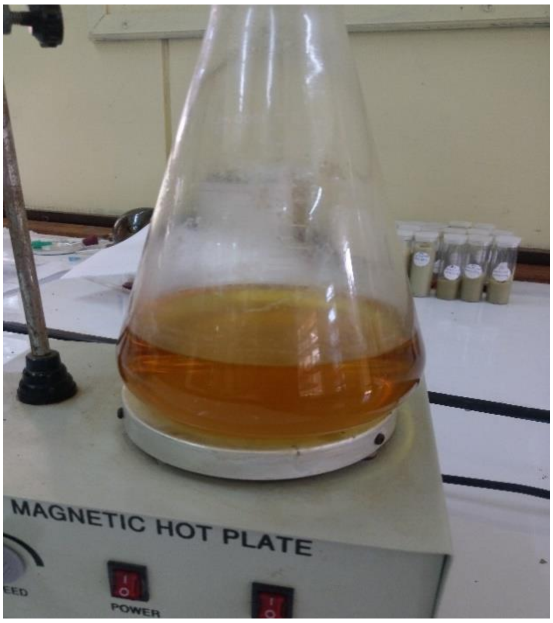


Figure 3.8: Evaporation of Water from Biodiesel Utilizing Vaporization technique

3.2 Characterization of Biodiesel and Diesel

Characterisation of biodiesel and diesel was carried out at Moi University lab and at Kenya Industrial Research and Development Institute where physical properties such as density, kinematic viscosity, flash point, and acid value, were determined.

3.2.1 Determination of bio-diesel Density

The determination of biodiesel density was in accordance with Biodiesel Test Standards: density (ISO3675, ISO 12185). The density was measured using an RD bottle (see Figure 3.9), with a known volume of 25ml and weighing 14.749 gm. The biodiesel was placed inside the bottle and weighed to get the mass. The density of the biodiesel was calculated using Equation 6. The process was repeated 3 times, and the average values reported.

$$Density = \frac{bio-diesel\ mass}{volume} \qquad \textbf{Equation } 6$$

Figure 3.9: RD Bottle - Specialized container for precise liquid density measurements in scientific investigations.

3.2.2 Determination of bio-diesel kinematic viscosity

The Brookfield Viscometer shown in Figure 3.10 was used to measure the viscosity of the blends at the KENGEN chemical lab.

The fluid samples were placed in the viscometer's sample holder, and the fluid samples to be examined were placed in the viscometer's spindle. Double-checked that the spindle was properly connected to the viscometer's sample holder. Turned the speed control dial on the viscometer to the desired speed setting of 6 rpm. Started the viscometer and waited between one to two minutes for the sample to reach 30°C. Examined the viscometer's display and recorded the viscosity data.

Figure 3.10: Brookfield Viscometer machine for precise fluid viscosity measurements in scientific and industrial applications.

3.2.3 Determination of bio-diesel flash point

The determination of flash point was carried out at the KIRDI laboratories, following the ISO standard ISO3104. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1

3.2.4 Determination of bio-diesel acid value

The determination of acid value was carried out at the KIRDI laboratories, following the ISO standard EN 140104. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1.

3.2.5 Determination of bio-diesel sulphur content

The determination of sulphur content was carried out at the KIRDI laboratories, following the ISO standard 20846 and 0884. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1.

3.2.6 Determination of bio-diesel calorific value

The determination of calorific value was carried out at the KIRDI laboratories, following the ISO standard 5165. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1.

3.2.7 Determination of bio-diesel ash content

The determination of calorific value was carried out at the KIRDI laboratories, following the ISO standard 3987. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1.

3.2.8 Determination of bio-diesel water content

The determination of water content was carried out at the KIRDI laboratories, following the ISO standard 12937. The procedure was also in accordance with the Kenya standard for automotive biodiesel. The details of the test method can be found in Appendix 24. The results are presented in Table 4.1.

3.2.9 Engine running test

The engine was serviced and test run using pure diesel while varying the speed and load. The maximum speed used to run the engine was 2000 RPM, and the lowest speed was 900 RPM with a maximum and minimum load of 45 N and 5 N respectively, during the test. The following parameters were selected for test run: speed of 2000 RPM, load of 25 N and brake power of 10 kW these parameters were selected based on the stability and effectiveness of the Engine.

3.3 Production of Ternary Blend

The build information of the blends is shown in Table 3.2 and were generated using a design mixture method in Design Expert Software. The ternary blend limits were set as shown in Table 3.3 and were based on values obtained from literature, where it was found that a 20% blend of biodiesel gave the best performance among all blends Manjula et al., 2016). The speed, load and brake power were kept constant while the responses recorded included time taken to consume 50ml of fuel, brake specific fuel consumption, brake thermal efficiency, carbon monoxide, carbon dioxide, and nitrogen oxide emissions. The emissions were recorded using a gas detector attached to machine exhaust system as shown in Figure 3.13, Figure 3.14 and Figure 3.15.

Table 3.2: Build information on the blends.

File Version	13.0.5.0			
Study Type	Mixture		**Subtype**	Randomized
Design Type	I-optimal	Coordinate Exchange	**Runs**	18.00
Design Model	Quadratic		**Blocks**	3.00
Build Time (ms)	7425.00			

Table 3.3: Components and quantities in the mixture, aiding precise in experimental contexts.

Component	**Name**	**Units**	**Type**	**Min**	**Max**	**Coded Low**	**Coded High**	**Mean**	**Std. Dev.**
A	Diesel	%	Mixture	75	100	+0 ↔ 75	+1 ↔ 100	86.12	8.14
B	Bio-Diesel	%	Mixture	0	25	+0 ↔ 0	+1 ↔ 25	11.52	7.80
C	Propanol	%	Mixture	0	5	+0 ↔ 0	+0.2 ↔ 5	2.36	2.01
			Total		100.00	**L_Pseudo Coding**			

The blending of diesel, bio-diesel and propanol was done using ratios given in Table 3.4 as follows:

- For every blend, the total volume of the fuel was 1 litre.
- Used a calculator to convert the % to litres taking 100% equal to 1 litre of pure diesel.

- Used a measuring volume beaker to measure 1 litre of diesel
- Used Table 3.4 to measure the other blends as per the percentages.
- Mixed the fuel in a beaker and placed it on the stirring machine to ensure a good mixer was obtained.
- Placed the blend in the cleaned 1 litre container and labelled the blend percentage ratio. Did this to all the blends, as shown in Figure 3.11.
- Ensured the blends were well sealed, waiting for engine test and characterization.

From Table 3.4 The design strategy involves blocking, a technique aimed at systematically removing variation attributed to identifiable experimental alterations. For instance, you may need to employ two distinct batches of raw materials to perform the experiment, or the experiment may span multiple shifts or days. In any of these instances, the change may result in a shift in the response data. This shift is eliminated by blocking, which effectively "normalizes" the data. Std Order, often known as standard order, is an index used to create designs with consistent run parameters. The usual sorting order sorts the factor settings from low to high. It is only presented for standard designs for convenience; by default, the design will be arranged by run number.

By default, the **Design ID** is not displayed. It's a way to keep track of all of the individual runs in a design. Same-ID runs are considered to be duplicates.

When a design is constructed using blocks, the term "block" is automatically applied to the finished product. The column operates like a set of categories. The analysis requires more block information if there is more than one block. Since it is not possible to randomly assign blocks, they must be given out in the sequence stated. According to

Table 3.4, the blocks were built according to the days, and each day was allotted a certain ternary fuel to be used throughout operation.

Within the design, blocks, and groups, the **Run Order** is assigned at random.

By default, **Build Point Type** is hidden. It is mostly used to demonstrate how the best algorithm selected the model, lack-of-fit, and replicates in the design.

By default, **Space Point Type** is hidden. It gives a common label for describing a run's geometric location in space. If a user modifies the run by integrating historical designs, the run will be "Unknown".

Table 3.4: Percentage breakdown of blend components for diesel, biodiesel, and alcohol

		Component 1	Component 2	Component 3
Block	Run	A: DIESEL %	B: BIO-DIESEL %	C: PROPANOL %
DAY 1	1	91.3457	3.65426	5
DAY 1	2	100	0	0
DAY 1	3	80.7498	16.5629	2.68725
DAY 1	4	78.9535	21.0465	0
DAY 1	5	91.5393	8.4607	0
DAY 1	6	80.7498	16.5629	2.68725
DAY 1	7	80.7498	16.5629	2.68725
DAY 2	8	87.7265	7.27347	5
DAY 2	9	75	20	5
DAY 2	10	75	20	5
DAY 2	11	97.4781	0	2.5219
DAY 2	12	97.4781	0	2.5219
DAY 2	13	87.514	12.486	0
DAY 3	14	95.6429	4.30803	0.0490477
DAY 3	15	86.3554	11.4719	2.17272
DAY 3	16	82.4382	12.5618	5
DAY 3	17	86.3554	11.4719	2.17272
DAY 3	18	75	25	0

Figure 3.11: Display of Ternary blend samples produced at KENGEN Chemical Lab

3.3.1 Characterization of the ternary blend

Determination of density and viscosity of ternary blends were carried out at Moi University and KENGEN chemical laboratories. The procedure followed in the determination density and kinetic viscosity is given in section 3.2.1 and 3.2.2. The densities and viscosities of every blended fuel were measured 3 times and average values recorded.

3.4 Engine Performance

This test was designed to determine the power train performance of various fuel blends and the blend concentration that delivers the best engine performance in terms BSFC and BTE with less exhaust gas emissions.

The experiment was carried out on a Petter's 2-cylinder engine (see Figure 3.12) with whose specification is given in Table 3.5. The blended fuel was used to run the CI engine, and the time was recorded after every 50 ml of the fuel consumed. The performance parameters for each combustion chamber were recorded for analysis.

The following procedure was followed during engine performance testing this was as per the operational manual.

- Cooling water of engine was turned on and adjusted to give a head of about 125 mm.
- The de-compressor was moved to open position and the fuel supply turned on.
- Engine was started and allowed to warm up.
- Resistors were switched with a small rack setting and speed adjusted to 2000rev/min.
- Load was adjusted to 25N and engine speed of 2000rev/min maintained.
- A timer was used to record the duration it took to consume 50 ml of fuel.
- Electrical load was switched off and engine was stopped.
- Engine fuel was turned off and water supply closed.
- Fuel from the tank was drained out and the fuel system was flushed with the next blend.
- The next blend was filled up and the same process repeated.
- All the measured parameters were recorded at the table of responses at RSM.

Figure 3.12: Petters Diesel Engine at Technical University of Kenya

Table 3.5: Petter’s 2-cylinder Engine Specifications-

Description	**Specification**
Engine type	Petters
Number of cylinders	2
Capacity	810 cm^3
Bore	96.8 mm
Stroke	110 mm
Displacement (RD)	0.842L
Compression ratio	17.5: 1
PB	FN * 0.002 kW
Max output	16.8 kW at max speed 2000 rev/min
Cooling system	Water-cooled

The statistical techniques of design of experiments (DoE) were used to generate an experimental design that optimized the performance of a process or product by systematically varying one or more input factors, while measuring the effect on one or more output variables. Creating an experimental design with DoE typically entailed the following steps:

1. Defined the objectives of the experiment: This includes determining the factors to be examined as well as the response variables to be measured.
2. Selected the type of design: that was response surface designs.

3. Determined the levels of the independent variables: The levels of the independent variables were chosen based on the objectives of the experiment.
4. Generated the design matrix: The design matrix is a table that lists the levels of the independent variables for each run of the experiment as shown in Table 3.6.
5. Selected the sample size and sampling method: The sample size and sampling method were chosen based on the objectives of the experiment, the number of factors and levels to be tested.
6. Performed the experiment: The experiment is conducted according to the design matrix, with the levels of the independent variables being varied systematically.
7. Analyzed the data: The data collected from the experiment was analyzed using statistical techniques to determine the effect of the independent variables on the dependent variables.
8. Optimized the design: Upon analyzing the data, the design was optimized to enhance its effectiveness or efficiency.

Table 3.6: An experimental design for engine performance test showing variables and responses.

Run	A: DIESEL	B: BIO-DIESEL	C: PROPANOL	BSFC	BTE	NOx	CO	Density	viscosity	HC
	%	%	%	Kg/kWh	%	ppm	ppm	g/cm³	P	ppm
1	91.3457	3.65426	5							
2	100	0	0							
3	80.7498	16.5629	2.68725							
4	78.9535	21.0465	0							
5	91.5393	8.4607	0							
6	80.7498	16.5629	2.68725							
7	80.7498	16.5629	2.68725							
8	87.7265	7.27347	5							
9	75	20	5							
10	75	20	5							
11	97.4781	0	2.5219							
12	97.4781	0	2.5219							
13	87.514	12.486	0							
14	95.6429	4.30803	0.0490477							
15	86.3554	11.4719	2.17272							
16	82.4382	12.5618	5							
17	86.3554	11.4719	2.17272							
18	75	25	0							

3.4.1 Determination of IC engine Performance

The following parameters were used to evaluate the performance of petter’s 2-cylinder internal combustion engine (IC) running on ternary fuel blends-:

- Brake power
- Indicated mean effective pressure
- Indicated power
- Mechanical efficiency
- Fuel consumption
- Brake Thermal efficiency

The engine braking power was computed following Equation 7.

$$Brake\ Power = \frac{2\Pi NT}{60000}\ \ kW$$ **Equation** 7

Where T = Torque and = FR

F = braking force in newton’s

R = effective radius of the brake drum (M)

N = speed of the engine in RPM

Π = 3.142

Mass of fuel consumed by the engine was given by Equation 8.

$$\dot{m}f = \frac{Vfuel \quad * \quad \rho\, fuel \quad * \quad 3600}{\triangle\, t}$$ **Equation** 8

$\dot{m}$f = Mass flow rate of the fuel

V fuel = volume of fuel in m^3 used at time t

ρ fuel = density of fuel

△t = time in seconds

Specific fuel consumption (S.F.C) was given by Equation 9

$$s.f.c = \frac{mass\ of\ fuel/3600}{BP} \quad \frac{kg}{kWh}$$ **Equation** 9

Where BP is the Brake power

Specific Fuel Consumption was calculated using Equation 10

$$BTC = \frac{LB}{heat\ supplied}$$ **Equation** 10

Heat supplied was calculated using Equation 11

$$heat\ supplied = \frac{mass\ of\ fuel}{time\ to\ consume\ fuel}$$ **Equation** 11

The Indicated Mean Effective Pressure (IMEP) of an engine was obtained from the indicator diagram given by the engine.

The power indicated is the power generated by the engine cylinder. It is based on information gathered from the engine's indication diagram.

Brake thermal efficiency is the ratio of heat equivalent to one kW hour to the heat in the fuel per B.P hour. This was calculated using Equation 12.

$$\eta = \frac{heat\ equivalent\ to\ one\ KW\ hour}{heat\ in\ fuel\ per\ BP\ hour} = \frac{BP * 3600}{CV\ *\ \dot{m}f}$$ **Equation** 12

Where BP = Brake power

C_V = Calorific valve of fuel in kJ / kg of fuel

$\dot{m}f$ = Mass flow rate of the fuel

Engine Performance plots were generated from Brake Specific Fuel Consumption and Brake Thermal Efficiency data. The plots were used to evaluate the efficacy of the fuel blend and any specific ratio.

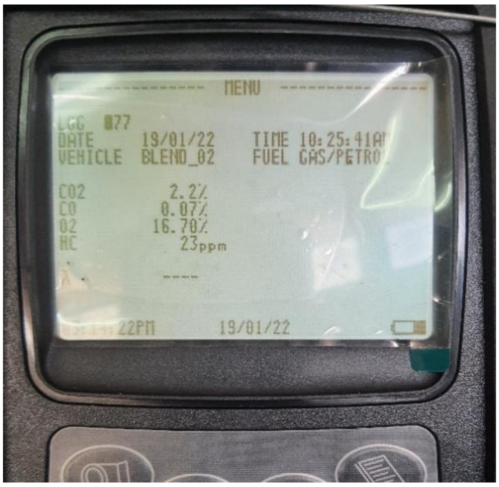
3.4.2 Determination of Exhaust gas composition

Exhaust gases were grouped into two parts; exhaust smoke and remnant emission. The gas detector machine was used to measure the following parameters of the exhaust gases: CO_2 (%), NOx (ppm), CO (ppm), HC (ppm), O_2 (%) and temperature (^oC). The following procedure was followed:

1. The gas detector was fixed at the exhaust engine pipe as shown in Figure 3.15 and Figure 3.13.
2. The composition of exhausted in terms of CO_2 (%), NOx (ppm), CO (ppm), HC (ppm), O_2 (%) was recorded for each blend run in the engine.

Figure 3.13: Installed gas detector for measuring emissions in exhaust gases

A gas detector machine is a device that was used to measure the concentration of CO_2, CO, O_2 and HC in exhaust. It typically consists of sensors that detect the presence of CO_2, CO, O_2 and HC and a display or alarm that indicates the level of the gases as shown in Figure 3.14. A vacuum is created to allow in the exhaust gas to pass through the sensors via a pipe connecting the machine and the probe connecting the exhaust pipe as shown in Figure 3.15.



```
------------ MENU ------------
LOG   077
DATE      19/01/22    TIME 10:25:41A
VEHICLE   BLEND_02    FUEL GAS/PETRO

CO2           2.2%
CO           0.07%
O2          16.70%
HC              23ppm

              ----

22PM        19/01/22
```

Figure 3.14: Gas detector displaying levels of CO_2, CO, O_2 and HC

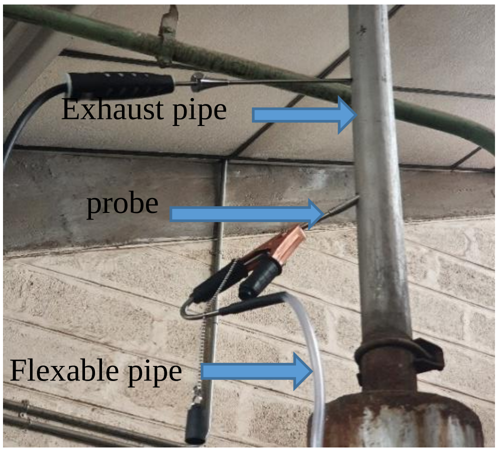


Figure 3.15: Exhaust gas collection point at the exhaust pipe, strategically placed for efficient emissions data capture in the experimental setup.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents results for experimental work conducted in this study. The results are given for each of the specific objective studied and include biodiesel and ternary blend properties, optimal engine performance and exhaust gas compositions.

4.1 Diesel, Bio diesel and Propanol Properties

Table 4.1 shows the determined properties of diesel and bio-diesel used in the study. The properties like ash content, calorific value, sulphur content and water were measured as per Kenya standard and compared with fuel specifications given in Appendix 23 and Appendix 24. The bio-diesel's flash point fell within the minimum requirement of 120°C according to KS 2227: 2010 standards, while diesel's flash point was slightly lower by 6°C. Both diesel and biodiesel met the recommended sulfur content outlined in KS 2227: 2010. The ash content was within the required range specified by the same standard. Density-wise, diesel and biodiesel were marginally higher by 0.08 g/cm³ and 0.05 g/cm³, respectively. Additionally, both diesel and biodiesel exhibited higher viscosity by 0.7 and 1.6, respectively, based on the KS 2227: 2010 criteria.

The properties of the propanol that was used in the study are given in Table 3.1.

Table 4.1: Physical properties of diesel and bio-diesel.

Parameters	units	Diesel	Bio-diesel
Calorific value	Kcal/g	8.792	7.338
Sulphur	%	1.93	2.32
Flashpoint	ºC	54	128
Kinematic viscosity	cP	6	6.6
Ash content	%	ND	0.51
Water	%	ND	ND
Density	g/cm^3	0.95	0.97
PH		8	8.2

4.2 Ternary Blended Properties

In these study ternary fuels blends were produced consisting of diesel, bio-diesel and propanol. This section presents results of ternary blend properties.

4.2.1 Ternary blend viscosity

Appendix 12 and Appendix 13 show viscosities of different ternary fuel blends. The viscosity of pure diesel was altered by the addition of propanol or biodiesel. Propanol or biodiesel change diesel's viscosity. ANOVA findings shown in Appendix 14 indicates that blend ratio affects fuel viscosity significantly. The Anova result can be trusted because the model F-value is 6.16, showing significance, and only 1.34 percent of F-values are artifacts of random chance (if P=0.0500).

The variation in viscosity that takes place as a direct result of mixing is seen in Figure 4.1, Figure 4.2 and Figure 4.3, in addition to Appendix 13 which displays the data. The reduction of viscosity is observed when blending with propanol this aligns with other reseachers (Lapuerta et al., 2010) research examines the impact of alcohol concentration on viscosity in fuel blends. The study reveals that even a small addition of alcohol leads to a significant decrease in viscosity, particularly noticeable with ethanol and propanol at low concentrations. At higher concentrations, this reduction becomes inversely proportional to the length of the alcohol's carbon chain. The viscosity changes observed in the blends do not follow a linear pattern concerning alcohol volume, mass, or molar content. The viscosity reduction is most pronounced with minimal alcohol concentration and varies concerning the type and concentration of alcohol used in the fuel blends.

Due to different viscosities of diesel and bio-diesel Figure 4.1 shows variation of viscosity in the blends without propanol whereby no big variation is noted.

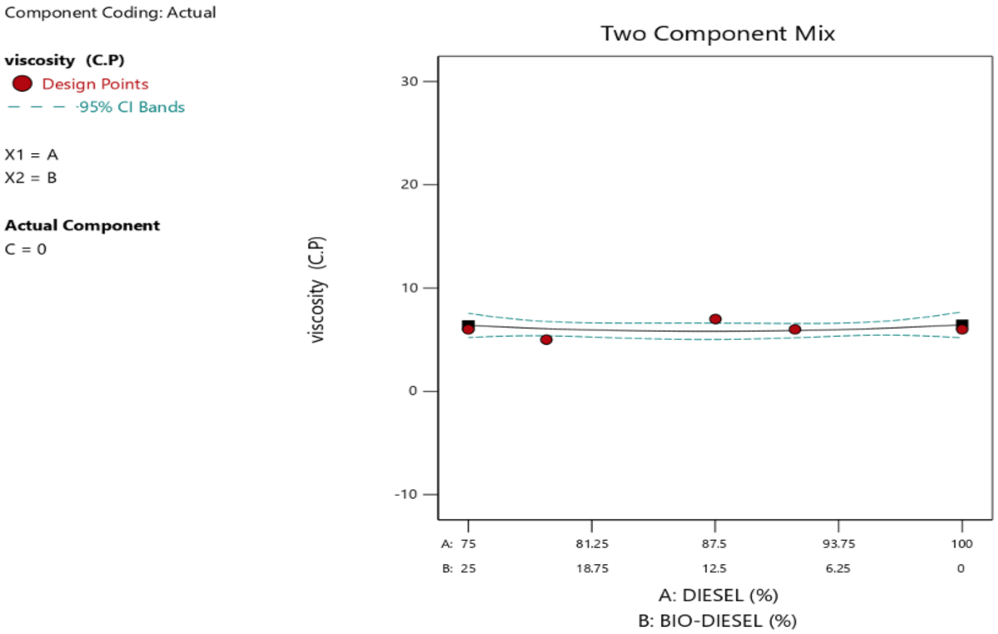


Figure 4.1: Shows variation of viscosity in blend of Diesel and Bio-diesel without Propanol.

Due to varying viscosities of diesel and Propanol, Figure 4.2 illustrates how the viscosity of blends without biodiesel changes in comparison to pure diesel; there are significant changes in viscosity.

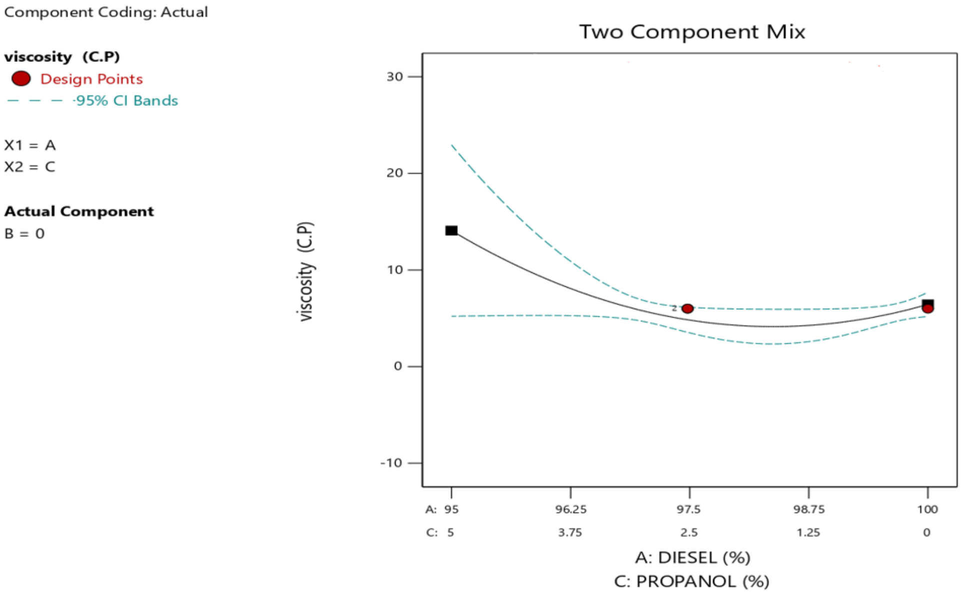


Figure 4.2: Shows variation of viscosity in blends of Diesel and Propanol without Bio-diesel.

Due to varying viscosities of biodiesel and Propanol, Figure 4.3 illustrates how the viscosity of blends without diesel changes in comparison to pure diesel; there are significant changes in viscosity.

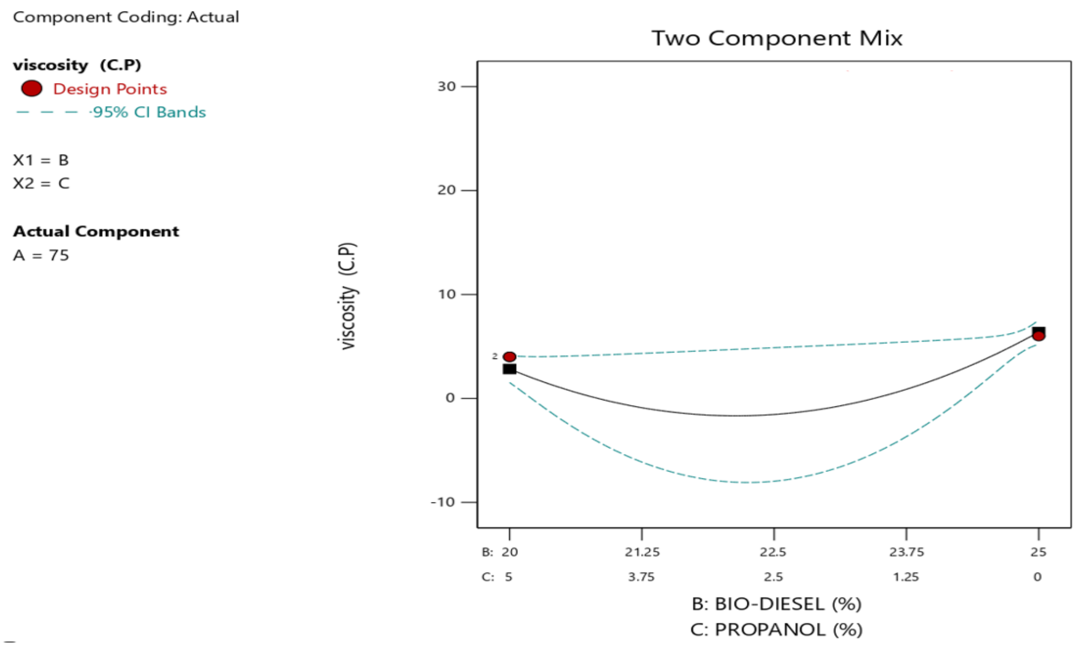


Figure 4.3: Shows variation of viscosity in blends with of Bio-diesel, Propanol while diesel is kept constant at 75%.

Viscosity can be described using Equation 13 which shows interactions between blending elements. The equation expresses viscosity in terms of coded factors that can be used to anticipate the reaction for given amounts of each constituent. By default, the high levels of the combination's components are assigned the value +1, while the low levels are assigned the value 0. By comparing the factor coefficients, as shown in Appendix 14, the coded equation is helpful for determining the relative impact of the factors.

$$\begin{aligned} Viscosity = {} & 6.45A + 6.39B + 480.5C - 2.43AB - 544.86AC \\ & - 614.87BC - 50.20A^2BC + 919.64AB^2C \\ & - 2197.57ABC^2 \end{aligned} \qquad \textbf{Equation 13}$$

Where A = Diesel, B = Biodiesel and C= Propanol

The ternary viscosity of the blend increases as the biodiesel content increases and decreases as the propanol content increases.

4.2.2 Ternary blend density

The density of biodiesel is affected by the raw material in its production. The density of the blended fuel was measured by the percentages of each fuel in a blend. Biodiesel had the highest density compared to diesel and propanol as shown in Appendix 12 and Appendix 15. Owing to the large proportion of diesel in the mixtures, there was only a very small variation in the density. The actual density was determined by applying Equation 6, and the results were recorded and displayed in Appendix 15

The density variations resulting from different blending compositions are visually represented in Figure 4.4, 4.5 and 4.6, as well as Appendix 15

In Figure 4.4, the comparison between diesel and biodiesel densities demonstrates that as the proportion of biodiesel in the blend increases, there's a noticeable elevation in the overall density of the blended fuel. This increase is expected due to the inherent properties of biodiesel, which typically possess a higher density compared to conventional diesel. According to (Yilmaz et al., 2018b), when the fundamental characteristics of the fuels were looked at, it emerged that biodiesel, which is a part of the quaternary blends, had a higher density and kinematic viscosity than the other fuels. Because of their huge molecular weight and intricate chemical structure, the quaternary blends were therefore denser than diesel.

Contrarily, Figure 4.5 illustrates the impact of adding propanol to diesel. Here, an inverse relationship is observed; as the quantity of propanol mixed with diesel increases, the overall density of the blended fuel decreases. Propanol, being less dense than diesel, causes this reduction in density when incorporated into the blend.

Similarly, in Figure 4.6, the influence of augmenting the quantity of propanol in biodiesel is highlighted. As the proportion of propanol in biodiesel rises, there is a subsequent decrease in the overall density of the blended fuel. This decrease aligns with the lighter density of propanol compared to biodiesel, resulting in a lower overall density of the blend, this also agrees with other researchers, as per the findings in (Atabani et al., 2012) , higher alcohol blends exhibited a slight reduction in both density and viscosity. Moreover, the fuel characteristics of these higher alcohol blends displayed comparable trends. As highlighted in the study by (Yilmaz et al., 2018b) the introduction of propanol and pentanol into ternary blends served to counteract the rise in density and kinematic viscosity observed in quaternary blends containing vegetable oil. Additionally, this inclusion improved fundamental fuel attributes.

These observations showcase the predictable impact of individual components on the density of the resulting fuel blend, providing insights into how variations in composition affect the overall density, crucial for understanding and predicting fuel characteristics based on blending ratios.

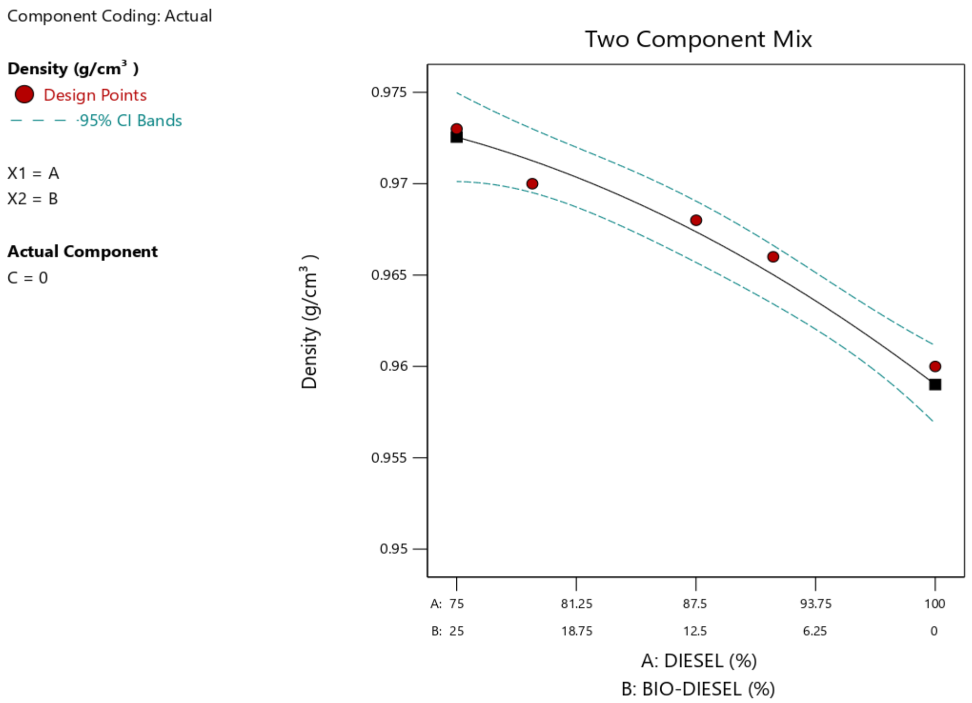


Figure 4.4: Shows the variation of Density in blends of Diesel and Bio-diesel without Propanol.

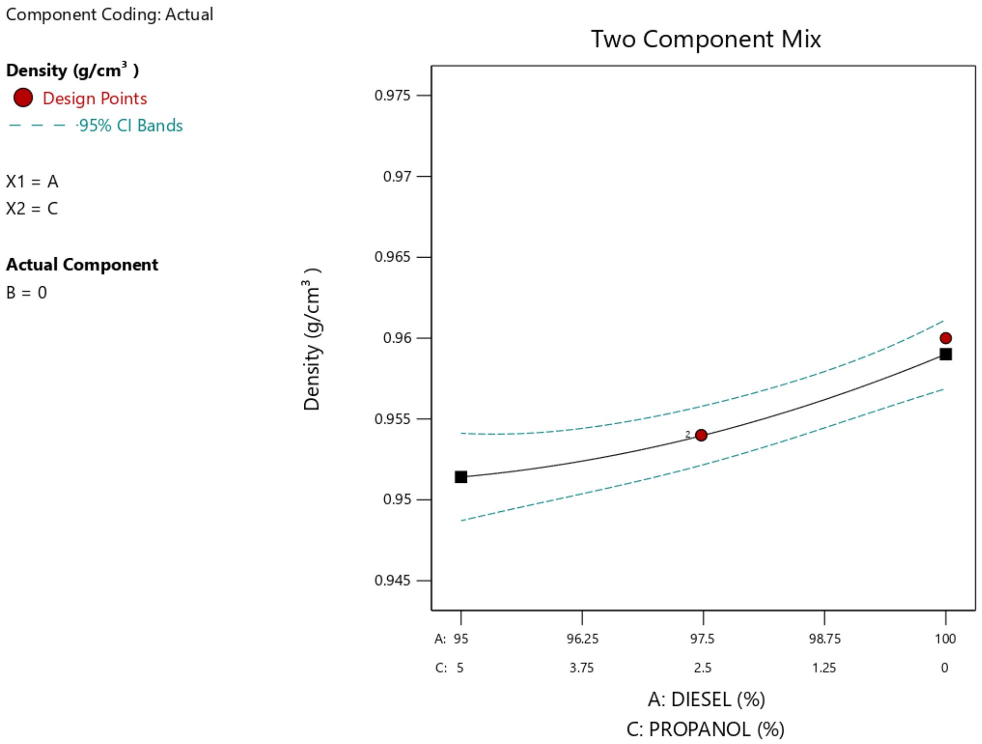


Figure 4.5: Shows variations of density in blends of Diesel and Propanol without Bio-diesel.

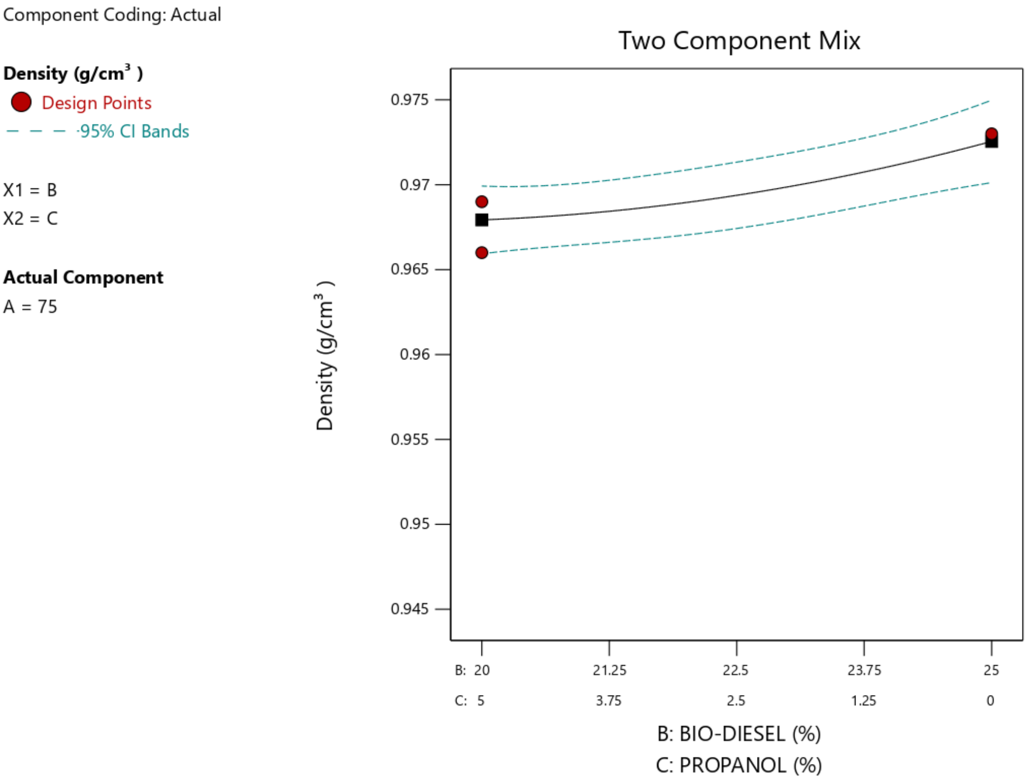


Figure 4.6: Shows variation of density in blends of Propanol and Bio-diesel while diesel is kept constant at 75%

For a given level of each element, it is possible to predict the density using Equation 14. By default, 1 indicates a high concentration of a combination component, and 0 indicates a low concentration.

$$Density = 0.9590A + 0.9725B + 1.02C + 0.0064AB - 0.1218AC - 0.0863BC \qquad \textbf{Equation 14}$$

Where A = Diesel, B = Biodiesel and C= Propanol

4.3 Engine Performance

The ternary blends of diesel, biodiesel, and propanol were generated according to the ratios stated in Chapter 3 Section 3.2, there were 13 different blends of diesel, bio-diesel and propanol. For each blend, 50ml of fuel was run in the engine and the time required to completely consume it was recorded. The results are presented in Table 4.2.

Table 4.2: Records the time taken to consume 50ml of various fuel blends

	Component 1	Component 2	Component 3	Response 1
Run	A: DIESEL %	B: BIO-DIESEL %	C: PROPANOL %	TIME TO CONSUME 50ML OF FUEL SEC
1	91.35	3.65	5	106
2	100	0	0	96
3	80.75	16.56	2.69	104
4	78.95	21.05	0	108
5	91.54	8.46	0	110
6	80.75	16.56	2.69	106
7	80.75	16.56	2.69	108
8	87.73	7.27	5	110
9	75	20	5	104
10	75	20	5	108
11	97.48	0	2.52	110
12	97.48	0	2.52	110
13	87.51	12.49	0	110
14	95.64	4.31	0.05	112
15	86.36	11.47	2.17	112
16	82.44	12.56	5	106
17	86.36	11.47	2.17	112
18	75	25	0	110

The brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) were computed with the use of the appropriate equations given in Chapter 3, results are presented in Table 4.3.

Table 4.3: Presents results of Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) for various fuel blends.

	Component 1	Component 2	Component 3	Response 2	Response 3
Run	A: DIESEL %	B: BIO-DIESEL %	C: PROPANOL %	BSFC kg/kWh	BTE %
1	91.35	3.65	5	0.1622	60
2	100	0	0	0.18	54
3	80.75	16.56	2.69	0.1672	58
4	78.95	21.05	0	0.1617	60
5	91.54	8.46	0	0.1581	62
6	80.75	16.56	2.69	0.1644	59
7	80.75	16.56	2.69	0.1613	61
8	87.73	7.27	5	0.1569	62
9	75	20	5	0.1677	58
10	75	20	5	0.161	61
11	97.48	0	2.52	0.1561	63
12	97.48	0	2.52	0.1561	63
13	87.51	12.49	0	0.1584	62
14	95.64	4.31	0.05	0.1544	63
15	86.36	11.47	2.17	0.1546	63
16	82.44	12.56	5	0.1635	60
17	86.36	11.47	2.17	0.1546	63
18	75	25	0	0.1592	61

BTE is a better measure of fuel performance than fuel consumption, besides heating value. Since thermal efficiency is normalized with fuel heating value, it depends on energy conversion. All blends increased BTE relative to pure diesel, as seen in Figure 4.7. Run 11, 12, 14, 15 and 17 have the highest BTE at 63%.

While run numbers 11 and 12 showed a BTE of 63%, the blends are less dense than diesel compared to run numbers 14, 15 and 17 which are dense. When comparing runs 11 and 12, the viscosity is exactly the same, but runs 14, 15 and 17 exhibit densities that are significantly different from pure diesel (Figure 4.8). As a result of the fact that the thermal efficiency is normalized to the fuel heating value, the manner in which the energy is transformed has a significant impact on BTE since thermal efficiency is the relationship between how much energy is produced when a combustion engine burns fuel and how much of that energy is turned into mechanical energy.

The blend ratio had an effect on the BTE. As can be seen in Figure 4.7, all of the blends had higher BTE values than the pure form.

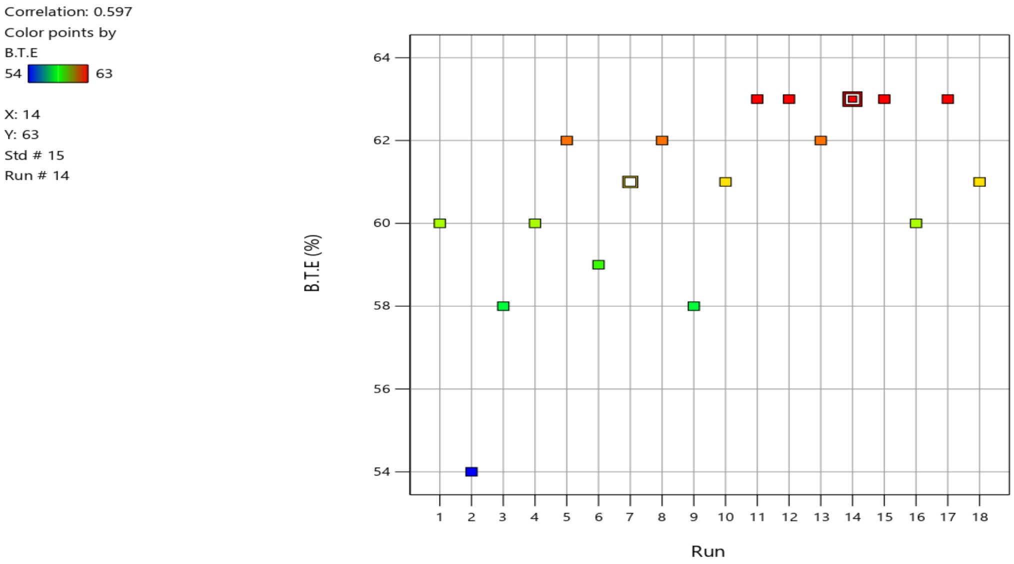


Figure 4.7: A comparison of BTE of 18 experimental fuel blends

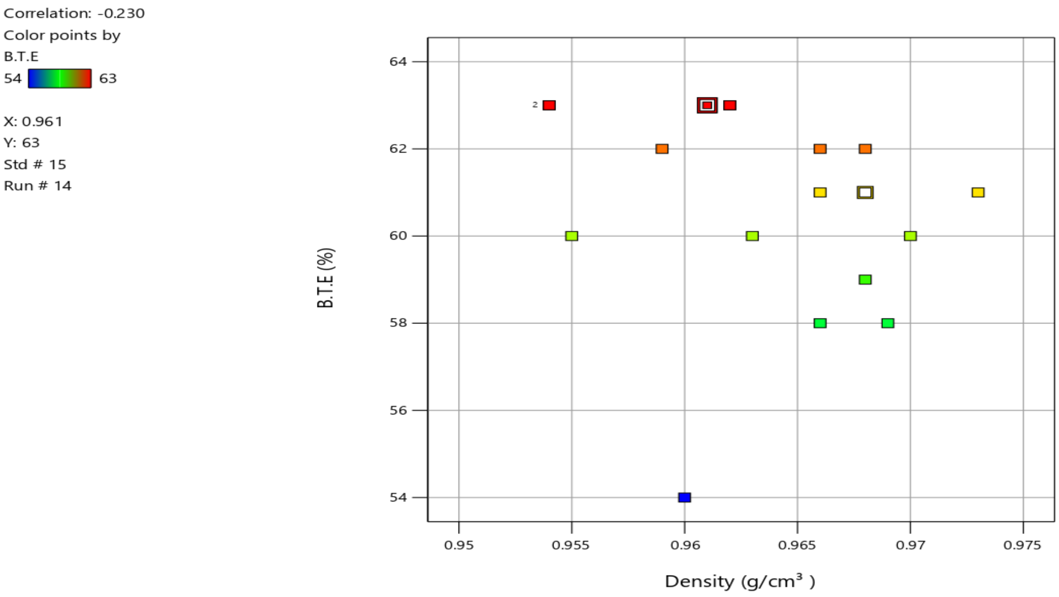


Figure 4:8: Comparison of BTE with density of the 18 experimental ternary blends

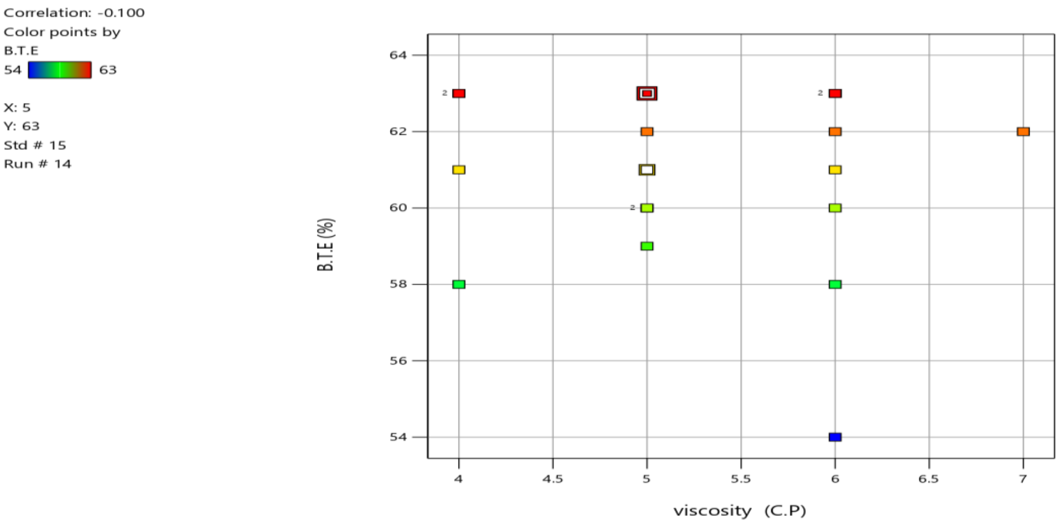


Figure 4.9: Comparison of BTE with the viscosity of the 18 experimental ternary blends

It is possible to utilize Equation 15 to make predictions about the BTE for different levels of each coded factor. The high levels of the components in the combination are assigned the value +1 by default, while the low levels are assigned the value 0. The relative significance of the different factors can be determined with the aid of the encoded equation by comparing the coefficients of the respective factors.

$$
\begin{aligned}
BTE = 5494A + 57.91B - 1277.28C + 29.87AB \\
+ 1593.21AC + 1691.44BC - 821.18A^2BC \\
- 2603.68AB^2C + 7474.41ABC^2
\end{aligned}
\qquad \textbf{Equation 15}
$$

Where A = Diesel, B = Biodiesel and C= Propanol

4.4 Optimization of IC Engine performance using RSM

Engine speed, blended fuel, and load were considered effective factors in engine performance, and they had an effect on parameters such as brake power (kW), Brake Specific fuel consumption (kg/KW_ h), and Brake thermal efficiency (per cent). The speed and load were maintained constant, and the effect of the blended fuel is summarized in Table 4.3.

RSM models can predict an ideal combination of reactions from diesel, biodiesel and propanol using a full factorial experimental design matrix. With the help of Equation 5, second-order models were constructed, which were then tested for significance using standard statistical tests and an analysis of variance (ANOVA). Response surface plots derived from these models were used to compare ternary blends. By using RSM's desirability technique, the best fuel blend combination was found. The raw data from the experimental matrix in Table 4.3 was processed by multiple regressions to obtain the response results of BTE and BSFC.

4.4.1 Desirability approach

Given that different types of blends have varying results when trying to minimize emissions, it was vital to demonstrate how doing so would affect engine performance. Appendix 1 shows minimization of BSFC, CO_2, CO, HC, NO_X and maximized BTE. Appendix 3, shows minimization of CO_2, BSFC and maximization of BTE. Appendix 5 shows minimization of BSFC, NO_X and maximization of BTE. Appendix 7 shows minimization of BSFC, HC and Maximization of BTE and Appendix 9 shows minimization of BSFC, CO, HC, NO_X and maximization of BTE. As a result, reducing one response to emissions will have the opposite effect as raising the other one. Multi-response optimization (MRO) is a process that simultaneously considers numerous competing goals, such as reducing HC, NOx, and BSFC emissions. The desire function is a single, dimensionless performance metric derived from merging several responses, such as NOx, HC, and BSFC, in the desirability approach. For each response, the goal can be to "minimize" or to "maximize" or to "target" or "equal to" the goal. It is our goal to maximize BTE while minimizing NOx, CO_2, CO_3, and BSFC concurrently as stated in Appendix 1 in the present work.

It is then established that the optimum value of factors is dictated by the values of the various desired functions that either maximize or minimize the factors. Hirkude & Padalkar, 2014 found that in order to verify the results of the desirability strategy, a series of experimental trials are carried out in accordance with the predetermined optimization criteria.

4.5 Diagnostics Plots

The following are graph plots of different responses.

Residual is the difference between Actual and Predicted values for each point. The normal probability Figure 4.10 of NO_X exhibits a normal distribution as it conforms to a straight line.

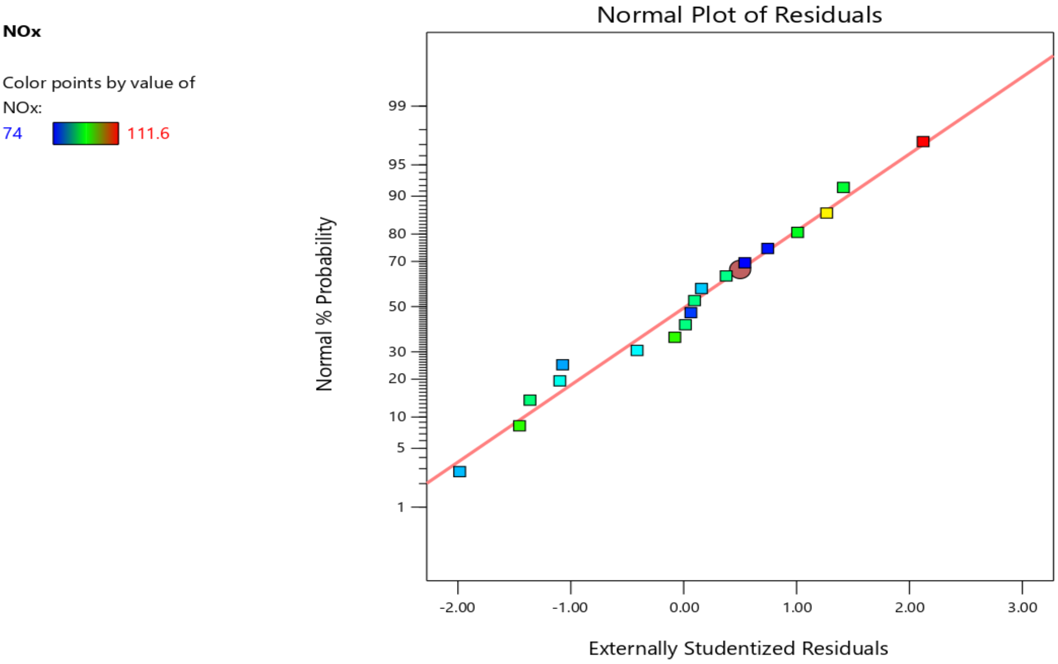


Figure 4.10: Normal % probability plot of residuals of NO_x

The normal probability Figure 4.11 for HC displays a characteristic of a normal distribution as it aligns with a straight line, though some variations are present within the normal distribution data.

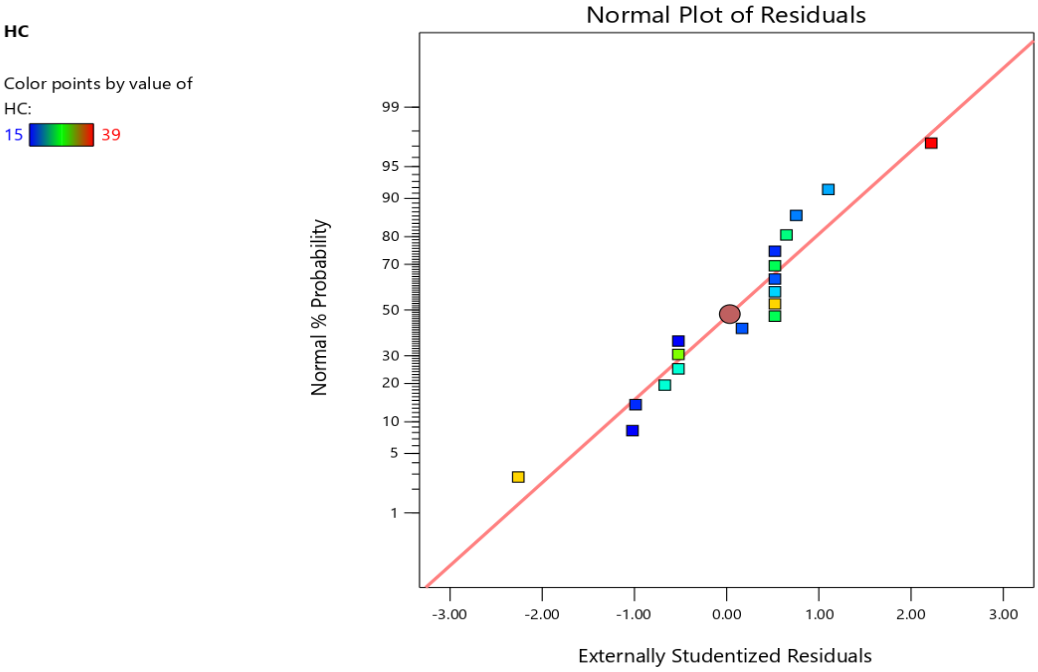


Figure 4.11: Normal % probability plot of residuals of HC

The normal probability Figure 4.12 of CO_2 exhibits a normal distribution as it conforms to a straight line.

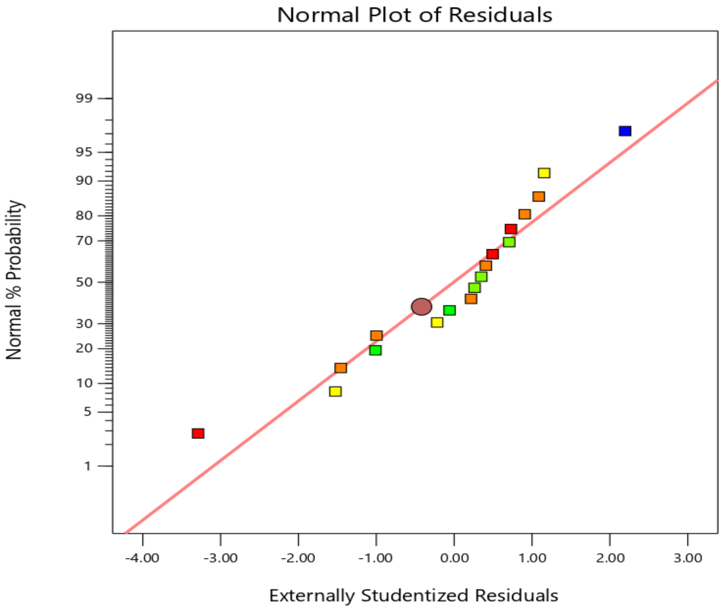


Figure 4.12: Normal % probability plot of residuals of CO_2

The normal probability Figure 4.13 of CO exhibits a normal distribution as it conforms to a straight line.

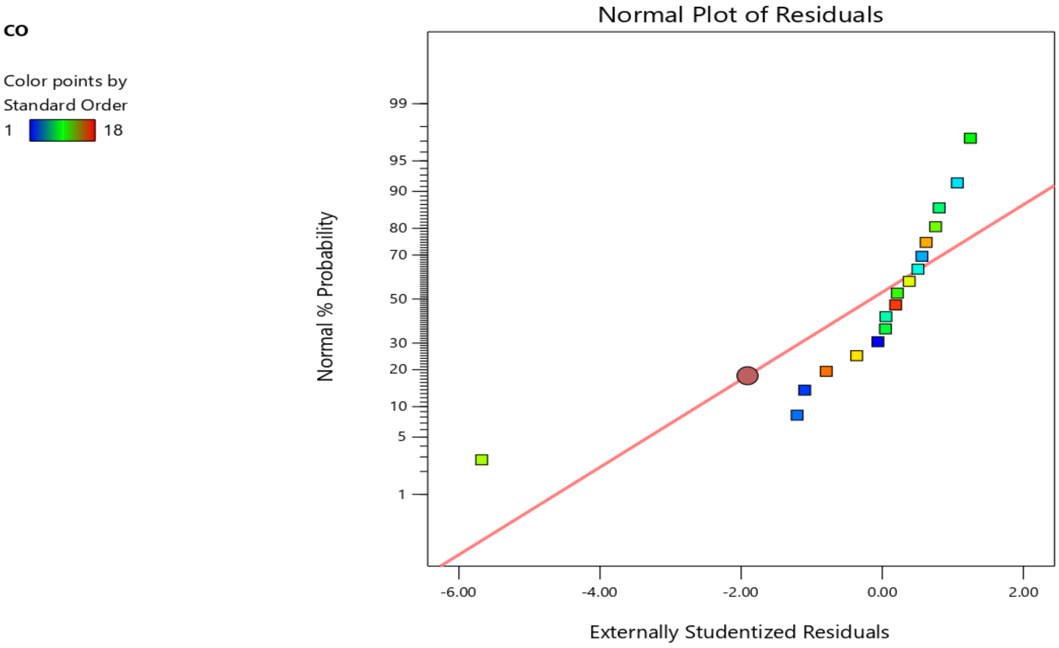


Figure 4.13: Normal % probability plot of residuals of CO

The normal probability Figure 4.14 of BSFC exhibits a normal distribution as it conforms to a straight line.

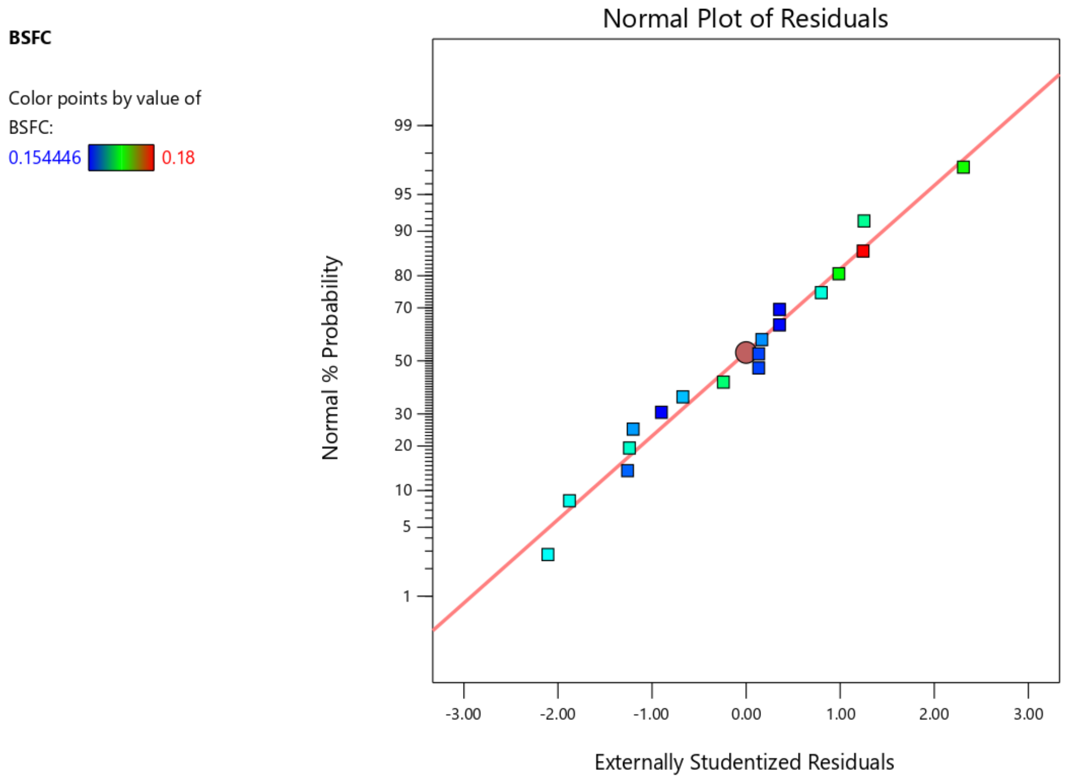


Figure 4.14: Normal % probability plot of residuals of BSFC

The normal probability Figure 4.15 for BTE displays a characteristic of a normal distribution as it aligns with a straight line, though some variations are present within the normal distribution data.

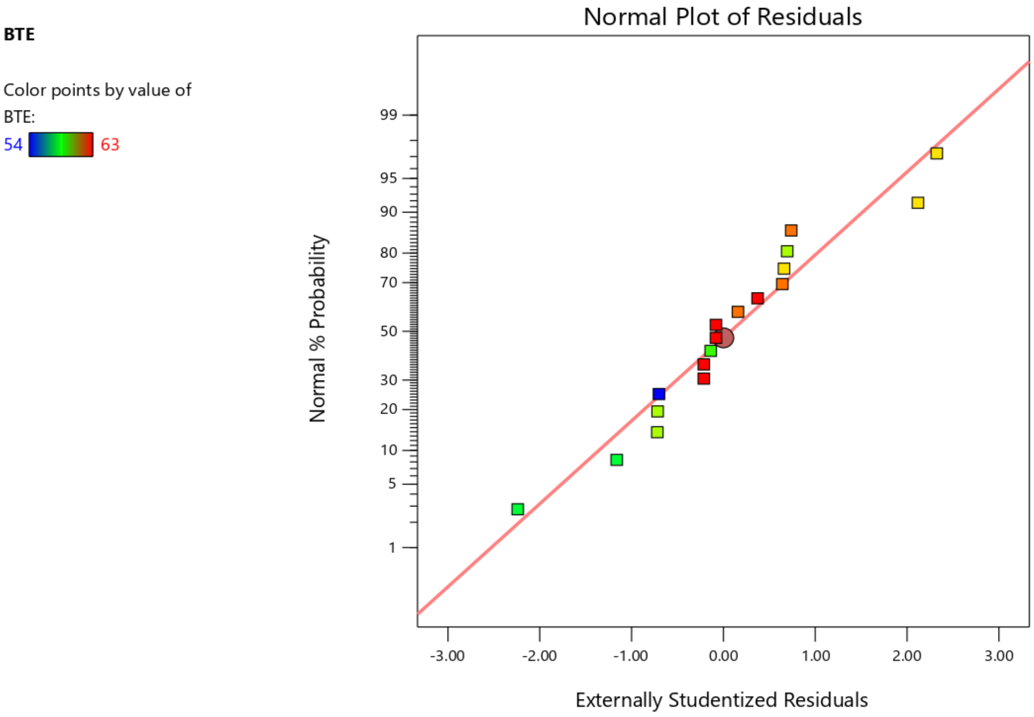


Figure 4.15: Normal % probability plot of residuals for BTE

Predicted vs. Actual response value: A line chart comparing the expected and actual response values. Finding an out-of-range value or range of values for the model is the goal of this activity. The following graphs are plots of predicted versus Actual for different response.

The residuals HC in Figure 4. 16 have a normal distribution, which is required for an analysis of variance to be valid. To examine variance homogeneity for ANOVA validation, residual vs. actual response plots were utilized. Figure 4.16 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings where the R^2 was 0.8789.

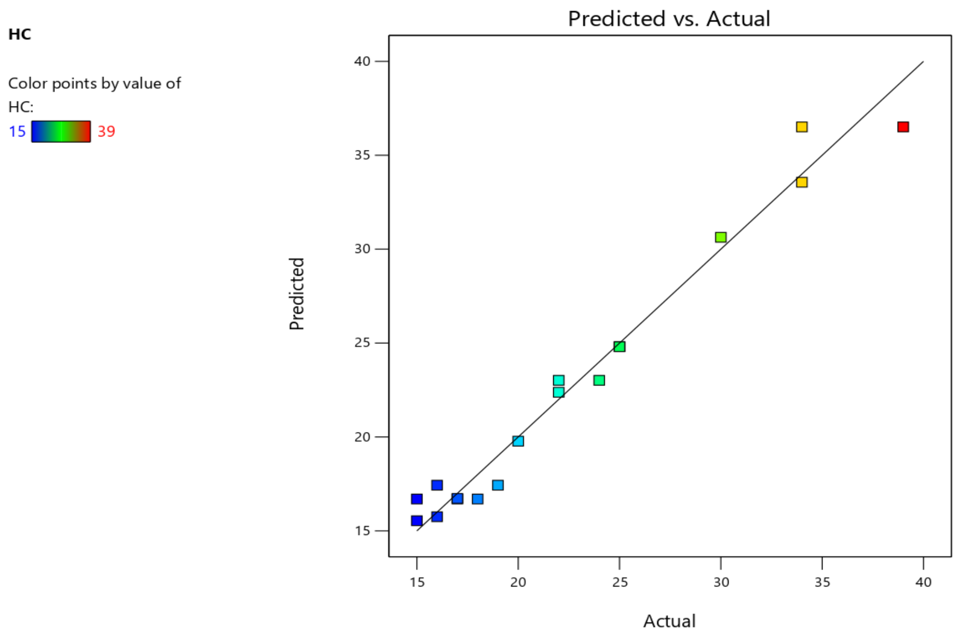


Figure 4.16: Actual and predicted values for HC

The residuals NOx in Figure 4.17 has a normal distribution, which is required for an analysis of variance to be valid. Figure 4.17 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings with the R2 of 0.6984.

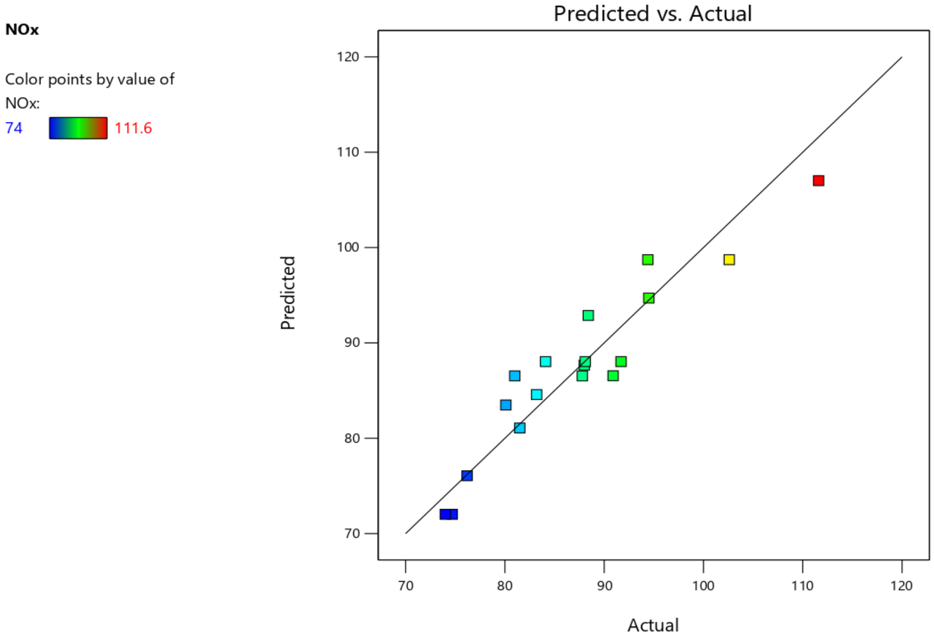


Figure 4.17: Actual and predicted values for NO$_x$

The residuals CO in Figure 4.18 have a normal distribution, Figure 4.18 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings.

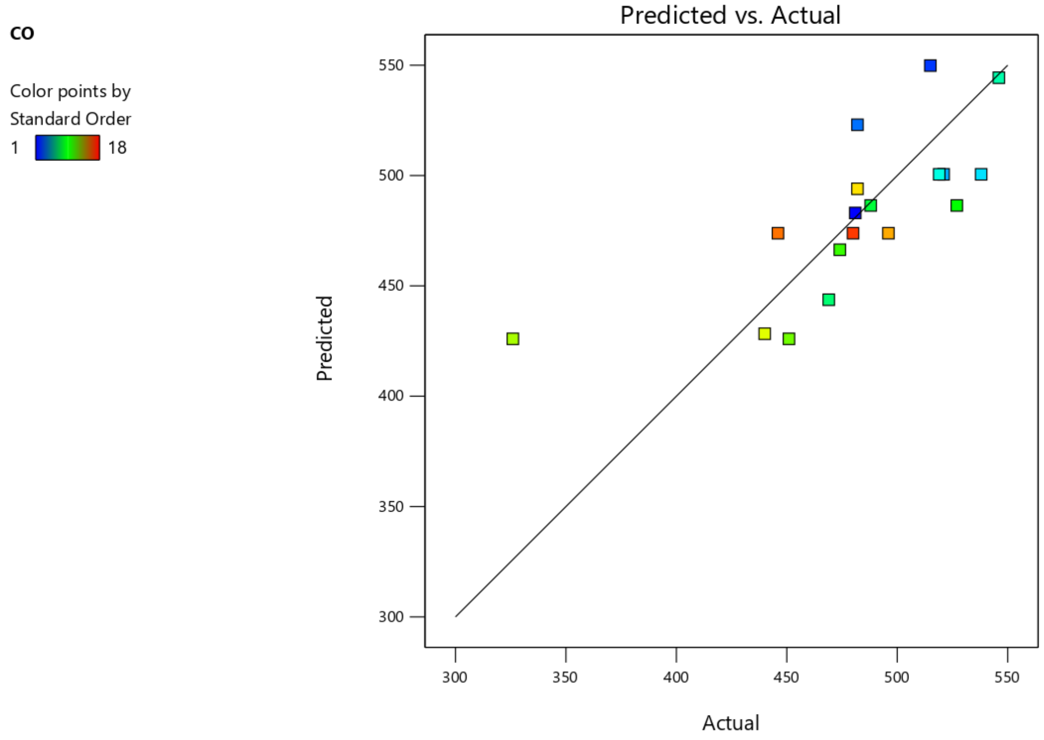


Figure 4.18: Actual and predicted values for CO

The residuals CO_2 in Figure 4.19 have a normal distribution, Figure 4.19 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings.

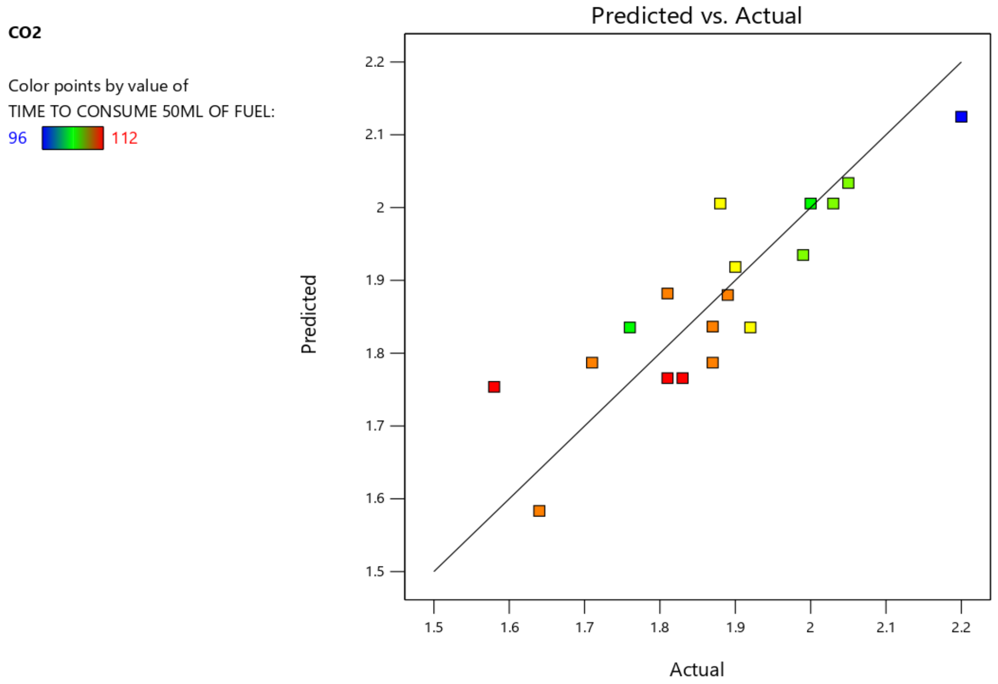


Figure 4.19: Actual and predicted values for CO_2

The residuals BSFC in Figure 4.20 have a normal distribution, Figure 4.20 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings.

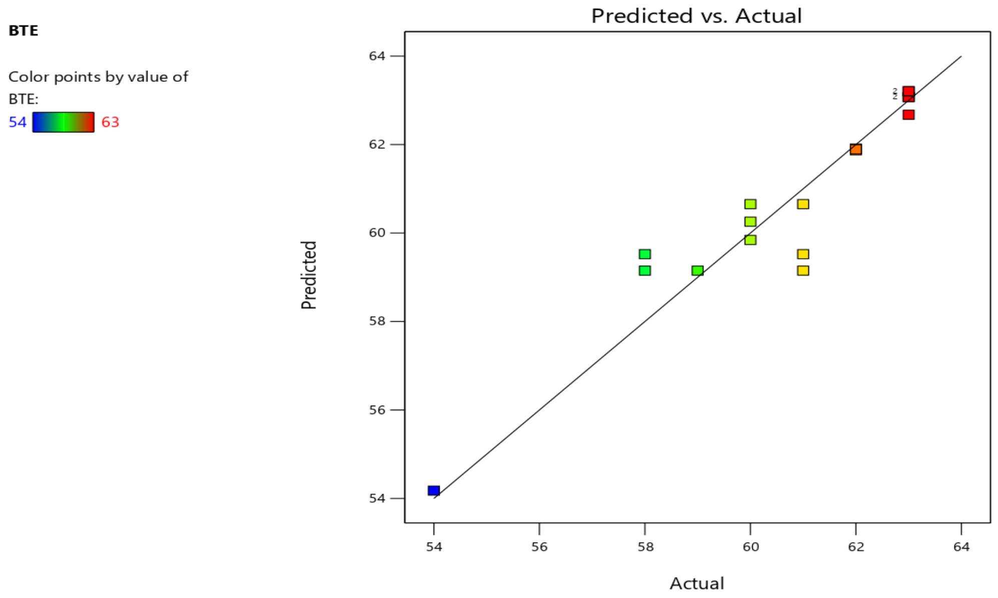


Figure 4.20: Actual and predicted values for BTE

The residuals BTE in Figure 4.21 have a normal distribution. Figure 4.21 depicts a reasonably accurate and strong connection between the model's predictions and the actual findings.

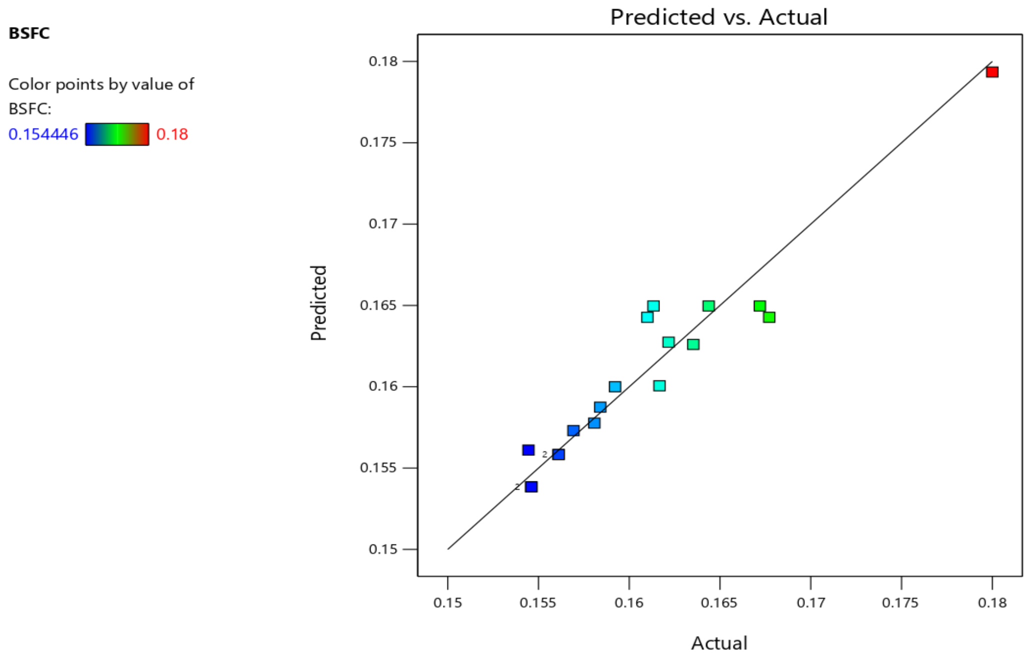


Figure 4.21: Actual and predicted values for BSFC

4.6 Residuals vs. Predicted

The residuals are plotted against the projected response values, and they are presented here in ascending order. The assumption of constant variance is put to the test as a result of this. The scatter plot ought to be completely random (constant range of residuals across the graph). The presence of expanding variance, sometimes known as the "megaphone pattern," reveals the necessity of a transition in this plot. The graphs at Appendix 26 to Appendix 31 are plots of residuals versus predicted of different response.

Residuals vs. Run: A plot of the residual’s vs the order in which the experimental runs were carried out. It investigates the possibility that there are undiscovered factors that influenced the results of the experiment. On the plot, the scatter should be completely random. The existence of trends suggests that there is a time-related variable operating in the background. Blocking and randomization are two methods that prevent trends from skewing the results of an analysis. The graphs at Appendix 32 to Appendix 36 are plots of residuals versus run.

4.7 Discussion

The data that was gathered from the experimental design matrix were used to create regression models, which were then used to evaluate the performance and emission characteristics of the engine. After that, these models were tested and optimized in order to achieve the desired goal, which is to reduce HC and NOx emissions as well as BSFC while simultaneously increasing BTE.

4.7.1 Analysis and evaluation of model

Analysis of Variance (ANOVA) was used to confirm the model's sufficiency because it provides quantitative data about the P-value. P values less than 0.05 indicated that the models were statistically significant within the framework of the ANOVA. Two statistics derived from the regression analysis, goodness of fit (R^2) and adjusted goodness of fit (Adjusted R^2), indicated that the model produced a superb fit to the data. Equation 15, Equation 16 and Equation 18 represent the projected responses based on quadratic models that were created in terms of non-dimensional coded factors. These models were used to forecast the responses. These equations hold true for the levels shown in Table 4.4 for the variables that are being entered. To make computations and analyses easier, the true ranges of the variables are sometimes converted into non-dimensional coded variables having a range of ±1.

The least-squares approach is a multiple regression technique that finds the best possible model fit to a given collection of experimental data. Model equations were constructed using this procedure, which allows for the fewest possible errors in setting the model to the data. For the purpose of defining the experimental data that were collected for NOx, HC, CO, BSFC, and BTE, it was determined that quadratic models were applicable. The assumed normality of the measured data was visually verified using normal probability plots. Relative distributions can be checked with this diagnostic plot. The residuals for NOx, HC, BTE, and BSFC have a normal distribution, which is a prerequisite for the validity of an analysis of variance (ANOVA). The residual vs actual response plots that were used to evaluate the homogeneity of variance for ANOVA validation. In general, the models were found to be reasonably accurate, and there is a high correlation between the model's predictions and the actual findings. For ANOVA and multiple regressions, this validates the model and helps evaluate whether the fit is significant for the second-order model

In the findings of ANOVA, the F-test was used to assess the models' statistical significance. Factors and their interactions were also examined statistically using F-statistics and Probability values (p) as shown in Appendix 14 to Appendix 20. Factors with higher F-statistics are more likely to have a significant impact on the response (Filgueiras et al., 2014) the relevance of each component was evaluated using probability values (p-values). To a greater extent, an effect's significance increases with decreasing p-value (Vera Candioti et al., 2014).

Even having a significant model does not necessarily guarantee that one can provide a comprehensive explanation for the differences in the data. The homogenous distribution of variance was established using diagnostic plots of normal probability and predicted vs actual values, which can be found in Figure 4.10 to Figure 4.21. Table

4.5 contains a listing of the created models along with a breakdown of the additional diagnostic factors that were employed in the evaluation. It is abundantly evident that the modified R^2 values of all of these models were likewise discovered to be high, which indicates that the models are accurate (Yolmeh et al., 2014). In addition to this, it should be mentioned that the high dependability of the experiments carried out is indicated by the low value of the coefficient of variation (CoV %) (Adalarasan et al., 2015). The values of CoV% for all models were found to be less than 10%.

From Table 4.5 under BTE, BSFC and CO a negative Predicted R^2 indicates that the overall mean may be a more accurate predictor of your answer than the model that is being used now. In certain circumstances, a higher-order model might also make more accurate predictions. The signal-to-noise ratio is evaluated to determine adequate precision. A ratio of at least 4 to 1 is ideal. An acceptable signal is shown by the ratios of 9.579, 12.177 and 6.049. The design space for NOx and HC can be explored using this approach. The difference between the Predicted R^2 of 0.3169 and 0.4321 and the Adjusted R^2 of 0.6984 and 0.8789, respectively, is higher than 0.2, which means that the model has a significant improvement in goodness of fit after taking into account the number of predictors used in the model. The higher the Adjusted R^2 value, the better the model fits the data, and the better it is at explaining the variability of the dependent variable based on the independent variables. There should be a ratio of at least 4 to 1.

Table 4.4: Factors Diesel Bio-diesel and Propanol

Component	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	DIESEL	86.36	75.00	100.00	0.0000	Actual
B	BIO-DIESEL	11.36	0.0000	25.00	0.0000	Actual
C	PROPANOL	2.27	0.0000	5.00	0.0000	Actual
	Total =	100.00				

Table 4.5: Displays fit statistics for the ANOVA, providing essential insights into the statistical model's adequacy and reliability.

Parameters	Std. Dev.	Mean	C.V. %	R²	Adjusted R²	Predicted R²	Adeq Precision
BTE	1.21	60.72	1.99	0.8466	0.6713	-2.0457	9.5785
BSFC	0.0027	0.1610	1.66	0.8945	0.7740	-4.1215	12.1765
NOx	4.24	87.38	4.85	0.7989	0.6983	0.3169	12.3825
HC	2.04	22.67	8.00	0.9516	0.8789	0.4321	12.5916
CO	38.84	482.28	8.054	0.3386	0.2369	-0.2750	6.0490

4.7.2 Brake Specific Fuel Consumption

Diesel and varied diesel, biodiesel, and propanol blends were tested for engine performance. These tests aimed to compare engine performance with blended fuel of varied ratios to mineral diesel and find the ideal high-performance blend by checking on the BSFC and BTE. All tests were run at 25N load, 2000 rpm, and 10kW braking power. Figure 4.22 shows the influence of blend ratios on brake fuel usage. BSFC measures the engine's efficiency in using fuel to produce work based on engine brake power and fuel mass flow rate, it's one of the most essential factors for evaluating engine performance with different fuels. From Figure 4.23 each blend ratio influences the BSFC. The effects of diesel fuel, biodiesel, and propanol concentrations on BSFC are depicted in Figure 4.22 and Figure 4.23. When the presence of propanol and biodiesel in ternary blends is compared to diesel fuel, there is a positive impact on the BSFC since less fuel is consumed while there is increase in power production. From Figure 4.23 the bluish, greenish and reddish zones denote low, medium and high levels of BSFC respectively.

Equation 16 was generated and will be used to predict the BSFC with any blend percentage ranging within the limits of the factors.

BSFC Equation

$$BSFC = 0.1778A + 0.1678B + 4.08C - 0.0812AB - 4.65AC + 2.20A^2BC + 7.65AB^2C - 21.89ABC^2 \qquad \textbf{Equation 16}$$

Where A = Diesel, B = Biodiesel and C= Propanol

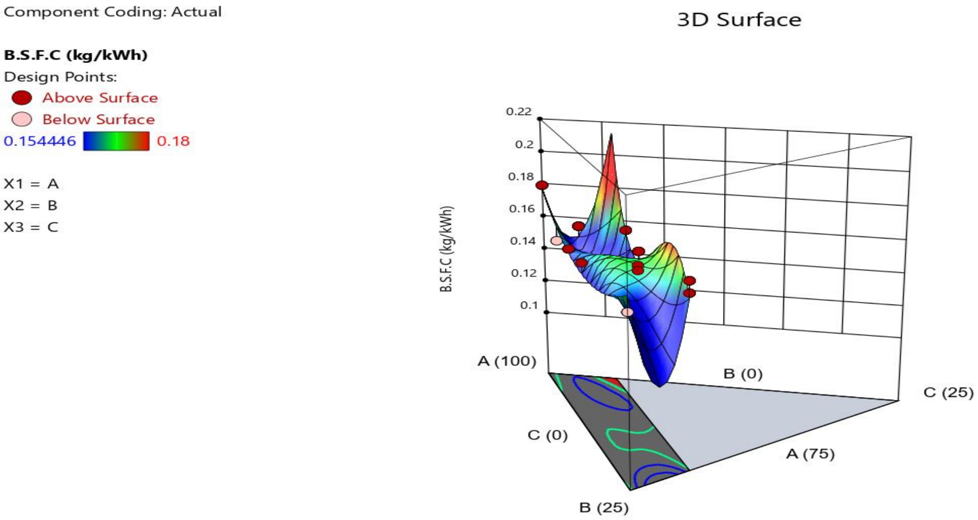


Figure 4.22: Illustrates how well BSFC performed in 3D Surface simulations with ternary blend of diesel, biodiesel, and propanol.

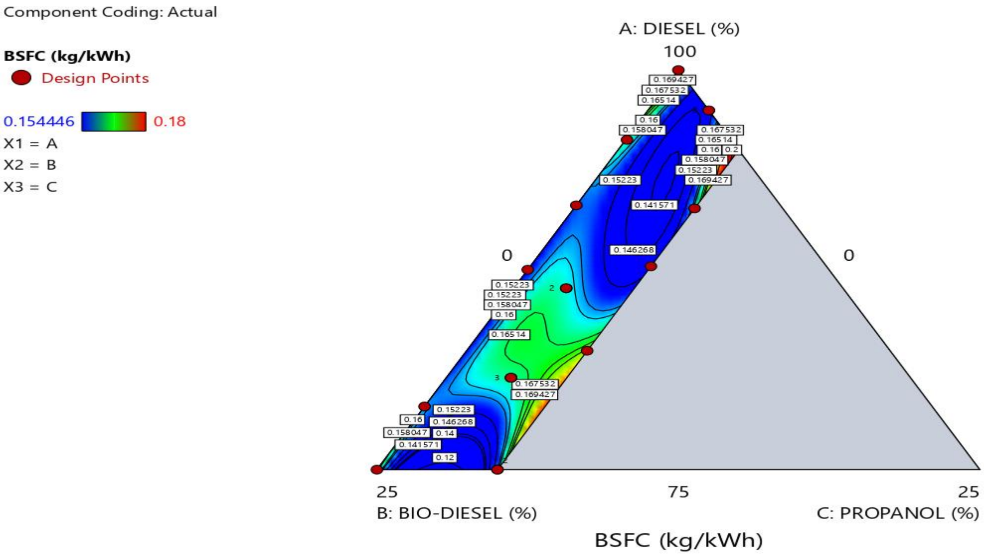


Figure 4.23: The Counter plot presents the results of the BSFC measurements about the performance of bio-diesel, diesel, and propanol

From Appendix 17 the Mixture Component coding is L Pseudo. Sum of squares is Type III – Partial the Model F-value of 7.42 implies the model is significant.

The effect that blending with a variable mix of diesel and bio-diesel has on BSFC can be seen in Figure 4.24 It is abundantly evident that the BSFC will improve in proportion to the amount of biodiesel included in the blend.

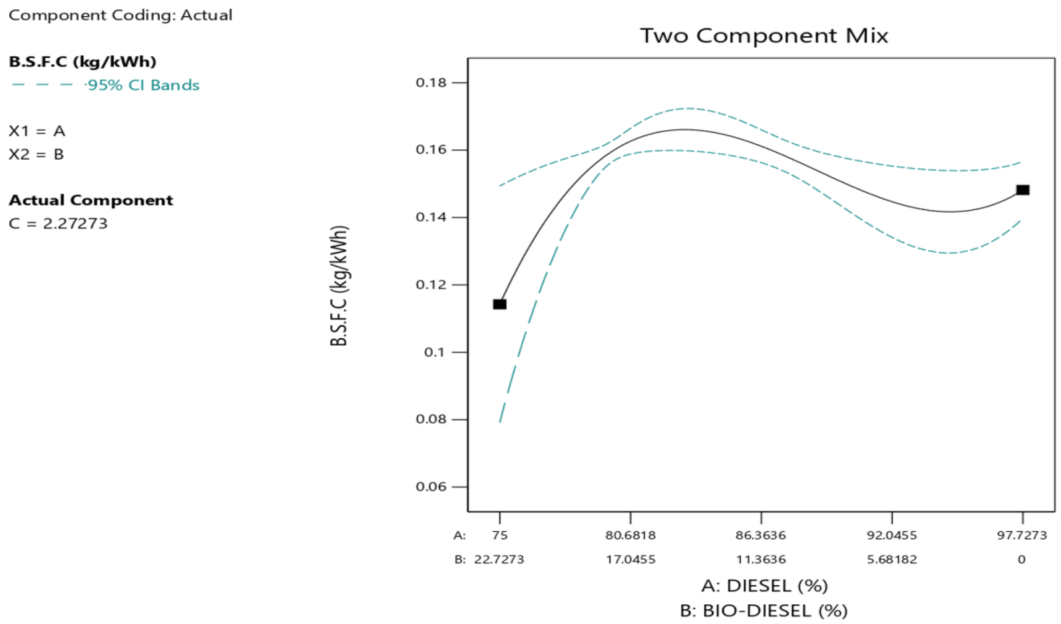


Figure 4.24: Demonstrates the performance of the BSFC when the diesel and bio-diesel ratios are varied while the propanol remains constant.

- According to Figure 4.25, it is evident that an increase in the proportion of propanol in the blend leads to an increase in brake specific fuel consumption (BSFC). This observation aligns with the findings of (Yasar, 2015) who reported a 19-22% increase in BSFC when the engine was fueled with a blend of 30% biodiesel and 20% propanol, as well as a blend of 30% biodiesel and 20% methanol. The study noted that an increase in BSFC of 19-22% was observed when the engine was fueled with biodiesel 30 propanol 20 and biodiesel 30 methanol 20, respectively. Oxygen makes about 26.7% of propane's weight. Increasing the oxygen concentration of the fuel reduces its calorific value, increasing the BSFC and necessitating more fuel to maintain the same engine performance (Kumar et al., 2013; Yilmaz & Vigil, 2014)

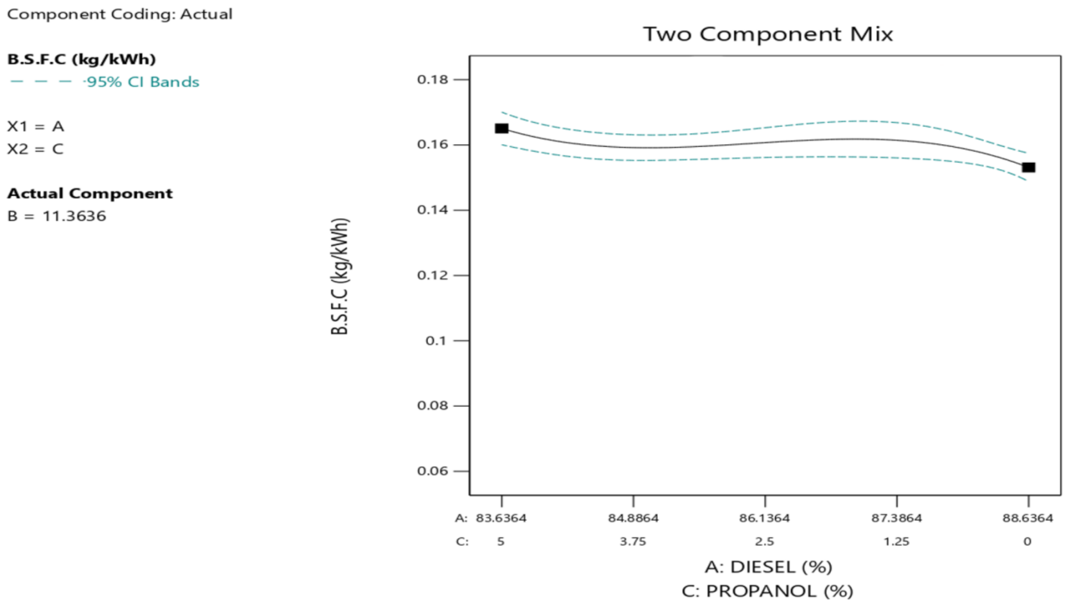


Figure 4.25: Depicts the performance of the BSFC when the diesel and propanol ratios are varied while the bio-diesel remains constant.

Figure 4.26 demonstrates that the addition of propanol to biodiesel does not have a significant impact on BSFC.

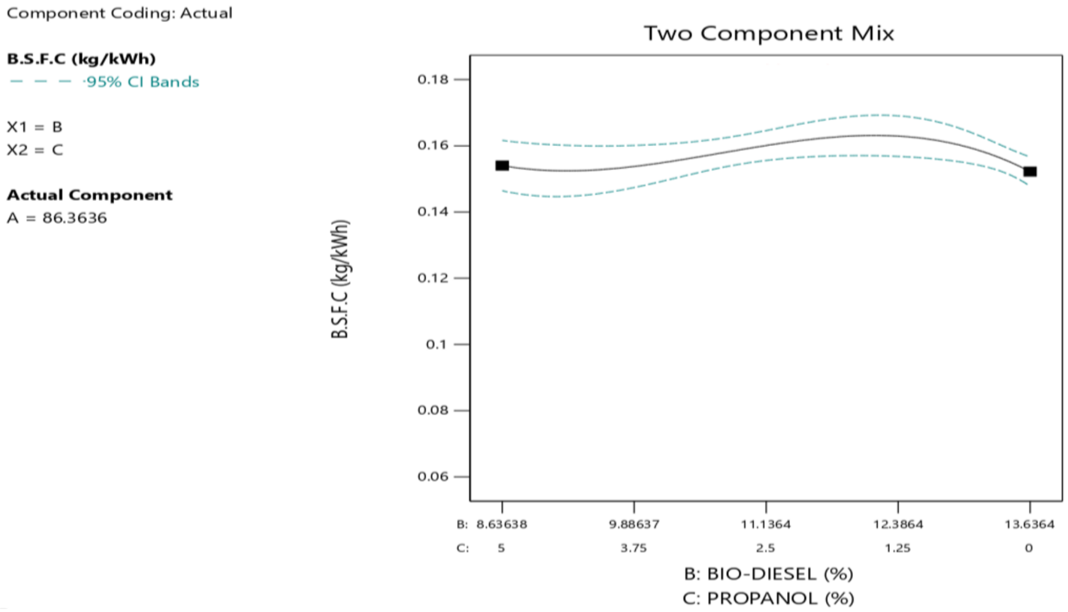


Figure 4.26: Demonstrates the performance of the BSFC when the biodiesel and propanol ratios are varied while the diesel remains constant.

4.7.3 BTE

The Figure 4.27 and Figure 4.28 shows the response surface and contour plots depicting the interaction effect of using different ratios of ternary blend of diesel, biodiesel and propanol on BTE the engine running at a constant speed and brake power of 2000 rpm and 10 kW, respectively. The blue, green, and red areas represent low, medium, and high concentrations of BTE, respectively. From ANOVA in Appendix 18 it could be seen different ratios of diesel, biodiesel and propanol has significant effects on BTE. From Figure 4.28 it’s clear that the reddish regions were found to deliver maximum BTE, with example of BTE of 75.49% and 67.61% for blends of 75.16% diesel, 22.25% biodiesel, 2.59% propanol and 93.44% diesel, 3.74% biodiesel, 2.82% propanol respectively. The bluish region shows the minimum BTE, of 44.58% for a 95.02% diesel, 0.04% biodiesel, and 4.94% propanol blend.

The addition of biodiesel and propanol to diesel, depending on their proportions, influences Brake Thermal Efficiency (BTE). This relationship aligns with the principle that BTE tends to rise as Brake Specific Fuel Consumption (BSFC) decreases, as supported by (Atmanli, 2016). Introducing propanol alcohols into the diesel-biodiesel mix notably enhances BTE, a finding consistent with research by (Campos-Fernández et al., 2012). Similarly, other studies, such as (Zhang & Balasubramanian, 2016) have observed increased BTE in butanol-biodiesel and pentanol-biodiesel blends, particularly at higher engine loads.

The examples and Figure 4.28 show that diesel blended with more propanol than biodiesel has a lower BTE than diesel blended with more biodiesel than propanol.

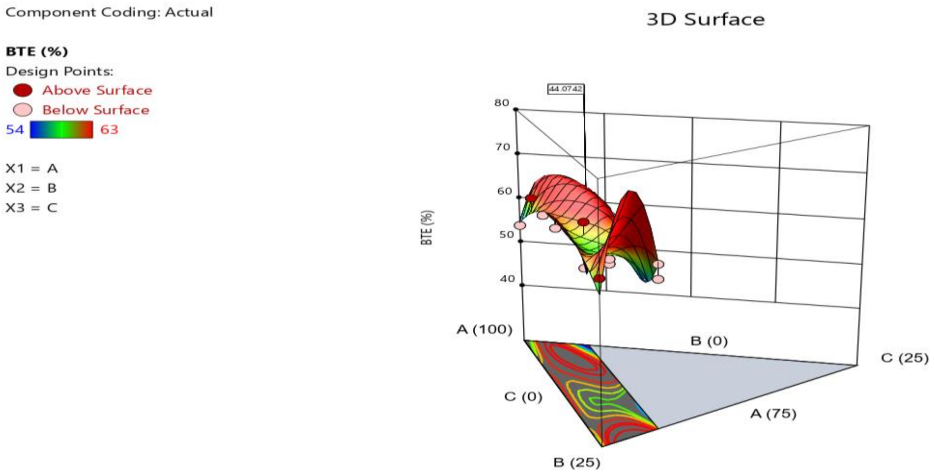


Figure 4.27: Illustrates how well BTE performed in 3D Surface simulations when it was blended with diesel, biodiesel, and propanol.

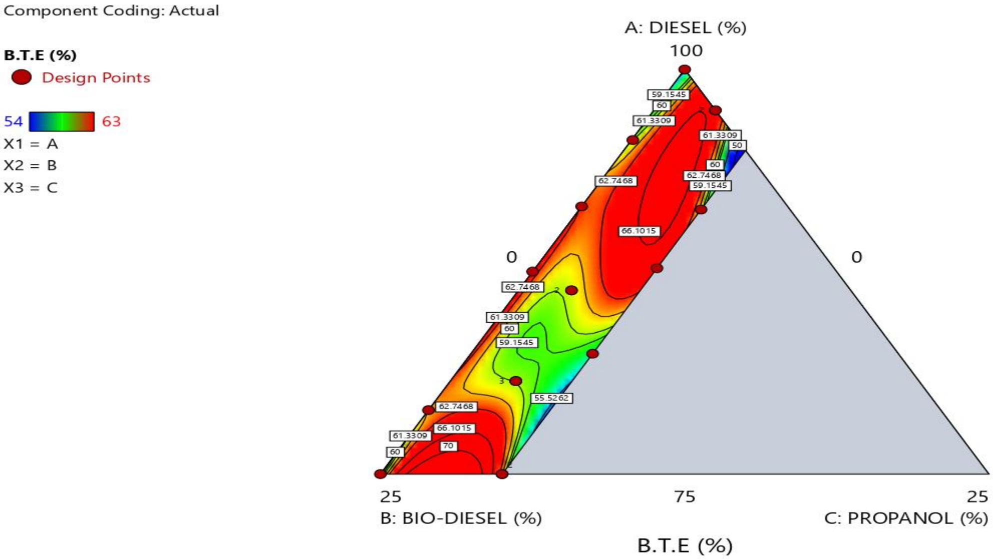


Figure 4.28: The Counter plot presents the results of the BTE measurements about the performance of bio-diesel, diesel, and propanol.

While increasing the amount of biodiesel in the blend and decreasing the proportion of diesel while maintaining the propanol level at 0.386%, the BTE is found to increase as shown in Figure 4.29.

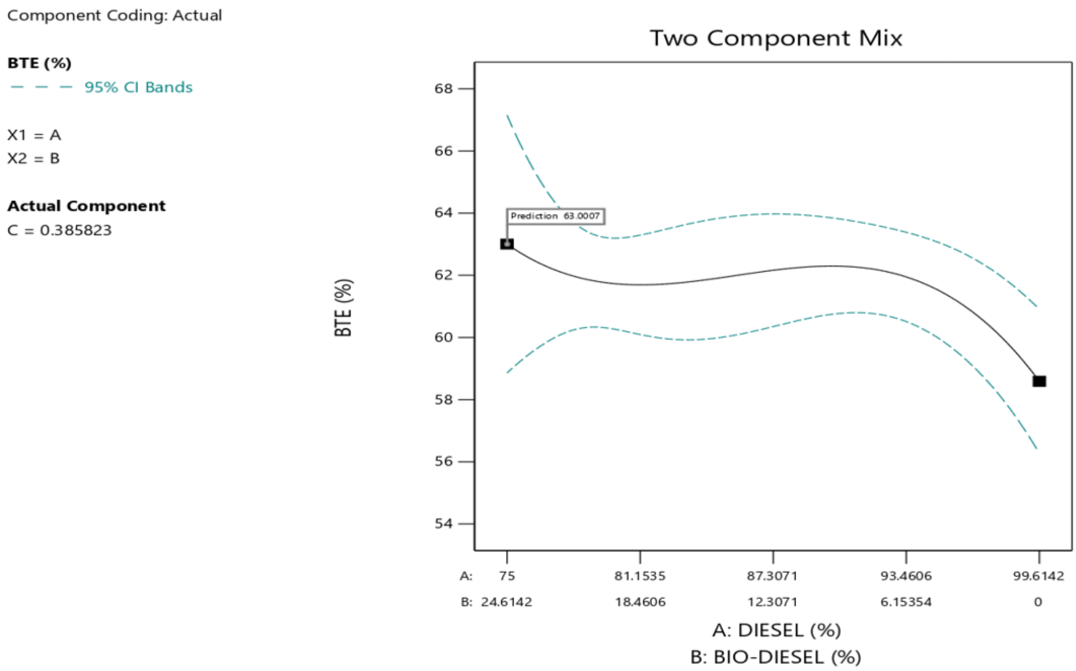


Figure 4.29: Demonstrates the performance of BTE when diesel and biodiesel are blended.

The fact that the Model F-value in Appendix 18 is 4.83 suggests that the model is significant. An F-value of this magnitude occurring as a result of noise has only a 2.60 percent chance of happening by chance. P-values that are lower than 0.0500 suggest that the model terms under consideration are significant.

NOx emissions

From the results, the response surface and contour plots depicting the interaction effect of different ternary blends with NOx emissions with engine running at the constant speed and brake power of 2000 rpm and 10 kW, respectively. The blue, green, and red sections, respectively, represent low, medium, and high NOx concentrations. According to ANOVA from Appendix 19 for NOx, each factor with different ratios at the blend has a significant effect on NOx emissions. This is evident from Figure 4.30 the 'bluish' low and 'greenish' mid-level NOx regions that were spread across. NOx emissions were found to be lower and optimal with a range of 78.22 ppm of blends ranging with different ratios such us 83.93%, 14.84% and 1.23% of diesel biodiesel and propanol respectively. NOx was also found to be high with 99.5 ppm with average blends of 98.5%, 1.75% and 3.5% of diesel, biodiesel and propanol respectively so from modifying the ratio of diesel in the mix it indeed influenced the creation of NOx. At higher temperatures, the nitrogen released into the air by the burning of diesel fuel mixes with oxygen to produce NOx. Diesel has a higher nitrogen concentration than other alternative fuels, hence using a higher diesel ratio may increase NOx emissions. The generation of NOx during combustion can be affected by varying the diesel ratio and using alternative fuels like biodiesel or propanol, which may have different combustion properties and lower nitrogen concentration. Diesel, biodiesel (B100), and blends containing propanol and pentanol were all studied for their NOx emissions (Yilmaz et al., 2018b) . It's mentioned that because of their lower cetane values, B100 and diesel, biodiesel (DB) generates less nitrogen oxide (NOx) than regular diesel does. At low and medium engine loads, the NOx emissions from diesel-biodiesel-vegetable-oil and propanol blends and diesel-biodiesel-vegetable-oil-and-pentanol blends are lower than those from diesel. Propanol and pentanol's properties of absorbing more heat during vaporization lead to lower exhaust gas temperatures and hence reduced NOx emissions, however these blends exhibit a modest rise in NOx emissions as the engine load increases (Yilmaz et al., 2018b). (Yasar, 2015) findings of the study suggest that propanol may be a more effective additive compared to methanol, and it has the potential to be a viable option for enhancing biodiesel by addressing the issue of NOx emissions. According to the findings of (Bencheikh et al., 2019) adding Pro greatly lowers NOx emissions while adding biodiesel raises them. However, the NOx emissions are still below the level of D100 because Pro is present in the ternary blends.

From Equation 17 pure diesel will give 99.71 ppm which is 100% of diesel, it’s clear that any addition of propanol or biodiesel reduces the ppm of NOx produced. Utilize

Equation 17 to achieve the NOx level while ensuring compliance within the permissible range of the remaining parameters.

$$NOx = +0.997097\mathrm{A} + 4.79076\mathrm{B} + 105.56833\mathrm{C} - 0.059697\,\mathrm{AB} - 1.12319\mathrm{AC} - 0.881950\mathrm{BC} \qquad \textbf{Equation 17}$$

Where A = Diesel, B = Biodiesel and C= Propanol

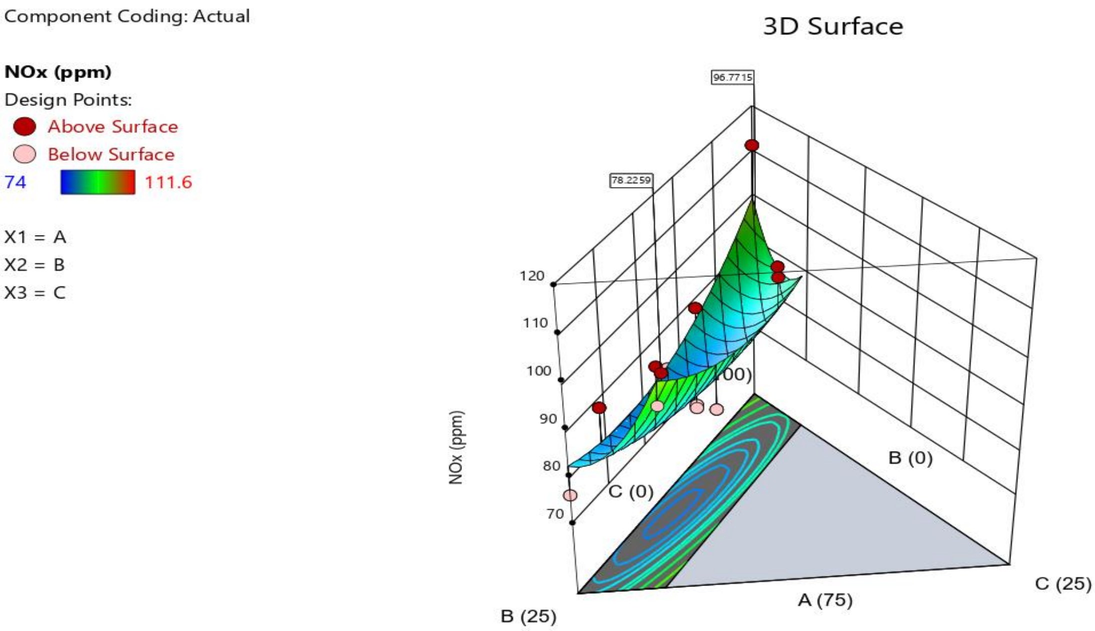


Figure 4.30: Illustrates how well NOx performed in 3D Surface simulations when it was blended with diesel, biodiesel, and propanol.

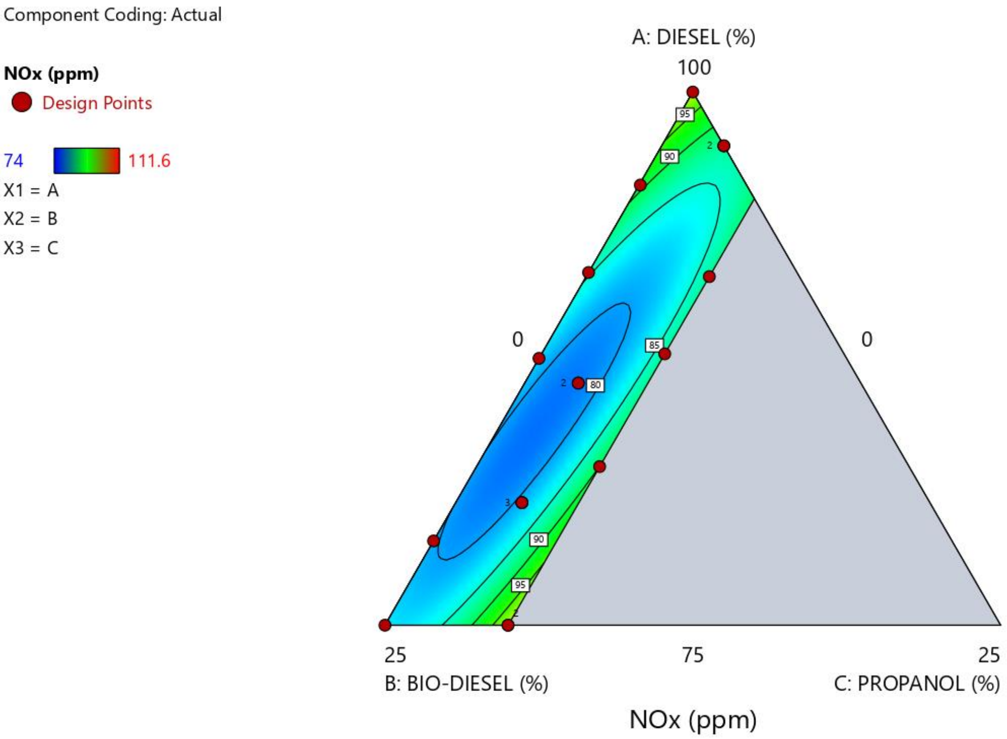


Figure 4.31: The Counter plot presents the results of the NOx measurements about the performance of bio-diesel, diesel, and propanol.

The model is statistically significant with an F-value of 7.95, as shown in Appendix 19. An F-value this high could only happen by chance 0.29 percent of the time. With a p-value below 0.0500, the model terms are significant.

4.7.4 HC emissions

With the use of the response surface and contour plots shown in Figure 4.32 and Figure 4.33 we can see how different ratios of diesel, biodiesel, and propanol have an impact on HC emissions. The blue, green, and reddish areas represent varying degrees of HC emission. Different ratios of fuel blends have a significant effect on HC emissions as suggested by ANOVA from Appendix 20 where HC emissions were found to increase with the addition of more propanol the increased emissions stem from alcohols having a high energy requirement for vaporization, leading to incomplete combustion. This pattern aligns with findings from (Yasar, 2015) and (Yilmaz & Vigil, 2014) who observed similar trends. In terms of CO emissions, incomplete combustion contributes to unburned hydrocarbon (HC) emissions. Comparatively, a 10% alcohol content in diesel-biodiesel-alcohol blends produces higher unburned HC emissions than a combination of 5% alcohol and 5% vegetable oil in diesel-biodiesel-alcohol-vegetable oil blends, as indicated in Figure 4.2. Notably, increasing the biodiesel ratio decreases HC emissions due to the influence of complete combustion facilitated by the presence of oxygen molecules in Biodiesel, as suggested by (Yasar, 2015).

From Appendix 20 the Model F-value of 13.10 implies the model is significant.

Utilize Equation 18 to achieve HC level while ensuring compliance within the permissible range of the remaining parameters. It is necessary to specify the levels for each factor in their original units here. This equation cannot be used to assess the relative impact of each factor as the coefficients are scaled to suit the units of each element, and the intercept is not located at the geometric center of the design space.

$$\begin{aligned} HC = {} & 0.224695\mathrm{A} - 16.57309\mathrm{B} - 433114.88446\mathrm{C} \\ & + 0.252727\mathrm{AB} + 66344785\mathrm{AC} - 4.702218\mathrm{ABC} \\ & - 0.000693\mathrm{AB}(\mathrm{A}-\mathrm{B}) - 2.32835\mathrm{AC}(\mathrm{A}-\mathrm{C}) \\ & - 2.31777\mathrm{BC}(\mathrm{B}-\mathrm{C}) \end{aligned}$$ **Equation** 18

Where A = Diesel, B = Biodiesel and C= Propanol

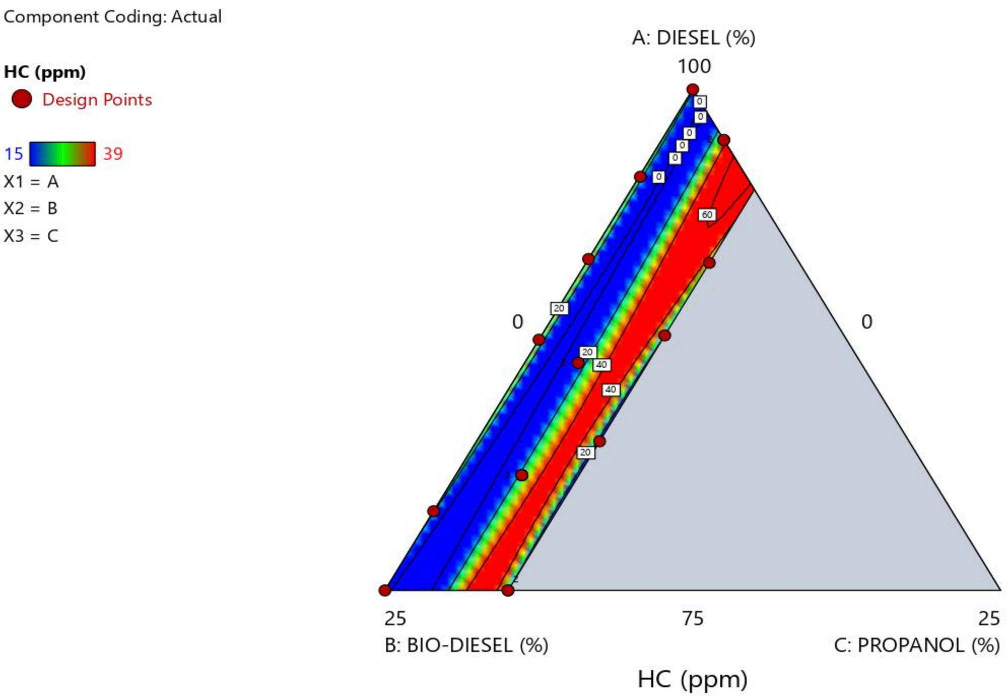


Figure 4.32: The Counter plot presents the results of the HC measurements about the performance of bio-diesel, diesel, and propanol

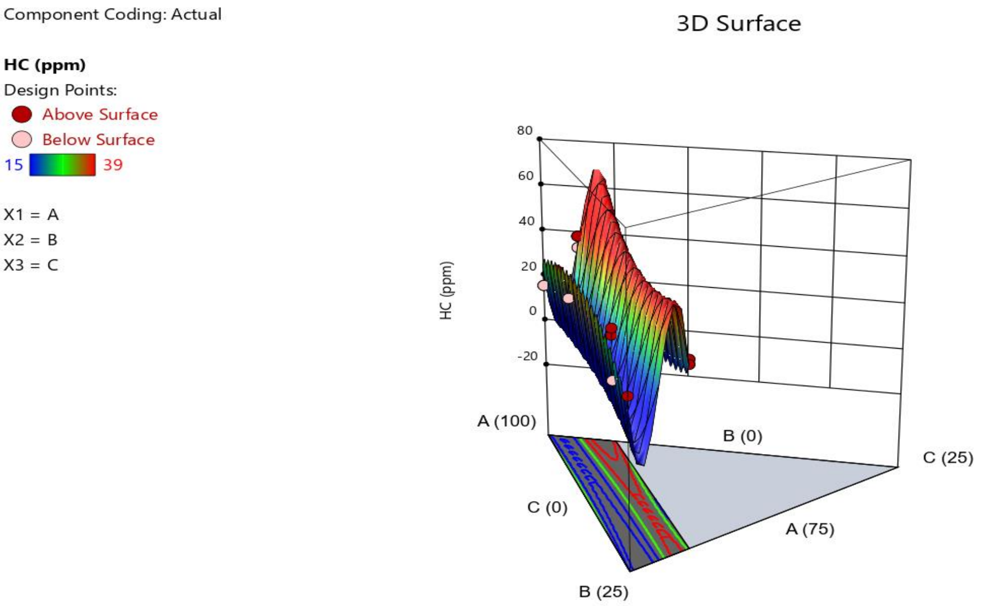


Figure 4.33: Illustrates how well HC performed in 3D Surface simulations when it was blended with diesel, biodiesel, and propanol.

4.8 Optimization

The goal of the optimization is to find propanol, biodiesel, and diesel blend that produces the lowest possible emissions and BSFC. The study results list the optimization criteria employed for achieving the objective of maximum BTE with minimum possible BSFC and minimum emissions.

1. Each variable was given the utmost consideration. A software Design Expert v13 was used to provide the best possible options, achieved by a strategy based on desire and according to the parameters specified. Among all the permutations that meet the optimization criteria, the top three solutions were the most desirable. With a maximum desirability of 0.828, the blend with 75.010 % diesel, 24.604 % biodiesel, and 0.386 % propanol is thought to give optimal emission and performance characteristics. The other highly desirable blends were made available as well. An optimization-derived bar chart depicting the relative desirability of all constraints for the 5 solutions is given in Figure 4.36, 4.37, 4.38, 4.39 ,4.40. According to (Najafi et al., 2015b)), RSM was successful in balancing engine output with exhaust emissions. Design of Experiments based on RSM made it easier to plan and execute experiments in a systematic fashion. The most important factors impacting emissions and performance were identified with the aid of statistical analysis. This study greatly shortened the time needed for experiments by using this experimental design. By doing as few experiments as possible while yet building statistically robust models for all response variables, this decrease was possible.(Hirkude & Padalkar, 2014) concluded that they conducted statistical analysis using Response Surface Methodology (RSM) based on a design of experiments. The purpose of this method was to determine which operating conditions most affected

performance and smoke characteristics. Within RSM, they used the desirability technique to zero down on the best settings for improving performance while cutting down on smoke. This strategy assisted in identifying the optimal set of conditions for maximizing efficiency and minimizing smoke output.

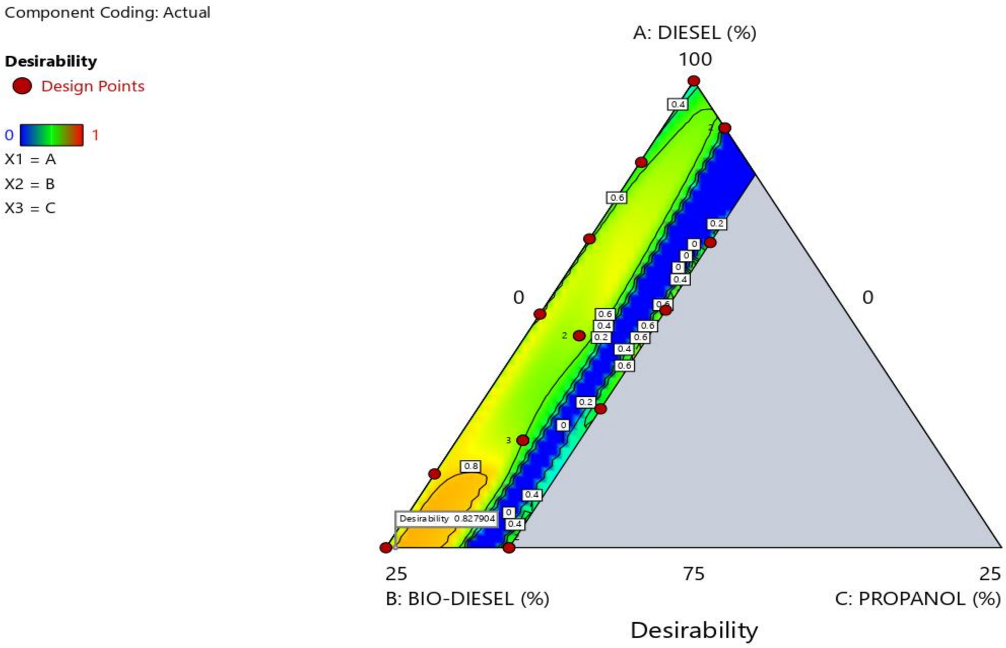


Figure 4.34: Displays a desirability counterplot with a value of 0.828 for blends of diesel, bio-diesel, and propanol.

Figure 4.35 makes it abundantly evident that when keeping the % of propanol at 0.386%, the desirability is observed to decline with decreasing the % of bio-diesel and increasing the % of diesel.

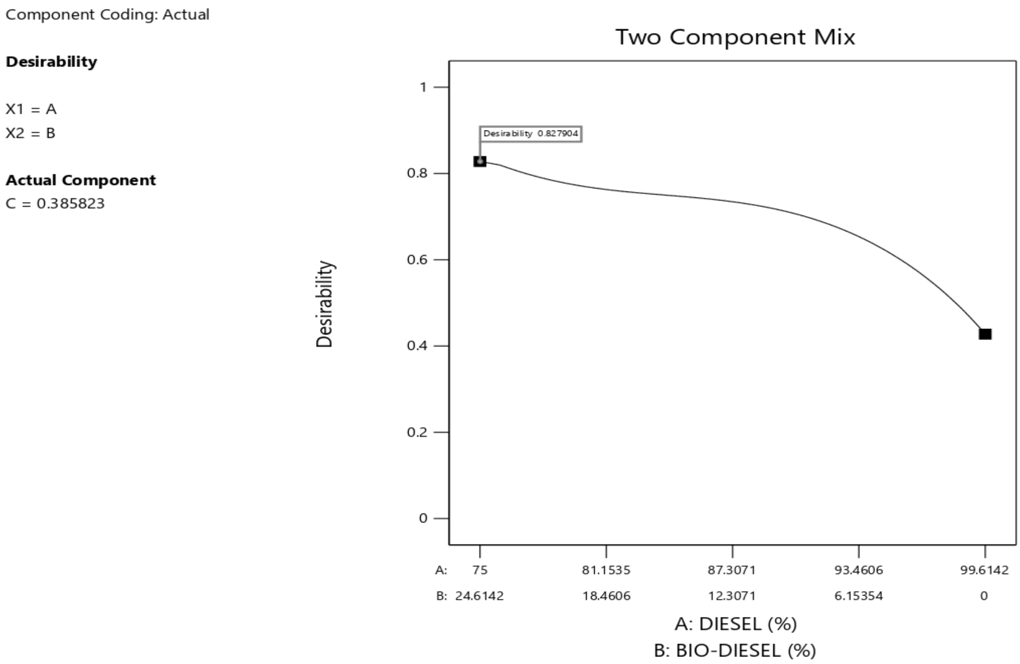


Figure 4.35: Depicts the Desirability plot for diesel and biodiesel while holding propanol constant.

Figure 4.36 Illustrates the desirability of the first optimal solution, which uses a combination of 75.010% diesel, 24.604% biodiesel and 0.386% propanol, when minimizing BSFC, CO, HC, and NOx and maximizing BTE.

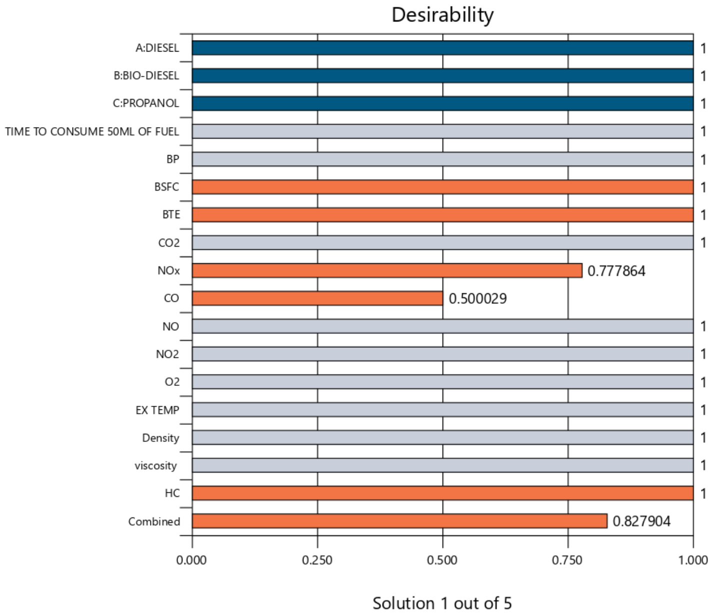


Figure 4.36: Bar graph shows the desirability of solution 1 of Appendix 10

Figure 4.37 Illustrates the desirability of the first optimal solution, which uses a combination of 80.893% diesel, 18.906% biodiesel, and 0.201% propanol, when minimizing BSFC, CO, HC, and NOx and maximizing BTE.

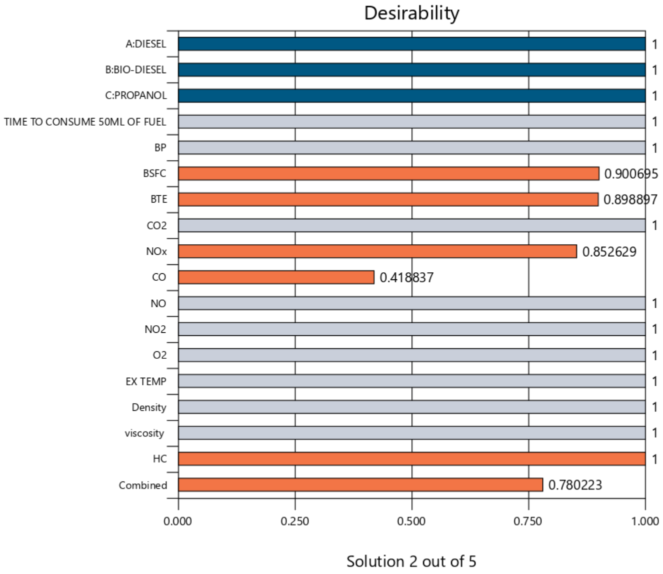


Figure 4.37: Bar graph shows the desirability of solution 2 of Appendix 10

Figure 4.38 Illustrates the desirability of the first optimal solution, which uses a combination of 88.867% diesel, 8.906% biodiesel, and 2.227% propanol, when minimizing BSFC, CO, HC, and NOx and maximizing BTE.

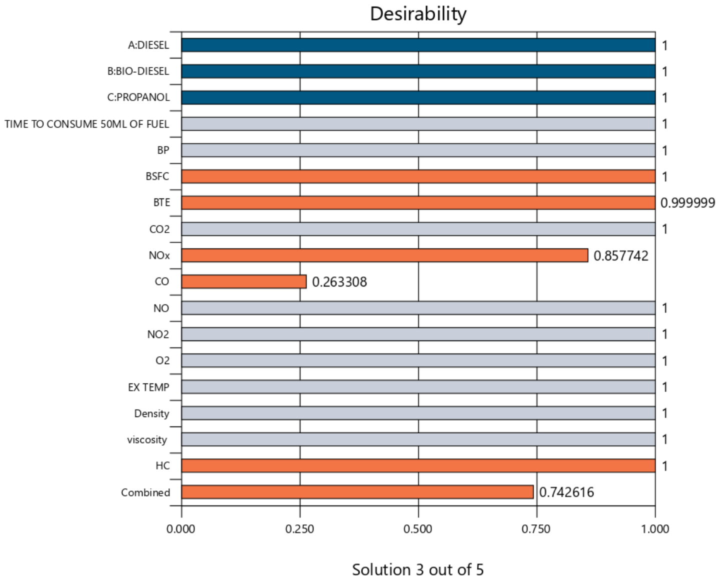


Figure 4.38: Bar graph shows the desirability of solution 3 of Appendix 10

Figure 4.39 Illustrates the desirability of the first optimal solution, which uses a combination of 79.565% diesel, 20.435% biodiesel, and 0% propanol, when minimizing BSFC, CO, HC, and NOx and maximizing BTE.

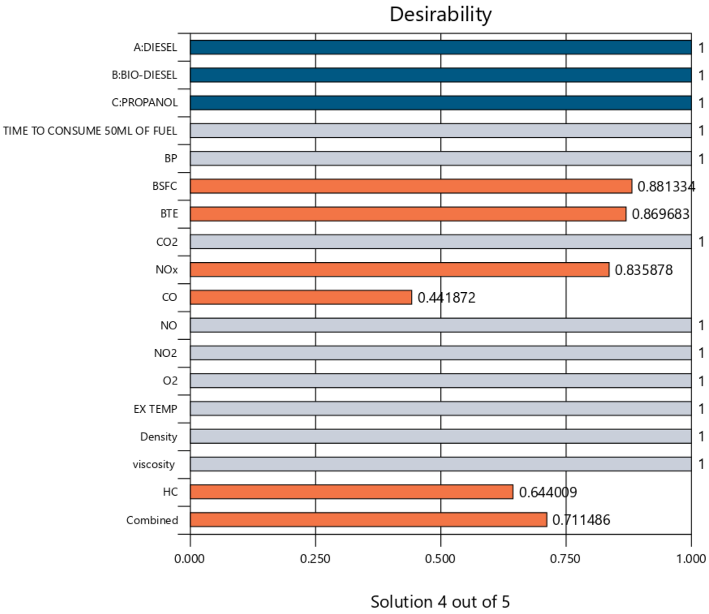


Figure 4.39: Bar graph shows the desirability of solution 4 of Appendix 10

Figure 4.40 Illustrates the desirability of the first optimal solution, which uses a combination of 86.235% diesel, 8.765% biodiesel, and 5% propanol, when minimizing BSFC, CO, HC, and NOx and maximizing BTE.

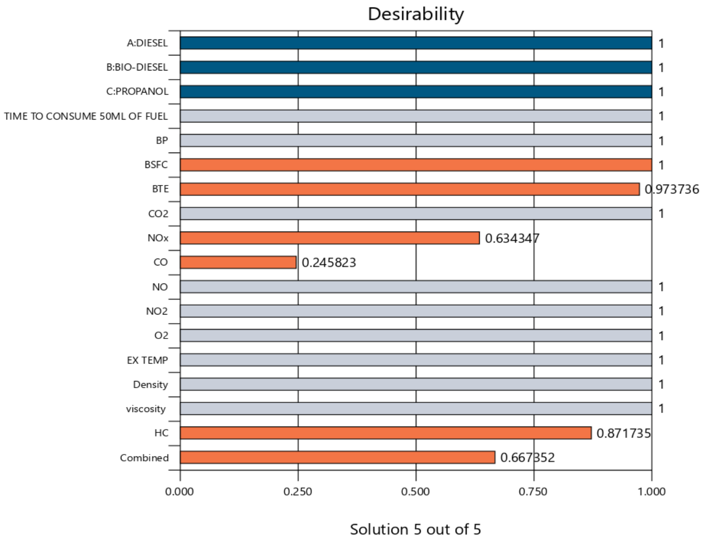


Figure 4.40: Bar graph shows the desirability of solution 5 of Appendix 10

The physical properties of the ternary blend of the optimal blend are as in Appendix 11

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The aim of this research was to determine the optimum ternary blend ratio of diesel, biodiesel and propanol that improve the engine performance and lower emissions

Employing a 3x3 complete factorial experimental design matrix, a response surface methodology-based optimization method was applied to blend propanol with biodiesel and diesel to get the best possible emissions and performance in the CI diesel engine. The ternary blends of the three fuels with different ratios percentages ranging from 75% to 100% of diesel, 0% to 25% of biodiesel and 0% to 5% of propanol were chosen as factors and their levels. Respondent-surface methodology (RSM) and the desirability approach (DA) were used to model and predict NO_X, HC, CO_2 and BSFC and BTE measurements from the full-factorial experimental design matrix. Based on the analysis, the following conclusion were drawn:

1. The physical properties of the ternary blend of diesel, biodiesel and propanol were as follows

   a. The ternary blend was effectively mixed, and no phase separation was observed during the process and after storage.
   b. The optimal fuel has only a few differences in physical properties from diesel fuel in its purest form. The density and viscosity of the diesel, bio-diesel, and propanol blend are both 0.97 and 4.37 cP, respectively, whereas those of pure diesel are 0.95 and 6.45, respectively. The density increased by 2.1% while the viscosity went down by 32.2%. A pH of 7.8 was achieved in the ternary mixture. In spite of being stored for an extended period of time, the ternary blend fuel

did not change color or develop any noticeable residue. The fuel's lifespan has to be studied further.

c. The optimal ternary blend closely resembles pure diesel fuel in physical properties, with minor differences in density and viscosity. Its neutral pH and stability during storage make it a promising alternative with potential advantages for specific applications, including environmental and fuel quality considerations.

2. RSM was able to successfully optimize the performance of the internal combustion engine while it was operating with a variety of ternary mixes.
   - The engine performance improved when using ternary blend by 9% and 15% in BTE and BSFC respectively by desiring to maximize BTE and minimize BSFC, NOx, HC and CO
   - The optimization criteria were used to minimize BSFC, CO, HC, and NOx while maximize BTE. The ternary blend diesel 75.01 % -biodiesel 24.604 % and -Propanol 0.386 % run at constant speed of 2000rpm and brake power of 10kW is predicted to deliver optimum emission and performance characteristics with a maximum desirability of 0.828 using the desirability approach.
   - BTE reached 63.001%, highlighting enhanced power generation, and BSFC decreased to 0.153%, indicating improved fuel efficiency.
   - The top five solutions with optimization criteria to minimize BSFC, CO, HC, and NOx and maximize BTE with engine fueled with the ternary blend predicted by desirability approach had desirability of 0.828, 0.78, 0.743, 0.711 and 0.667.

- The carefully crafted ternary blend offers a compelling solution that enhances engine efficiency, reduces emissions, and aligns with environmental and performance objectives.

3. The analysis of exhaust gas emissions revealed that the optimal ternary blend had lower levels of NO_X (82.34 ppm), CO (436.03 ppm), and HC (4.872) compared to pure diesel. Specifically, there were decreases of 12.87%, 15.26%, and 75% for NO_X, CO, and HC respectively. These emission reductions signify a positive environmental impact, contributing to cleaner and more sustainable engine operation.
4. The study found that when optimizing for different criteria such as minimizing BSFC and maximizing BTE, different blend ratios and desirability of the blends were obtained. For example, when minimizing BSFC and HC and maximizing BTE, 39 solutions were generated with the top solutions having a desirability of 1.00. Similarly, when minimizing BSFC and NO_x and maximizing BTE, different blend ratios and desirability of the blends were obtained. Furthermore, when considering to minimize CO_2, BSFC and maximize BTE, different blend ratios and desirability of the blends were obtained. The study also found that when maximizing BTE without considering the emissions 65 solutions were generated with a desirability of 1.00 as shown in Appendix 121.

5.2 Recommendation

- Based on the results, it can be recommended to use the ternary blend of diesel, biodiesel, and propanol as a fuel for internal combustion engines as it has improved engine performance (9% improvement in BTE and 15% in BSFC) and lower emissions (decreased NO_X by 12.87%, CO by 15.26%, and HC by 75%). The optimal blend for performance and emissions was found to be diesel

75.01%, biodiesel 24.604%, and propanol 0.386%. The findings of the research can be applied in real-world settings by encouraging the use of ternary blends in transportation and power generation, potentially reducing emissions and dependence on traditional diesel fuel. Based on the research, policymakers should consider promoting the use of ternary blends in compression ignition engines to reduce environmental impact and promote sustainability. This could be achieved through incentives and regulations supporting the adoption of these fuels.

Additionally, we recommend that future studies investigate the long-term effects of using ternary fuel blends on engine components. This could be done by conducting durability tests and monitoring emissions over extended periods of use. In addition, we recommend that future research also investigate the possibility of using other biofuels such as bioethanol or biogasoline in the ternary blend, to see if they could also improve engine performance, emissions, and fuel consumption. However, further research is required to establish the life span of the optimal blend and to determine if its efficiency decreases over time.

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APPENDICES

Appendix 1: Optimization Constraints of minimizing BSFC, CO_2, CO, NOx, and HC and maximize BTE

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: DIESEL	in range	75	100	1	1	3
B: BIO-DIESEL	in range	0	25	1	1	3
C: PROPANOL	in range	0	5	1	1	3
BSFC	minimize	0.154446	0.18	1	1	3
BTE	maximize	54	63	1	1	3
CO_2	minimize	1.58	2.2	1	1	3
NOx	minimize	74	111.6	1	1	3
CO	minimize	326	546	1	1	3
HC	minimize	15	39	1	1	3

Appendix 2: Solutions from Appendix 1

NO	Diesel	Bio-Diesel	Propanol	BSFC	BTE	CO_2	NO_x	CO	HC	Desirability
1	78.163	21.028	0.808	0.154	63.000	1.830	79.935	447.886	-7.029	0.779
2	82.442	17.313	0.245	0.157	62.238	1.716	79.376	458.985	15.000	0.777
3	89.892	8.350	1.758	0.154	63.000	1.801	79.969	489.264	4.939	0.720
4	80.965	19.035	0.000	0.155	62.628	1.730	79.919	453.223	26.122	0.715

Appendix 3: Optimization Constraints for minimize CO_2, BSFC, maximize BTE

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: DIESEL	is in range	75	100	1	1	3
B: BIO-DIESEL	is in range	0	25	1	1	3
C: PROPANOL	is in range	0	5	1	1	3
BSFC	minimize	0.154446	0.18	1	1	3
BTE	maximize	54	63	1	1	3
CO_2	minimize	1.58	2.2	1	1	3

Appendix 4: 6 Solutions found from Appendix 3

No	**DIESEL**	**BIO-DIESEL**	**PROPANOL**	**BSFC**	**BTE**	**CO_2**	**NOx**	**CO**	**NO_2**	**HC**	**Desirability**
1	86.935	13.065	0.000	0.152	63.945	1.661	81.470	472.163	42.926	31.952	0.954
2	87.500	12.500	0.000	0.153	63.893	1.662	81.837	473.956	43.106	32.110	0.954
3	91.845	7.080	1.075	0.154	63.001	1.777	82.556	492.460	44.080	-0.885	0.880
4	78.411	20.633	0.955	0.154	63.000	1.828	79.781	449.319	39.844	-7.934	0.843
5	95.750	0.854	3.396	0.154	63.341	1.844	85.408	515.042	44.436	59.004	0.831
6	97.033	0.000	2.967	0.154	63.473	1.850	86.608	517.229	45.009	49.837	0.826

Appendix 5: Optimization Constraints for minimize BSFC, NOx maximizes BTE

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: DIESEL	is in range	75	100	1	1	3
B: BIO-DIESEL	is in range	0	25	1	1	3
C: PROPANOL	is in range	0	5	1	1	3
BSFC	minimize	0.15445	0.18	1	1	3
BTE	maximize	54	63	1	1	3
NOx	minimize	74	111.6	1	1	3

Appendix 6: 4 Solutions found from Appendix 5

No	DIESEL	BIO-DIESEL	PROPANOL	BSFC	BTE	CO_2	NOx	CO	NO_2	HC	Desirability
1	88.519	9.084	2.397	0.154	63.000	1.835	79.302	487.715	42.514	19.223	0.951
2	78.651	20.149	1.200	0.154	63.000	1.831	79.697	451.155	39.827	-7.774	0.947
3	81.782	18.218	0.000	0.154	63.009	1.712	79.880	455.817	41.284	27.403	0.945
4	97.033	0.000	2.967	0.154	63.473	1.850	86.608	517.229	45.009	49.834	0.873

Appendix 7: Optimization Constraints for minimize BSFC, HC, maximize BTE

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: DIESEL	is in range	75	100	1	1	3
B: BIO-DIESEL	is in range	0	25	1	1	3
C: PROPANOL	is in range	0	5	1	1	3
BSFC	minimize	0.154446	0.18	1	1	3
BTE	maximize	54	63	1	1	3
HC	minimize	15	39	1	1	3

Appendix 8: 39 Solutions found from Appendix 7

No	**DIESEL**	**BIO-DIESEL**	**PROPANOL**	**BSFC**	**BTE**	**CO_2**	**NOx**	**CO**	**NO_2**	**HC**	**Desirability**
1	**77.578**	**21.094**	**1.328**	**0.148**	**65.106**	**1.855**	**80.493**	**448.313**	**39.436**	**-8.129**	**1.000**
2	92.451	6.462	1.086	0.154	63.309	1.786	83.161	494.434	44.268	-0.858	1.000
3	95.568	2.557	1.875	0.144	66.717	1.855	85.400	507.786	44.960	11.412	1.000
4	97.634	0.547	1.819	0.146	65.939	1.885	88.460	514.093	45.640	11.968	1.000
5	77.758	20.055	2.188	0.146	65.691	1.872	81.707	452.657	39.165	9.166	1.000
6	91.900	6.998	1.103	0.154	63.085	1.780	82.550	492.756	44.086	-0.923	1.000
7	93.402	4.912	1.686	0.147	65.531	1.825	83.083	500.082	44.342	5.437	1.000
8	94.854	3.835	1.311	0.149	64.918	1.834	85.527	503.043	44.948	0.466	1.000
9	75.000	23.750	1.250	0.128	71.495	1.914	82.706	439.791	38.645	-12.373	1.000
10	78.169	20.294	1.538	0.150	64.230	1.849	80.268	451.106	39.544	-4.935	1.000
11	78.354	19.405	2.241	0.151	64.146	1.868	81.327	454.782	39.334	10.824	1.000
12	91.949	6.272	1.778	0.149	64.816	1.815	81.539	495.881	43.844	6.447	1.000
13	95.436	3.501	1.063	0.151	64.082	1.839	86.976	503.801	45.229	-0.750	1.000
14	93.566	5.581	0.852	0.154	63.057	1.793	85.068	496.944	44.713	0.489	1.000
15	78.649	19.898	1.454	0.153	63.238	1.839	79.862	452.260	39.730	-5.656	1.000
16	94.038	4.266	1.696	0.146	65.880	1.832	83.780	502.145	44.541	6.031	1.000
17	96.190	2.090	1.720	0.145	66.337	1.863	86.500	509.076	45.217	8.082	1.000
18	90.200	7.683	2.117	0.151	64.122	1.822	80.041	491.820	43.157	13.131	1.000
19	91.215	6.806	1.978	0.149	64.733	1.819	80.784	494.431	43.533	10.440	1.000
20	98.689	0.257	1.054	0.154	63.276	1.923	92.316	514.082	46.269	-0.749	1.000
21	94.565	4.376	1.060	0.152	63.943	1.821	85.778	501.021	44.952	-0.754	1.000
22	89.144	8.646	2.209	0.153	63.254	1.824	79.471	488.876	42.785	14.738	1.000
23	89.816	8.166	2.019	0.153	63.504	1.815	79.818	490.167	43.072	10.460	1.000
24	95.394	3.005	1.602	0.146	65.998	1.849	85.630	506.031	45.009	4.978	1.000
25	93.087	5.873	1.040	0.153	63.448	1.793	83.983	496.247	44.489	-0.739	1.000
26	90.575	7.602	1.823	0.152	63.765	1.808	80.395	491.717	43.388	6.580	1.000
27	92.900	5.015	2.084	0.144	66.321	1.834	82.174	500.242	44.030	14.488	1.000
28	75.902	21.948	2.150	0.127	72.018	1.893	83.442	446.604	38.588	7.353	1.000
29	96.875	1.443	1.682	0.146	66.107	1.874	87.569	511.084	45.450	7.749	1.000
30	91.230	7.295	1.474	0.153	63.487	1.793	81.267	492.265	43.731	1.101	1.000
31	97.672	1.119	1.208	0.151	64.410	1.893	90.034	511.533	45.886	0.171	1.000
32	78.152	19.761	2.087	0.149	64.640	1.865	81.155	453.467	39.329	6.683	1.000
33	95.825	3.044	1.131	0.150	64.377	1.849	87.349	505.333	45.327	-0.588	1.000
34	92.346	5.566	2.088	0.145	65.951	1.831	81.663	498.499	43.852	14.091	1.000
35	76.189	22.456	1.355	0.137	68.563	1.885	81.668	444.025	38.984	-9.538	1.000
36	75.660	22.843	1.497	0.130	70.846	1.897	82.362	442.971	38.760	-8.175	1.000
37	88.778	10.897	0.325	0.157	62.438	1.694	81.754	479.437	43.390	15.000	0.950
38	86.474	8.526	5.000	0.154	63.000	1.974	87.664	492.660	40.866	18.470	0.949
39	80.300	19.700	0.000	0.156	62.271	1.746	80.010	451.116	40.812	24.959	0.793

Appendix 9: Optimization Constraints for minimize BSFC, CO, HC, and NOx and maximize BTE

Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: DIESEL	Is in range	75	100	1	1	3
B: BIO-DIESEL	is in range	0	25	1	1	3
C: PROPANOL	is in range	0	5	1	1	3
BSFC	minimize	0.154446	0.18	1	1	3
BTE	maximize	54	63	1	1	3
NOx	minimize	74	111.6	1	1	3
CO	minimize	326	546	1	1	3
HC	minimize	15	39	1	1	3

Appendix 10: 5 Solutions found from Appendix 9

No	DIESEL	BIO-DIESEL	PROPANOL	BSFC	BTE	NOx	CO	HC	Desirability
1	75.010	24.604	0.386	0.153	63.001	82.344	436.027	-4.872	0.828
2	80.887	18.913	0.200	0.157	62.090	79.541	453.856	15.000	0.780
3	88.867	8.906	2.227	0.154	63.000	79.349	488.072	15.000	0.743
4	79.567	20.433	0.000	0.157	61.827	80.171	448.788	23.544	0.711
5	86.240	8.760	5.000	0.154	62.764	87.749	491.919	18.078	0.667

Appendix 11: Solutions found for physical properties of the optimal ternary blend

No	DIESEL	BIO-DIESEL	PROPANOL	BTE	Density	viscosity	Desirability
1	**75.026**	**24.588**	**0.386**	**63.000**	**0.972**	**4.369**	**0.828**
2	80.893	18.906	0.201	62.091	0.970	5.961	0.780
3	88.867	8.906	2.227	63.000	0.962	3.571	0.743
4	79.565	20.435	0.000	61.826	0.971	6.033	0.711
5	86.235	8.765	5.000	62.758	0.960	4.370	0.667
6	98.095	0.000	1.905	65.577	0.955	4.216	0.606

Appendix 12: Measurements of Physical properties of ternary blends

	Component 1	Component 2	Component 3	Response 12	Response 13
Run	A: DIESEL	B: BIO-DIESEL	C: PROPANOL	Density	viscosity
	%	%	%	g/cm³	cP
1	91.35	3.65	5	0.955	5
2	100	0	0	0.96	6
3	80.75	16.56	2.69	0.966	6
4	78.95	21.05	0	0.97	5
5	91.54	8.46	0	0.966	6
6	80.75	16.56	2.69	0.968	5
7	80.75	16.56	2.69	0.968	5
8	87.73	7.27	5	0.959	5
9	75	20	5	0.969	4
10	75	20	5	0.966	4
11	97.48	0	2.52	0.954	6
12	97.48	0	2.52	0.954	6
13	87.51	12.49	0	0.968	7
14	95.64	4.31	0.05	0.961	5
15	86.36	11.47	2.17	0.962	4
16	82.44	12.56	5	0.963	6
17	86.36	11.47	2.17	0.962	4
18	75	25	0	0.973	6

Appendix 13: Report on viscosity for both actual and predicated value with the blend runs

Run	Actual Value	Predicted Value[(1)]	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS
1	5.00	4.95	0.0494	0.968	0.575	0.545	0.912	3.005(2)
2	6.00	6.06	-0.0589	0.959	-0.603	-0.574	0.771	-2.769(2)
3	6.00	5.27	0.7292	0.291	1.799	2.271	0.121	1.454
4	5.00	5.68	-0.6843	0.466	-1.946	-2.659	0.301	-2.485(2)
5	6.00	5.49	0.5061	0.604	1.672	1.997	0.388	2.469(2)
6	5.00	5.27	-0.2708	0.291	-0.668	-0.639	0.017	-0.409
7	5.00	5.27	-0.2708	0.291	-0.668	-0.639	0.017	-0.409
8	5.00	4.96	0.0442	0.986	0.789	0.765	4.125(2)	6.534(2)
9	4.00	4.01	-0.0075	0.499	-0.022	-0.020	0.000	-0.020
10	4.00	4.01	-0.0075	0.499	-0.022	-0.020	0.000	-0.020
11	6.00	6.02	-0.0240	0.493	-0.070	-0.065	0.000	-0.064
12	6.00	6.02	-0.0240	0.493	-0.070	-0.065	0.000	-0.064
13	7.00	6.98	0.0188	0.988	0.352	0.329	0.905	2.947(2)
14	5.00	5.17	-0.1727	0.540	-0.529	-0.500	0.030	-0.541
15	4.00	4.07	-0.0671	0.444	-0.187	-0.173	0.003	-0.155
16	6.00	6.10	-0.0953	0.918	-0.690	-0.662	0.483	-2.211
17	4.00	4.07	-0.0671	0.444	-0.187	-0.173	0.003	-0.155
18	6.00	5.60	0.4022	0.826	2.004	2.841	1.735(2)	6.193(2)

(1) Predicted values include block corrections.

(2) Exceeds limits.

Appendix 14: Analysis of variance of viscosity

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Block	0.5635	2	0.2817			
Model	11.43	8	1.43	6.16	0.0134	significant
(1)Linear Mixture	3.85	2	1.93	8.31	0.0142	
AB	0.2155	1	0.2155	0.9303	0.3669	
AC	1.21	1	1.21	5.21	0.0563	
BC	1.26	1	1.26	5.45	0.0522	
A^2BC	0.0418	1	0.0418	0.1803	0.6839	
AB^2C	1.25	1	1.25	5.41	0.0529	
ABC^2	0.7194	1	0.7194	3.10	0.1214	
Residual	1.62	7	0.2317			
Lack of Fit	0.9552	2	0.4776	3.58	0.1083	not significant
Pure Error	0.6667	5	0.1333			
Cor Total	13.61	17				

(1) Inference for linear mixtures uses Type I sums of squares.

Appendix 15: Report on Density for both actual and predicated value with the blend runs

Run	Actual Value	Predicted Value(1)	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS
1	0.9550	0.9556	-0.0006	0.656	-0.823	-0.809	0.162	-1.118
2	0.9600	0.9596	0.0004	0.650	0.523	0.503	0.064	0.686
3	0.9660	0.9668	-0.0008	0.267	-0.694	-0.675	0.022	-0.408
4	0.9700	0.9718	-0.0018	0.404	-1.835	-2.137	0.285	-1.760
5	0.9660	0.9656	0.0004	0.345	0.374	0.357	0.009	0.259
6	0.9680	0.9668	0.0012	0.267	1.099	1.112	0.055	0.672
7	0.9680	0.9668	0.0012	0.267	1.099	1.112	0.055	0.672
8	0.9590	0.9584	0.0006	0.423	0.560	0.540	0.029	0.462
9	0.9690	0.9680	0.0010	0.451	1.024	1.027	0.108	0.930
10	0.9660	0.9680	-0.0020	0.451	-2.082	-2.625	0.445	-2.377(2)
11	0.9540	0.9540	-0.0000	0.438	-0.043	-0.041	0.000	-0.036
12	0.9540	0.9540	-0.0000	0.438	-0.043	-0.041	0.000	-0.036
13	0.9680	0.9674	0.0006	0.646	0.713	0.694	0.116	0.937
14	0.9610	0.9615	-0.0005	0.427	-0.472	-0.453	0.021	-0.391
15	0.9620	0.9628	-0.0008	0.314	-0.737	-0.719	0.031	-0.487
16	0.9630	0.9621	0.0009	0.435	0.954	0.949	0.088	0.833
17	0.9620	0.9628	-0.0008	0.314	-0.737	-0.719	0.031	-0.487
18	0.9730	0.9719	0.0011	0.807	1.960	2.369	2.004(2)	4.841(2)

(1) Predicted values include block corrections.

(2) Exceeds limits.

Appendix 16: Analysis of variance of Density

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Block	0.0000	2	0.0000			
Model	0.0005	5	0.0001	57.56	< 0.0001	significant
(1)Linear Mixture	0.0005	2	0.0002	137.55	< 0.0001	
AB	4.566E-06	1	4.566E-06	2.69	0.1320	
AC	5.914E-06	1	5.914E-06	3.48	0.0915	
BC	2.818E-06	1	2.818E-06	1.66	0.2266	
Residual	0.0000	10	1.698E-06			
Lack of Fit	9.809E-06	5	1.962E-06	1.37	0.3695	not significant
Pure Error	7.167E-06	5	1.433E-06			
Cor Total	0.0005	17				

(1) Inference for linear mixtures uses Type I sums of squares.

Appendix 17: Analysis of variance of BSFC

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Block	0.0002	2	0.0001			
Model	0.0004	8	0.0001	7.42	0.0079	significant
(1)Linear Mixture	9.220E-06	2	4.610E-06	0.6424	0.5544	
AB	0.0002	1	0.0002	33.43	0.0007	
AC	0.0001	1	0.0001	12.26	0.0100	
BC	0.0001	1	0.0001	11.41	0.0118	
A^2BC	0.0001	1	0.0001	11.16	0.0124	
AB^2C	0.0001	1	0.0001	12.10	0.0103	
ABC^2	0.0001	1	0.0001	9.95	0.0161	
Residual	0.0001	7	7.176E-06			
Lack of Fit	0.0000	2	5.270E-06	0.6638	0.5550	not significant
Pure Error	0.0000	5	7.939E-06			
Cor Total	0.0007	17				

(1) Inference for linear mixtures uses Type I sums of squares.

Appendix 18: Analysis of variance of BTE

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Block	29.25	2	14.63			
Model	56.18	8	7.02	4.83	0.0260	significant
⁽¹⁾Linear Mixture	2.74	2	1.37	0.9439	0.4336	
AB	32.50	1	32.50	22.36	0.0021	
AC	10.33	1	10.33	7.11	0.0322	
BC	9.56	1	9.56	6.58	0.0373	
A^2BC	11.18	1	11.18	7.69	0.0276	
AB^2C	10.06	1	10.06	6.92	0.0339	
ABC^2	8.32	1	8.32	5.72	0.0480	
Residual	10.18	7	1.45			
Lack of Fit	1.01	2	0.5053	0.2756	0.7699	not significant
Pure Error	9.17	5	1.83			
Cor Total	95.61	17				

(1) Inference for linear mixtures uses Type I sums of squares.

Appendix 19: Analysis of variance of NOx

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Block	679.04	2	339.52			
Model	713.95	5	142.79	7.95	0.0029	significant
(1)Linear Mixture	50.64	2	25.32	1.41	0.2890	
AB	156.66	1	156.66	8.72	0.0145	
AC	196.36	1	196.36	10.93	0.0079	
BC	114.92	1	114.92	6.39	0.0299	
Residual	179.72	10	17.97			
Lack of Fit	93.82	5	18.76	1.09	0.4626	not significant
Pure Error	85.89	5	17.18			
Cor Total	1572.71	17				

(1) Inference for linear mixtures uses Type I sums of squares.

Appendix 20: Analysis of variance HC

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Block	388.54	2	194.27			
Model	490.50	9	54.50	13.10	0.0027	significant
(1)Linear Mixture	247.01	2	123.50	29.68	0.0008	
AB	133.80	1	133.80	32.16	0.0013	
AC	104.36	1	104.36	25.08	0.0024	
BC	103.47	1	103.47	24.87	0.0025	
ABC	105.96	1	105.96	25.47	0.0023	
AB(A-B)	0.8753	1	0.8753	0.2104	0.6626	
AC(A-C)	104.96	1	104.96	25.23	0.0024	
BC(B-C)	102.49	1	102.49	24.63	0.0025	
Residual	24.96	6	4.16			
Lack of Fit	1.30	1	1.30	0.2740	0.6230	not significant
Pure Error	23.67	5	4.73			
Cor Total	904.00	17				

Appendix 21: Constraints of minimizing BSFC and maximizing BTE

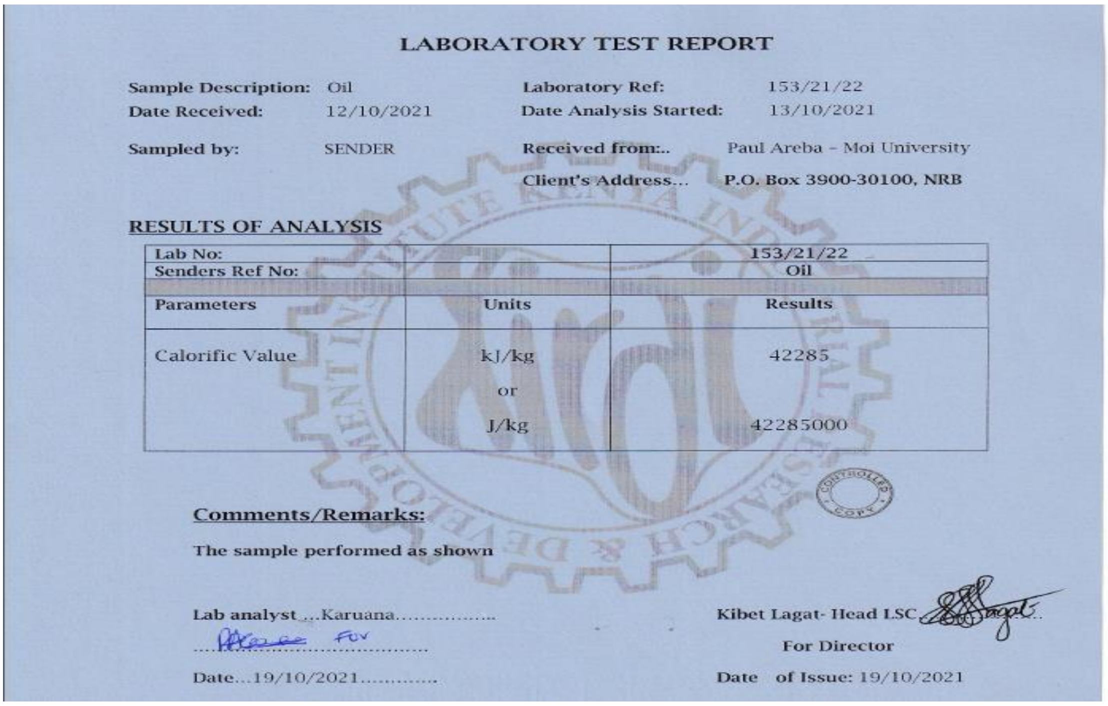
Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: DIESEL	is in range	75	100	1	1	3
B: BIO-DIESEL	is in range	0	25	1	1	3
C: PROPANOL	is in range	0	5	1	1	3
TIME TO CONSUME 50ML OF FUEL	none	96	112	1	1	3
BP	none	10	10	1	1	3
BSFC	minimize	0.154446	0.18	1	1	3
BTE	maximize	54	63	1	1	3
CO_2	none	1.58	2.2	1	1	3
NOx	none	74	111.6	1	1	3
CO	none	326	546	1	1	3
NO	none	34.3	81.8	1	1	3
NO_2	none	23.8	50	1	1	3
O_2	none	16.6	17.5	1	1	3
EX TEMP	none	106.19	129	1	1	3
Density	none	0.954	0.973	1	1	3
viscosity	none	4	7	1	1	3
HC	none	15	39	1	1	3

Appendix 22: Solutions found from Appendix 21

No	DIESEL	BIO-DIESEL	PROPANOL	BSFC	BTE	NOx	CO	Density	viscosity	HC	Desirability
1	77.273	20.227	2.500	0.142	67.109	82.987	452.491	0.968	2.747	17.853	1.000
2	87.727	7.273	5.000	0.151	63.874	87.324	496.633	0.958	3.782	20.928	1.000
3	97.478	0.000	2.522	0.150	65.056	87.313	516.686	0.954	4.850	35.059	1.000
4	76.094	20.312	3.594	0.136	68.981	88.769	453.554	0.968	1.410	44.230	1.000
5	88.541	7.709	3.750	0.146	65.521	81.921	493.728	0.959	2.590	48.215	1.000
6	84.014	15.986	0.000	0.153	63.726	80.180	462.898	0.969	5.846	30.094	1.000
7	87.448	12.552	0.000	0.152	63.899	81.801	473.790	0.967	5.807	32.098	1.000
8	88.846	6.154	5.000	0.151	63.934	87.178	500.184	0.957	3.721	23.641	1.000
9	91.300	6.200	2.500	0.145	66.097	80.827	496.990	0.959	2.277	24.623	1.000
10	95.227	2.273	2.500	0.142	67.337	84.432	509.449	0.956	2.695	30.061	1.000
11	77.519	19.356	3.125	0.147	65.455	84.915	456.015	0.968	3.314	34.671	1.000
12	88.324	8.171	3.505	0.148	65.012	81.175	491.965	0.960	2.743	45.147	1.000
13	89.864	6.394	3.742	0.143	66.568	82.170	497.889	0.958	2.180	50.396	1.000
14	85.560	14.440	0.000	0.152	63.943	80.736	467.803	0.968	5.817	31.301	1.000
15	75.182	20.260	4.558	0.145	65.850	95.938	454.897	0.968	1.616	39.909	1.000
16	85.941	14.059	0.000	0.152	63.962	80.917	469.011	0.968	5.813	31.520	1.000
17	92.686	5.150	2.164	0.144	66.379	81.933	499.912	0.959	2.328	16.474	1.000
18	90.798	4.382	4.820	0.154	63.132	86.426	505.587	0.956	4.124	38.062	1.000
19	93.649	2.904	3.447	0.144	66.525	83.544	508.601	0.955	2.914	54.327	1.000
20	87.231	9.176	3.593	0.151	63.869	81.352	488.883	0.961	3.302	44.964	1.000
21	96.958	1.011	2.031	0.145	66.499	87.086	512.879	0.956	3.437	17.413	1.000
22	88.571	11.429	0.000	0.153	63.711	82.638	477.353	0.967	5.814	32.240	1.000
23	86.940	8.060	5.000	0.152	63.408	87.516	494.137	0.959	4.033	19.314	1.000
24	89.324	10.627	0.049	0.154	63.320	83.107	479.957	0.966	5.803	29.158	1.000
25	97.260	1.540	1.200	0.150	64.508	89.374	510.189	0.958	3.713	0.020	1.000
26	83.330	16.670	0.000	0.153	63.557	80.024	460.727	0.969	5.865	29.391	1.000
27	88.306	6.694	5.000	0.151	64.003	87.230	498.473	0.958	3.702	22.272	1.000
28	96.375	2.064	1.561	0.146	65.901	87.084	508.968	0.957	3.153	4.790	1.000
29	88.931	11.069	0.000	0.153	63.625	82.938	478.497	0.967	5.819	32.236	1.000
30	86.816	13.184	0.000	0.152	63.952	81.397	471.785	0.968	5.807	31.911	1.000
31	87.886	12.114	0.000	0.153	63.840	82.110	475.179	0.967	5.809	32.182	1.000
32	87.939	8.153	3.908	0.148	65.036	82.399	492.512	0.960	2.860	48.040	1.000
33	82.810	17.190	0.000	0.153	63.398	79.944	459.076	0.970	5.882	28.786	1.000
34	76.867	21.386	1.746	0.140	67.832	81.610	447.895	0.969	2.579	-2.225	1.000
35	76.394	20.970	2.636	0.133	70.215	84.346	450.299	0.969	1.330	21.762	1.000
36	75.000	21.585	3.415	0.118	75.015	89.373	449.297	0.969	-1.366	42.235	1.000
37	98.304	0.000	1.696	0.148	65.313	89.801	515.678	0.955	4.151	9.333	1.000
38	95.563	3.586	0.850	0.154	63.215	87.814	503.271	0.960	4.095	0.127	1.000
39	85.119	14.881	0.000	0.152	63.905	80.548	466.403	0.969	5.824	31.009	1.000
40	75.000	20.653	4.347	0.137	68.720	94.790	453.391	0.968	0.504	45.039	1.000
41	92.799	3.629	3.573	0.143	66.816	83.156	506.455	0.956	2.551	54.590	1.000
42	78.206	18.982	2.813	0.151	64.096	83.073	456.822	0.967	3.985	26.639	1.000
43	89.218	8.418	2.364	0.152	63.688	79.571	489.789	0.961	3.236	18.881	1.000
44	95.663	2.539	1.798	0.144	66.547	85.644	507.747	0.957	2.811	9.527	1.000
45	87.884	8.948	3.167	0.151	63.921	80.274	489.085	0.961	3.160	38.391	1.000
46	75.100	21.162	3.739	0.125	72.840	90.935	451.037	0.968	-0.649	46.788	1.000
47	96.934	0.156	2.910	0.153	64.074	86.473	516.663	0.954	5.336	47.601	1.000
48	97.481	0.859	1.660	0.147	65.814	88.547	512.909	0.956	3.584	7.715	1.000
49	77.012	19.331	3.657	0.147	65.316	87.914	456.747	0.967	3.144	44.252	1.000
50	93.483	5.596	0.921	0.154	63.235	84.770	496.980	0.961	4.119	-0.139	1.000
51	76.774	20.353	2.873	0.138	68.471	84.760	452.547	0.968	2.037	28.476	1.000

52	93.396	5.227	1.377	0.150	64.585	83.593	498.706	0.960	3.298	0.714	1.000
53	76.439	23.083	0.478	0.153	63.063	81.162	440.965	0.971	4.689	-3.934	1.000
54	91.880	4.030	4.090	0.146	65.745	83.969	505.812	0.956	2.962	56.313	1.000
55	92.456	3.134	4.410	0.154	63.028	85.310	509.045	0.955	4.399	55.224	1.000
56	91.616	6.647	1.737	0.150	64.441	81.288	494.642	0.961	3.137	5.428	1.000
57	94.813	1.522	3.665	0.154	63.486	84.905	513.251	0.954	4.869	61.792	1.000
58	87.295	8.263	4.442	0.149	64.460	84.595	492.815	0.959	3.332	41.722	1.000
59	77.635	19.865	2.500	0.145	65.981	82.635	453.641	0.968	3.237	17.900	1.000
60	96.861	2.063	1.076	0.151	64.074	89.106	508.379	0.958	3.785	-0.712	1.000
61	86.521	8.479	5.000	0.154	63.046	87.648	492.810	0.959	4.222	18.552	1.000
62	75.159	22.505	2.337	0.116	75.645	84.826	445.066	0.969	-1.037	12.580	1.000
63	89.917	5.083	5.000	0.153	63.170	87.179	503.584	0.956	4.076	26.706	1.000
64	93.144	4.495	2.361	0.142	67.063	82.296	502.230	0.958	2.135	22.670	1.000
65	75.670	20.757	3.573	0.130	70.937	89.236	452.119	0.968	0.472	44.307	1.000

Appendix 23: Laboratory test for biodiesel on calorific value



LABORATORY TEST REPORT

Sample Description: Oil
Laboratory Ref: 153/21/22
Date Received: 12/10/2021
Date Analysis Started: 13/10/2021
Sampled by: SENDER
Received from:.. Paul Areba – Moi University
Client's Address... **P.O. Box 3900-30100, NRB**

RESULTS OF ANALYSIS

Lab No:		**153/21/22**
Senders Ref No:		**Oil**
Parameters	**Units**	**Results**
Calorific Value	kJ/kg or J/kg	42285 42285000

CONTROLLED COPY

Comments/Remarks:

The sample performed as shown

Lab analyst ...Karuana................

.... For

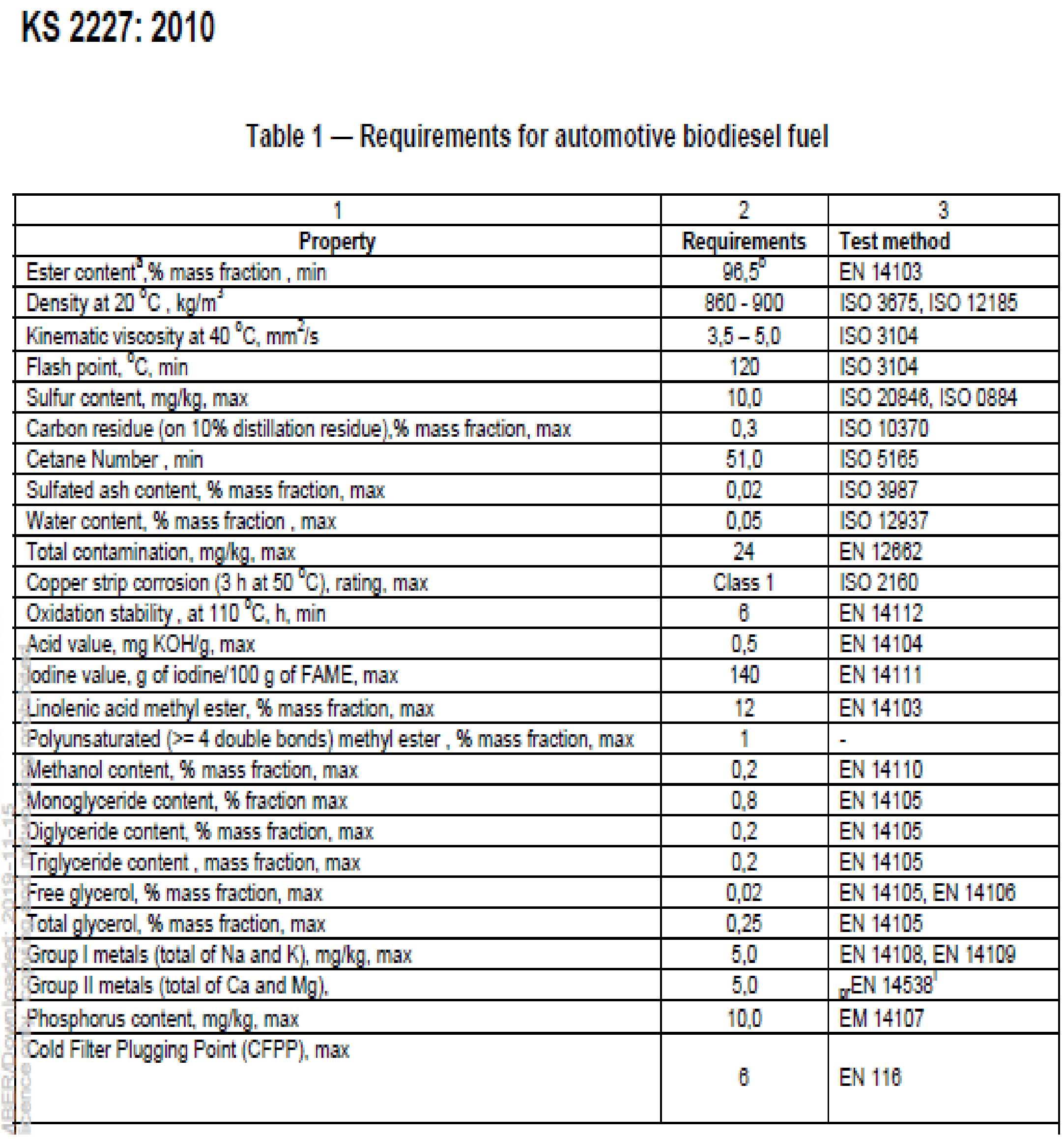
Date...19/10/2021............

Kibet Lagat- Head LSC...

For Director

Date of Issue: 19/10/2021

Appendix 24: Kenya standard for automotive biodiesel fuel- specification



KS 2227: 2010

Table 1 — Requirements for automotive biodiesel fuel

1 Property	2 Requirements	3 Test method
Ester content^{a},% mass fraction , min	96,5^{b}	EN 14103
Density at 20 ^{0}C , kg/m^{3}	860 - 900	ISO 3675, ISO 12185
Kinematic viscosity at 40 ^{0}C, mm^{2}/s	3,5 – 5,0	ISO 3104
Flash point, ^{0}C, min	120	ISO 3104
Sulfur content, mg/kg, max	10,0	ISO 20846, ISO 0884
Carbon residue (on 10% distillation residue),% mass fraction, max	0,3	ISO 10370
Cetane Number , min	51,0	ISO 5165
Sulfated ash content, % mass fraction, max	0,02	ISO 3987
Water content, % mass fraction , max	0,05	ISO 12937
Total contamination, mg/kg, max	24	EN 12662
Copper strip corrosion (3 h at 50 ^{0}C), rating, max	Class 1	ISO 2160
Oxidation stability , at 110 ^{0}C, h, min	6	EN 14112
Acid value, mg KOH/g, max	0,5	EN 14104
Iodine value, g of iodine/100 g of FAME, max	140	EN 14111
Linolenic acid methyl ester, % mass fraction, max	12	EN 14103
Polyunsaturated (>= 4 double bonds) methyl ester , % mass fraction, max	1	-
Methanol content, % mass fraction, max	0,2	EN 14110
Monoglyceride content, % fraction max	0,8	EN 14105
Diglyceride content, % mass fraction, max	0,2	EN 14105
Triglyceride content , mass fraction, max	0,2	EN 14105
Free glycerol, % mass fraction, max	0,02	EN 14105, EN 14106
Total glycerol, % mass fraction, max	0,25	EN 14105
Group I metals (total of Na and K), mg/kg, max	5,0	EN 14108, EN 14109
Group II metals (total of Ca and Mg),	5,0	$_{gr}$EN 14538^{f}
Phosphorus content, mg/kg, max	10,0	EM 14107
Cold Filter Plugging Point (CFPP), max	6	EN 116

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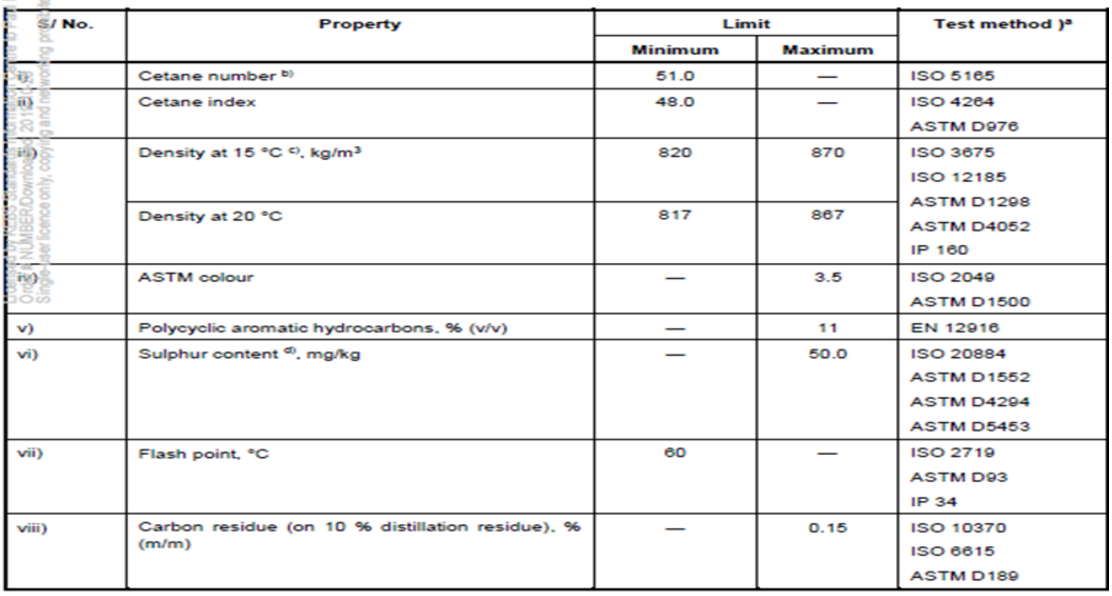
Appendix 25: Kenya standard specific quality requirements for automotive diesel fuel



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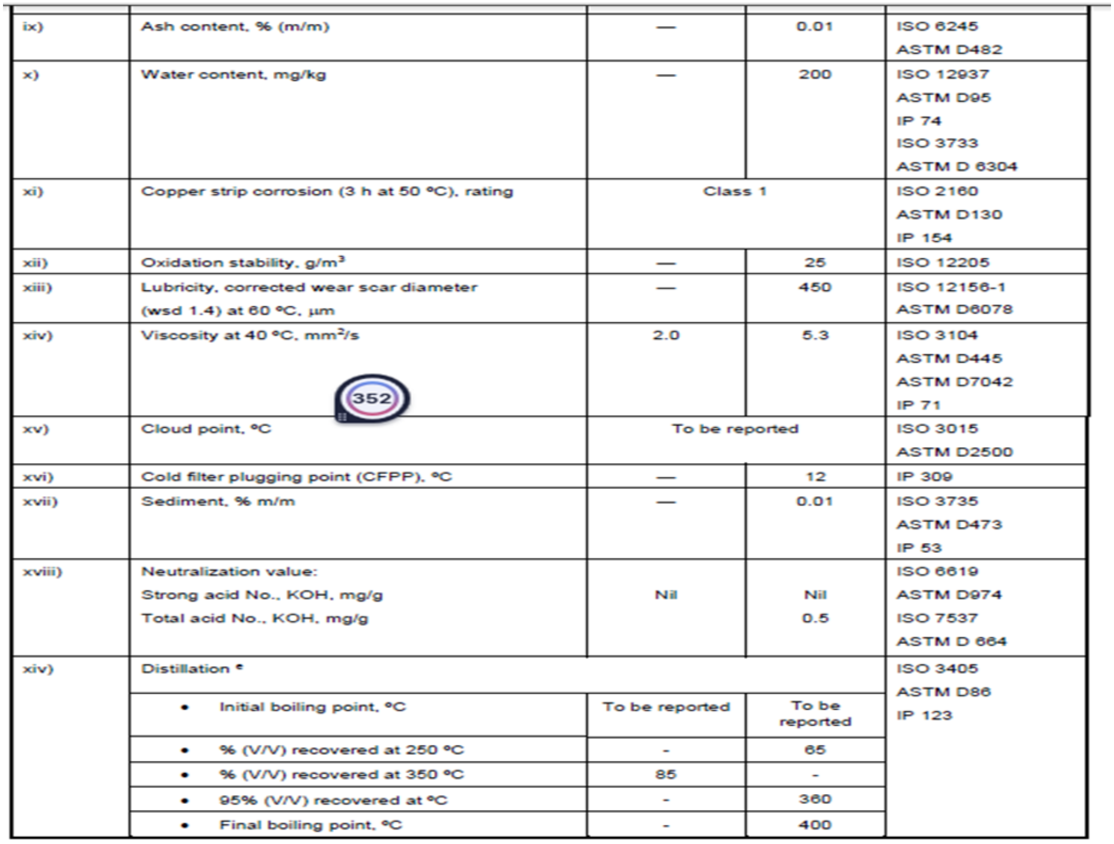
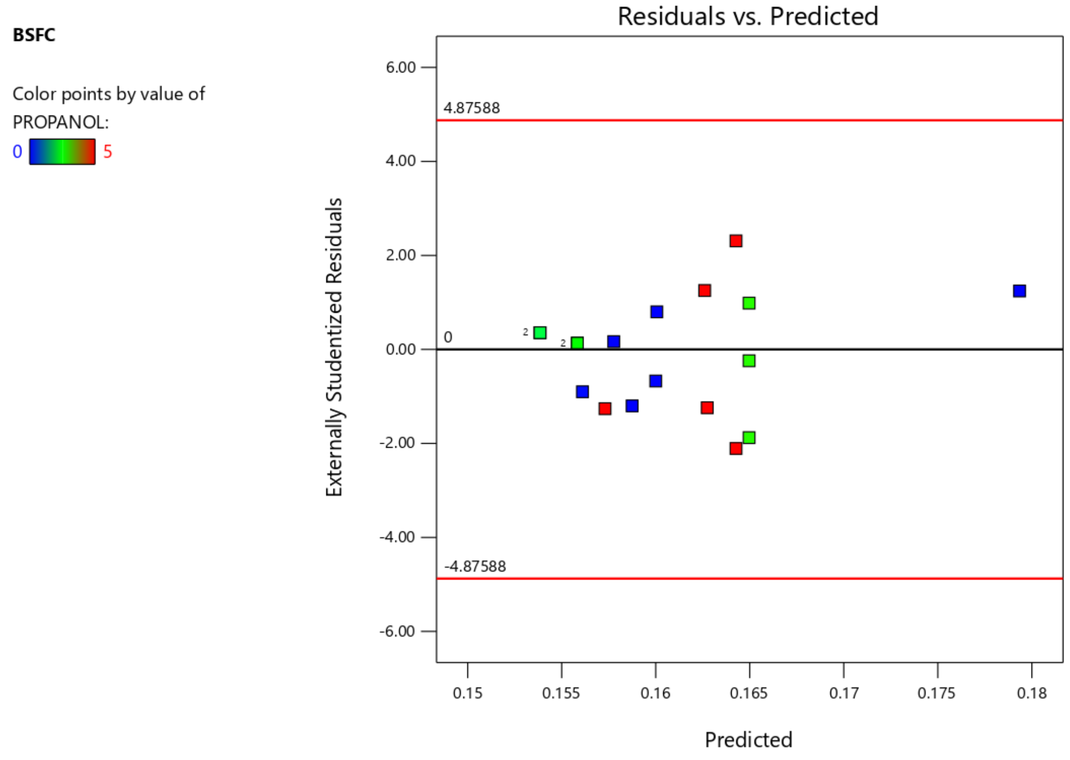
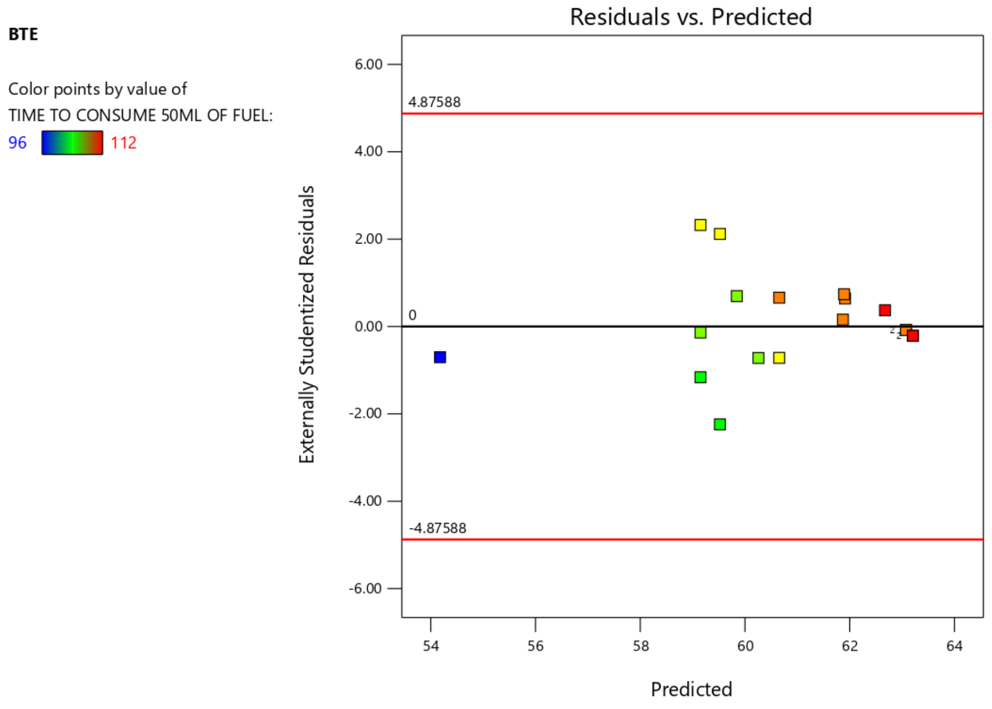


S/ No.	Property	Limit		Test method)a
		Minimum	Maximum	
i)	Cetane number b)	51.0	—	ISO 5165
ii)	Cetane index	48.0	—	ISO 4264 ASTM D976
iii)	Density at 15 °C c), kg/m^3	820	870	ISO 3675 ISO 12185 ASTM D1298 ASTM D4052 IP 160
	Density at 20 °C	817	867	
iv)	ASTM colour	—	3.5	ISO 2049 ASTM D1500
v)	Polycyclic aromatic hydrocarbons, % (v/v)	—	11	EN 12916
vi)	Sulphur content d), mg/kg	—	50.0	ISO 20884 ASTM D1552 ASTM D4294 ASTM D5453
vii)	Flash point, °C	60	—	ISO 2719 ASTM D93 IP 34
viii)	Carbon residue (on 10 % distillation residue), % (m/m)	—	0.15	ISO 10370 ISO 6615 ASTM D189
ix)	Ash content, % (m/m)	—	0.01	ISO 6245 ASTM D482
x)	Water content, mg/kg	—	200	ISO 12937 ASTM D95 IP 74 ISO 3733 ASTM D 6304
xi)	Copper strip corrosion (3 h at 50 °C), rating	Class 1		ISO 2160 ASTM D130 IP 154
xii)	Oxidation stability, g/m^3	—	25	ISO 12205
xiii)	Lubricity, corrected wear scar diameter (wsd 1.4) at 60 °C, µm	—	450	ISO 12156-1 ASTM D6078
xiv)	Viscosity at 40 °C, mm^2/s	2.0	5.3	ISO 3104 ASTM D445 ASTM D7042 IP 71
xv)	Cloud point, °C	To be reported		ISO 3015 ASTM D2500
xvi)	Cold filter plugging point (CFPP), °C	—	12	IP 309
xvii)	Sediment, % m/m	—	0.01	ISO 3735 ASTM D473 IP 53
xviii)	Neutralization value: Strong acid No., KOH, mg/g Total acid No., KOH, mg/g	 Nil	 Nil 0.5	ISO 6619 ASTM D974 ISO 7537 ASTM D 664
xiv)	Distillation e			ISO 3405 ASTM D86 IP 123
	• Initial boiling point, °C	To be reported	To be reported	
	• % (V/V) recovered at 250 °C	-	65	
	• % (V/V) recovered at 350 °C	85	-	
	• 95% (V/V) recovered at °C	-	360	
	• Final boiling point, °C	-	400	

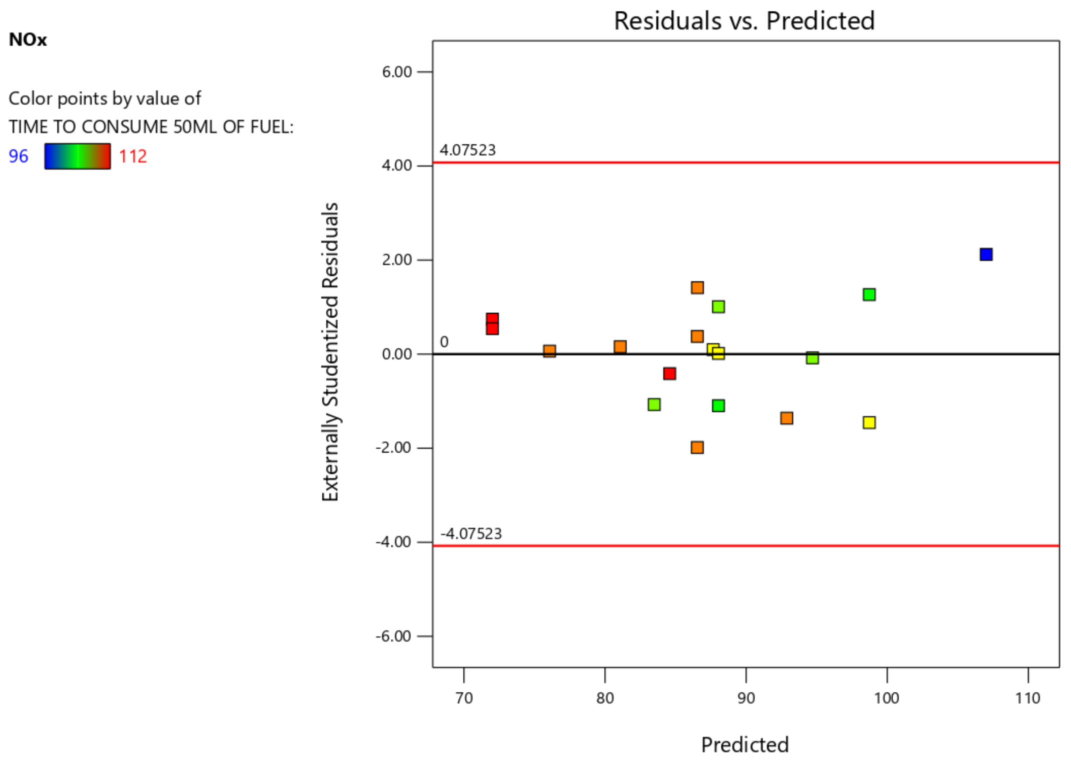
Appendix 26: Externally Studentized Residuals versus predicted BSFC



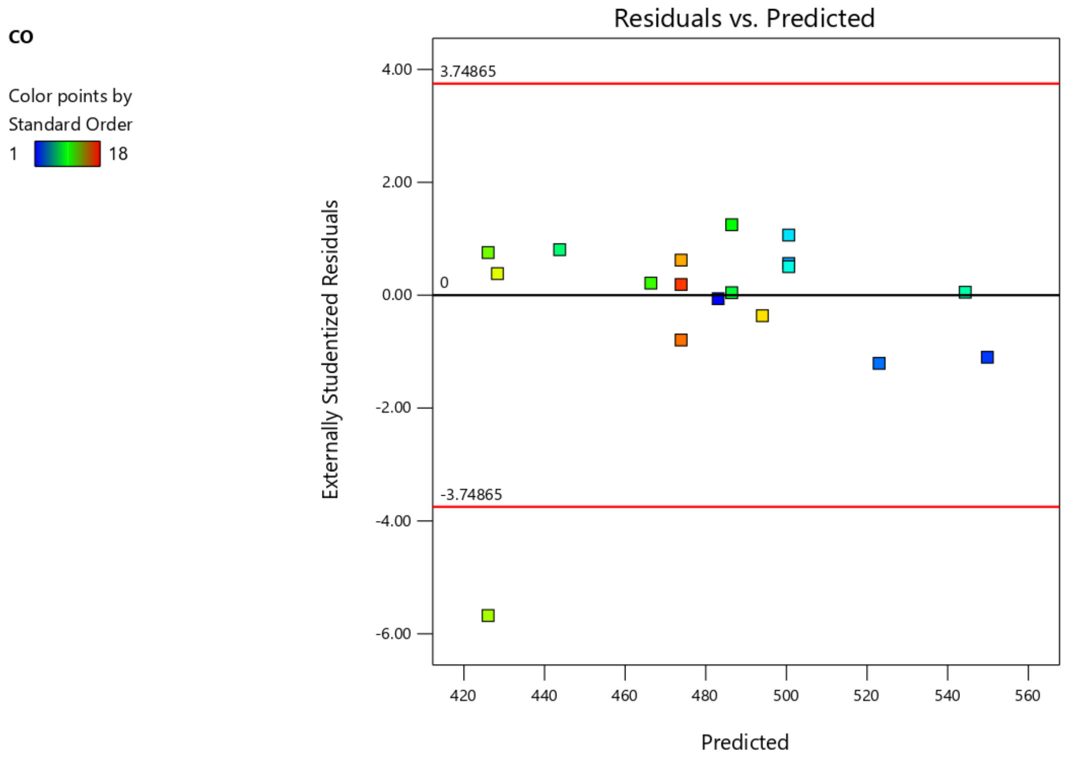
Appendix 27: Externally Studentized Residuals versus predicted BTE



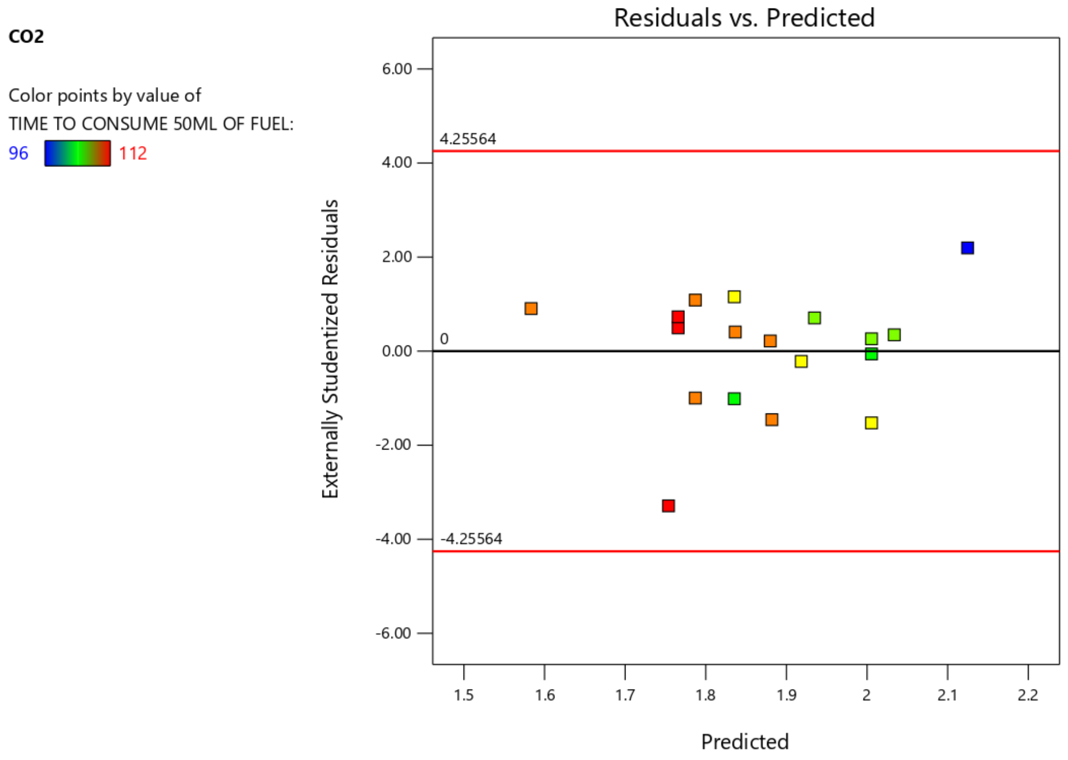
Appendix 28: Externally Studentized Residuals versus predicted NOx



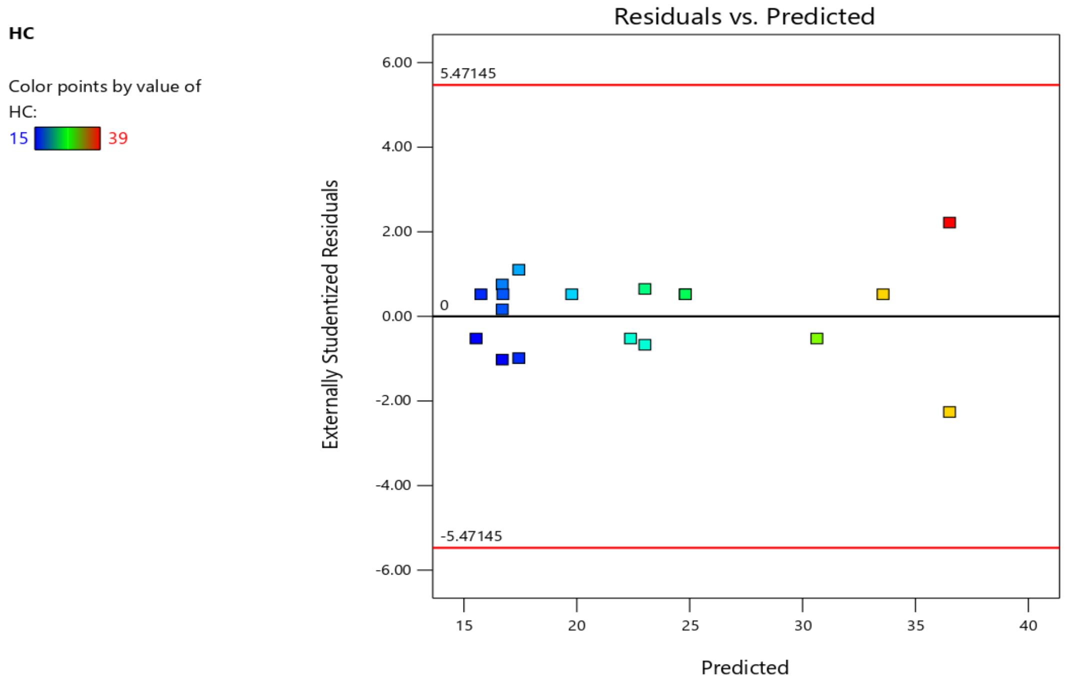
Appendix 29: Externally Studentized Residuals versus predicted CO



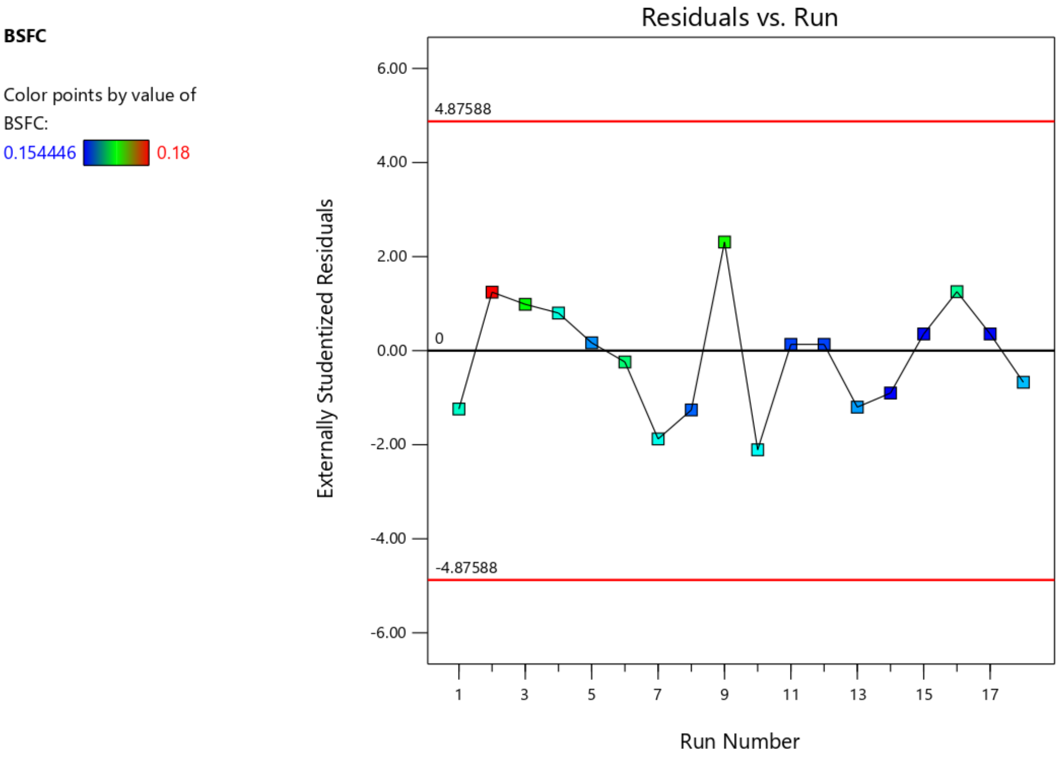
Appendix 30: Externally Studentized Residuals versus predicted CO_2



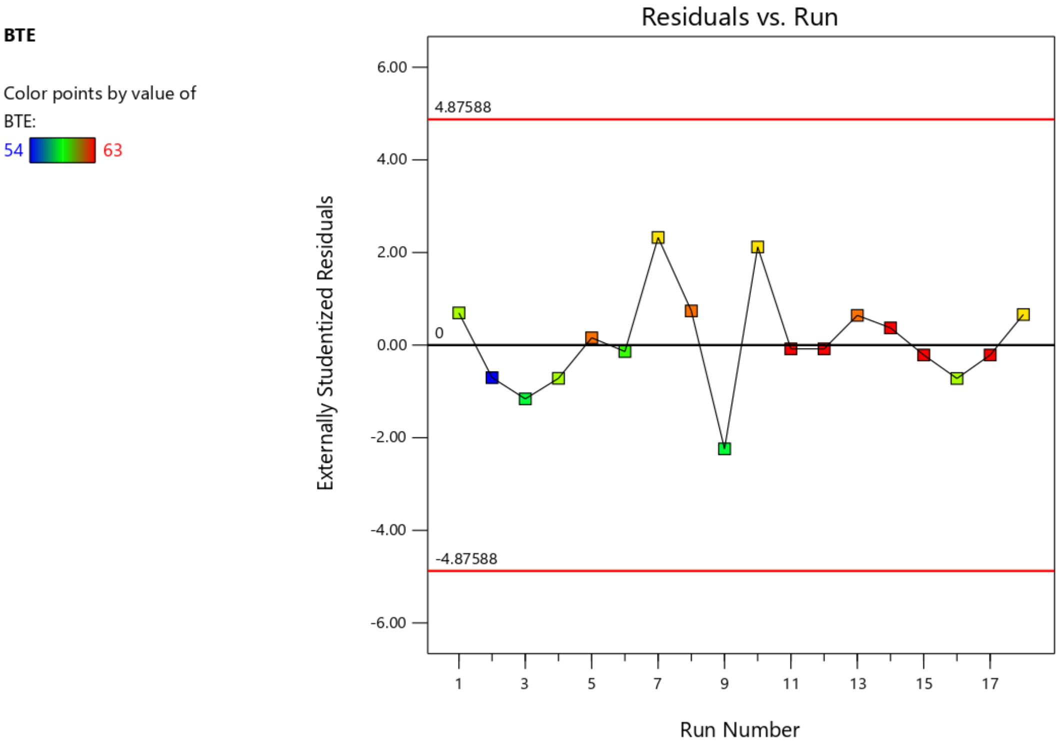
Appendix 31: Externally Studentized residuals versus predicted HC



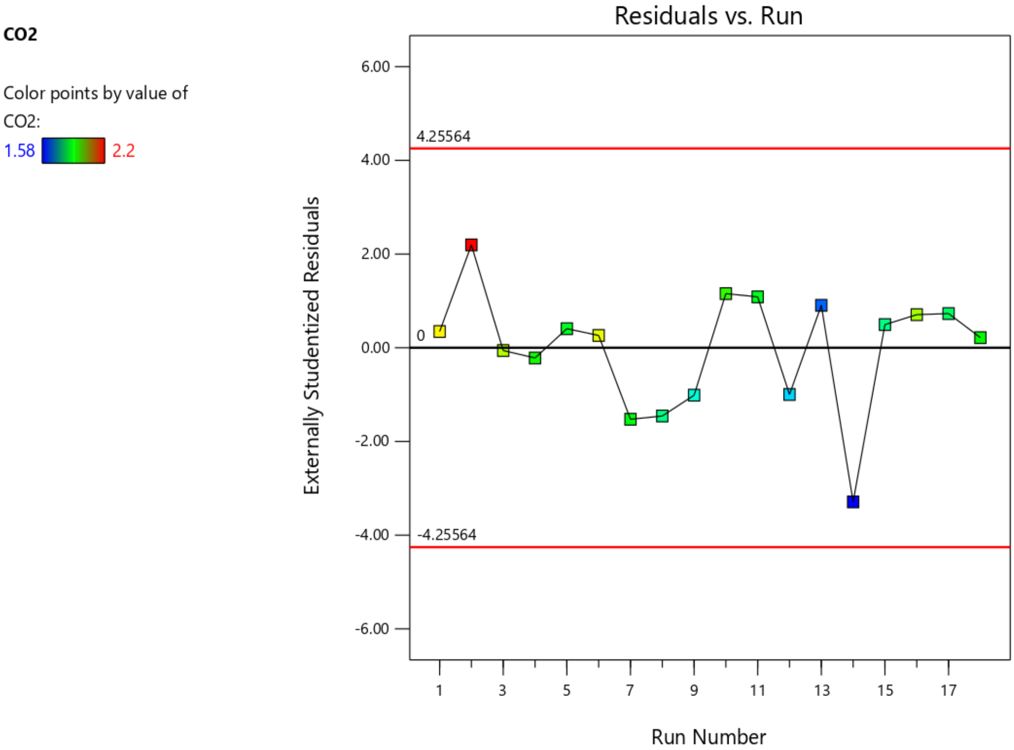
Appendix 32: Residuals versus run considering BSFC



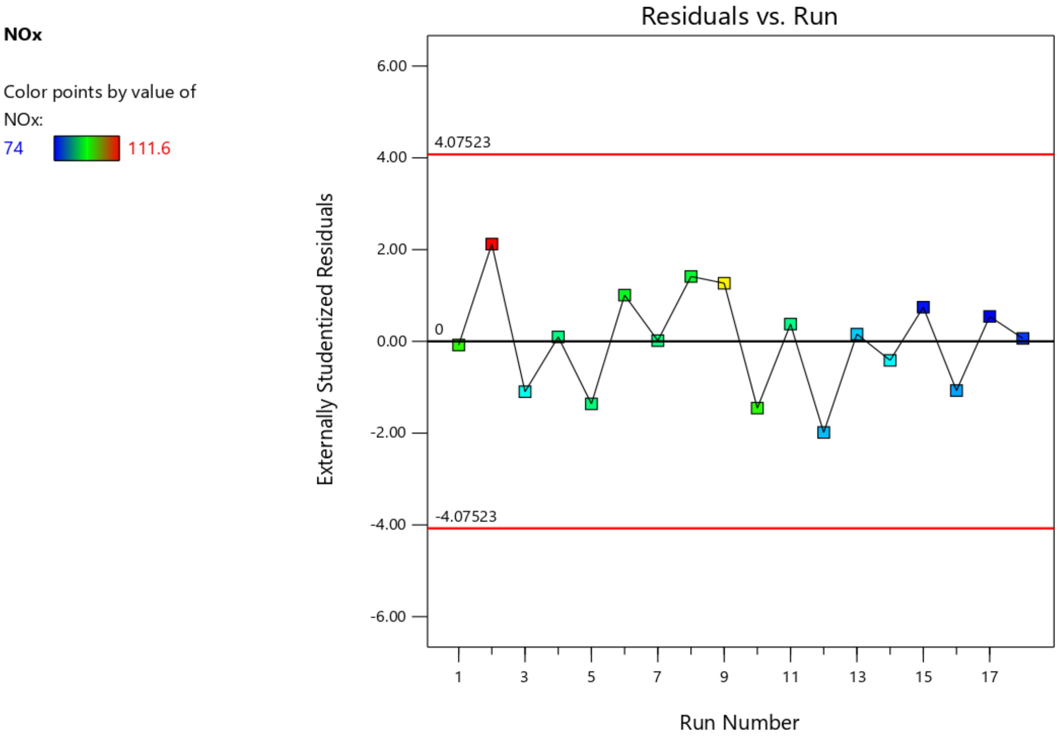
Appendix 33: Residuals versus run considering BTE



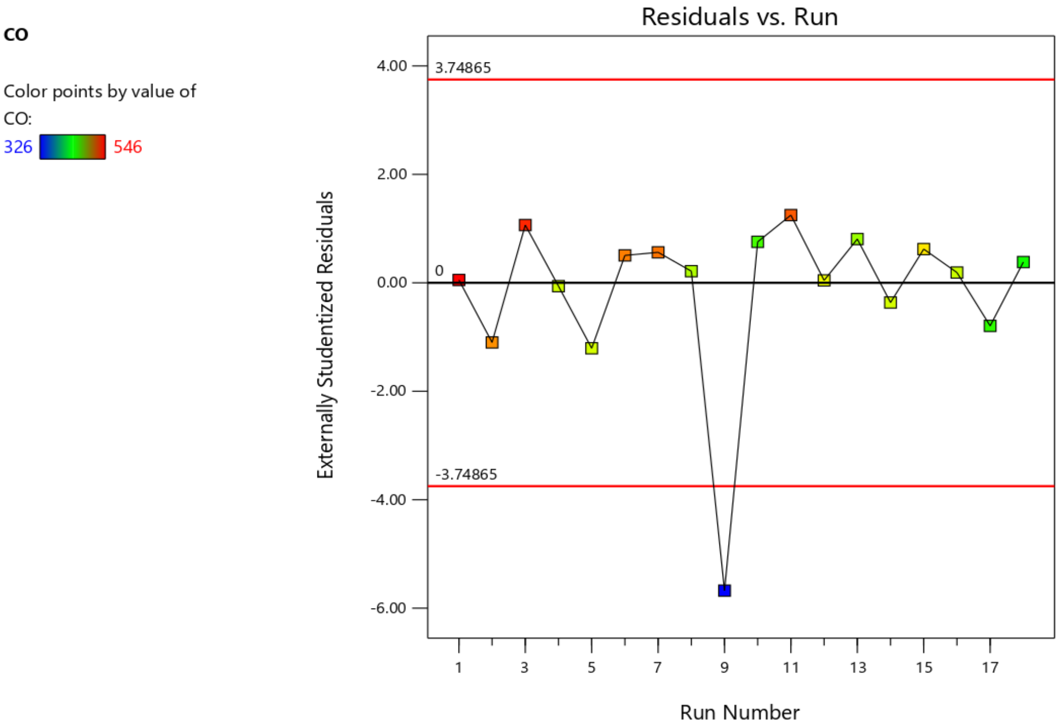
Appendix 34: Residuals versus run considering CO_2



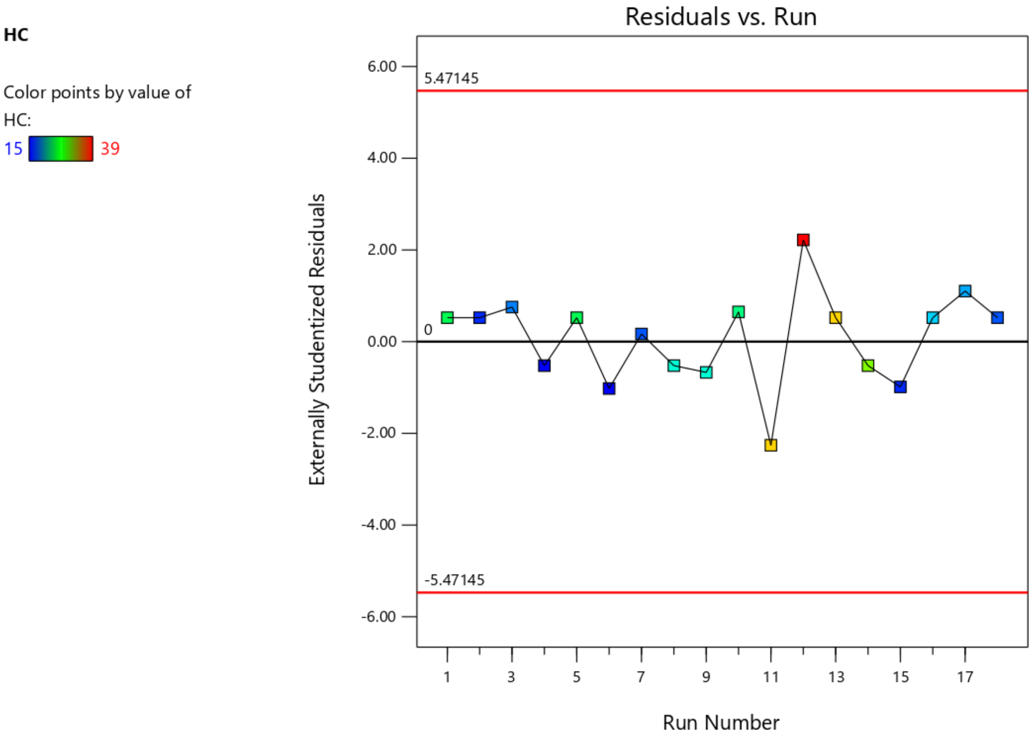
Appendix 35: Residuals versus run considering NOx



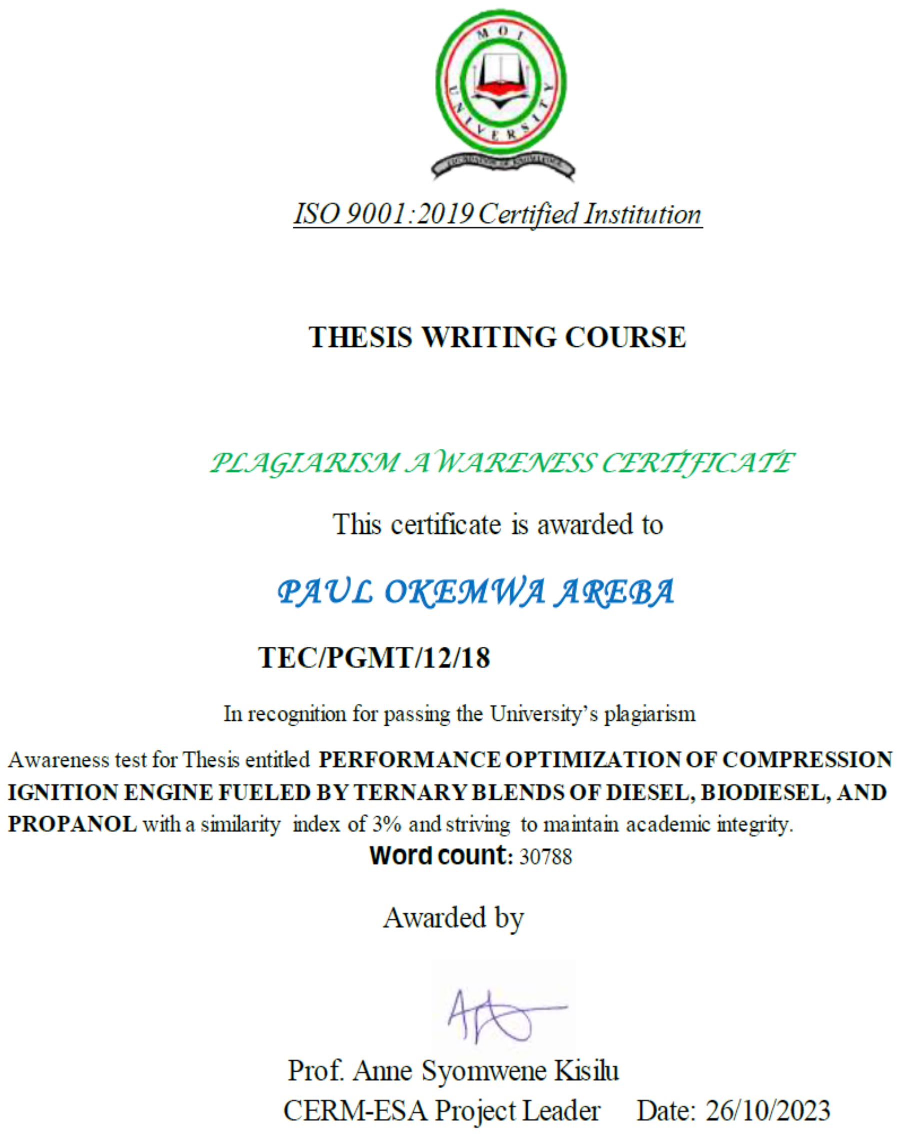
Appendix 36: Residuals versus run considering CO.



Appendix 37: Residuals versus run considering HC.



Appendix 38: Plagiarism Certificate



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CERM-ESA Project Leader Date: 26/10/2023

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