SOME STUDIES ON ENHANCEMENT OF DIESEL ENGINE CHARACTERISTICS AND FUEL PROPERTIES BY USING FUEL ADDITIVES

A thesis submitted to the Delhi Technological University, Delhi in fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Engineering

by

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DECLARATION

I hereby declare that the thesis entitled **"SOME STUDIES ON ENHANCEMENT OF DIESEL ENGINE CHARACTERISTICS AND FUEL PROPERTIES BY USING FUEL ADDITIVES"** is an original work carried out by me under the supervision of Dr. Naveen Kumar, Professor, and Dr. Raghvendra Gautam, Associate Professor, Mechanical Engineering Department, Delhi Technological University, Delhi. This thesis has been prepared in conformity with the rules and regulations of the Delhi Technological University, Delhi. The research work reported, and results presented in the thesis have not been submitted either in part or full to any other university or institute for the award of any other degree or diploma.

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CERTIFICATE

This is to certify that the work embodied in the thesis entitled **“ SOME STUDIES ON ENHANCEMENT OF DIESEL ENGINE CHARACTERISTICS AND FUEL PROPERTIES BY USING FUEL ADDITIVES”** by **Vipul Saxena, (Roll No.-2K18/PhD/ME/35)** in partial fulfilment of requirements for the award of Degree of **DOCTOR OF PHILOSOPHY in Mechanical Engineering**, is an authentic record of student’s own work carried by him under my supervision.

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

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Dedicated to my parents

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(Vipul Saxena)

ABSTRACT

Diesel engines continue to hold a dominant position in the global energy and transportation divisions due to their high efficiency, robustness, and cost-effectiveness. According to the International Energy Agency (IEA), diesel engines account for over 40% of the energy used in global transportation and are pivotal in freight logistics, power generation, and agricultural mechanization. In India, diesel engines power approximately 70% of freight vehicles and over 60% of agricultural machinery, making them indispensable to economic activity. However, their extensive use poses a significant environmental challenge. Diesel combustion emits high levels of nitrogen oxides, particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC), contributing to both regional pollution and worldwide environment concerns.

To counteract these environmental impacts, governments have enforced stringent emission regulations. In India, the implementation of Bharat Stage VI (BS VI) norms, aligned with Euro 6 standards, has mandated a substantial reduction in vehicular emissions. A cornerstone of this transition is the shift to Ultra-Low Sulfur Diesel (ULSD), which contains sulfur content below 10 ppm. While this has effectively reduced sulfur-related emissions, it has simultaneously led to deteriorated fuel lubricity, lower energy density, and an increase in engine component wear, particularly in fuel injection systems. Though renewable energy solutions are being promoted as long-term alternatives, their universal implementation is constrained by intermittency, high upfront infrastructure costs, and limited feasibility in remote, off-grid locations. In India alone, millions of agricultural diesel engines operate in regions lacking consistent electricity, making full-scale replacement with renewables impractical in the near term.

To diversify energy sources, the National Biofuel Policy (2018) encourages biodiesel production from waste cooking oil and other non-edible feedstocks. However, challenges persist in feedstock collection, supply chain logistics, and fuel quality assurance. These limitations hinder the large-scale implementation of biodiesel blending, despite its potential to reduce fossil fuel dependence and carbon emissions.

This research addresses the dual challenge of diesel fuel degradation post-desulfurization and limited biofuel integration by developing a novel multi-purpose additive. The additive is synthesized by combining a Lubricity Enhancer, Cetane Booster, Antioxidant, Combustion Catalyst, and Surfactant, mixed in specific ratios into a refined base oil to optimize physical and chemical compatibility with diesel fuels. A novel multipurpose solution was blended with ULSD and diesel-biodiesel blends in three volumetric concentrations: 0.5, 1.0, and 2.0 ml per 100 ml of fuel. The test samples for pure diesel were designated as D100MPS 0.5, D100MPS 1.0, and D100MPS 2.0, while blends containing 95% ULSD and 5% waste cooking oil-based biodiesel were labelled as D95WCB5MPS 0.5, D95WCB5MPS 1.0, and D95WCB5MPS 2.0.

In accordance with the National Biofuel Policy, WCO was collected and converted into biodiesel via base-catalyzed transesterification. The resulting fuel was characterized using Gas Chromatography-Mass Spectrometry (GC-MS) to analyze Fatty Acid Methyl Ester (FAME) profiles, focusing on the percentage of unsaturated fatty acids that influence combustion behavior and oxidation stability. Physicochemical properties of all fuel samples were assessed using ASTM standard methods. All tested blends conformed to ASTM standards and showed compatibility with baseline diesel.

Tribological performance was evaluated using a High-Frequency Reciprocating Rig (HFRR) to determine wear scar diameter and coefficient of friction. The aromatic-rich composition of MPS facilitated tribo-film formation, leading to MWSD reductions of 25.79%, 46.08%, and 56.23% for D100MPS 0.5, 1.0, and 2.0, respectively. Notably, D100MPS 2.0 also reduced the coefficient of friction by 55.08% compared to untreated BS-VI diesel. Results showed that D100MPS 2.0 significantly reduced both parameters, confirming enhanced lubricity due to the additive.

Engine trials were conducted on a Kirloskar make single-cylinder, four-stroke, direct injection compression ignition engine to evaluate engine characteristics. Findings indicated that the addition of additive solution improved brake thermal efficiency and reduced brake-specific energy consumption in both pure diesel and biodiesel blends on an unmodified engine. The incorporation of MPS, enriched with antioxidants and cetane improvers, led to NOx emission reductions from 1196 ppm to 1154 ppm for neat diesel and from 1298 ppm to 1185 ppm for the D95WCB5 blend at peak BMEP. All MPS-treated fuels showed consistent decreases in HC, CO, and smoke emissions. These outcomes highlight the additive's effectiveness in reducing overall exhaust emissions. However, increase in exhaust gas temperature (EGT) were observed, although all values remained within acceptable emission limits.

In summary, this research presents a comprehensive, scalable, and cost-effective strategy to overcome the tribological, performance, and emission challenges associated with ULSD and biodiesel-diesel blends. The Multipurpose Additive Solution (MPS) not only restores the lubricity lost during desulfurization but also enhances combustion characteristics and reduces harmful emissions without necessitating changes to existing engine hardware. The findings hold relevance for countries like India, where diesel engines remain critical to agriculture and transportation and where the transition to full electrification is a long-term endeavour. By bridging current fuel use with future sustainability targets, this research supports the advancement of cleaner and efficient diesel engine technologies aligned with national biofuel strategies and global energy commitments.

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NOMENCLATURE

@	At the rate
°C	Degree Celsius
°CA	Degree Crank Angle
aBDC	After Bottom Dead Centre
ASTM	American Society for Testing and Materials
aTDC	After Top Dead Centre
AVL-437	AVL-437 Smoke Meter
B.P	Brake Power
B100	Biodiesel 100%
B20	20% biodiesel/80% Diesel
bBDC	Before Bottom Dead Centre
BHA	Butylated Hydroxyl Anisole
BHT	Butylated Hydroxyl Toluene
BMEP	Brake Mean Effective Pressure
BS	Bharat Stage Emission Standards
BSEC	Brake Specific Energy Consumption
BSES	Bharat Stage Emission Standards
BSFC	Brake Specific Fuel Consumption
BSIV	Bharat Stage IV
BSVI	Bharat Stage VI
bTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
C.P	Cloud Point
cc	cubic centimetre
CFPP	Cold Filter Plugging Point
CI	Compression Ignition
cm	Centimetre
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COF	Coefficient of friction
cSt	Centistokes
CV	Calorific Value
DI	Direct Injection
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation

EGT	Exhaust Gas Temperature
EHN	2-ethylhexyl Nitrate
EN	European Union Standard
eq	Equation
FAME	Fatty Acid Methyl Ester
FFA	Free Fatty Acids
FSSAI	Food Safety and Standards Authority of India
ft	Feet
FTIR	Fourier Transform Infrared
g/kWhr	Gram per KiloWatt hour
GC-MS	Gas Chromatography Mass Spectrometry
.gm	Gram
HC	Hydrocarbon
HFRR	High-Frequency Reciprocating Rig
HP	Horsepower
hr	Hour
HRR	Heat Release Rate
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IS	Indian standard
J	Joule
J/kg	Joules/Kilogram
J/kgK	Joule per kelvin per kilogram
Kg	Kilogram
kHz	Kilohertz
KJ/Kg	Kilojoule per kilogram
kW	Kilowatt
ltr	Litre
MJ/kg	Mega Joules / Kilogram
ml	Millilitre
mm	Millimetre
MMT	Million Metric Tonnes
ms	Millisecond
Mtoe	Million tonnes of oil equivalent
MUFAs	Monounsaturated Fatty Acids
mV	Millivolt
MWDXRF	Monochromatic Wavelength Dispersive X-ray Fluorescence

MWSD	Mean Wear Scar Diamater
nm	Nanometer
NO_2	Nitrogen dioxide
NOx	Oxides of Nitrogen
OECD	Economic Co-operation and Development
P.P	Pour Point
PID	Proportional-Integral-Derivative
PM	Particulate Matter
ppm	Parts per million
PUFAs	Polyunsaturated Fatty Acids
PY	Pyrogallol
P-Ө	Pressure-Crank Angle
RPM	Revolutions Per Minute
RUCO	Repurpose Used Cooking Oil
TBHQ	Tert-butylhydroxyquinone
TDC	Top Dead Centre
UBHC	Unburnt Hydrocarbon
UNFAs	Unsaturated Fatty Acids
v/v	Volume by Volume
vol.	Volume
w/w	Weight by Weight
WCB	Waste Cooking Oil Biodiesel
WCO	Waste Cooking Oil
WEO	World Energy Outlook
wt	Weight
η	Efficiency
$\mu g/m^3$	Micrograms per Cubic Mete
µl	Microliter
µm	Micrometre
µmol/L	Micromole per litre

Chapter 1

INTRODUCTION

1.1 Global Energy Landscape

The world's energy demand keeps rising, with a growth of 2.2% in 2023, which is far higher than the 1.5% average annual growth rate experienced between 2010 and 2019 [1]. The growth was mainly driven by the BRICS countries accounting for a combined 42% of the world's energy consumption in 2023, with China alone recording a whopping growth of 6.6%. On the other hand, the OECD nations experienced a decline in energy consumption of 1.5% in the same year [1].

- **Total World Primary Energy Consumption:** Approximately **15 Gtoe** (gigatonnes of oil equivalent) [2].
- **World Power Generation Mix:** Approximately **29,800 TWh** (terawatt-hours) [3].
- **Renewable Capacity (Solar and Wind):** Approximately **2,400 GW** (gigawatts) [4].

Despite the rapid growth of renewable energy, fossil fuels still dominate the global energy mix, accounting for over 80% of total primary energy consumption in 2023 [1]. Figure 1.1 showed the summary of primary energy consumption.

1.1.1 Renewable Energy Growth

Renewable energy sources are seeing record expansion, as seen in the installation of a record 585 gigawatts (GW) of renewable power capacity in 2024 [5]. This represents 92.5% of the overall capacity growth and represents a 15.1% annual growth rate. Solar and wind power remain the principal drivers of the growth, providing 96.6% of all net renewable additions in 2024 [5]. IRENA's 2025 report states that the cumulative renewable power capacity reached a record level of 4,448 GW in 2024. The increase was spearheaded largely by a record 451.9 GW increase in photovoltaics to a total of 1,865 GW, the largest contribution from China at 278 GW.

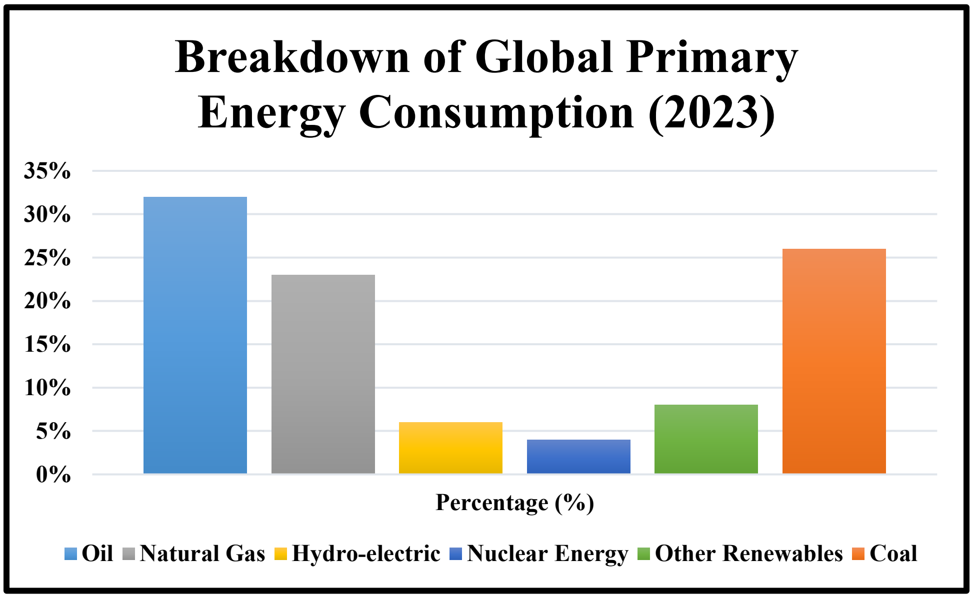

Figure 1.1: Global Primary Energy consumption (2023)
(Source: *Energy Institute, 2024)*

Wind capacity also experienced significant growth, increasing by 11.1% to 1,133 GW, the bulk of growth from China and the United States. Hydropower experienced a spectacular recovery to 1,283 GW. Bioenergy and geothermal capacities also rose by 4.6 GW and 0.4 GW, respectively.

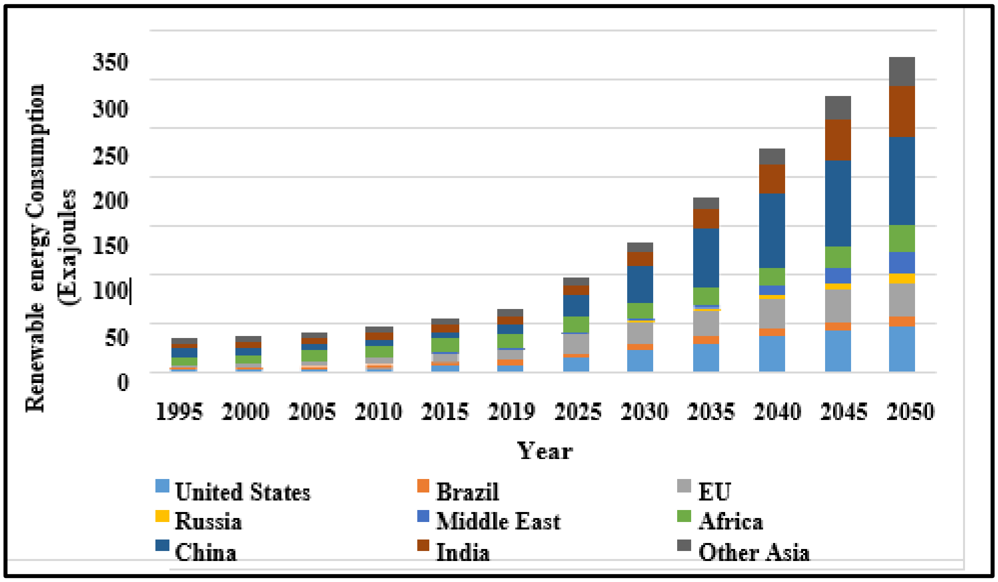

Figure 1.2: Leading countries consuming primary renewable energy in 2023

1.1.2 Fossil Fuel Trends

While renewable energy is growing rapidly, fossil fuel consumption also reached a historic high in 2023, increasing by 2% compared to 2022 [1]. This record consumption was primarily driven by increased energy demand in the Global South.

- **Coal:** Global coal consumption exceeded **164 EJ** for the first time, with **China** accounting for **56%** of the world's total consumption. However, **India's** coal consumption surpassed the combined total of Europe and North America for the first time in 2023[1].
- **Oil:** Oil consumption rebounded strongly in 2023, largely due to the relaxation of COVID-19 restrictions in China [1].
- **Natural Gas:** Natural gas demand grew by **2.7% in 2024**, reaching a new all-time high, driven by increased industrial use and power generation [6].

1.2 Current Trajectory of India's Energy Sector

The Indian energy sector is marked by a complicated interplay of increasing demand, ongoing confidence on fossil fuels, and a speeding shift towards renewable energy sources. The following is a technical overview of the present energy situation in India, including demand for different types of fuels, the geographical balance of oil production and consumption, and a comparative study of trends in oil production and consumption from 2019 onwards to projections up to 2050. The electricity generation mix, as per Ember report [3], is characterized by a diverse mix with low-carbon sources accounting for 22% of total generation in 2024. Precisely, hydroelectric power accounted for 9%, while the sum of wind and solar power contributed 10%, a remarkable turnabout from last year. In contrast, fossil fuel thermal generation accounts for the whopping 78%, with coal power stations accounting for 64% of incremental electricity demand during the period. The Central Electricity

Authority (CEA) has fixed a specific target of 1900 billion units (BU) of electricity generation during the fiscal year 2024-25, a growth rate of 9.3% as projected. Generation targets in detail by fuel sources are as follows: 1444.943 BU from thermal power, 147.709 BU from hydroelectric schemes, 55.348 BU from nuclear power stations, and 244 BU from renewable energy sources excluding large hydro. India has a total installed power generation capacity of 462.002 GW, with the detailed breakdown as per fuel types shown in Table 1.1 (CEA, "Power Sector at a Glance") [7]. Interestingly, cumulative capacity from non-fossil fuel sources stands at 217.625 GW, representing 47.1% of total installed capacity. The proportionate contribution of different sources of energy to electricity generated for the year 2024 is depicted in Figure 1.3 India's per capita electricity consumption has recorded a steady increase to 1,395 kWh in fiscal year 2023-24. It represents a compound annual growth rate (CAGR) of about 3.9% from 957 kWh in the fiscal year 2013-14 [8].

Table 1.1: Installed Generation Capacity (Fuel wise) as on (31.12.2024) [7]

Category	Installed Generation Capacity (MW)	% Share in Total
Fossil Fuel	**244,377**	**52.9%**
Coal	212,350	46.0%
Lignite	6,620	1.4%
Gas	24,818	5.4%
Diesel	589	0.1%
Non-Fossil Fuel	**217,625**	**47.1%**
RES (Incl. Hydro)	209,445	45.3%
Hydro	46,968	10.2%
Wind, Solar & Other RE	162,477	35.2%
Nuclear	8,180	1.8%

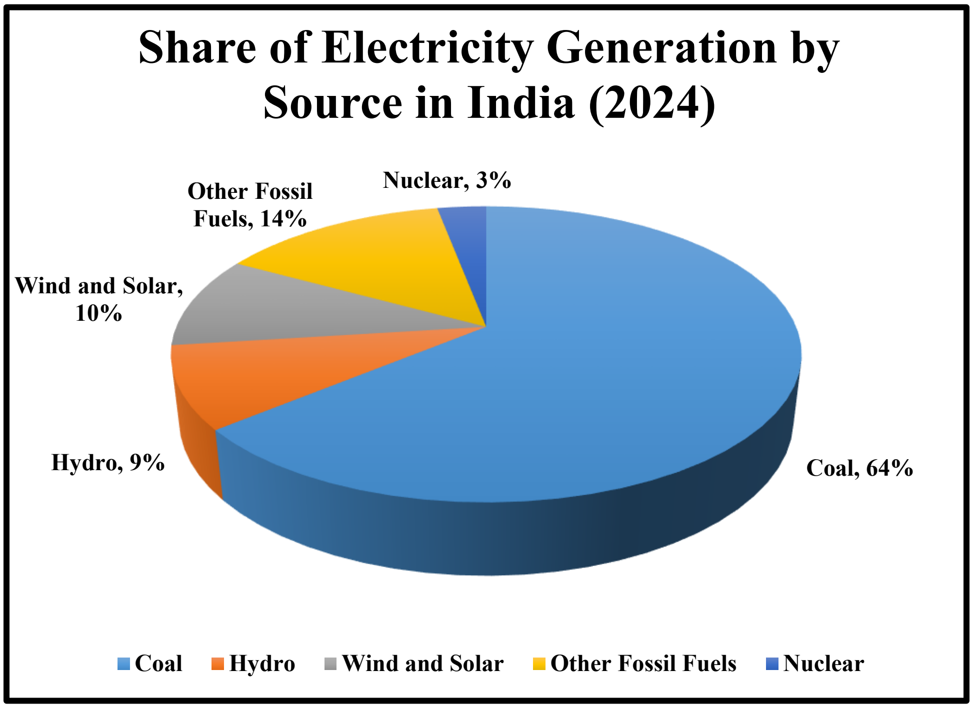

Figure 1.3: Share of Electricity Generation by Sources in India (2024)

1.3 Regional Analysis of Oil Production and Consumption

Granular, real-time data on oil production and consumption disaggregated by specific sub-national regions within India is not routinely disseminated publicly. However, analysis of data from the U.S. EIA's Country Analysis Brief on India [9] and the Petroleum Planning and Analysis Cell (PPAC) [10] provides insights into regional dynamics.

Oil Production (Approximate 2023 Data, Thousand Barrels per Day - kb/d):

- **Onshore Production (Aggregate):** ~294 kb/d, with key contributions from states including Assam, Gujarat, and Rajasthan [9].
- **Offshore Production (Aggregate):** ~298 kb/d, predominantly from offshore fields along the western continental shelf, notably the Mumbai High [9].

National oil consumption in 2023 was approximately 5.3 million barrels per day (mb/d) [9]. While precise regional consumption figures in mb/d are limited, higher consumption is inferred in states with significant industrial and commercial activity, including Maharashtra, Gujarat, and Tamil Nadu, as well as densely populated metropolitan areas across various states. National-level data from PPAC [10] indicates an indigenous crude oil production of 2.5 MMT and a total crude oil processed of 23.9 MMT for December 2024. The cumulative consumption of petroleum products for the period April-December 2024 reached 178.5 MMT.

The historical and projected trends in India's oil production and consumption are summarized in Table 2. The data highlights the persistent deficit between domestic production and consumption, necessitating significant import volumes. The trends from 2019 to 2024, along with illustrative short-term and long-term projections, are provided in Table 2. Diversification towards renewables and enhanced energy efficiency are crucial for India's energy security and sustainability goals.

Table 1.2: India Oil Production and Consumption (Approximate mb/d) [11]

Year	Production (mb/d)	Consumption (mb/d)	Net Import (mb/d)	Sources
2019	0.73	5	4.27	[9] [10]
2023	0.94	5.3	4.36	[9]
2024 (Estimate)	0.94	5.5	4.56	[9]
2025 (Short-Term Proj.)	-	6.5 - 7.0	-	[12]
2030 (Medium-Term Proj.)	Highly Variable	6.0 - 8.0	Highly Variable	[13]
2040 (Long-Term Proj.)	Highly Variable	6.5 - 9.0	Highly Variable	[13]
2050 (Long-Term Proj.)	Highly Variable	7.0 - 10.0	Highly Variable	[13] [14]

1.4 Diesel Engines and Their Significance: Current and Future Context

Diesel engines have been a core part of heavy-duty industrial and transport industries for a long time, due to their long lifetime, torque output, and efficiency in energy use. Their use varies from freight transport, maritime shipping, agriculture, to construction equipment. According to the IEA, diesel powered more than 96% of heavy-duty road transport energy consumption in 2022, thus consolidating its dominance in the global economy [15]. Additionally, Figure 1.4, as per IEA statistics, indicates the end-consumption of diesel by sector in the world in 2023, indicating the dominance of the transport sector. Diesel generators play a vital role in power security, acting as a backup power to essential infrastructure and as a primary power source in off-grid societies, thus sustaining economic activities in different environments.

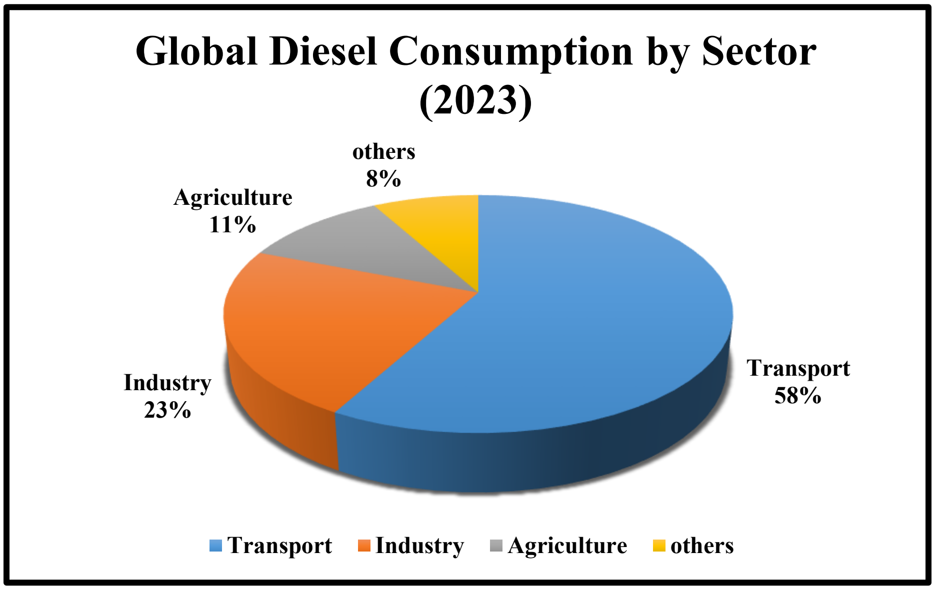

Figure 1.4 Globally Diesel Consumption by Sectors

(Source: IEA, World Energy Statistics 2024)

The diesel engine remains priceless today, particularly in regions and applications where electrification is economically or technologically unviable. Modern diesel engines have advanced considerably with the use of emission management technologies such as DPF, SCR and EGR. This has led to a substantial reduction in NO_x and PM, with current diesel engines conforming to aggressive emissions standards [16]. Concurrently, alternative fuels such as biodiesel and synthetic diesel also offer the possibility of minimizing emissions without engine design changes at a large scale. For instance, biodiesel has been indicated to reduce lifecycle CO_2 emissions while offering as good energy content as conventional diesel. Diesel engines that utilized biodiesel blends registered reduced NO_x emissions and improved lubricant properties, hence extending engine life and reducing maintenance intervals [17]. Even though these have been improved, diesel engines have come under criticism for their role in GHS emissions. The transport industry accounts for almost a quarter of CO_2 emissions worldwide, with diesel engines being a major contributor [15].

However, there have been new discoveries indicating potential avenues for reducing their effect on the environment. Yu et al. [18] developed new modelling methods that balance combustion efficiency with the minimization of unburned hydrocarbons for improved diesel engine performance, with lower emissions.

In the future, diesel engines are projected to serve a bridging role as hybrid technologies and alternative fuels move toward maturity. Hybrid diesel-electric drivetrains are already employed in public transit and rail service, combining the high energy density of diesel fuel with the improved efficiency of electric drivetrains [19]. While the global movement toward decarbonization poses substantial challenge to the continued application of diesel engines, technological advancements and the diversification of fuel sources offer viable solutions to their development.

Diesel engines will remain a vital part of the transportation and industrial sectors during the ongoing energy transition, evolving to become progressively cleaner and more efficient.

1.5 Environmental Impact and Degradation

Air pollution is a significant environmental risk that impacts negatively on public health, the environment, and the global climate system. Significant air pollutants such as $PM_{2.5}$ and PM_{10}, NO_x, SO_2, volatile organic compounds (VOCs), and carbon monoxide (CO) are mainly emitted as a by-product of fossil fuel combustion in transportation, energy, and industries [20]. These emissions are the foundation in the cause of air quality deterioration and long-term environmental degradation. The health impacts for humans are enormous. The World Health Organization [21] estimates around 7 million premature deaths worldwide annually from indoor and ambient air pollution. The pollutants link with cardiovascular illness, stroke, chronic obstructive pulmonary disease (COPD), and lung cancer [22]. Recent worldwide burden studies prove that exposure to $PM_{2.5}$ ranks as one of the greatest causes of premature mortality, especially among low- and middle-income countries [23].

Air pollution also impacts ecosystems significantly. SO_2 and NO_x deposition leads to acidification of soil and water, which harms forests and aquatic ecosystems [24]. Ground-level ozone, which is formed by the photochemical oxidation of VOCs and NO_x, harms crop yields and forest growth, which can damage food security and biodiversity [25]. In addition, most air pollutants are also short-lived climate pollutants (SLCPs). Black carbon, methane, and surface-level ozone have high global warming potential and are drivers of climate change and subsequently of air pollution through pathways like enhanced wildfires and heatwaves [26]. Toxic air pollutants such as lead, mercury, and dioxins bioaccumulate in environmental processes, impacting not only human health but also reproductive health and viability in numerous different species of wildlife [27].

These impacts have especially harmful implications in ecologically sensitive areas. To prevent air pollution and its resulting cascading effects, overall mitigation efforts are justified. These include shifting to clean sources of energy, stricter enforcement of higher emissions, improved public transportation infrastructure, and international cooperation [28].

1.6 Emission Regulations and Standards

Emission rules have long been a key means to curb pollution and ease environmental harm. Countries use these guidelines to put a cap on the amount of nasty pollutants released by everything from cars, factories, and power plants. The idea is simple to protect public health, reduce damage to our surroundings, and nudge innovators toward greener technologies [29]. In United States, a major shift happened with the Clean Air Act of 1970, a law, that in many respects, reshaped how we think about air quality. By giving the EPA, the power to set ambient air quality standards for pollutants like $PM_{2.5}$, NO_2, SO_2, and ozone, the act set the stage for real change. Over the years and even when the economy was booming, and energy demand was up—this legislation has helped bring pollutant levels down noticeably [30].

Over in Europe, a different approach emerged with the introduction of Euro emission standards. Starting with Euro 6 in 2014, automakers were required to drastically cut nitrogen oxides and particulate matter from CI engines. This move pushed the widespread use of solutions such as DPF and SCR systems, and by 2017 the European Union had even rolled out Real Driving Emissions testing to check performance in everyday conditions [31] [32].

In Asia, countries like China and India have introduced aggressive regulatory structures to address serious air quality issues. Both were introduced in China's "China VI" standards and India's India Stage VI (BS VI), which has been closely aligned with Euro 6 criteria and reflects a sufficient leap in air pollution control [33]. These standard no_x, PM and hydrocarbons, and encourage cleaner fuel and advanced emission control systems.

In addition, international bodies have increased emission regulation beyond road transport. The International Maritime Organization (IMO) introduced the IMO 2020 regulation, reducing the permissible sulfur content in marine fuel from 3.5% to 0.5%, aimed at more than 75% to the sulfur dioxide emissions [34]. The International Civil Aviation Organization (ICAO) has also developed CO and emission standards for the aircraft, improving fuel efficiency and emissions performance [35]. Finally, emission rules and standards are important to achieve air quality and climate goals. While many countries have made adequate progress, global harmony, technological innovation and strict enforcement are essential for their long -term success.

1.7 Diesel Desulfurization Techniques and Challenges with Ultra-Low Sulfur Diesel (ULSD)

Global push for cleaner air and low environmental pollution has led to strict rules on fuel quality, especially about sulfur content in diesel fuel. Sulfur, while naturally present in crude oil, contributes significantly to harmful emissions when burnt. The transition to ULSD, diesel fuel containing 15 parts per million (ppm) sulfur or less has been a pivotal step in mitigating these emissions. However, this infection is not without challenges, especially about engine performance and fuel system durability. Diesel fuel produces sulfur compounds, on combustion, sulfur dioxide (SO_2), which is detrimental to both human health and environment, a precursor for acid rain and fine particulate matter. High sulfur material also disrupts the efficiency of advanced emission control systems such as DPF and catalyst converters. Recognizing these issues, regulatory bodies worldwide have made a decrease in sulfur content in diesel fuel.

Desulfurization Techniques

Desulfurization refers to the exclusion of sulfur compounds from fuels such as diesel, kerosene, and gasoline. This process is crucial for reducing sulfur oxide emissions, which are harmful to both the ecosystem and human being health. Several techniques are employed in industry, each with its own advantages and limitations.

Hydrodesulfurization (HDS)

HDS is the most widely used industrial process for desulfurization. It involves treating petroleum fractions with hydrogen in the presence of a catalyst at extreme temperatures (up to 400°C) and pressures (up to 100 atm). While effective for many sulfur compounds, HDS struggles with refractory sulfur species like 4,6-dimethyldibenzothiophene, and it is energy-intensive and costly due to the harsh operating conditions required [36] [37] [38]

Oxidative Desulfurization (ODS)

ODS is gaining attention as an alternative to HDS, especially for ultra-deep desulfurization. It operates under milder conditions and uses oxidants (e.g., hydrogen peroxide, organic peracids) to convert sulfur compounds into their corresponding sulfones or sulfoxides, which are more easily removed by extraction or adsorption. Catalysts such as heteropolyacids, ionic liquids, and polyoxometalates are often used to enhance the oxidation process [36][37][38][39].

Adsorptive Desulfurization

This technique utilizes adsorbents (e.g., activated carbon, zeolites, metal-organic frameworks) to selectively capture sulfur compounds from fuels. It is considered a green, energy-efficient, and economical alternative, especially when optimized with advanced materials such as nano-catalysts. Adsorptive desulfurization can potentially achieve up to 100% removal of certain sulfur species [36][38]. It operates effectively at mild conditions, eliminating the need for high temperature and pressure typically required in hydrodesulfurization. The efficiency of this method is highly dependent on the surface area, pore size, and functional groups of the adsorbent material.

Extractive Desulfurization

In this method, solvents (including ionic liquids) are employed to isolate sulfur combinations from fuel. The process can be combined with ODS (extractive–oxidative desulfurization) for enhanced efficiency. Ionic liquids are particularly effective due to their tunable properties and selective solubility for sulfur compounds [38][39].

Bio desulfurization

Bio desulfurization employs microorganisms or enzymes to selectively degrade sulfur compounds in fuels. This method is environmentally friendly and operates under mild conditions, but it is currently limited by slow reaction rates and challenges in scaling up for industrial use [38][40].

Emerging Techniques and Nano-catalysts

Research is ongoing into the use of nano-catalysts (e.g., graphene, carbon nanotubes, metal-organic frameworks) to improve the efficiency and selectivity of desulfurization processes. Nano-catalysts offer higher surface area and unique properties that can enhance catalytic activity and sulfur removal rates [36].

Table 1.3. Summary Table of Desulfurization Techniques

Technique	Principle	Key Advantages	Key Limitations
Hydrodesulfurization (HDS)	Hydrogenation with catalyst	Industrial standard, effective	High energy/cost, limited for refractory compounds
Oxidative Desulfurization (ODS)	Oxidation of sulfur compounds	Mild conditions, effective for refractory sulfur	Requires oxidants, post-treatment needed
Adsorptive Desulfurization	Selective adsorption	Green, economical, high efficiency	Adsorbent regeneration/disposal
Extractive Desulfurization	Solvent extraction	Selective, can be combined with ODS	Solvent recovery, cost
Bio-desulfurization	Microbial/enzymatic degradation	Environmentally friendly, mild	Slow, scale-up challenges

Challenges with ULSD in diesel engine

Ultra-Lo Sulfur Diesel (ULSD) fuel, which was defined by being 15 ppm or less sulfur content, was mainly introduced to enable the use of advanced emission control technologies such as the DPFS and the SCR system. However, despite its environmental benefits, the ULSD makes several operating challenges for the diesel engine:

a) Low Lubricity

Sulfur compounds in diesel fuel historically contributed to its natural lubrication properties. The removal of sulfur during the hydro desulfurization process also eliminates many polar compounds that provide lubrication. As a result, ULSD has usually reduced the lubrication, increasing the wear in fuel pumps and injectors [41]. Prolonged operation with low-lubricity fuel may result in premature component failure.

b) Injector fouling

Injector fouling is another important problem associated with ULSD. Removing sulfur also affects fuel stability, which leads to the formation of deposits in high pressure injector ducts, especially in modern normal-rail systems. They restrict the accumulated fuel flows, disrupt spray patterns, and reduce combustion efficiency [42]. Additives and detergents are often required to reduce injector fouling when using ULSD.

c) Cold flow properties

ULSD has inferior cold flow characteristics compared to traditional diesel fuel. The processes used to remove sulfur can also change the paraffinic structure of fuel, increase cloud points and put points. At low temperatures, ULSD can create a wax crystal that can prevent fuel filters and lines, allowing fuel starvation and engine stalling [43].

d) Microbial Development

The higher water solubility of ULSD also creates a more hospitable environment for microbial growth at the fuel-water interface. Microbial contamination can indicate to the establishment of biofilms and sludge, which clog fuel filters, corrode tanks, and create operational issues [44]. Proper tank maintenance, biocide treatments, and water separation systems are critical to managing microbial growth in ULSD storage systems.

1.8 Diesel Lubricity: Significance and Measurement Methods

Diesel lubricity is a vital property that substantially impacts the performance, effectiveness, and longevity of diesel engines. This property indicates the fuel's ability to provide sufficient lubrication to fuel system components, particularly high-pressure fuel pumps and injectors that rely on the fuel itself for lubrication. As environmental regulations have pushed for cleaner diesel fuels with reduced sulfur content, the importance of understanding and measuring lubricity has grown substantially.

Lubricity in diesel fuels refers to the fuel's ability to decrease friction and wear between surfaces in relative motion under load. In diesel engines, the fuel serves not only as a combustible fluid but also as a lubricant for precision fuel system components [45]. Without adequate lubricity, these components experience accelerated wear, potentially leading to premature failure and costly repairs.

Diesel fuel lubricity largely depends on its chemical makeup. Trace surface-active compounds within the fuel form a protective boundary layer that helps minimize wear on components like pumps and injectors [46]. These compounds typically contain polar molecules with oxygen, nitrogen, or sulfur atoms that can adhere to metal surfaces and form protective films. Historically, conventional diesel fuels contained sufficient naturally occurring lubricity agents, primarily due to their sulfur content. However, modern environmental regulations have directed the production of ULSD fuels, which undergo hydro-processing to remove sulfur compounds [45]. This desulfurization process inadvertently removes many of the polar mixtures that supply natural lubricity to the fuel [47].

Significance of Diesel Lubricity

Critical Role in Engine Performance and Durability

Fuel lubricity is an essential property that ensures the longevity and efficiency of diesel CI engines [47]. The fuel injection systems in modern CI engines operate at extremely elevated pressures often exceeding 2,000 bar in common rail systems-and rely on the diesel fuel to lubricate moving components such as pumps, injectors, and valves [48]. Due to lack of lubricity, the following problems may occur:

- Accelerated wear of fuel pumps and injectors
- Reduced efficiency of the fuel delivery system
- Increased maintenance costs and downtime
- Shortened service life of engine components
- Potential catastrophic failure of fuel system components

Economic Implications

The economic impact of poor diesel lubricity extends beyond the immediate cost of component replacement. Engine downtime, reduced fuel economy, and increased maintenance intervals all contribute to higher operational costs for diesel equipment owners [49]. For commercial fleets, transportation companies, and industrial operations, these costs can be substantial.

Environmental Considerations

The push for cleaner diesel fuels has created a paradox: while lower sulfur content reduces harmful emissions, it also compromises the natural lubricity of the fuel [50]. This environmental trade-off has necessitated the development of lubricity additives and alternative solutions to maintain adequate protection for engine components while still meeting emission standards [51].

Factors Affecting Diesel Lubricity

Sulfur Content

Historically, sulfur-containing compounds in diesel fuel contributed significantly to its lubricity. Traditional diesel fuels with higher sulfur content (>500 ppm) generally exhibited good lubricity properties [50]. However, environmental regulations have progressively reduced allowable sulfur levels to as low as 10-15 ppm in many regions, creating lubricity challenges [50]. Research has shown that dibenzothiophene, a sulfur compound contained in non-desulfurized diesel, does not enhance diesel lubricity on its own [45]. Rather, it's the polar compounds that are removed during the hydrodesulfurization process that primarily contribute to lubricity [45].

Chemical Composition and Polarity

The chemical organization of fuel elements plays a crucial role in revealing lubricity properties. Compounds with polar functional groups, particularly those containing oxygen atoms, demonstrate superior lubricity characteristics compared to non-polar hydrocarbons [45]. Fatty compounds, such as those found in biodiesel, have improved lubricity than hydrocarbons because of their polarity-imparting oxygen atoms [45]. Free fatty acids, monoacylglycerols, and glycerol have been shown to exhibit excellent lubricity properties [45].

Polycyclic Aromatic Hydrocarbons (PAH)

Research has demonstrated that certain polycyclic aromatic hydrocarbons (PAH) present in diesel fuels contribute to lubricity through their surface-active properties [46]. These compounds can adsorb onto metal surfaces, forming protective films that reduce friction and wear [46]. Through direct measurement using 1H and 13C nuclear magnetic resonance spectroscopy, studies have related the presence of PAH with fuel lubricity measured with a high-frequency reciprocating rig [46]. However, carboxylic acids and nitrogen heterocyclic PAH were not detected in some diesel fuels tested, suggesting that other surface-active PAH compounds are responsible for improved lubricity [46].

Biodiesel Components and Blending

Biodiesel, identified as mono-alkyl esters of vegetable oils and animal fats, has been broadly recognized for its competence to improve the lubricity of petroleum-derived diesel fuels [45]. Even at low mix levels, biodiesel can significantly improve the lubricity of ULSD [45]. The methyl ester structure in biodiesel is primarily responsible for lubrication improvement in base fuels with poor lubricity properties [52]. When biodiesel is blended with petroleum diesel or hydrogenated vegetable oil (HVO), the ester molecules adsorb on metallic surfaces, acting as a protecting layer during the rubbing procedure [52].

Studies have shown that palm oil biodiesel (POB) successfully improves the tribological characteristics of various diesel fuels and efficiently acts as a lubricity improver, showing a minimum friction coefficient and improved specific wear rate [52]. Interestingly, 60-90% v/v POB blend with HVO showed competitive lubricity capacity, resulting in non-ideal contribution to changes in COF, WSD, and specific wear rate [52].

Nanoparticle Additives

Recent research has explored the potential of nanomaterials to improve diesel fuel lubricity. Various nanoparticles, including carbon nanoplates, carbon nanotubes, aluminum oxide, zinc oxide, and cerium oxide, have been investigated as lubricity-enhancing additives [47]. The addition of nanoparticles can improve the lubricity of both conventional diesel and biodiesel fuels, although the effect differs among nanoparticle types and base fuels [47]. Carbon nanotubes have shown promising results for both fuel types, while zinc oxide improved the lubricity of conventional diesel fuel, and carbon nanoplatelets and aluminum oxide nanoparticles enhanced biodiesel lubricity [47].

Vegetable Oil Additives

Vegetable oils have demonstrated potential as lubricity-enhancing additives for low-sulfur diesel fuels [51][48]. Research has shown that adding vegetable oil in small concentrations can significantly improve the lubricating properties of diesel fuels, even those that initially do not comply with standard lubricity requirements [48]. Experiments using the standard HFRR method have demonstrated that vegetable oil additives can reduce the wear scar diameter in diesel fuel almost linearly as the percentage of vegetable oil increases [48]. This provides a potentially cost-effective and renewable option for improving diesel lubricity.

Measurement Methods for Diesel Lubricity

High-Frequency Reciprocating Rig

The High-Frequency Reciprocating Rig (HFRR) test is the most widely accepted method for measuring diesel fuel lubricity [45][46][52][47]. This test is standardized under several methods, including ASTM D6079, and is specified in many fuel quality standards worldwide [53][54]. The WSD on the ball is measured after the test and used as an indicator of fuel lubricity [52][47]. Smaller wear scar diameters indicate better lubricity. For acceptable diesel fuel lubricity, standards typically specify a maximum WSD of 460 micrometers [52][55]. The HFRR method has gained widespread acceptance due to its good correlation with field performance and repeatability [53]. However, it does have limitations, particularly when testing volatile fuels like ethanol-diesel blends, as the elevated temperature can lead to evaporation and composition changes during testing [55].

Four-Ball Machine Method

The four-ball machine method represents an alternative approach to measuring fuel lubricity, especially useful for volatile fuel blends where the HFRR method may face limitations due to evaporation issues [55]. Three steel balls are fixed in a stationary position in a cup filled with the test fuel and a fourth ball rotates against the three stationary balls under load. The load is continuously increased until scuffing (localized welding and tearing) occurs. The scuffing load is used as the lubricity criterion [55]. Research on ethanol-diesel blends has demonstrated that this method can provide insights into lubricity properties while limiting the ethanol evaporation process [55]. The results have shown that increasing the fraction of ethanol up to 14% (v/v) in diesel fuel results in a reduction in lubricity as measured by the scuffing load criterion [55].

Scuffing Load Ball-on-Cylinder Lubricity Evaluator

The Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SLBOCLE) is another method used to assess diesel fuel lubricity [53]. This method differs from the HFRR in its approach. A steel ball is loaded against a rotating steel cylinder, The load at which scuffing occurs provides a measure of lubricity. Results are reported as the maximum load (in grams) that the fuel can sustain before scuffing occurs. Comparative studies between HFRR and SLBOCLE methods have been conducted to understand the correlation between these different measurement techniques and their ability to predict field performance [53]. Each method has its strengths and may be more suitable for specific types of fuels or testing conditions.

Other Specialized Methods

Several other methods have been developed for specific applications or research purposes:

Simulated Distillation Method: For FAME (Fatty Acid Methyl Esters) and fuels based on vegetable oils, the simulated distillation method is often used as a complementary approach to understand the distribution of compounds that may contribute to lubricity [54].

Worn Surface Analysis: Beyond quantitative measurements of wear scar diameter or scuffing load, microscopic and spectroscopic analysis of worn surfaces can provide valuable insights into lubrication mechanisms [47]. These analyses help elucidate how different additives or fuel components interact with metal surfaces to provide protection.

1H and 13C NMR Spectroscopy: Nuclear magnetic resonance spectroscopy has been used to directly measure polycyclic aromatic hydrocarbons in diesel fuels and correlate their presence with lubricity performance [46]. This approach provides a deeper understanding of the specific compounds responsible for lubricity enhancement.

Standards and Specifications

EN 590 (European Standard): Specifies a maximum HFRR wear scar diameter of 460 μm at 60°C

ASTM D975 (American Standard): Requires a maximum HFRR wear scar diameter of 520 μm

ISO 12156: Provides the standard test method for estimating diesel fuel lubricity using the HFRR

As environmental regulations continue to push for cleaner fuels with lower sulfur content, understanding and addressing lubricity concerns becomes increasingly important for ensuring reliable operation of diesel engines. The HFRR test has emerged as the predominant method for measuring diesel lubricity, though alternative approaches like the four-ball machine method and SLBOCLE provide valuable complementary data, particularly for fuels with high volatility or unconventional compositions.

1.9 National Biofuel Policy and Implementation Challenges

India's National Biofuel Policy (NBP), established in 2018 and amended in 2022, aims to enhance energy security, reduce crude oil imports, and curb greenhouse gas emissions through ethanol blending targets and waste-to-energy initiatives. However, its implementation faces multifaceted challenges spanning technological limitations, feedstock shortages, financial constraints, and socio-environmental trade-offs. This analysis examines the policy's evolution, objectives, and operational hurdles while proposing actionable solutions.

Policy Framework and Strategic Objectives

The NBP operates under a two-pronged strategy: 20% ethanol blending in petrol by 2025-26 (Ethanol Blending Programme) and 5% biodiesel blending by 2030 [56] [57]. To achieve this, the government introduced:

- **Differential pricing mechanisms** for ethanol from sugarcane (₹65.61/L) vs. grain-based sources (₹56.87/L) [57]
- **Viability Gap Funding** for 2G bioethanol plants using agricultural residues [58]
- **Tax incentives** for biodiesel production under GST regime [59]

The policy prioritizes non-food feedstocks in Phase-III (2021-26), emphasizing municipal solid waste, agricultural residues, and energy crops like Jatropha [60]. This aligns with India's Nationally Determined Contributions to reduce emission intensity by 45% from 2005 levels by 2030 [57].

Implementation Challenges

1. Feedstock Supply Chain Constraints

Despite 160 million tonnes of agricultural surplus annually, only 20% gets utilized due to:

- **Geographical dispersion** of biomass sources
- **Seasonal variability** in sugarcane production (300 days/year operational gap) [61]
- **Storage losses** (15-20% for rice straw, 30% for sugarcane bagasse) [62]

2. Technological Barriers

Second-generation (2G) biofuel plants show **45% lower efficiency** than global benchmarks due to:

- Immature enzymatic hydrolysis processes
- High silica content in Indian crop residues damaging machinery [61]
- Only 12 operational 2G biorefineries against 35 planned [57]

3. Financial Viability Issues

Cost Factor	**1G Ethanol**	**2G Ethanol**
Capital Cost (₹/KL)	35,000	1,10,000
Production Cost (₹/L)	48-52	65-70
ROI Period	5 years	8+ years

Data from NITI Aayog 2023 [57] [58]

Banks charge 12-14% interest for biofuel projects vs 7-8% for solar energy [58], discouraging private investments.

4. Policy Inconsistencies

- **State-level variations**: Maharashtra offers ₹2/L ethanol subsidy while UP imposes ₹750/tonne sugarcane cess [63]
- **Import paradox**: 20% customs duty on biodiesel vs 0% on crude palm oil [59]
- **Delayed payments**: OMCs owe ₹12,800 crore to ethanol suppliers as of March 2024 [57]

5. Environmental Trade-offs

Waste-to-energy plants like Delhi's Okhla facility face criticism:

- **Emission concerns**: Dioxin levels at 0.25 ng/m³ vs EU standard of 0.1 ng/m³ [64]
- **Ash disposal**: 25-30% incineration residue contains heavy metals [64]
- **Land use change**: 4.2 million hectares needed for Jatropha cultivation risks displacing food crops [65]

While India's biofuel policy demonstrates visionary intent, its success hinges on resolving structural contradictions between agricultural priorities and energy goals. The ₹15,000 crore investment planned under the National Green Hydrogen Mission could catalyze advanced biofuel adoption if coupled with farmer-centric incentives and robust environmental safeguards. A 2025 review of blending targets suggests recalibrating to 18% ethanol and 3% biodiesel would balance feasibility with ambition [57][58].

1.10 Biodiesel Industry: Present Status, Challenges, and Future Opportunities

The worldwide energy landscape is experiencing a transformative shift as nations seek sustainable alternatives to fossil fuels. Biodiesel has emerged as a promising solution to address the twin challenges of energy security and environmental sustainability. The present status of the biodiesel industry, the multifaceted challenges it faces, and the future opportunities that lie ahead, with a focus on technological advancements, policy frameworks, and market dynamics.

Present Status of the Biodiesel Industry

Biodiesel production has witnessed significant growth over the past two decades, driven by the volatility in worldwide fuel prices, the urgent need to reduce GHG emissions, and mandates for sustainable energy in transport, industry, and power generation [66]. Countries such as Indonesia, Malaysia, Brazil, the United States, and members of the European Union have established themselves as key players in the biodiesel market, leveraging abundant feedstocks and supportive policy frameworks [67][68].

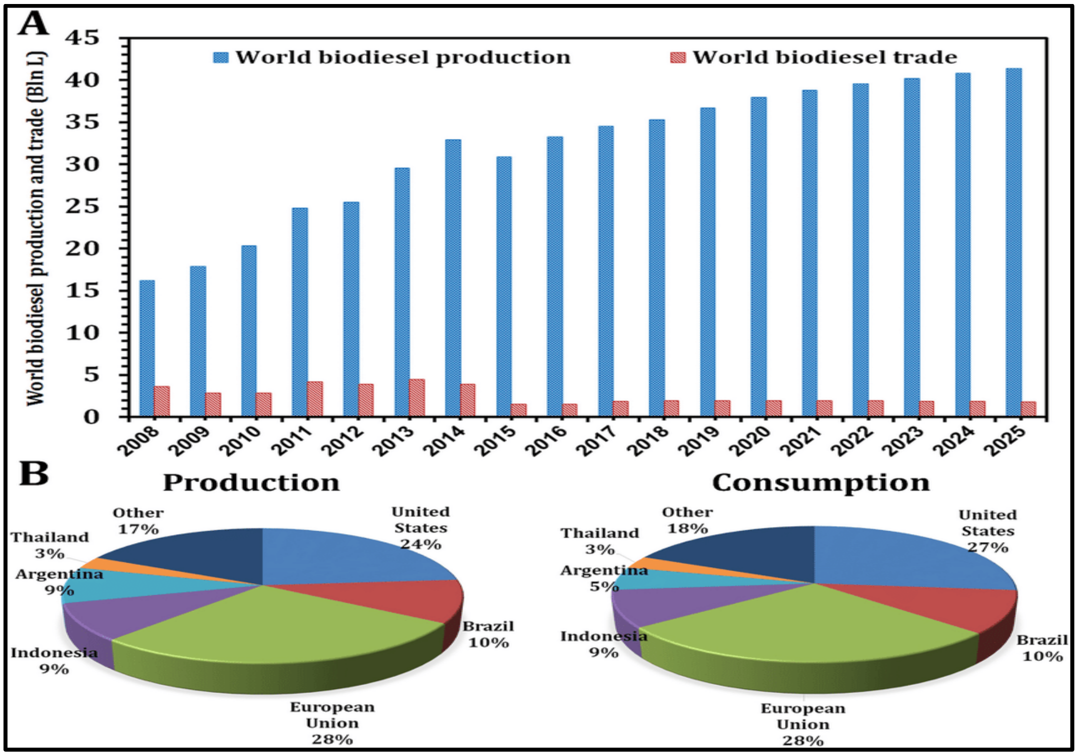

**Figure 1.5: Production and trade of biodiesel on a global scale (A).
Regional distributions of global biodiesel production and consumption in 2025 (B)**

Feedstock Diversity

The choice of feedstock is central to the feasibility and sustainability of biodiesel production. Traditional feedstocks include edible vegetable oils (soybean, rapeseed, palm), but concerns over food security and the food-versus-fuel debate have spurred interest in non-edible and waste-derived sources. Notably, Jatropha curcas has emerged as a promising non-edible oilseed, offering high oil content and favourable fuel properties without competing with food crops [69]. Waste animal fats and used cooking oils are also gaining traction as cost-effective and environmentally friendly alternatives, particularly in regions with large meat processing industries [66].

Technological Advancements

Biodiesel production technologies have evolved from simple batch processes to sophisticated, multi-stage operations. The most common method involves transesterification, where triglycerides respond with alcohol (usually methanol) in the presence of a catalyst to produce biodiesel (fatty acid methyl esters) and glycerol as a byproduct [66]. Innovations in catalysis, such as the use of polymeric and nano catalysts, have improved process efficiency, yield, and environmental performance [70][71][72]. Furthermore, the integration of waste-to-energy approaches and the valorisation of byproducts are enhancing the economic viability of biodiesel plants.

Market and Regulatory Environment

The biodiesel market is shaped by a complex interplay of policy incentives, blending mandates, and international trade dynamics. For instance, Malaysia and Indonesia have implemented progressive biodiesel blending mandates (B20, B30), while the European Union enforces sustainability criteria through its Renewable Energy Directive [73][67]. In Brazil, robust policy support and a focus on domestic feedstocks have established the country as a leader in biodiesel production and revolution [68].

Challenges Facing the Biodiesel Industry

Feedstock Availability and Cost

Feedstock procurement remains the single largest cost component in biodiesel production, often accounting for up to 70-80% of total costs. The reliance on edible oils can exacerbate food security concerns and price volatility. While non-edible and waste-derived feedstocks offer a solution, their availability, collection, and preprocessing present logistical and technical hurdles [69][66].

Technological and Process Limitations

Despite advancements, several technical challenges persist:

Catalyst Performance: Conventional catalysts can be sensitive to impurities (e.g., free fatty acids, water), leading to soap formation and reduced yields. The development of robust, reusable, and environmentally benign catalysts is ongoing [70][71].

Process Integration

Efficient integration of upstream (feedstock preparation) and downstream (product purification, byproduct management) processes is critical for economic viability.

Engine Compatibility

While biodiesel is largely friendly with existent CI engines, issues related to cold flow properties, oxidative stability, and energy density can affect performance, especially in colder climates [71].

Environmental and Social Concerns

The expansion of biodiesel production, particularly from palm oil and other monocultures, has raised concerns about deforestation, biodiversity loss, and indirect land-use change. Sustainable certification schemes and the promotion of marginal lands for non-edible crops are being explored to mitigate these impacts [69][73].

Policy and Market Uncertainties

The biodiesel industry is highly policy dependent. Sudden changes in subsidies, blending mandates, or trade policies can disrupt markets and investment flows. The COVID-19 pandemic, for example, led to a historic drop in fuel demand and exposed vulnerabilities in the supply chain, particularly in countries like Indonesia and Malaysia [67].

Economic Competitiveness

Biodiesel must compete with fossil diesel and other alternative fuels on both price and performance. The volatility of crude oil prices, coupled with the cost of feedstocks and processing, can affect the competitiveness of biodiesel, especially in the absence of supportive policies or carbon pricing mechanisms [66][73].

Future Opportunities for the Biodiesel Industry

Feedstock Innovation and Diversification

The future of biodiesel lies in the diversification and sustainable sourcing of feedstocks. Promising avenues include:

Non-edible Oilseeds: Crops like Jatropha curcas, Pongamia, and Camelina can thrive on marginal lands, reducing competition with food crops and enhancing rural livelihoods [69].

Waste Streams: Harnessing waste animal fats used cooking oils, and agricultural residues can lower production costs and environmental impacts while supporting circular economy principles [66][72].

Algal Biodiesel: Microalgae offer exceptional oil yields and can be cultivated on non-arable land with wastewater, though commercial-scale production remains a challenge due to high costs and technical barriers [74]. Algae can grow on non-arable land using saline or wastewater, minimizing competition with food crops and freshwater resources. Algal biodiesel production involves cultivation, harvesting, lipid extraction, transesterification, and purification processes.

Technological Advancements

Nanotechnology: The application of nanoparticles as catalysts and process enhancers is showing promise in improving biodiesel yields, reducing reaction times, and enabling the use of low-quality feedstocks [70].

Polymeric Materials: The use of polymeric catalysts and cold-flow improvers can enhance fuel properties and process efficiency, making biodiesel more aggressive with established diesel [71].

Process Optimization: Advances in process integration, automation, and waste valorization can drive down costs and improve the environmental footprint of biodiesel plants.

Policy and Market Development

Blending Mandates and Incentives: Expanding and enforcing biodiesel blending mandates can create stable demand and spur investment in production capacity [73][67].

Sustainability Certification: Strengthening sustainability standards and certification schemes can address environmental concerns and enhance market access, particularly in export-oriented countries [73][68].

Integration with Broader Bioeconomy: Biodiesel production generates valuable byproducts such as glycerol, biochar, and animal feed, which can be integrated into broader bio-refinery concepts. This approach enhances resource efficiency, creates additional revenue streams, and supports the development of a circular bioeconomy [75][66].

Resilience and Adaptation: The COVID-19 pandemic highlighted the need for resilience in the biodiesel supply chain. Future strategies may include diversifying feedstock sources, investing in digitalization and automation, and fostering public-private partnerships to weather market disruptions [67].

Regional Perspectives

India

India holds significant potential for biodiesel production due to its diverse agro-climatic zones and abundance of biofuel crops. The government has initiated several programs to promote non-edible oilseeds and waste-based feedstocks, aiming to reduce dependence on imported petroleum and enhance rural incomes. However, challenges related to feedstock collection, processing infrastructure, and policy coherence remain [76].

Brazil

Brazil's biodiesel industry is characterized by strong policy support, technological innovation, and a focus on domestic feedstocks. The country's experience offers valuable lessons in integrating biodiesel into national energy strategies while addressing social and environmental objectives [77][68].

Malaysia and Indonesia

As leading producers of palm oil, Malaysia and Indonesia have leveraged their agricultural strengths to become major biodiesel exporters. Progressive blending mandates, technological innovation, and efforts to address sustainability concerns are shaping the future trajectory of the industry in these countries [73][67].

The biodiesel industry exists at a decisive stage, poised to play a pivotal role in the worldwide shift to sustainable energy. While significant challenges persist-ranging from feedstock availability and technological limitations to policy uncertainties and environmental concerns-ongoing innovations and supportive policy frameworks offer a pathway to a resilient and sustainable biodiesel sector. The future will likely be shaped by feedstock diversification, technological advancements, integration with the broader bioeconomy, and a steadfast commitment to sustainability.

1.11 Role of Fuel Additives

Fuel additives have become an essential component in modern fuel technology, playing a multifaceted role in enhancing fuel performance, improving combustion efficiency, reducing emissions, and addressing the challenges associated with alternative fuels such as biodiesel. As the global energy landscape shifts towards sustainability and environmental responsibility, the significance of fuel additives continues to grow, particularly in the context of I C engines and the integration of biofuels into mainstream use.

Enhancing Engine Performance and Combustion Efficiency

Fuel additives are chemical compounds or materials blended with base fuels to improve their properties and performance in engines. They can be broadly categorized based on their primary function, such as detergents, antioxidants, cetane improvers, lubricity enhancers, corrosion inhibitors, and cold-flow improvers. In current years, the advent of nanotechnology has introduced a new class of additives-nano-additives-which have demonstrated remarkable effects on fuel characteristics and engine operation [78].

One of the primary roles of fuel additives is to enhance combustion efficiency. By optimizing the fuel-air mixture, additives can promote more complete burning, leading to higher BTE and reduced BSFC [79][80]. For example, the addition of titanium dioxide (TiO_2) nanoparticles to biodiesel-diesel blends has been shown to improve combustion characteristics, resulting in increased HRR and higher cylinder pressures. This, in turn, translates to better engine performance and fuel economy [80][78].

Similarly, graphene oxide (GO) nanofluids, when mixed with tomato oil methyl ester and diesel, have been found to enhance the premixed combustion phase, increase maximum pressure, and improve BTE at full engine load. The improved fuel characteristics, such as quicker ignition delay and more efficient combustion, contribute to overall engine performance gains [81].

Emission Reduction and Environmental Impact

A critical motivation for the use of fuel additives is the mitigation of detrimental outflows from I C engines. Conventional diesel and gasoline engines are significant sources of pollutants, including NOx, CO, UBHC, and PM. The integration of biofuels, while beneficial for reducing greenhouse gas emissions, often leads to increased NOx emissions due to higher oxygen content in the fuel [79][82][83]. Fuel additives, particularly oxygenated compounds and nanoparticles, play a pivotal role in addressing these emission challenges. For instance, the addition of butyl Di glycol to diesel/biodiesel blends has been shown to significantly reduce CO and HC emissions, as well as smoke opacity, while improving combustion efficiency [84]. Similarly, TiO_2 and silicon dioxide (SiO_2) nanoparticles have demonstrated the ability to reduce ignition delay, enhance combustion completeness, and decrease emissions of CO, HC, and Nox [80][78].

Aluminium nanoparticles, when incorporated into waste cooking oil biodiesel, have also been found to increase combustion efficiency and reduce emissions, owing to their high surface-to-volume ratio and catalytic activity [85]. These findings underscore the potential of nanotechnology in advancing sustainable and efficient biofuel production while addressing environmental concerns.

Improving Fuel Properties and Stability

Beyond combustion and emissions, fuel additives are instrumental in modifying the physicochemical properties of fuels to ensure optimal performance under varying operating conditions. Additives can improve fuel stability, viscosity, density, cetane number, and cold-flow properties, which are particularly important for biodiesel and its blends [83][85].

For example, cerium oxide nanoparticles added to algae-diesel blends have been shown to optimize dynamic viscosity and calorific value, resulting in improved fuel stability and energy content [83]. The use of surfactants and stabilizers, such as QPAN80 in conjunction with TiO_2, enhances the homogeneity and stability of nano-additive fuel blends, preventing phase separation and sedimentation [80].

Cold-flow improvers are another class of additives that address the poor low-temperature properties of biodiesel, which can lead to fuel gelling and filter plugging in cold climates. By modifying the crystallization behavior of biodiesel, these additives ensure reliable engine operation across a wide temperature range [79].

Synergistic Effects in Hybrid and Alternative Fuels

The integration of biofuels with conventional fossil fuels presents unique challenges and opportunities. Hybrid biofuels, formulated by blending bio-derived components such as ethanol, biodiesel, and vegetable oils with diesel, can benefit significantly from the inclusion of additives [86]. These additives not only enhance the miscibility and stability of the blends but also improve engine performance and emissions. Microemulsion techniques, which involve the use of surfactants and co-solvents, have emerged as innovative approaches to producing stable and efficient hybrid biofuels. Additives in these systems facilitate the formation of microemulsions, resulting in improved fuel atomization, combustion, and reduced emissions [86].

Moreover, the catalytic production of fuel additives through methods such as glycerol etherification, utilizing surface-modified carbons, offers a sustainable pathway for generating high-value additives from renewable feedstocks [87]. This methodology associates with the broader goals of circular economy and resource efficacy in the fuel industry.

Challenges and Future Perspectives

While the benefits of fuel additives are well-documented, several challenges remain. The selection of appropriate additives and their optimal concentrations is critical to achieving the desired performance without adverse effects on engine components or fuel infrastructure. Compatibility issues, potential toxicity, and the environmental impact of certain additives, particularly nanoparticles, require careful evaluation and regulation [78][85]. Fuel additives occupy a central role in the quest for cleaner, more efficient, and sustainable transportation fuels. By enhancing combustion efficiency, reducing emissions, improving fuel properties, and enabling the integration of alternative fuels, additives contribute significantly to the performance and environmental compatibility of internal combustion engines. As the transition towards renewable energy sources accelerates, the innovation and application of advanced fuel additives will remain a cornerstone of modern fuel technology, supporting the dual objectives of energy security and environmental stewardship [79][86][84][80][78][81][85].

1.12 Organization of Thesis

The dissertation is structured into five chapters, organized as follows:

CHAPTER 1: (INTRODUCTION)

This segment provides a comprehensive summary of the current research. It begins by presenting the global energy scenario, the relevance of diesel engines, and the broader energy outlook, setting the stage for the motivation behind this study. The chapter underscores the growing need for cleaner fuel alternatives in response to stringent emission regulations, particularly the shift from Bharat Stage IV to Bharat Stage VI standards. A key focus is placed on the impact of diesel desulfurization, particularly in terms of reduced lubricity and lower energy density. The chapter explores various lubricity enhancers along with additives that facilitate efficient clean combustion to enhance engine performance and reduce emissions. Furthermore, the importance of diesel engines, alongside prospective alternative fuels, aligns with the National Biofuel Policy 2022, emphasizing sustainable fuel options to enhance energy security and reduce environmental impact. Chapter 1 closes by introducing various additives to evaluate the tribological characteristics of ULSD and engine characteristics on an unmodified diesel engine.

CHAPTER 2: (LITERATURE REVIEW)

This chapter presents a comprehensive review of the impact of the desulfurization process on commercial diesel properties and engine performance. It examines various additives designed to enhance diesel's lubricity and overall performance, addressing the challenges posed by desulfurization. The review then explores the use of additives in WCO and diesel blends, highlighting their role in enhancing combustion efficiency, restoring lubricity, and reducing engine outflows. The conclusions provide a holistic understanding of optimizing additives to mitigate desulfurization's negative effects and support the use of alternative fuels. The chapter concludes by reviewing key understandings, identifying research gaps, problem statement, and outlining well-defined objectives and strategies to advance this field.

CHAPTER 3: (SYSTEM DEVELOPMENT AND METHODOLOGY)

This chapter outlines the experimental approach, detailing the instruments and methodologies used to assess the physicochemical properties of prepared fuel samples in accordance with ASTM/BIS standards. A detailed explanation of the High-Frequency Reciprocating Rig (HFRR) and its principle for evaluating lubricity is included. The chapter describes the development of a robust system for analyzing engine characteristics, emphasizing the selection of appropriate instruments and equipment crucial for the research's success. The methodology begins with a comparative study of BS IV and VI diesel performance on an unmodified engine. It further details the selection, preparation, and incorporation of hybrid additives to address desulfurization challenges. Additionally aligning with the National Biofuel Policy-2022, detailed process of production of biodiesel from WCO. The characterization of prepared biodiesel is also discussed. Instruments for finding physicochemical properties and their prepared blend values are explained in detail. The engine performance and emission tests were conducted with diesel and blended fuel on a small capacity, natural aspirated compression ignition engine.

CHAPTER 4: (RESULTS AND DISCUSSION)

This segment provides a comprehensive analysis of the results obtained from the experimental investigations, incorporating statistical evaluations and advanced characterization techniques. It presents a critical discussion of the findings, benchmarking them against prior studies documented in the literature. The focus is on the performance trials carried out on diesel engines to assess and compare the engine characteristics of commercial diesel and diesel–biodiesel blends, with and without the inclusion of hybrid additives, relative to baseline diesel. In addition to engine trials, this section also highlights the tribological characterization of the fuel blends, examining their lubricity, wear behavior, and frictional performance. The results are thoroughly interpreted, supported by relevant literature, to validate the influence of additive-enhanced blends on fuel tribological properties.

CHAPTER 5: (CONCLUSION)

This closing chapter summarizes the key findings and highlights the noticeable points derived from the present research. Logical conclusions, formulated based on the facts and figures obtained during the study, are presented alongside recommendations for future work. Finally, detailed references and relevant appendices pertaining to the research are provided at the end of the thesis.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter highlights the critical role of diesel/compression ignition (CI) engines in the global economy, while addressing concerns about environmental impact and the challenges posed by stringent emission norms and the integration of biodiesel. The modification of fuel chemistry, particularly through hybrid additive formulations, offers a potential solution to improve engine lifespan via improving lubricity and engine characteristics in CI engines. The chapter begins with an overview of the evolution of emission standards in India, the desulfurization of commercial diesel and its implications, and the use of waste cooking oil in engines, along with the associated challenges. After that the role of fuel additives in enhancing engine performance is discussed in detail. The chapter further reviews studies on the tribological characteristics of diesel, emphasizing the importance of lubricity in improving engine efficiency and durability. Finally, it identifies gaps in existing research, outlines the research objectives, and presents the scope of the current study.

2.2 Evolution of Emission Standards in India

India has experienced rapid urbanization and motorization, leading to significant increases in vehicular emissions and deteriorating air quality, especially in urban centres like Delhi. Vehicular outflows are a foremost sponsor to ambient air pollution, prompting the evolution and tightening of emission standards over the past decades to mitigate environmental and public health impacts [88][89][90].

2.2.1 Introduction of Bharat Stage Emission Standards

India introduced the Bharat Stage Emission Standards (BSES) in 2000 to address the growing problem of air pollution in urban areas. The standards were modelled after the European Euro norms but adapted to India's unique conditions, including its diverse fleet composition and varying climatic conditions [91] [92]. The primary objective of these standards is to reduce vehicular emissions and thereby mitigate their impact on air quality, human health, and the environment.

Historical Evolution of Emission Standards

Early Phase (Pre-1990s to Early 2000s)

Initial Emission Trends: Emissions of particulate matter (PM), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs) peaked in the late 1990s to early 2000s, driven by rapid growth in vehicle numbers and lack of stringent controls [88].

First Interventions: The initiation of regulatory action was marked by the introduction of the first vehicular emission standards, the elimination of lead from fuels, the reduction of sulfur content, and the mandatory phasing out of older commercial vehicles [88][93].

Progressive Tightening (2000s–2010s)

Implementation of Bharat Stage (BS) Norms: India adopted the Bharat Stage (BS) emission standards, modelled after European norms, with progressive tightening from BS-I to BS-IV. These standards set limits for key pollutants (CO, NOx, PM, HC) and differentiated between vehicle types and fuel categories [89][90].

Technological Shifts: Conversion of public transport vehicles to CNG, and the transfer from two-stroke to four-stroke engines in two-wheelers, contributed to emission reductions [88][93].

Impact: These measures led to substantial drops in PM, SO_2, CO, and VOCs between 1998 and 2012, although NOx and CO_2 emissions continued to rise due to increased vehicle numbers and changing fleet composition [88][93][94].

Recent Developments (2010s–Present)

BS-VI Implementation: India leapfrogged from BS-IV to BS-VI standards in 2020, skipping BS-V, to align with global best practices. BS-VI norms require an 80% reduction in PM and a 70% reduction in NOx emissions for diesel engines compared to BS-IV, and mandate advanced after-treatment technologies [89].

Policy Impact: Advancements in emission norms and fuel efficiency improvements have led to substantial reductions in gaseous pollutants, as confirmed by recent emission inventories [94][95].

Technological Adaptations in India

To meet the BS-VI norms, Indian automakers have adopted advanced technologies such as downsized turbocharged engines, SCR systems, and DPFs [96]. The implementation of these technologies has been complemented by the introduction of cleaner fuels, including BS-VI-compliant diesel and petrol, which are now widely available across the country [97] [98].

Table 2.1. Overview of Indian Emission Standards

Emission Standard	Year Introduced	Key Features	Impact/Notes
Pre-BS (Pre-2000)	Before 2000	No formal standards; high emissions	High PM, SO_2, CO, VOCs [88]
BS-I	2000	First formal standards; basic limits for CO, HC, NOx	Initiated emission control [89][90]

Emission Standard	Year Introduced	Key Features	Impact/Notes
BS-II	2001–2005	Stricter limits; phased rollout	Further reductions, especially in urban areas [89][90]
BS-III	2005–2010	Tighter limits, expanded to more cities	Required improved engine tech [89][90]
BS-IV	2010–2017	Nationwide implementation; lower sulfur fuels	Significant PM and NOx reduction [88][89][90]
BS-VI	2020	Skipped BS-V; 80% PM and 70% NOx reduction for diesels; advanced after-treatment	Major leap in emission control; aligned with Euro-VI [89]

Table 2.2. Evolution of Bharat Stage Emission Standards

Standard	Year	PM Limit (Diesel, g/km)	NOx Limit (Diesel, g/km)	Key Technology Requirement
BS-I	2000	0.36	0.97	Basic catalytic converter
BS-II	2001	0.20	0.70	Improved combustion
BS-III	2005	0.10	0.50	Electronic fuel injection
BS-IV	2010	0.025	0.25	Advanced EGR, DPF
BS-VI	2020	0.0045	0.08	SCR, DPF, OBD

Challenges and Industry Response

The transition to BS-VI norms has posed significant challenges for the Indian automotive industry, particularly for commercial vehicle manufacturers. These challenges include the high cost of compliance, the need for advanced after-treatment technologies, and the requirement for real-world emissions testing [99][100]. Despite these challenges, the industry has responded positively, with many manufacturers investing in R&D and adopting sustainable practices to meet the new standards [97] [98].

2.2.2 Environmental Outcomes of Emission Standards

The implementation of BS norms has led to measurable improvements in air quality and reductions in pollutant emissions. Key environmental outcomes include:

Reduction in Pollutant Emissions:

The introduction of BS-VI norms has followed in a substantial decline in outflows of NOx, PM2.5, and CO from heavy commercial vehicles. For instance, NOx emissions are projected to decrease by 91.5%, while PM2.5 emissions are expected to reduce by 96.6% by 2035 compared to 2020 levels [101]. In Delhi, the implementation of BS-VI norms has contributed to a 4.9% reduction in PM10 concentrations and a 44.1% decrease in ozone levels [102].

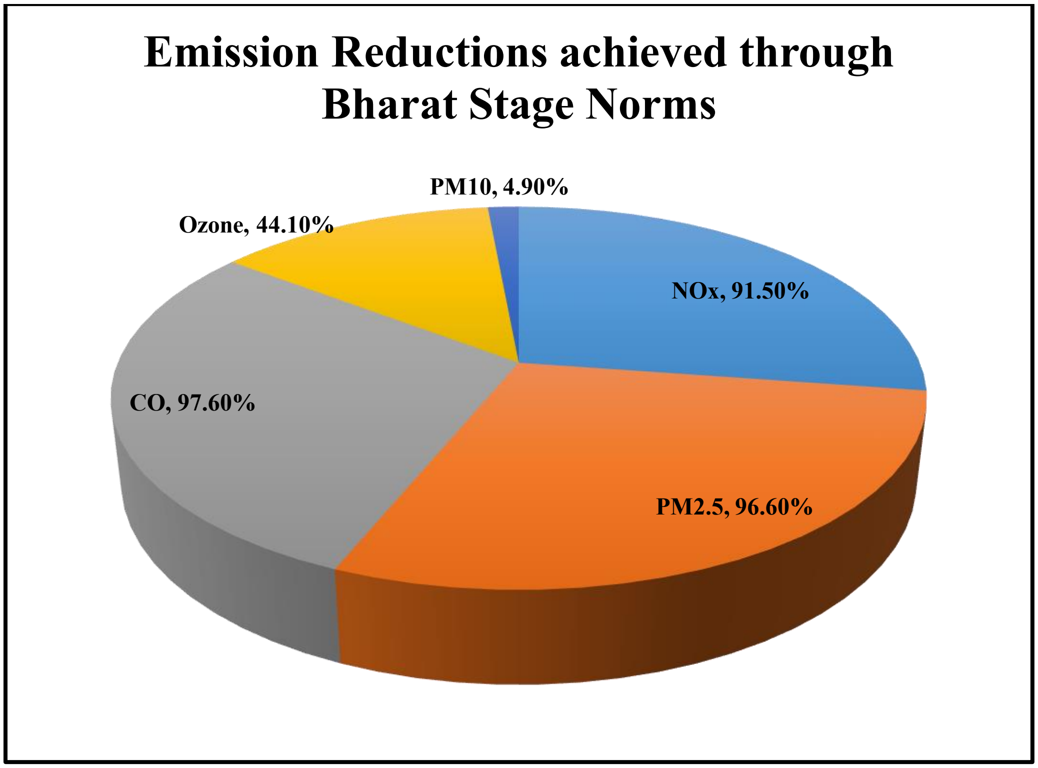

Figure 2.1. Emission Reduction achieved through Bharat Stage Norms

Improved Air Quality

The transition to BS-VI has improved ambient air quality in urban areas, particularly in megacities like Delhi, where transportation contributes significantly to air pollution. The decrease in emissions has also led to a decrease in the growth of secondary pollutants such as ozone and particulate matter [102][103].

Health Benefits

The reduction in air pollutants has positive implications for public health, as lower levels of NOx, PM2.5, and CO contribute to fewer respiratory and cardiovascular diseases [104][105].

Industry Practices and Challenges

The evolution of emission standards has necessitated significant changes in industry practices, particularly in the automotive sector. Key developments include:

Technological Upgrades

The transition to BS-VI norms has driven the adoption of advanced technologies such as DPFs, SCR, and onboard diagnostics (OBD). These technologies help reduce emissions and ensure compliance with stricter norms [98][100].

Fuel Quality Improvements

The implementation of BS-VI norms has led to the production of cleaner fuels with lower sulfur content. This has been critical in reducing emissions and improving air quality [97] [104].

Challenges Faced by the Industry

The transition to BS-VI has posed challenges for original equipment manufacturers (OEMs), particularly in terms of cost and technology adoption. Small and medium-sized enterprises (SMEs) have faced difficulties in upgrading their manufacturing processes to meet the new standards [99].

The implementation of BS-VI norms has also led to an increase in vehicle prices, affecting consumer demand and leading to a decline in car sales [97].

The evolution of emission standards in India has had a profound impact on both industry practices and environmental outcomes. While significant progress has been made in reducing pollutant emissions and improving air quality, challenges remain. Continued policy support, technological innovation, and public awareness are essential for achieving long-term environmental sustainability.

2.3 Desulfurization of Commercial Diesel: Processes and Implications

Environmental concerns regarding air quality have brought significant attention to the sulfur content in diesel fuels. When sulfur compounds in diesel undergo combustion, they produce SOx emissions that contribute to acid rain and respiratory diseases [106]. Additionally, sulfur compounds can poison catalytic converters in vehicles, reducing their effectiveness in controlling other harmful emissions [107]. Consequently, environmental regulations worldwide have become increasingly stringent, mandating the production of ultra-low sulfur diesel (ULSD). This regulatory pressure has driven the petroleum industry to develop and improve desulfurization technologies This literature review examines the current state of diesel desulfurization technologies.

2.3.1 Hydro Desulfurization (HDS) Process

Hydrodesulfurization is a catalytic chemical process that uses hydrogen to remove sulfur from organic compounds present in diesel fuel. During HDS, sulfur compounds react with hydrogen over specialized catalysts, forming hydrogen sulfide (H_2S) and desulfurized hydrocarbons [108]. The process effectiveness varies depending on the type of sulfur compounds present, with some being more refractory than others. The process typically employs heterogeneous metal catalysts and operates under hydrogen-rich conditions [107][109].

Chemical Reactions

The general reaction mechanism of HDS involves:

- Adsorption of sulfur compounds on the catalyst surface
- Hydrogenation of the sulfur compound
- C-S bond cleavage
- Formation of H_2S
- Desorption of products from the catalyst surface

For aliphatic sulfur compounds like thiols, sulfides, and disulfides, the reactions are relatively straightforward. However, for aromatic sulfur compounds such as thiophenes, benzothiophenes, and dibenzothiophenes, the reactions follow more complex pathways involving either direct desulfurization or hydrogenation followed by desulfurization [107].

Catalysts for Hydrodesulfurization

The effectiveness of the HDS process is extremely contingent on catalyst execution. Conventional HDS catalysts typically consist of molybdenum sulfide promoted by cobalt or nickel, supported on alumina (Al_2O_3) [107].

Traditional CoMo and NiMo Catalysts

Cobalt-molybdenum (CoMo) and nickel-molybdenum (NiMo) catalysts represent the industry standard for hydrodesulfurization processes [107]. The catalytic activity is attributed to the "Co-Mo-S" or "Ni-Mo-S" phase, where the promoter (Co or Ni) is located at the edges of MoS_2 slabs [107]. CoMo catalysts generally exhibit higher activity for direct desulfurization routes, while NiMo catalysts show superior performance in hydrogenation pathways, making them more effective for refractory sulfur compounds [107].

Advanced Nano catalysts

Nano catalysts represent a significant advancement in HDS technology. The reduced particle size provides increased surface area and a higher proportion of edge sites, which are the active centers for catalysis [110]. Various nano catalyst morphologies have been developed, including nanosheets, nanotubes, and core-shell structures [110]. These nano catalysts demonstrate superior activity compared to conventional catalysts, particularly for refractory sulfur compounds like 4,6-dimethyldibenzothiophene [110].

Reactor Systems

The trickle bed reactor (TBR) stands as the most widely employed reactor configuration for industrial HDS processes. In TBRs, hydrogen gas and diesel feed flow concurrently downward through a fixed catalyst bed [108][111]. Studies have demonstrated that hydrodynamic factors such as radial and axial dispersion significantly impact reactor performance [111]. Recent research has focused on comprehensive modelling and simulation of HDS processes in TBRs, with experimental validations showing standard errors of up to 5% between simulated and experimental data [111].

Alternative Support Materials

Research has expanded beyond conventional alumina supports to explore materials with enhanced properties:

- Zr-modified SBA-15 supports for NiMo catalysts have shown promising results for the HDS of dibenzothiophene (DBT) and dimethyl dibenzothiophene (DMDBT) [112]. The direct synthesis approach, followed by confinement of Ni into as-synthesized Zr-SBA-15-Mo without calcination, generated greater dispersion and active sites for efficient sulfidation [112].

- Aluminum-modified mesoporous TUD-1 (PAT) materials mixed with commercial γ-Al_2O_3 have demonstrated enhanced HDS performance for FCC diesel [113]. The material designated as PAT-3 exhibited the highest total acidity sites and Bronsted acid sites among the series of composites tested [113].

Operating Parameters and Their Effects

Temperature

Temperature exerts a significant influence on HDS performance. Research has shown that enhancing the temperature from 250°C to 350°C can improve conversion rates from 68.77% to 91.57% [108]. However, excessively high temperatures may promote undesirable side reactions or accelerate catalyst deactivation.

Pressure

Hydrogen pressure typically shows a moderate positive effect on HDS efficiency [108]. Higher pressures increase hydrogen availability at catalyst active sites, promoting more complete desulfurization, though the impact is less pronounced compared to temperature effects.

Liquid Hourly Space Velocity (LHSV)

LHSV, which represents the feed volumetric flow rate divided by the catalyst bed volume, significantly impacts conversion. Studies have observed that increasing LHSV from 1 to 3 h^{-1} results in decreased conversion (from 91.57% to 75.58%) [108]. This indicates that longer residence times allow for more complete reactions between sulfur compounds and hydrogen. LHSV widely used in hydro processing, hydrotreating, hydrocracking, and adsorptive desulfurization processes. It helps optimize reaction conditions by balancing conversion efficiency and processing capacity.

Challenges in Diesel Desulfurization

Refractory Compounds

One of the most significant challenges in diesel desulfurization is the removal of sterically hindered compounds such as 4,6-dimethyldibenzothiophene (4,6-DMDBT). These molecules exhibit resistance to conventional HDS due to steric hindrance that prevents the sulfur atom from interacting effectively with catalyst active sites [1]. Advanced catalyst formulations and alternative processes like ODS are being explored to address this challenge.

Catalyst Deactivation

Catalyst deactivation presents an ongoing challenge for industrial HDS processes. Deactivation mechanisms include:

- Coke formation and deposition
- Poisoning by nitrogen compounds
- Sintering of active phases
- Metal deposition from feed contaminants

Process Integration

Integrating advanced desulfurization technologies into existing refinery operations presents both technical and economic challenges. The commercial application of deep diesel hydrodesulfurization catalysts requires careful consideration of process parameters, catalyst life cycle, and economic feasibility [114]. Hydrodesulfurization remains the primary industrial method for removing sulfur from commercial diesel, with continuous advancements in catalyst formulations, reactor designs, and process conditions. Nano catalysts, alternative support materials, and novel preparation methods have demonstrated enhanced desulfurization performance compared to traditional approaches. Future research directions should focus on developing catalysts with improved activity, selectivity, and stability; optimizing process conditions for energy efficiency; and exploring novel reactor configurations.

2.3.2 Oxidative Desulfurization (ODS)

Oxidative desulfurization (ODS) has developed as a favourable alternative to conventional hydrodesulfurization (HDS) processes, offering operation under milder conditions without requiring hydrogen pressure [115]. Traditional hydrodesulfurization processes operate under high temperature and pressure conditions with hydrogen gas, making them energy-intensive and costly [116]. These conventional methods face limitations when dealing with sterically hindered dibenzothiophene derivatives that are common in heavy oil fractions [115]. Interestingly, these bulky thiophenic structures that resist conventional HDS treatment show higher reactivity in oxidative desulfurization processes [115]. ODS offers significant advantages for removing refractory sulfur compounds under mild conditions (atmospheric pressure, moderate temperatures) without hydrogen consumption [116].

Mechanisms and Processes of ODS

The fundamental principle of ODS involves the selective oxidation of sulfur compounds to their corresponding sulfoxides and sulfones, which exhibit increased polarity and can be more easily removed through extraction or adsorption [115][116]. The process typically involves two main steps:

- **Oxidation phase:** Sulfur compounds are converted to their corresponding sulfoxides and sulfones using various oxidants
- **Separation phase:** The oxidized compounds are removed through extraction, adsorption, or other separation techniques [116]

Common oxidants employed in ODS include hydrogen peroxide (H_2O_2), organic peroxides, ozone, air, and oxygen [117]. The oxidation potential follows the order: ozone > oxygen > air, though availability follows the reverse trend [117]. Hydrogen peroxide is widely used due to its effectiveness and relatively benign environmental impact, producing only water as a byproduct [115][118].

Catalysts in ODS

Catalyst development plays a necessary role in enhancing ODS efficiency. Various homogeneous and heterogeneous catalytic systems have been investigated:

Keggin-Type Polyoxometalates: Phosphotungstate $[PW_{12}O_{40}]^{3-}$ (PW12) has shown high efficiency in oxidative desulfurization when modified appropriately [118]. Strategies to enhance its performance include:

- Replacing acid protons with ionic liquid cations to form hybrid compounds like $[BMIM]_3PW_{12}$, $[BPy]_3PW_{12}$, and $[HDPy]_3PW_{12}$ [118]
- Immobilizing the Keggin polyanion on functionalized supports such as positively-charged SBA-15 (PW_{12}@TM–SBA-15) [118]

These modified polyoxometalates demonstrate complete desulfurization of multicomponent model diesel (2000 ppm S) within one hour using moderate H_2O_2 excess ($H_2O_2/S = 8$) at 70°C [118].

Molybdenum-Based Catalysts: Molybdenum oxides show excellent catalytic properties for ODS:

- Amorphous molybdenum oxides exhibit high catalytic activity due to increased covalency, allowing for efficient oxidation of sulfur compounds [119]
- Peroxo- and diperoxomolybdate complexes form as active species during the oxidation process [120]

- Binary metal composite oxides such as Bi_2O_3-MoO_3 systems show structure-dependent activity for aerobic oxidative desulfurization [121]

Challenges and Future Perspectives

Despite the promising aspects of ODS, several challenges remain:

Catalyst Stability: Some catalytic systems show decreased activity after multiple cycles. For example, hybrid Keggin compounds with ionic liquid cations demonstrate high initial activity but reduced stability in continuous reuse [118]. Immobilization on supports like functionalized SBA-15 improves stability but may impact other performance parameters [118].

Selective Oxidation: Achieving selective oxidation of sulfur compounds in the presence of other fuel components remains challenging, particularly for complex real-world feedstocks [115].

Scale-Up Issues: Most successful ODS systems have been demonstrated at laboratory scale, with limited information on industrial implementation [117].

Catalyst Recovery: Efficient recovery of catalysts, especially in homogeneous systems, presents operational challenges.

Oxidative desulfurization represents a promising alternative to conventional hydrodesulfurization, particularly for treating refractory sulfur compounds in heavy oil fractions. The development of novel catalysts, innovative process intensification methods, and integrated systems combining extraction and catalysis has significantly enhanced ODS efficiency. While challenges remain, particularly in catalyst stability and industrial-scale implementation, the continued development of ODS technology holds significant promise for meeting increasingly stringent environmental regulations on fuel sulfur content.

2.3.3 Adsorptive Desulfurization (ADS)

Adsorptive desulfurization (ADS) has emerged as a promising alternative, offering operation under mild conditions and the potential for selective removal of sulfur species [122][123][124]. ADS relies on the selective adsorption of sulfur-containing compounds from fuels onto solid adsorbents. The process can occur via physical adsorption (physisorption) or chemical adsorption (chemisorption), with the latter often providing higher selectivity and capacity [122][125]. The efficiency of ADS depends on the nature of the adsorbent, the type of sulfur compounds, and the operating conditions.

Types of Adsorbents

Activated Carbons

Activated carbons are widely used due to their high surface area and tenable pore structure. Their performance can be enhanced by surface modification or impregnation with metals [122][123].

Zeolites

Zeolites, especially Y-type, are effective for ADS due to their well-defined pore structure and ion-exchange capabilities. Metal ion-exchange (e.g., Cu, Ce) further improves their selectivity towards sulfur compounds [126][127][122].

Metal Oxides and Supported Metals

Transition metal oxides (e.g., NiO, FeOOH) and supported noble metals exhibit strong interactions with sulfur compounds. The choice of support material (e.g., SiO_2, Al_2O_3) significantly affects adsorption performance and selectivity [128][4].

Carbon Nanomaterials

Materials such as graphene, graphene oxide, carbon nanotubes, and nanofibers offer high surface area, tunable chemistry, and ease of functionalization, making them promising candidates for ADS [123].

Biomass-Derived Adsorbents

Recent studies have explored low-cost, sustainable adsorbents derived from biomass (e.g., pig dung, agricultural waste), often activated or chemically modified to enhance performance [8].

Adsorption Mechanisms and Selectivity

The mechanism of ADS involves several interactions:

π-Complexation: Transition metals (e.g., Cu^+, Ag^+) can form π-complexes with the aromatic rings of sulfur compounds, leading to high selectivity [127][122].

Acid-Base Interactions: Metal oxides and modified carbons provide acidic or basic sites that interact with sulfur species.

Physical Adsorption: High surface area and pore volume facilitate the uptake of sulfur compounds via van der Waals forces. Selectivity is influenced by the competitive adsorption of aromatics and other fuel components. Modifying adsorbents to suppress aromatic adsorption while enhancing sulfur uptake is a key research focus [122][128].

Challenges and Future Prospects

Challenges

- Competitive adsorption with aromatics reduces selectivity.
- Regeneration can cause adsorbent degradation.
- Scale-up and cost-effectiveness remain concerns.

Future Directions

- Development of new adsorbents with high selectivity, capacity, and stability.
- Use of green and low-cost materials.
- Integration with other desulfurization technologies (e.g., oxidative desulfurization).

- Advanced characterization and modeling to understand adsorption mechanisms at the molecular level [125][122][123].

Adsorptive desulfurization is a promising alternative to conventional HDS, especially for achieving ultra-low sulfur levels in fuels. Advances in adsorbent materials, particularly nanomaterials, metal-exchanged zeolites, and biomass-derived carbons, have significantly improved performance.

2.3.4 Extractive Desulfurization (EDS)

Extractive desulfurization (EDS) is a process used to eliminate sulfur compounds from fuels, which is crucial for reducing harmful emissions and improving air quality. Conventional desulfurization methods, such as HDS, have limitations, including high energy consumption and the need for expensive catalysts [129]. In recent years, ionic liquids (ILs) and deep eutectic solvents (DESs) have emerged as promising alternatives for EDS due to their high selectivity and efficiency [130][131]. Sulfur compounds in fuels, such as thiophene, benzothiophene, and dibenzothiophene (DBT), are difficult to remove using conventional methods [130]. The combustion of these compounds results in sulfur dioxide emissions, contributing to environmental pollution [129]. Regulatory agencies have set stringent limits on sulfur content in fuels, necessitating the development of more effective desulfurization techniques [130].

Ionic Liquids in Extractive Desulfurization

Ionic liquids have been extensively studied for their potential in EDS due to their tenable properties, such as solubility and selectivity [132]. Phosphonium-based ILs, like trihexyl tetradecyl phosphonium bis(2-ethylhexyl) phosphate [THTDP][D2EHP], have shown significant sulfur removal efficiency from model fuels and crude oils [133]. The synthesis and application of these ILs involve optimizing parameters such as reaction time, temperature, and IL/fuel ratio to achieve maximum desulfurization efficiency [133].

Molecular dynamics simulations have been used to inspect the interactions between ILs and sulfur compounds. These studies suggest that ILs with larger anions enhance solvation of sulfur compounds through favorable solute-anion interactions [130]. For instance, the 1-butyl-3-methylimidazolium [BMIM] cation paired with various anions has been evaluated for its effectiveness in extracting thiophene and DBT [130].

Deep Eutectic Solvents in Extractive Desulfurization

Deep eutectic solvents, composed of choline chloride with ethylene glycol or glycerol, offer a cheaper and more environmentally friendly alternative to ILs [131]. These solvents have been used in extractive oxidative desulfurization (EODS) processes, achieving high extraction efficiencies under optimized conditions [131]. The use of DESs in EODS combines the benefits of high selectivity and low cost, making them a promising option for industrial applications [131].

Other Solvents and Methods

In addition to ILs and DESs, other solvents like diamine-terminated polyethylene glycol have been explored for EDS. These solvents offer advantages such as low vapor pressure and reusability, making them suitable for green desulfurization processes [134]. The application of these solvents involves understanding their extraction mechanisms and optimizing conditions for maximum sulfur removal efficiency [134]. Cupric chloride piperidinium complex salts have also been investigated for their potential in EDS. These compounds are derived from organic salts and have shown promising results in removing sulfur compounds from model oils [135].

Challenges and Future Directions

Despite the advancements in EDS using ILs and DESs, several challenges remain. These include the high cost of ILs, the need for efficient regeneration methods, and the environmental impact of solvent disposal [129][131]. Future research should focus on developing cost-effective, biodegradable solvents and optimizing process conditions to enhance desulfurization efficiency while minimizing environmental footprint.

Extractive desulfurization using ionic liquids and deep eutectic solvents represents a significant step forward in reducing sulfur emissions from fuels. These methods offer improved efficiency and selectivity compared to traditional techniques.

2.3.5 Bio Desulfurization (BDS)

Bio desulfurization (BDS) is a process that employs microorganisms to remove sulfur atoms from organic sulfur compounds, such as those found in fossil fuels. This method is gaining attention due to its environmental benefits and cost-effectiveness compared to traditional chemical processes like hydrodesulfurization (HDS) and oxidative desulfurization (ODS) [136][137].

Mechanisms and Applications

Bio desulfurization typically involves the use of bacteria such as Rhodococcus species, which can selectively cleave carbon-sulfur bonds in sulfur-containing compounds without degrading the fuel's energy content [136]. This process is particularly useful for removing sulfur from complex molecules like dibenzothiophenes, which are difficult to desulfurize using conventional methods [136].

Challenges and Future Directions

Despite its advantages, bio desulfurization faces challenges such as slow reaction rates and the need for large bioreactors. Research is ongoing to improve the efficiency of bio desulfurization by optimizing microbial strains and reactor designs [136]. Additionally, integrating bio desulfurization with other desulfurization methods could enhance overall efficiency and reduce environmental impact [136].

Plasma-Based Methods: Surface Modification and Biofunctionalization

Plasma-based technologies have emerged as powerful tools for surface modification and biofunctionalization. These methods involve using plasma to create reactive species that can alter the surface properties of materials, making them more biocompatible or bioactive [138].

Applications in Biomedical Fields

In biomedical applications, plasma surface functionalization is used to create cell-instructive surfaces that can modulate cellular interactions. This is crucial for developing implantable devices, biosensors, and drug delivery systems [138]. Plasma-based methods offer a dry, reagent-free alternative to traditional wet chemical approaches, reducing toxicity and environmental impact [138].

Challenges and Future Directions

While plasma-based methods show great promise, challenges include ensuring uniform surface modification and scaling up these processes for industrial applications [138]. Ongoing research focuses on optimizing plasma conditions and integrating plasma technologies with other surface modification techniques to enhance efficiency and reproducibility [138]. Emerging bio desulfurization and plasma-based methods represent significant advancements in environmental sustainability and biomedical technology. Bio desulfurization offers a cleaner alternative for removing sulfur from fuels, while plasma-based methods enhance material properties for biomedical applications. As these technologies continue to evolve, addressing current challenges will be crucial for their widespread adoption.

2.3.6 Impact of Desulfurization Process on Engine Components, Performance, and Storage Issues

The transition to Ultra-Low Sulfur Diesel has been driven by environmental regulations to reduce sulfur emissions, but this shift has introduced unintended challenges affecting diesel engine components, performance, and storage/handling protocols. Below is a structured synthesis of these impacts, supported by current research.

Impact on Diesel Engine Components

Lubricity Reduction and Wear

Desulfurization processes, such as hydrotreating, remove sulfur-containing compounds that naturally contribute to fuel lubricity. The loss of these compounds increases friction in fuel injection systems, accelerating wear in pumps and injectors [139]. While not directly quantified in the provided studies, this phenomenon is implicit in the technological shifts described in ULSD production.

Material Compatibility

ULSD's lower sulfur content alters chemical interactions with engine materials. For instance, reduced aromatic content from hydrotreating can cause elastomer seals to shrink, leading to leaks. Additionally, microbial byproducts like acetic acid in storage tanks corrode tank components, including steel and sensors [140].

Engine Performance Considerations

Combustion and Emissions

ULSD enables cleaner combustion, reducing particulate matter and enabling advanced after-treatment systems like diesel oxidation catalysts [141]. However, blends of ULSD with biodiesel (e.g., BD20) show increased viscosity over time, potentially affecting fuel atomization and combustion efficiency [142]. The overall combustion efficiency and energy content of ULSD slightly less to conventional diesel, so there is marginal change in engine performance. ULSD significantly cuts sulfur emissions and improves engine cleanliness, its impact on other emission types and combustion characteristics in unmodified engines tends to be modest.

Additive Dependency

To mitigate lubricity loss, additives are essential. Their long-term stability in ULSD remains a concern, as oxidative byproducts like peroxides and gums can form during storage, clogging filters and injectors [143].

Storage Challenges

Microbial Corrosion

ULSD storage tanks are prone to microbial contamination due to trace ethanol and water ingress. Aerobic bacteria metabolize ethanol into acetic acid, corroding tank linings and components. This corrosion manifests within months, risking structural failure [140].

Oxidative Degradation

ULSD exhibits oxidative instability, with peroxides and soluble gums forming during extended storage. These compounds degrade fuel quality and necessitate stabilizers, though their efficacy in naval or long-term civilian storage is understudied [143].

Handling Risks

Electrostatic Hazards

ULSD's low conductivity increases electrostatic charge accumulation during transfer, elevating explosion risks. This contrasts with high-sulfur diesel, where sulfur content naturally dissipates charge [144].

Temperature Sensitivity

Storage temperature fluctuations affect ULSD's physical properties. For example, biodiesel-ULSD blends experience viscosity and density increase over 12 weeks at 40°C, complicating cold-weather handling [142].

This review highlights the complex trade-offs in ULSD adoption. While environmental benefits are clear, addressing material degradation, additive stability, and storage risks requires ongoing innovation in fuel chemistry and infrastructure design.

2.4 Waste Cooking Oil: Indian Scenario & Engine Use

Waste cooking oil (WCO) has emerged as a significant area of interest due to its dual advantages in environmental sustainability and economic feasibility. Several critical factors contribute to its recognition as a valuable and renewable resource.

Waste Management

WCO is an organic waste product commonly generated by households, restaurants, and food processing units. Improper disposal practices often lead to the clogging of drainage systems, increased pollution levels, and heightened health hazards. India possesses substantial potential to manage and recycle WCO effectively by converting it into a usable resource. This strategy could considerably reduce the volume of WCO discharged into aquatic ecosystems, thereby mitigating environmental degradation and promoting public health [145, 146].

Renewable Energy Sources

Waste cooking oil (WCO) is typically converted into biodiesel through transesterification, a chemical reaction between triglycerides and alcohol in the presence of a catalyst. The resulting biodiesel possesses properties like those of conventional diesel, allowing its use in existing diesel engines without requiring any modifications. As a renewable and biodegradable fuel, biodiesel derived from WCO offers a more environmentally friendly alternative, contributing to reduced emissions of harmful pollutants and carbon dioxide, and thus playing a significant role in addressing climate change [146].

Energy Security

India's energy needs are heavily met through the import of crude oil, making the country vulnerable to external supply and price fluctuations. Using waste cooking oil (WCO) as a raw material for biodiesel production provides a sustainable solution to lessen this reliance on imported fossil fuels. This strategy not only strengthens the nation's energy security but also helps insulate the domestic economy from the impacts of global oil market instability [147].

Economic Benefits

The integration of WCO into the biodiesel value chain advocates the concept of a circular economy. Establishing systems for the collection, processing, and conversion of WCO creates new economic opportunities, including job creation and income generation. It supports the development of infrastructure for WCO handling while also reducing the financial burden of crude oil imports.

Reduced Carbon Footprint

Compared to conventional diesel, biodiesel produced from WCO has a substantially lower carbon footprint. The carbon dioxide emitted during combustion is partially balanced by the CO_2 absorbed by the crops used in feedstock production. Adopting WCO as a biodiesel feedstock supports India’s commitment under the Paris Agreement and contributes to significant reductions in greenhouse gas emissions.

Health and Environmental Benefits

Traditional diesel fuel emits pollutants such as SOx, NOx, and PM, which have adverse effects on air quality and human health. Biodiesel derived from WCO produces lower concentrations of these harmful emissions, thereby contributing to better air quality and reduced health risks for both urban and rural communities [146].

Regulatory Initiatives

To encourage the use of WCO in biodiesel production, the Indian government has introduced several regulatory frameworks. Key among these is the RUCO (Repurpose Used Cooking Oil) initiative led by the FSSAI, which mandates the collection of WCO through authorized agencies and stipulates blending targets for biodiesel in diesel fuels. These policies foster an enabling environment for WCO utilization and actively engage stakeholders in sustainable practices. By recognizing and harnessing the potential of WCO as a valuable feedstock, India can achieve multifaceted benefits encompassing effective waste disposal, renewable fuel production, energy self-reliance, economic development, environmental conservation, and public health improvements. Embracing WCO as a strategic resource marks a pivotal step toward realizing the nation's sustainable development goals.

2.4.1 Waste Cooking Oil Availability and Consumption in India

The Food Safety and Standards Authority of India introduced a novel program called Repurpose Used Cooking Oil (RUCO) on World Fuel Day in 2018. This effort aims to establish an effective system that facilitates the transformation of discarded cooking oil in biodiesel. According to the national biofuel policy, 2018, the utilization of biodiesel which is derived from non-edible feedstock and WCO is employed in various sectors such as transportation, stationary, portable, and other applications [146, 148-150]. The policy also establishes an indicative objective of incorporating a 5% biodiesel blend into diesel. The proposition is set to be implemented by the year 2030.

India uses a significant quantity of 24660 ML yearly, making it the third-largest edible oil consumer globally. Among the total amount of edible oil, 40% is allocated for commercial use, specifically for the food and beverage industry, while the remaining 60% is intended for household consumption.

Table 2.3: Total consumption and availability of edible oil along with biodiesel generation from waste edible oil (RUCO Booklet) [69]

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

2.4.2 WCO-Derived Biodiesel in Diesel Engines

Biodiesel, composed of long-chain fatty acid methyl esters (FAME), is typically produced via the transesterification of vegetable oils or waste cooking oil in the presence of a catalyst [151]. The process can utilize either homogeneous or heterogeneous catalysts. Although homogeneous catalysts offer high biodiesel yields, their application is limited by economic and environmental concerns. These include the need for costly chemicals, complex purification procedures, and safe disposal of byproducts [152]. Consequently, solid heterogeneous catalysts are increasingly favoured due to their low production cost, ease of separation from the reaction mixture, and reusability [153]. Among them, zeolite minerals functionalized with acidic or basic groups have demonstrated high catalytic efficiency and practical biodiesel yields [154,155]. Calcium oxide derived from waste materials such as eggshells has also shown promising results in achieving high biodiesel conversion rates [156].

Abed et al. [157] evaluated the performance and emission behavior of a single-cylinder diesel engine operating on various blends of waste cooking oil biodiesel with conventional diesel. The results indicated a decline in brake thermal efficiency and an increase in specific fuel consumption as compared to neat diesel. Despite these drawbacks, the biodiesel blends led to notable reductions in CO, UBHC, and smoke emissions. On the other hand, a rise in CO_2 and NO_x emissions was observed with increasing biodiesel content in the fuel mixtures.

Wei et al. [158] investigated waste cooking oil biodiesel blends using the Japanese 13-mode test cycle and observed earlier combustion onset due to biodiesel's higher viscosity and bulk modulus, which led to advanced fuel injection. While in-cylinder pressure increased and heat release rate decreased, emissions of ethene, propene, aldehydes, and aromatic hydrocarbons also rose with higher biodiesel content likely from pyrolysis of long-chain molecules. Conversely, biodiesel blends reduced particle mass, number concentration, and size, attributed to improved oxidation from biodiesel's higher oxygen content.

Yesilyurt [159] examined how different fuel injection pressures affect engine performance and emissions when using waste cooking oil biodiesel-diesel blends. The results showed that raising the injection pressure to 210 bar enhanced brake power, torque, and thermal efficiency. The blends also reduced smoke and unburned hydrocarbons, though CO_2 and NO_x emissions increased with higher pressure. Kuti et al. [160] simulated the spray combustion characteristics of waste cooking oil biodiesel and diesel using the Converge Computational Gas Dynamics (CGD) code. The simulation results aligned well with experimental findings across various injection pressures. The study revealed that a cool flame ignition phase preceded the main ignition, producing formaldehyde, followed by the formation of OH radicals during main combustion. Increasing injection pressure reduced spray-flame interaction, though waste cooking oil exhibited a higher level of spray-flame interaction compared to diesel at all pressures. This characteristic, combined with the higher oxygen content of biodiesel, contributed to reduced smoke formation. Bencheikh et al. [161] developed ternary fuel blends combining waste cooking oil biodiesel, propanol, and diesel. Incorporating propanol improved cold flow characteristics and lowered fuel density. Although these blends resulted in higher energy consumption during engine operation, they significantly reduced emissions of hydrocarbons, carbon monoxide, nitrogen oxides, and smoke, demonstrating their potential for cleaner combustion.

2.5 Fuel Additives, Types and their Role in CI engine

Additives refer to chemical substances introduced into base fuels to enhance their properties and improve engine performance. They play a crucial role in complying with stringent emission standards and improving the physico-chemical characteristics of fuels. Additives also help mitigate challenges associated with the widespread use of biodiesel in diesel engines, thereby reducing reliance on conventional fossil fuels.

The use of additives in the petroleum industry dates to the early 1990s. Some of the major benefits of incorporating additives include: (i) prevention of corrosion in fuel lines, storage tanks, and engine components; (ii) enhancement of cold flow characteristics and improved compatibility for blending biodiesel with diesel; (iii) reduction of harmful emissions during combustion; (iv) improved combustion efficiency and engine performance; and (v) better fuel storage stability under varying operating conditions [162–164].

The quantity of additives blended with base fuels depends on their chemical interactions and the composition of the fuel. Optimal dosing is typically determined through a series of experimental evaluations. As previously mentioned, additives can be categorized based on various factors such as their source, size, chemical structure, and physical state (solid or liquid).

Selecting a suitable additive for biodiesel or its blends is a critical task and must consider factors like cost-effectiveness, blending compatibility, toxicity, solubility, flash point, blend viscosity, water solubility, and additive partitioning in the fuel [163]. Based on global availability, additives are broadly classified into several categories, as illustrated in Figure 2.4 [165–167].

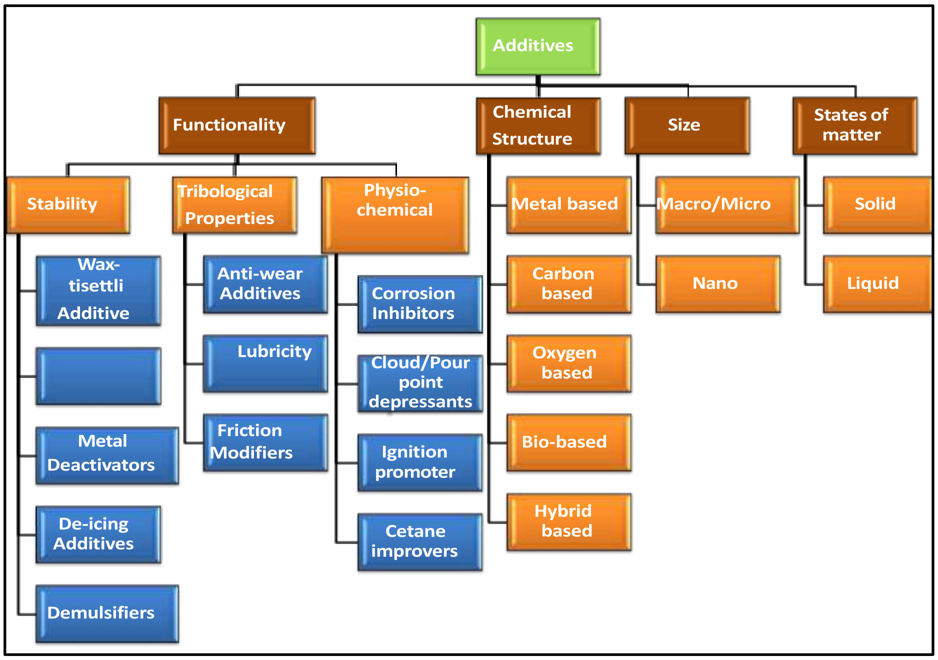

Figure 2.2. Categorization of fuel additives

This section summarizes various research findings that inspect the influence of diverse additives on fuel characteristics and engine attributes. It also highlights the limitations and drawbacks associated with using macro and micro fuel additives. One of the main challenges in biodiesel is the reduced oxidative stability due to the presence of unsaturated fatty acids, which adversely affects engine performance over time. To address this issue, incorporating small amounts of antioxidants—such as Butylated Hydroxytoluene (BHT), alkyl/aryl-aminophenol, 2,6-di-tert-butyl-phenol (2,6-dtbp), alkyl/aryl-phenylenediamine, neem extract (derived from crushed neem leaves), 2,4-dimethyl-6-tert-butyl-phenol, and ethylene-diamine—into biodiesel blends has shown significant improvement in oxidation stability, as reported by Borsato et al.[168] and Sindhi et al. [169]. Furthermore, certain additives can mitigate issues such as wax formation, corrosion of engine components, and deterioration of the combustion chamber surfaces when operating on biofuels under cold conditions. Market-available metal deactivators like N, N-disalicylidine-1,2-propane-diamine help in deactivating the metal surfaces, thereby minimizing oxidation and extending the engine's operational life (Sorate and Bhale [170]; Srivyas and Charoo [171]). Similarly, challenges related to poor ignition delay and low calorific value can be addressed by adding bio-derived copolymers like 2-ethylhexyl methacrylate and dimethyl aminoethyl methacrylate, as demonstrated by Fangsuwannarak et al. [172]. Engine tests conducted with and without these additives on fuels ranging from B10 to B100 indicated that B40 with 0.1 g additive yielded superior combustion efficiency, engine performance, and lower emissions compared to conventional diesel.

Alcohol-based additives such as ethanol, n-butanol, diethyl ether, and methanol—extracted from biological sources—offer high oxygen content and beneficial properties like high volatility, elevated flammability, and significant latent heat of vaporization. These characteristics help improve cold flow properties and combustion efficiency in diesel-biodiesel blends, particularly under colder climatic conditions [173].

Previous studies have shown that metal-based, alcohol-based, and copolymer additives can effectively improve the cold flow behavior of methyl esters. Guru et al. [174], for instance, reported that adding magnesium-based additives to chicken fat methyl ester lowered the pour point to 7°C as the concentration increased up to 16 mmol/L. Similarly, Cao et al. [175] investigated the effect of Ethylene Vinyl Acetate Copolymer (EVAC) on Waste Cooking Oil Methyl Ester (WCOME) in B20 blends for standard diesel engines. Adding 0.04 wt.% EVAC significantly improved cold flow performance, reducing the cloud point by 8°C, CFPP by 11°C, and pour point by 10°C, compared to neat diesel.

Bhale et al. [176] studied the effects of ethanol, kerosene (at 5–20% concentrations), and Lubrizol 7671 (from 0.5% to 4%) on the flow and injection characteristics of biodiesel in compression ignition engines. They observed that adding 20% ethanol reduced the cloud point of Mahua Methyl Ester (MME) from 18°C to 8°C, while 20% kerosene brought it down further to 5°C. The pour point also dropped by 11°C with ethanol and 15°C with kerosene. In a related study, blending Ethyl Levulinate

(EL), a renewable additive, with Cotton Seed and Poultry Fat Methyl Esters led to moderate improvements in cold flow properties, lowering the cloud point by 4–5°C, the pour point by 3–4°C, and the CFPP by approximately 3°C [177].

The combustion behavior of a fuel is primarily influenced by its chemical makeup. A critical combustion parameter is the speed at which the air-fuel mixture ignites within the engine's optimal timing window. Since fuel ignition is a radical-driven process, the appropriate concentration of fuel additives significantly affects ignition characteristics by either enhancing or delaying ignition capability. Sivalakshmi and Balusamy [178] examined the impact of a bio-derived additive on the combustion behavior of neem oil-based biodiesel. Their tests were conducted on a naturally aspirated, single-cylinder, four-stroke, direct injection diesel engine using biodiesel blended with ethanol and conventional diesel. The study found that increasing ethanol concentration in the fuel blends led to higher peak cylinder pressures. However, ignition delay for BE5 (5% ethanol in biodiesel) and BE10 blends showed no notable deviation from pure biodiesel.

In addition to single-cylinder engine research, Kivevele et al. [179] investigated the effects of antioxidant additives—including 2-tert-butyl-4-methoxy phenol (BHA), Propyl Gallate (PG), and Pyrogallol (PY)—in a four-cylinder, turbocharged, direct injection diesel engine using biodiesel from croton megalocarpus oil. Their study found that under normal operating conditions, peak cylinder pressures remained comparable to those of conventional diesel. However, at increased engine loads, fuels with additives showed higher peak pressures. Among all tested fuels, the B20 blend containing additives demonstrated the greatest peak heat release rate.

In a separate study, Musthafa et al. [180] examined the impact of di-tert-butyl peroxide (DTBP), an additive known to improve cetane index, on combustion characteristics in a single-cylinder, four-stroke, water-cooled compression ignition engine. The engine was fueled with a B20 blend of palm oil biodiesel, 1% DTBP by volume, and standard diesel. Results showed that the addition of DTBP led to a decrease in peak cylinder pressure compared to pure diesel (D100), while the heat release rate was notably higher in the blend containing the additive.

2.5.1 Review of Additive Use in CI Engines: Performance and Emission Aspects

Extensive research has explored the use of various additives with different biodiesel feedstocks to improve the performance and emissions of compression ignition engines. Careful selection of suitable additives remains essential. Sathiyamoorthi and Sankaranarayanan [181] investigated biodiesel from lemongrass oil in a CRDI diesel engine, using Butylated Hydroxyanisole (BHA) and Butylated Hydroxytoluene (BHT) as antioxidant additives. Their results showed that increasing the amount of BHA in the LGO25 blend (25% lemongrass oil biodiesel and 75% diesel) led to a noticeable decrease in Brake Specific Fuel Consumption (BSFC). BHT exhibited a similar effect. Moreover, both additives contributed to improved brake thermal efficiency (BTE) as their concentrations increased.

The study observed that carbon monoxide (CO) levels increased with the addition of BHA—rising by 5.8% at 500 ppm, 10.1% at 1000 ppm, and 14.8% at 2000 ppm. Similarly, BHT led to CO increases of 8.5%, 13.2%, and 16.6% at the same concentrations under full engine load. This increase was attributed to the shortened ignition delay caused by the antioxidants, which favored CO formation. Unburned hydrocarbon (HC) emissions also showed a slight uptick with antioxidant use. In contrast, nitrogen oxide (NOx) emissions were slightly reduced when antioxidants were present in the fuel blends.

Calder et al. [182] examined acetone's effect as a stabilizer in fuel blends of castor oil biodiesel, diesel, and recycled EPS in a HATZ two-cylinder engine. The results showed that biodiesel blends with EPS and acetone had better BSEC and higher BTE than diesel, with the B50 blend achieving the highest BTE. However, these blends produced more smoke emissions compared to diesel.

Devarajan et al. [183] investigated biodiesel derived from non-edible grapefruit seed waste, blended at 30% with diesel. The addition of 10% antioxidant additives like BHA and BHT improved fuel quality, reducing BSFC by 1.2–1.4% and increasing BTE by 0.7–1.1%. Emission levels of CO, HC, smoke, and NOx also showed a notable reduction, ranging between 1.8–3.7%. Similarly, Dhahad et al. [184] evaluated antioxidant effects on diesel, neat sunflower biodiesel, and a 20% biodiesel blend (B20). Four antioxidants—BHT, BHA (phenols), and DPPD, PPD (aromatic amines)—were used. Although B20 resulted in slightly higher BSFC, it enhanced thermal efficiency. Among the antioxidants tested, PPD demonstrated the most substantial NOx reduction (up to 52%). When 1000 ppm of antioxidants were added, NOx emissions dropped by 5.7–11.3%. Antioxidants also decreased CO and HC emissions, although smoke number (SN) increased with higher antioxidant doses and engine load. Ashok et al. [185] examined the influence of BHT and Ethanox on Calophyllum inophyllum biodiesel at various concentrations. Both additives reduced BSFC and improved BTE. Notably, BHT achieved a 21% NOx reduction at 500 ppm, while Ethanox yielded a 12.6% reduction at 1000 ppm. However, both additives led to an increase in CO, HC, and smoke emissions, although Ethanox demonstrated superior overall performance.

In another study, Rashedul et al. [186] used BHT and MBEBP in Moringa oleifera biodiesel blends. A 30% biodiesel blend (MB30) with these antioxidants effectively lowered NO emissions. While CO, HC, and smoke emissions were marginally higher compared to pure biodiesel, they were still lower than those from diesel. Additionally, thermal efficiency improved and peak heat release and BSFC decreased, indicating that MB30 could serve as a practical alternative fuel without engine modifications. Şimşek et al. [187] explored 2-ethylhexyl nitrate (EHN) as a cetane enhancer.

Incorporating EHN into diesel fuel improved combustion, increasing BTE by 11.57% in the best-performing blend (D99EHN2). It also reduced HC and CO emissions by 60.61% and 31.25%, respectively, although it caused a slight increase in NOx.

Li et al. [188] tested cetane improvers including 2-EHN, cyclohexyl nitrate, and 2-methoxyethyl ether in methanol-biodiesel blends. These additives boosted cetane numbers, decreased ignition delays, and elevated in-cylinder pressure and heat release rates. Notably, 2-methoxyethyl ether provided the best reductions in NOx and smoke, though CO and HC emissions rose slightly. Other engine parameters such as BTE, viscosity, and exhaust temperature remained stable. Ma et al. [189] studied a ferrous picrate-based catalyst in diesel fuel, finding improved combustion and fuel efficiency. Emissions of particulate matter, CO, and unburned hydrocarbons decreased by 39.5%, 21.1%, and 13.1%, respectively, though NOx emissions slightly increased by 6%, corresponding with enhanced combustion. Nadeem et al. [190] analyzed emulsified water-diesel fuels stabilized with conventional and Gemini surfactants. These emulsions, particularly with 15% water, significantly reduced NOx, SOx, CO, and particulate matter without compromising engine performance. Gemini surfactants, due to finer water dispersion, performed better in emission reduction.

Samie et al. [191] investigated diesel blended with CeO_2 nanoparticles (NPs), both stabilized and non-stabilized, and EHN. These blends improved diesel properties and increased cetane index while reducing CO and HC emissions. The most stable formulation contained 20 mg/L CeO_2 and an HLB number of 7.6. EHN further enhanced ignition properties without notably affecting physical fuel parameters. Lastly, Soudagar et al. [192] used graphene oxide nanoparticles in dairy scum oil biodiesel blends, achieving improved thermal efficiency (up by 11.56%) and reduced BSFC (down by 8.34%). Emissions including CO, HC, NOx, and smoke were significantly reduced. Molea et al. [193]

stabilized diesel-ethanol blends using tetrahydrofuran (THF), noting improvements in performance and emissions in simulations, thus confirming their potential as alternative fuels.

2.5.2 Review of Lubricity Enhancement in Diesel via Additives

The lubricity of ultra-low sulfur diesel (ULSD) has been a significant concern following the mandatory reduction of sulfur content, which also eliminated many naturally occurring polar compounds that aid in reducing friction and wear. To address this, various researchers have explored the effectiveness of biodiesel and other oxygen- or nitrogen-rich additives in restoring or enhancing the lubricity of ULSD. Knothe et al. [45] conducted a comparative study using the High-Frequency Reciprocating Rig (HFRR) test, where they found that fatty compounds, particularly those with oxygen atoms like free fatty acids and monoacylglycerols, significantly enhanced lubricity more than esters. They emphasized that even small additions of polar compounds, such as 1% to 2% commercial biodiesel, were effective in improving the lubricity of petro-diesel. Anastopoulos et al. [194] extended this work by testing various oxygen- and nitrogen-based additives—including biodiesel, amides, amines, esters, and acetoacetates—and concluded that all contributed to improved lubricity in low-sulfur diesel by enhancing the steel-on-steel tribological interface. Topaiboul et al. [195] tested palm and jatropha oil-based biodiesel blends and discovered that even biodiesel concentrations below 1% significantly improved the lubricity of ULSD, with jatropha-based biodiesel showing superior performance. Muñoz et al. [196] examined biodiesel derived from waste vegetable oil and demonstrated that just 100 ppm of biodiesel could reduce the wear scar diameter (WSD) to 338 μm, meeting the European standard (EN 590, max 460 μm), while also cutting emissions of hydrocarbons, particulates, and carbon monoxide. Maru et al., [197] using a ball-on-disc test, compared biodiesel samples certified by NIST from soybean oil (SRM 2772) and animal fats (SRM 2773), revealing a descending order of friction coefficients—diesel > soybean biodiesel > animal fat biodiesel—

suggesting that higher contaminant levels (e.g., mono- and diglycerides, and sulfur) in animal fat biodiesel enhanced lubrication. Agarwal et al. [198] provided a theoretical underpinning by asserting that diesel lubricity is primarily influenced by the presence of oxygen- and nitrogen-based polar molecules rather than sulfur. The refining process strips these compounds, thus necessitating the use of anti-wear additives like biodiesel to restore lubricity. They noted that biodiesel's unsaturation level, molecular polarity, and presence of hydroxyl groups are key factors in its lubricity-enhancing potential. Lapuerta et al. [199] investigated environmental influences, showing that ambient humidity and water content can degrade diesel lubricity, with paraffinic fuels more hygroscopic than aromatics but less so than methyl esters and alcohols, highlighting the complexity of fuel-environment interactions.

Further insight was provided by Nicolau et al. [200], who used electrical impedance measurements to show a strong inverse correlation between resistivity and WSD. By blending 1% to 10% soybean biodiesel into low-sulfur diesel, they achieved a significant WSD reduction from ~500 µm to 200 µm. Hsieh et al. [201] explored the chemical basis of lubricity, identifying polycyclic aromatic hydrocarbons (PAHs) and their nitrated derivatives (NPAHs) as contributors to boundary lubrication due to their chemisorption on metal surfaces, a property lost during the desulfurization process. Hazrat et al. [202] examined unrefined biodiesels and found that blends containing even less than 0.8% monoacylglycerides and free fatty acids improved lubricity, with hydroxylated fatty acid methyl esters (FAMEs) outperforming their non-hydroxylated counterparts, making them a natural and effective alternative to synthetic additives.

Matzke et al. [203] studied the molecular structure of nitrogen-containing additives and found that diaromatic structures with polar substituents and nitrogen atoms were particularly effective in improving lubricity. Hu et al. [204] tested tall oil fatty acids (TOFA) as a lubricity additive and found them highly effective, reducing WSD by 60.3% and the coefficient of friction (COF) by 95.7% at just 500 µg/g. TOFA was also stable for 180 days, demonstrating long-term applicability. Anastopoulos et al. [205] also investigated monoethanolamides derived from various vegetable oils (e.g., sunflower, soybean, olive, and used cooking oil), and found that these compounds significantly reduced WSD in marine gas oil when used at concentrations between 80–140 ppm, although lower doses were ineffective.

Prasad et al. [206] analyzed wild castor oil and its methyl/ethyl esters and reported that less than 1% addition could reduce WSD by more than 70%, affirming their viability as biodiesel-based lubricity enhancers. Geller et al. [207] focused on individual FAMEs and found that while they do improve lubricity, mixtures of FAMEs (as found in actual vegetable oils) provided superior results due to synergistic interactions among various fatty acids. Lastly, Anastopoulos et al. [208] also tested a range of alkyl ethers and alcohols, finding that six out of seven ethers performed well at 750–1500 ppm, but alcohols, owing to their stronger polarity, were even more effective at enhancing lubricity at concentrations of 750 ppm and above.

In summary, these studies collectively demonstrate that biodiesel and its derivatives, especially when rich in polar oxygenated or nitrogenated functional groups, offer a robust, sustainable solution to address the lubricity deficits in ULSD. Their effectiveness depends not only on concentration and chemical structure but also on environmental factors and interactions with other fuel components, underlining the multifaceted nature of diesel fuel formulation.

2.6 Literature Review Findings

An extensive review of the literature has led to significant insights into the impacts of desulfurization, biodiesel blending, and the incorporation of various additives on diesel fuel properties and engine performance. While the shift to ULSD has facilitated improved emissions, it introduces several challenges, including diminished lubricity, reduced energy density, and an increased vulnerability to storage-related issues such as microbial growth. Additives such as antioxidants, nanoparticles, and cetane improvers have shown promise in mitigating these drawbacks, though they come with certain trade-offs. The following points encapsulate the key findings from the literature, highlighting existing gaps and suggesting avenues for future research.

1. It can be summarized from exhaustive literature review that the lubricity of diesel fuel significantly deteriorates following desulfurization, primarily due to the removal of nitrogen- and oxygen-based polar trace compounds that act as natural lubricants, increasing wear and reducing injector life.
2. Beyond lubricity loss, desulfurized fuels (ULSD) suffer from lower energy density and increased injector fouling due to changes in hydrocarbon composition. Additionally, the absence of sulfur reduces the fuel's natural antimicrobial properties, thereby increasing susceptibility to microbial growth during storage, which can lead to fuel degradation and system corrosion.
3. A comprehensive review of existing literature reveals that Free fatty acids and glycerol have been found to provide superior lubricity compared to neat esters, due to the presence of free hydroxyl groups that form stronger boundary films on metal surfaces.
4. In accordance with existing literature, small amounts of biodiesel blending from various feedstocks into low-sulfur diesel significantly reduces wear scar diameter (WSD), enhancing lubricity and protecting fuel system components.

5. High ambient humidity and water content in diesel fuel increase wear scar sizes, adversely affecting lubricity. Paraffinic fuels are especially vulnerable compared to oxygenated alternatives like methyl esters and alcohols.
6. The researcher decided on a solution by incorporating antioxidants such as BHA, BHT, and Ethanox added to biodiesel blends to improve oxidative stability, thermal efficiency, and NOx control, although they may slightly elevate CO and HC emissions.
7. Numerous researchers underscore the inclusion of nanoparticles such as cerium oxide, graphene oxide, and ferrous picrate enhances combustion efficiency and significantly lowers CO, HC, and NOx emissions through catalytic and surface area effects.
8. As per available research, it becomes evident that cetane improvers and catalysts reduce ignition delay and improve combustion efficiency. However, these may cause slight increases in NOx emissions due to elevated in-cylinder temperatures.
9. A comprehensive review of existing literature reveals that increased biodiesel blending typically reduces CO and unburned hydrocarbons due to better oxygen availability, though NOx emissions tend to rise with the blend ratio due to higher combustion temperatures.
10. Most existing research has focused on single nano-additives for both fuel properties and engine characteristics.

2.7 Research Gap Analysis

After the exhaustive review of literature, the following research gaps were identified.

1. There is a lack of comprehensive studies comparing the performance and physicochemical properties of BS IV and BSVI commercial diesel.
2. The impact of sulfur content variation on diesel engine performance has not been thoroughly examined.

3. Limited studies have been focused on the combined effects of additives on diesel fuel lubricity and engine performance, particularly in the context of ultra-low-sulfur fuels.
4. There are limited research investigations that had the combined effects of biodiesel blending and hybrid additive doping on both engine characteristics and fuel properties.
5. Exhaustive literature summary shows that the effect of hybrid additives (ternary) on fuel properties & engine characteristics is yet to be explored.
6. A very less work has been carried out on Oxidation stability, storage stability & thermal stability of hybrid additives.
7. Spray characteristics and particle size distribution of hybrid nanoparticle doped diesel/biodiesel is unexplored.
8. A very little quantum of work has been carried out on CFD analysis related to atomization of fuel.
9. Very little quantum of work has been carried out on the impact of diesel additives on engine corrosion to ensure their reliability.

2.8 Problem Statement

The transition from Bharat Stage IV to Bharat Stage VI emission norms in India has necessitated the adoption of ULSD, which, while effective in reducing harmful emissions, has inadvertently compromised critical fuel properties such as lubricity, oxidative stability, and overall engine performance. Despite this shift, there is a noticeable lack of comparative studies analyzing the performance and physicochemical differences between BS-IV and BS-VI diesel fuels, especially under real-world engine operating conditions.

Although fuel additives are widely used to mitigate the adverse effects of desulfurization, existing research has primarily focused on single-function additives. There is a research void in the domain of hybrid or multi-functional additives that can simultaneously enhance lubricity, combustion, oxidative stability, and emissions. Similarly, the synergistic effects of biodiesel blending with such hybrid additives, particularly from sustainable sources like waste cooking oil.

2.9 Research Objectives

The objectives for the present research work are outlined as follows.

1. Comparative study of Bharat Stage IV and Bharat Stage VI commercial diesel performance on unmodified engine.
2. To study the effect of sulfur variation on tribological characteristics of diesel.
3. Selection & preparation of hybrid additive based on desirable parameters to be enhanced.
4. Production of biodiesel from waste cooking oil using transesterification process & its characterization.
5. Determination of various physicochemical properties of prepared test fuels.
6. Comparison of the tribological properties like wear Scar Diameter, and Coefficient of friction using High Frequency Reciprocating Rig (HFRR) for test fuels.
7. Development of the engine test rig for experimental trial.
8. Experimental investigation on performance, emission and combustion with prepared test fuels on the unmodified diesel engine and compare with base line data.

Chapter 3

SYSTEM DEVELOPMENT AND METHODOLOGY

3.1. Introduction

This chapter presents a detailed account of the research methodology used to achieve the objectives outlined in the previous chapter. Figure 3.1 provides a flow chart summarizing the overall approach adopted in this study. The research focuses on addressing the limitations of ultra-low sulfur diesel (ULSD) and identifying effective mitigation strategies.

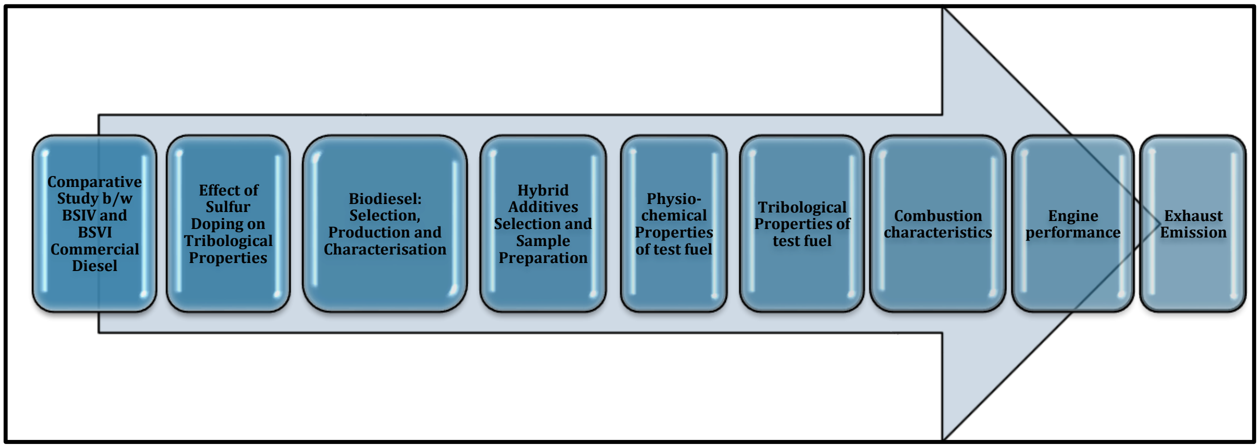

Figure 3.1. Research methodology process flow

The study begins with a comparative analysis of Bharat Stage IV and Bharat Stage VI diesel fuels, emphasizing their tribological properties and engine performance. To investigate the effect of sulfur content on lubricity, controlled sulfur doping is carried out on BS VI diesel.

To counter the drawbacks of desulfurization, biodiesel from waste cooking oil and a hybrid additive formulation—developed based on literature insights—are introduced. The methodology includes selection criteria for test fuels, biodiesel production, and synthesis of a multifunctional additive aimed at improving fuel and engine performance. The fuel-additive blends are evaluated for chemical and colloidal stability under varying environmental conditions.

Standard ASTM procedures are used to assess key physico chemical properties. Tribological analysis is conducted using HFRR to measure wear scar diameter and coefficient of friction. A single-cylinder diesel engine test setup is used to evaluate combustion behavior, performance metrics, and emission profiles. All experimental procedures, instrumentation, and analytical techniques used for performance, combustion, and emission testing are thoroughly described. Finally, the accuracy and uncertainty of each measurement are assessed to validate the reliability of the results.

3.2 Biodiesel Production Methodology

1. Feedstock Preparation

The process begins with selecting suitable raw materials such as used cooking oil or other non-edible waste oils. These are first filtered to remove particulates, residues, and moisture. To ensure complete dehydration, the oil is heated above 100 °C.

2. Pre-Treatment

If the oil contains a high percentage of free fatty acids (FFAs), an acid esterification step is employed to lower FFA levels. This involves reacting the FFAs with alcohol in the presence of an acid catalyst to convert them into esters, making the feedstock suitable for transesterification.

3. Transesterification

This is the main step in biodiesel production, where triglycerides react with methanol in the presence of a catalyst to produce fatty acid methyl esters (biodiesel) and glycerol. Depending on FFA content, either of the following methods is used:

Base-Catalyzed Method: Suitable for feedstocks with low FFA content (<2%), using alkaline catalysts like NaOH or KOH.

Acid-Catalyzed Method: Applied when FFA content exceeds 2%, utilizing acids like sulfuric or hydrochloric acid.

4. Separation

After the reaction, the mixture settles into two layers due to density differences—biodiesel on top and glycerol at the bottom. Glycerol is removed, and the biodiesel is collected for purification.

5. Purification

To remove residual contaminants, the crude biodiesel undergoes:

Washing: Warm water is used to extract soaps, catalysts, and unreacted methanol.

Drying: The washed biodiesel is heated to eliminate moisture, enhancing storage and combustion stability.

Filtration: Finally, the fuel is filtered to remove any remaining solids, ensuring it meets engine-grade quality standards.

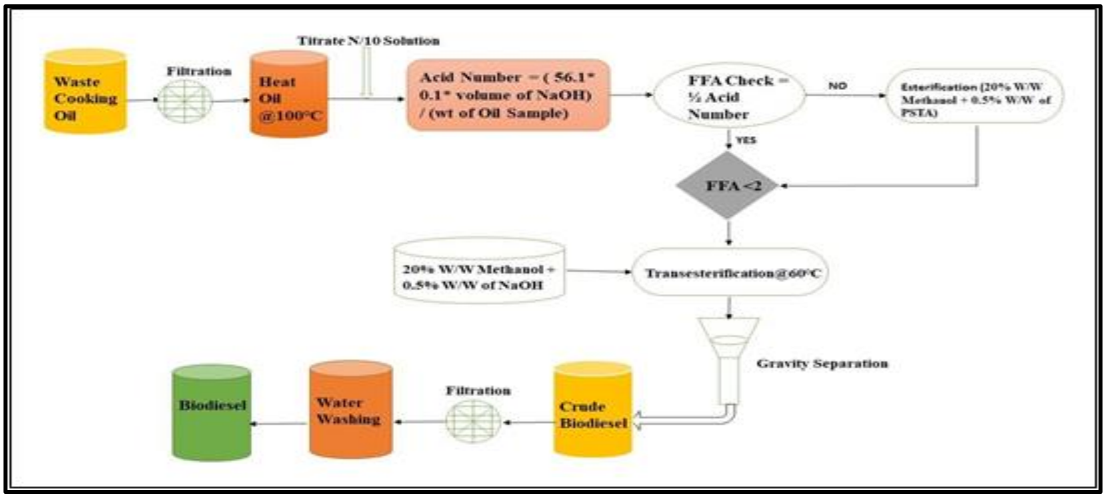

Figure 3.2. Biodiesel Production Process

Glycerol Recovery

The glycerol byproduct from the separation stage can be further purified and utilized in various sectors, including pharmaceuticals, chemicals, and other value-added applications. In this study, waste cooking oil is chosen as the primary feedstock. Its free fatty acid (FFA) content, determined via titration with a N/10 standard solution, ranges from 1.122% to 1.402%. As this is below the 2% threshold, a single-step base-catalyzed transesterification method is used for biodiesel production.

Figure 3.3. Production of waste cooking oil biodiesel

3.3 Biodiesel Characterization by Gas Chromatography–Mass Spectrometry

Gas Chromatography–Mass Spectrometry (GC-MS) is employed for the qualitative and quantitative characterization of biodiesel. This analytical technique enables the identification of individual components within a biodiesel sample, particularly fatty acid methyl esters (FAMEs), based on their chemical properties and mass spectra. The operational procedure of GC-MS involves several critical steps, as outlined below and illustrated in Figure 3.4.

1. Sample Preparation

A representative biodiesel sample is prepared by dissolving it in a suitable organic solvent. If required, derivatization is carried out to improve the volatility and thermal stability of the constituents, thereby enhancing chromatographic performance and spectral clarity.

2. Injection and Separation (GC Component)

The prepared sample is injected into a gas chromatograph equipped with a capillary column. The components in the sample are separated based on physicochemical properties such as boiling point, volatility, and polarity. As the sample passes through the column, each compound elutes at a characteristic retention time.

3. Ionization (MS Interface)

Upon exiting the GC column, the separated compounds enter the mass spectrometer's ionization chamber. Here, they are bombarded with high-energy electrons, typically using Electron Ionization (EI), leading to fragmentation and ion formation. EI is widely used for biodiesel analysis due to its reproducibility and extensive spectral libraries.

4. Mass Analysis

The generated ions are sorted based on their mass-to-charge ratio (m/z) using a mass analyzer. GC-MS systems commonly use quadrupole or time-of-flight (TOF) analyzers for high-resolution analysis. Each compound yields a unique mass spectrum, which reflects the distribution and relative intensities of its fragment ions [213].

5. Compound Identification

The mass spectra obtained are compared with standard spectral databases such as NIST or Wiley libraries for compound identification. Advanced software tools and algorithms assist in matching experimental spectra with reference data, ensuring accurate identification of FAMEs and other biodiesel constituents.

6. Quantification

Quantification is performed by analyzing the intensity or area of characteristic ion peaks in the spectra. This typically involves comparison with internal or external calibration standards of known concentration, allowing precise determination of the concentration of each identified component.

7. Data Analysis and Reporting

The results—including chromatograms, spectral data, and quantitative measurements—are compiled into a comprehensive report. This report details the molecular composition of the biodiesel sample, listing each identified compound and its corresponding concentration, thereby providing an accurate chemical fingerprint of the fuel.

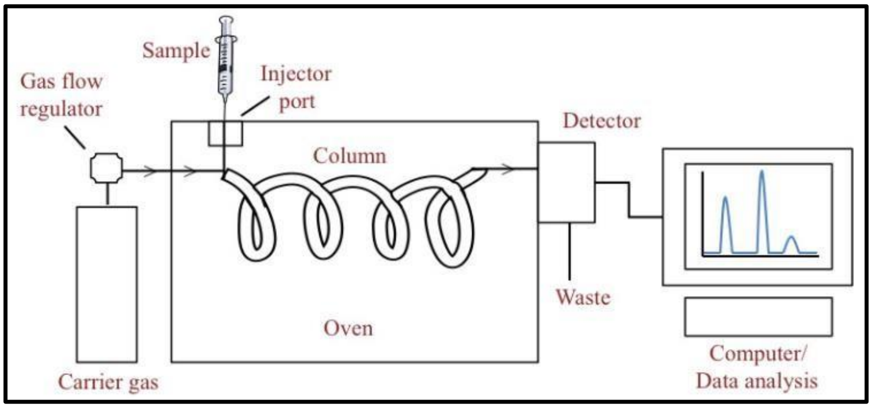

Figure 3.4: Working Principle of gas-chromatography

3.4 Selection of Additives

The shift towards ultra-low sulfur diesel (ULSD) has been a critical move to reduce sulfur-related emissions and enable the use of advanced after-treatment technologies. However, this desulfurization process significantly alters the fuel's physicochemical properties, introducing several performance and storage challenges. Chief among these is the loss of natural lubricity, as sulfur-containing compounds also contribute to lubricating properties. This can lead to increased wear in fuel injection systems and higher maintenance costs (Monyem & Van Gerpen, 2001; Marchetti & Errazu, 2008). To counter this, Trimethylbenzene, an aromatic hydrocarbon, was selected as a lubricity enhancer for its compatibility with diesel and its ability to restore boundary lubrication between moving parts [45].

Another pressing issue linked to ULSD, and biodiesel blends, is fuel instability during storage, particularly due to microbial contamination and oxidative degradation. Sulfur compounds previously served as natural biocides and antioxidants; their absence makes the fuel more prone to microbial growth, leading to filter plugging, corrosion, and phase separation [44]. To mitigate this, Tertiary Butylhydroquinone (TBHQ), a potent synthetic antioxidant, has been incorporated. TBHQ is known for its strong free radical scavenging ability and has been proven effective in stabilizing biodiesel and petro-diesel blends under varying storage conditions [214-215]. It not only enhances the oxidative stability of the fuel but also indirectly helps suppress microbial growth by delaying the breakdown of organic matter in the fuel.

Additionally, ULSD and biodiesel blends are associated with reduced energy density, resulting in a lower cetane number and poorer ignition quality. This can affect cold-start performance, increase ignition delay, and produce higher combustion noise. To address this, 2-Ethylhexyl Nitrate (2-EHN) was chosen as a cetane improver. 2-EHN promotes earlier and more controlled combustion, enhancing fuel efficiency and reducing engine knock. Studies have consistently shown that 2-EHN can significantly improve the cetane number of biodiesel blends and ULSD fuels, aligning their performance closer to that of conventional diesel [216-217].

Finally, the inclusion of Ferrous Picrate serves a dual purpose. As a combustion catalyst, it facilitates more complete combustion of hydrocarbon molecules, reducing unburnt fuel emissions and improving fuel economy. Furthermore, it promotes cleaner engine operation by reducing carbon and soot formation [218]. These attributes are especially valuable in the context of the National Biofuel Policy (NBP) of India, which mandates increasing biodiesel blending to 20% by 2030. The performance and emission challenges associated with biodiesel blends, especially their lower energy content and higher NOx emissions require additive-based solutions to ensure compliance without compromising engine reliability. By integrating these four additives Trimethylbenzene, TBHQ, 2-EHN, and Ferrous Picrate this research aims to develop a multi-functional additive package that not only compensates for the adverse impacts of fuel desulfurization but also supports the effective implementation of the National Biofuel Policy by enhancing the performance, storage stability, and environmental compatibility of biodiesel-diesel blends.

Tri-methyl Benzene (Mesitylene)	2-Ethyl Hexyl Nitrate (2-EHN)	Tert-Butyl Hydro Quinone (TBHQ)	Sorbitan Monooleate (SPAN 80)

Figure 3.5: Representation of Various Additives

Table 3.1: Detail of different categories of Additives

Type of Additive	Additive name	Molecular weight	Molecular formula	Morphology	Solubility	Color
Lubricity Enhancer	Trimethyl Benzene	120.19 g/mol	C_9H_{12}	liquid	Soluble	Colourless
Antioxidant	TBHQ	166.22 (g/mol)	$C_{10}H_{14}O_2$	Powdered Crystal	Soluble	Light tan
Cetane Booster	2-Ethyl-Hexyl Nitrate (2-EHN)	175.23 g/mol	$C_8H_{17}NO_3$	liquid	Soluble	Pale yellow
Combustion Catalyst	ferrous picrate	512.06 g/mol	$C_6H_2(NO_2)_3OFe$	liquid	Soluble	Light yellow
Surfactant	Sorbitan monooleate (Span 80)	428.6 g/mol	$C_{24}H_{44}O_6$	viscous liquid	soluble in oil, ethanol, and some organic solvents	Yellow

3.5 Synthesis of Multi-Purpose Solution

In response to the operational limitations associated with ultra-low sulfur diesel (ULSD) and diesel–biodiesel blends—namely poor lubricity, lower cetane number, oxidative instability, and microbial degradation—a multifunctional additive solution was systematically formulated. The selection of additives was strategically based on the specific parameters requiring enhancement. A multifunctional solution was formulated by integrating established additives, including surfactants, lubricity enhancers, cetane boosters, antioxidants, and combustion catalysts, each performing distinct physicochemical roles.

The formulation process commenced with petroleum distillate serving as a non-reactive carrier fluid, ensuring full solubility and dispersion of the active agents. Sorbitan Monooleate, a non-ionic surfactant, was incorporated to reduce hydrocarbon surface tension and improve atomization, leading to enhanced air–fuel mixing and cleaner combustion.

Trimethylbenzene acted as a dual-purpose solvent enhancing lubricity and cleaning internal fuel system components, which is essential given the reduced lubricity of desulfurized fuels. An ester-based lubricity enhancer was optionally included to meet EN 590 and ASTM D975 wear scar limits. To address the reduced cetane number and poor cold-start characteristics, 2-Ethylhexyl Nitrate (2-EHN) was added as a cetane improver, promoting shorter ignition delay and efficient combustion phasing. To prevent oxidative degradation and gum formation—side effects of cetane improvers and biodiesel blends—Tertiary Butylhydroquinone (TBHQ), a phenolic antioxidant, was incorporated to scavenge free radicals and ensure fuel stability during long-term storage. Additionally, TBHQ reduced microbial growth potential by limiting reactive species available for microbial metabolism.

Finally, Ferrous Picrate, an organometallic combustion catalyst, was introduced in trace quantities to facilitate complete oxidation of long-chain hydrocarbons, leading to reductions in unburnt hydrocarbons, carbonaceous emissions, and improved brake thermal efficiency.

The formulation was carried out using a high-speed magnetic stirrer with temperature and RPM control, operated under ambient laboratory conditions (25 ± 2 °C). The total mixing duration was 60 minutes, with each additive introduced in a defined sequence to prevent component incompatibility and ensure homogeneous blending.

The resulting multifunctional additive solution was subsequently blended into commercial diesel fuel to mitigate the inherent shortcomings of desulfurized diesel, while also addressing the operational and stability issues commonly observed in diesel–biodiesel blends. This tailored approach aligns with the objectives of enhancing fuel performance, combustion quality, and emissions control under India's National Biofuel Policy and global sustainability targets.

Table 3.2: Chemical Composition of Multi-Purpose Solution with Quantity

Multi-Purpose Solution (MPS)		
Chemical Name	**Particulars**	**Quantity (%wt.)**
Mineral Oil	Base oil	95
Trimethyl Benzene	Lubricity Enhancer	1.5
2-Ethyl-Hexyl Nitrate	Cetane Improver	1.5
Tert-butylhydroquinone	Antioxidant	1.5
ferrous picrate	Combustion Catalyst	0.1
Sorbitan Monooleate	Surfactant	0.2

3.6 Characterization of Multi-Purpose Solution

The characterization of a novel multipurpose solution is essential to assess its suitability for enhancing the performance and emission characteristics of compression ignition engines. Key physicochemical properties such as flash point, density, boiling range, freezing point, and solubility in water are evaluated using standard ASTM methods. The flash point is determined to ensure safe handling and storage, as it indicates the temperature at which the additive emits flammable vapors. Density plays a crucial role in fuel injection and atomization, directly influencing combustion efficiency. The boiling range offers insights into the additive's volatility and thermal stability under engine operating conditions, while the freezing point is assessed to ensure fluidity and functionality in low-temperature environments. Additionally, solubility in water is examined to evaluate potential risks of phase separation or moisture-related degradation. Collectively, these characterization parameters provide a foundational understanding of this novel solution behavior in fuel systems, supporting its practical application in improving engine performance and reducing harmful emissions.

Table 3.3: Properties of Multi-Purpose Solution

Property	**Value**
PH	6.52
Flash Point (°C)	49
Density (Kg/m^3)	798
Solubility in water	Insoluble
Boiling Range (°C)	148-295
Freezing Point (°C)	-18

3.7 Preparation of Test Fuel Blend with Multi-Purpose Solution

This study investigates the influence of a newly developed multifunctional additive on the wear characteristics, performance, and emission behavior of commercially available BS6 diesel. BS6 fuel was procured from a fuel station in New Delhi and blended with the additive at three concentrations: 0.5%, 1.0%, and 2.0% by volume, labelled as D100MPS0.5, D100MPS1.0, and D100MPS2.0, respectively. Additionally, a diesel-biodiesel blend was prepared by mixing BS6 diesel with 5% waste cooking oil biodiesel (WCB). This blend was similarly treated with the multifunctional additive at the same three concentrations i.e. 0.5%, 1.0%, and 2.0% by volume and labelled as D95WCB5MPS0.5, D95WCB5MPS1.0, and D95WCB5MPS2.0, respectively. To assess blend stability, samples were stored under varied conditions for six months. No phase separation or instability was observed during this period.

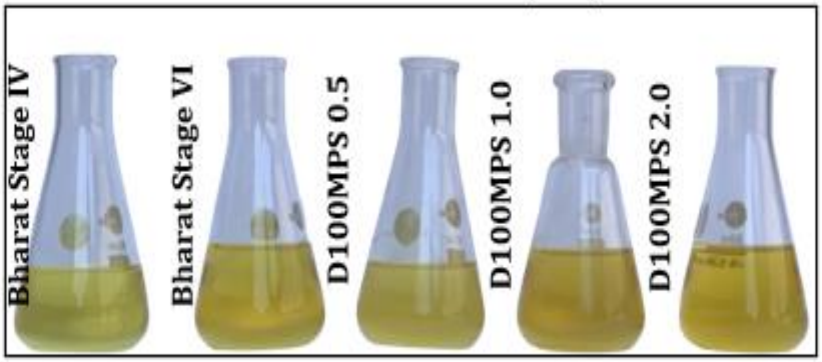

Figure 3.6. Bharat Stage VI Commercial Diesel with MPS

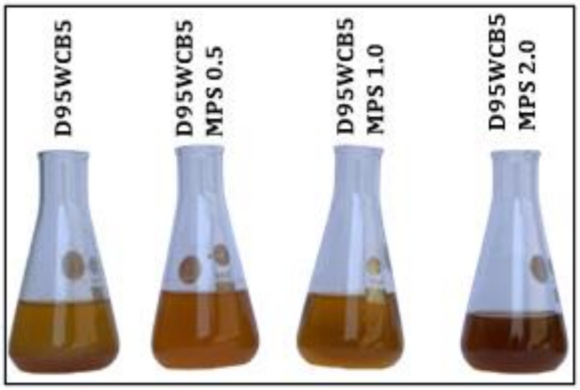

Figure 3.7. Diesel-Biodiesel Blend (D95WCB5) with MPS

Table 3.4. Designation and compositional details of diesel-based test fuel samples

Test fuel blends	**Representation**
D100	Pure Diesel (Bharat Stage VI)
D100MPS0.5	Diesel + 0.5 ml Multipurpose Sol.
D100MPS1.0	Diesel + 1.0 ml Multipurpose Sol.
D100MPS2.0	Diesel + 2.0 ml Multipurpose Sol.

Table 3.5. Designation and compositional details of diesel- Biodiesel based test fuel samples

Test fuel blends	**Representation**
D100	Pure diesel
D95WCB5	95% Diesel 5% Waste Cooking Biodiesel
D95WCB5MPS0.5	95% Diesel 5% Waste Cooking Biodiesel + 0.5 ml
D95WCB5MPS1.0	95% Diesel 5% Waste Cooking Biodiesel + 1.0 ml
D95WCB5MPS2.0	95% Diesel 5% Waste Cooking Biodiesel + 2.0 ml

3.8 Stability Analysis of the Blends by Visual Inspection Method

The stability of various nano-fuel samples was evaluated using a visual inspection method, wherein ultrasonicated fuel blends were stored in conical flasks and monitored over time. This approach, being straightforward, involves observing the gradual settling of suspended nanoparticles under ambient conditions. Evidence of phase separation and sedimentation was documented by capturing periodic photographs of each sample to visually track changes. To assess the influence of environmental factors, each fuel sample was stored under naturally varying local climatic conditions, reflecting seasonal room temperatures of approximately 10°C, 25°C, and 40°C. The inspection continued for a total duration of six months, with regular monitoring intervals to study the impact of both time and temperature on nanoparticle dispersion and stability.

3.9 Commercial Feasibility of the Multi-Purpose Diesel Fuel Additive

The multi-purpose additive developed in this research integrates five functional components like trimethyl benzene (lubricity enhancer), 2-ethylhexyl nitrate (2-EHN, cetane improver), tertiary-butylhydroquinone (TBHQ, antioxidant), ferrous picrate (combustion catalyst), and sorbitan monooleate (surfactant)—to address key challenges in Ultra-Low Sulfur Diesel (ULSD) and biodiesel blends. This formulation demonstrates strong commercial potential due to its cost-effectiveness, scalable synthesis, alignment with emission norms, and compatibility with existing fuel infrastructure.

All selected components are well-established industrial chemicals with proven compatibility in fuel systems. 2-EHN is a commonly used cetane improver and is widely available in bulk. Trimethyl benzene, derived from petroleum refining byproducts, is both inexpensive and abundant. TBHQ, a synthetic antioxidant, is used extensively in the fuel and food industries, while sorbitan monooleate is a biodegradable, non-toxic surfactant commonly employed in emulsions. Ferrous Picrate, though more specialized, has recognized applications in enhancing fuel combustion and is producible at industrial scale. The optimized combination of these additives allows for synergistic performance while minimizing the required dosage of each component, keeping formulation costs low.

Manufacturing the additive involves a simple blending process, eliminating the need for high-pressure equipment or complex synthesis steps. This allows for decentralized production at fuel depots or refineries, reducing logistics and operational costs. The additive is fully miscible with both petroleum diesel and biodiesel, requiring no changes to existing supply chains or storage infrastructure. Its thermal and oxidative stability ensures it can be stored and transported under standard fuel handling conditions without degradation.

The additive meets increasing market demand driven by stricter emissions regulations, such as Bharat Stage VI (BS VI) in India and Euro 6 globally. Its ability to improve lubricity, cetane number, oxidation stability, and combustion efficiency helps fuel producers meet these regulations while maintaining engine performance. Moreover, the additive enhances the compatibility and cold flow characteristics of biodiesel blends.

Economic modeling based on component costs and blend ratios indicates the additive can be marketed at a competitive cost per liter of treated fuel. At dosing concentrations of 0.5–2.0%, the marginal increase in fuel cost is offset by benefits such as improved fuel economy, reduced engine wear, and potential incentives linked to emissions compliance. Overall, the formulation presents strong commercial feasibility, with economic, regulatory, and operational advantages. With appropriate regulatory approvals and pilot-scale validation, the additive is well-positioned for commercial adoption in transportation, power generation, and agricultural sectors.

3.10 Evaluation of Sulfur Content

The Sindie 7039 MWDXRF sulfur analyzer utilizes Monochromatic Wavelength Dispersive X-ray Fluorescence (MWDXRF) technology to precisely determine the sulfur content in liquid hydrocarbon samples, including diesel fuel.

Plate 3.1. MWDXRF Sulfur Analyzer

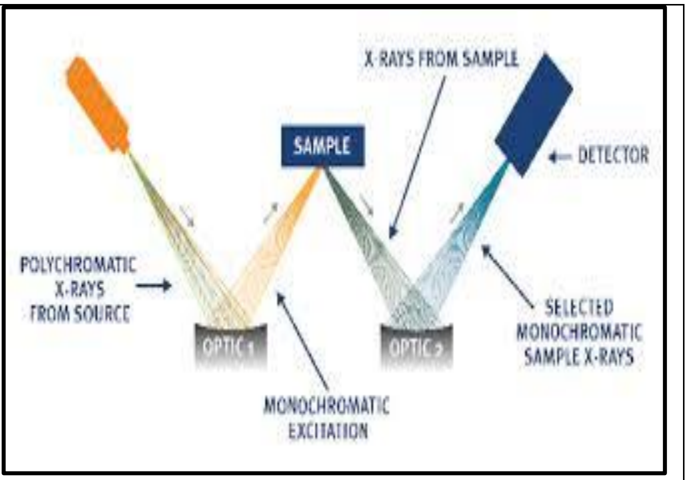

Figure 3.8. Working Principle of MWDXRF Sulfur Analyzer

A low-power X-ray tube emits a polychromatic (multi-wavelength) beam of X-rays towards a Doubly Curved Crystal (DCC) optic. The first DCC optic is specifically designed and aligned to select and focus a narrow, monochromatic (single wavelength) beam of X-rays with the optimal energy to excite sulfur atoms in the sample. This monochromatic excitation significantly reduces spectral interference and improves the signal-to-background ratio compared to traditional WDXRF instruments that use a polychromatic beam.

Sample Interaction

The focused monochromatic X-ray beam irradiates the liquid fuel sample contained in a sample cup with a thin, transparent film window. When the incident X-rays strike the sulfur atoms in the sample, they cause the inner-shell electrons of the sulfur atoms to be ejected. As the electron vacancies are filled by electrons from higher energy levels, characteristic secondary X-rays are emitted. The energy of these secondary X-rays is specific to the sulfur element.

Detection of Sulfur X-rays

A second DCC optic is precisely positioned to collect the characteristic sulfur X-rays emitted from the sample. This second DCC optic acts as a highly selective monochromator, focusing only the sulfur's characteristic X-rays onto the detector. This further enhances the signal-to-background ratio and improves the sensitivity and accuracy of the measurement.

Signal Processing and Quantification

A solid-state detector measures the intensity (number of X-ray photons detected per unit time) of the focused sulfur characteristic X-rays. The intensity of the detected sulfur X-rays is directly proportional to the concentration of sulfur in the sample. The analyzer's software processes the detector signal using pre-established calibration curves (obtained by analyzing samples with known sulfur concentrations) to determine and display the sulfur concentration in the unknown sample, typically in parts per million (ppm) or weight percent (wt%). A key advantage of the MWDXRF technology used in the Sindie 7039 is that it is a direct measurement technique. It does not require high-temperature combustion, chemical reactions, or the use of consumable gases (like oxygen or carrier gases) that are common in other sulfur analysis methods like Ultraviolet Fluorescence (UVF) or Gas Chromatography with Sulfur Chemiluminescence Detection (GC-SCD). This simplifies operation and reduces maintenance requirements.

3.11 Friction and Wear Test Method

The High-Frequency Reciprocating Rig (HFRR) is an advanced tribological testing device used primarily to evaluate the lubricity of diesel fuels, following the standardized method outlined in ASTM D6079. The main principle of the HFRR test lies in simulating metal-to-metal contact under lubricated conditions to replicate what happens inside fuel injection systems. It involves rubbing a precisely specified steel ball against a stationary steel disc while submerged in a sample of test fuel. This rubbing occurs with a high-frequency reciprocating motion over a short stroke length, thereby generating a wear scar on the surface of the steel ball. The size of this wear scar is later measured and used as an indicator of the lubricating ability of the tested fuel. The test setup includes a 6 mm diameter steel ball (AISI E-52100 steel with a hardness of HRC 58–66) mounted on a reciprocating arm. This ball is held under a constant 200-gram load against a 10 mm diameter steel disc made from the same material but polished to a very fine finish (Ra < 0.02 microns). The test fuel, typically 2 mL, is added into a small reservoir where the disc is submerged. The temperature of the test fuel is precisely controlled using an electrically heated reservoir, typically set to 60°C, which is considered optimal for such tests. The reciprocating movement has a 1 mm stroke length and operates at a frequency of 50 Hz, continuing for a total of 75 minutes. During this time, data such as friction force and stroke frequency are monitored and recorded using a dedicated PC software called Winducom 2008.

Before the test begins, both the steel disc and ball must be meticulously cleaned. The cleaning process involves removing the disc from toluene storage, cleaning it in an ultrasonic bath for 7 minutes, and then rinsing with acetone for 2 minutes. Both components are dried and stored in a desiccator to prevent contamination. After mounting the test components, the operator sets up the software interface, inputs the sample data and test parameters, and activates the heater. Once the system stabilizes at the desired temperature, the reciprocating motion is initiated, and the ball begins rubbing against the disc, generating a wear scar.

Upon completion of the test duration, the ball is carefully removed, cleaned, and its wear scar is examined under a CCD camera system. This camera, mounted vertically over the test specimen, captures the scar image and sends it to a computer. The image is analyzed using SCARVIEW software, which allows the user to measure the major and minor axes of the wear scar with high precision (least count of 0.1 microns).

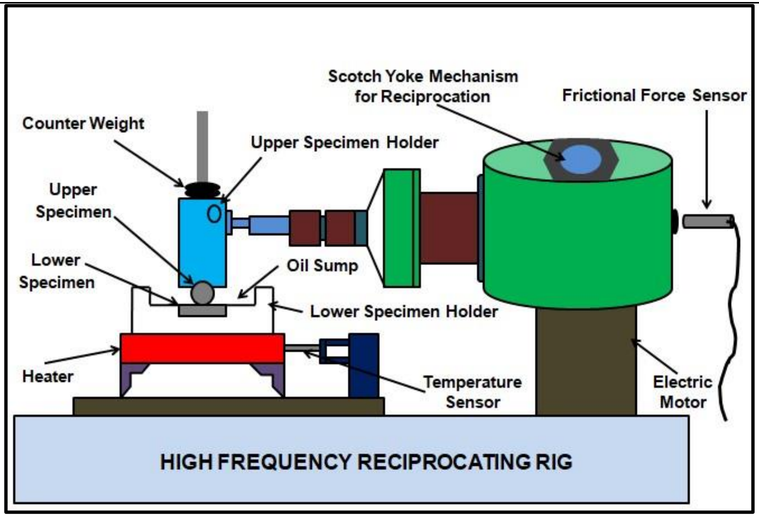

Figure 3.9 Schematic of High Frequency Reciprocating Rig Setup

Plate 3.2. High Frequency Reciprocating Rig Setup

Features like auto-focus, image contrast adjustment, and sharpness enhancement ensure the image is clear for accurate measurement. The final scar dimensions are recorded, which reflect the lubricity of the fuel: smaller scars indicate better lubrication, while larger scars point to poor lubricating properties.

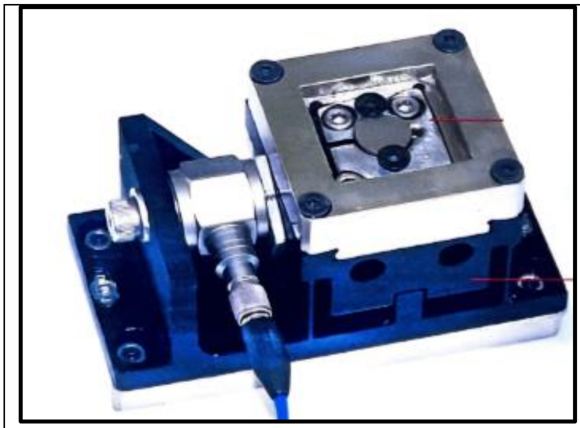	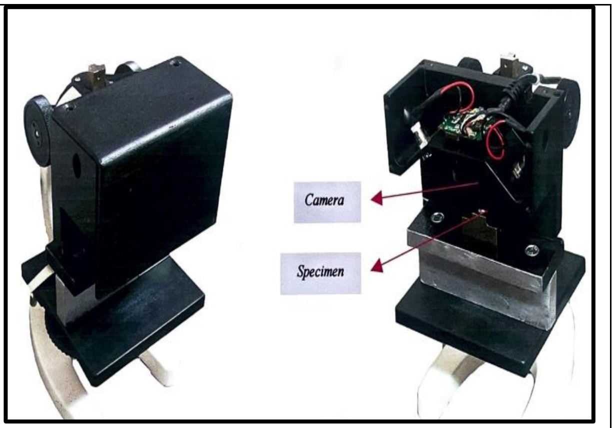
Plate 3.3. Bottom Specimen Holder with Specimen (Circular Disc)	**Plate 3.4. CCD Camera with Upper Specimen**

3.12 Methodology for Evaluation of Physicochemical Properties

The performance of a diesel engine is significantly influenced by the physicochemical properties of the test fuels. Enhanced fuel quality tends to improve engine efficiency and output. Hence, it was essential to analyze the properties of all selected fuels and their blends to ensure an accurate assessment of engine performance. These properties were experimentally determined using standard instruments and ASTM procedures. The following sections detail the methodologies, equipment, and protocols used for fuel property evaluation.

3.12.1 Kinematic Viscosity

The kinematic viscosity of each fuel sample was determined using a Petrotest Viscometer, maintained at 40°C in compliance with ASTM D445. Factors such as testing temperature, fuel composition, and nanoparticle concentration were considered due to their influence on viscosity. Maintaining viscosity within the optimal range is critical for efficient fuel atomization and air-fuel mixing during combustion [219–220].

The apparatus, shown in Plate 3.5, employs a U-shaped Ostwald capillary tube submerged in a temperature-controlled water bath. A fixed volume of fuel is introduced into the bulb via syringe until it reaches the upper calibration mark. The time taken for the sample to flow from the upper to the lower mark is recorded, and viscosity (P) is calculated using the standard formula.

$$P = k \times t \tag{3.1}$$

where k is the capillary constant specific to the viscometer tube and t is the measured flow time of the fuel sample between the two marks.

3.12.2 Density

Density significantly affects fuel injection, spray characteristics, and combustion efficiency, also influencing related properties like calorific value and cetane number. Generally, lower density enhances engine performance and fuel combustion [221].

In this study, the densities of the fuel samples were precisely measured using an Anton Paar Density Meter (Model DMA 4500), as illustrated in Plate 3.6. The measurements were conducted following the standard procedure outlined in ASTM D4052, which specifies the method for determining the density and relative density of liquids using a digital density meter. To ensure accuracy and consistency, all density measurements were performed at a controlled temperature of 15°C, since temperature fluctuations can significantly affect density values.

The Anton Paar DMA 4500 operates on the principle of oscillating U-tube technology. A small volume of the fuel sample is introduced into a U-shaped glass tube, which is mechanically excited to oscillate at its natural frequency. Before testing, the U-tube was cleaned with 10 ml of toluene to eliminate contaminants. Each fuel sample was tested three times, and the average value was recorded to ensure accuracy.

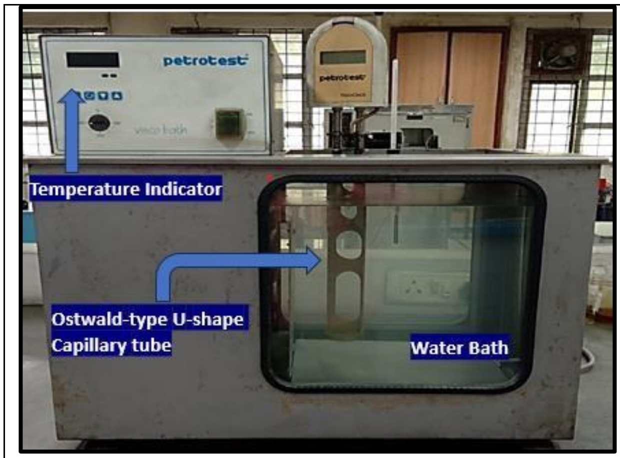	
Plate 3.5. Viscometer	**Plate 3.6. Density Meter**

3.12.3 Calorific Value

The calorific value, or lower heating value, indicates the amount of heat released during the complete combustion of one kilogram of fuel in the presence of air. In this study, it was determined using a Compensated Calorimeter (Model 6100, Anton Paar), as shown in Plate 3.7, following ASTM D240 standards [222]. The calorimeter is equipped with a computer-controlled electric arc ignition system and an automated oxygen charging unit. A measured amount of fuel is placed in a sample holder within the combustion bomb. An electrode immersed in the sample ignites the fuel when an electric current is applied. Combustion occurs in a high-pressure oxygen environment, and the heat released is recorded to calculate the fuel's calorific value.

3.12.4 Flash Point

The flash point of a fuel is the lowest temperature at which its vapours can ignite when mixed with air. Although it does not directly affect engine performance, it is a critical parameter for evaluating the fuel's flammability and ensuring safe storage and handling. Conventional diesel tends to have a lower flash point than biodiesel, primarily due to the presence of low molecular weight and branched hydrocarbons, which necessitates more stringent handling precautions. In this study, the flash point was measured using an automated Pensky-Marten’s apparatus (Scavini make), as illustrated in Plate 3.8, following ASTM D93 standards [223].

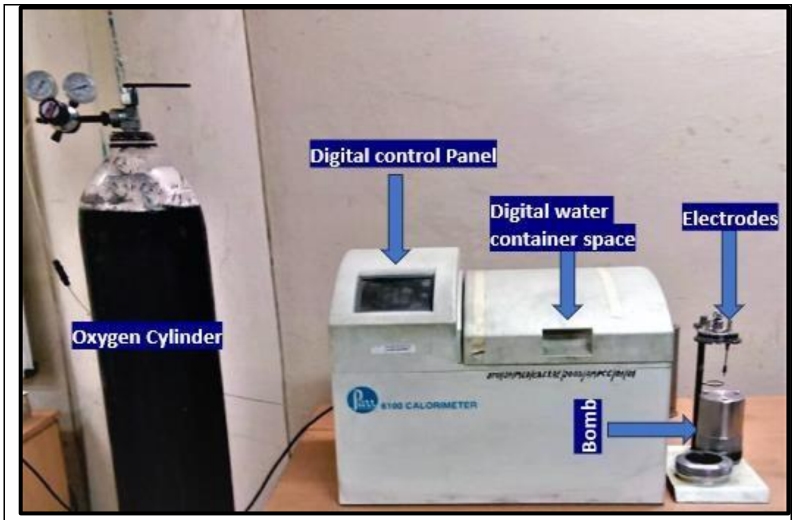

Plate 3.7: Bomb Calorimeter Setup

Plate 3.8: Flash Point Apparatus

The apparatus consists of a cup for holding the fuel, an ignition port for introducing a flame, and a temperature sensor. During testing, the ignition source is applied automatically at set intervals, and the flash point is recorded as the lowest temperature at which a distinct flash is observed.

3.12.5 Cetane Index

Cetane index is a key property of petroleum diesel and similar fuels that indicates their ignitability in compression ignition (CI) engines. It plays a crucial role in ensuring efficient and reliable engine performance. This index reflects the combustion quality within the engine cylinder by providing insight into the fuel's tendency to auto-ignite when injected into high-temperature, compressed air. A low cetane index increases the likelihood of engine knocking, while an excessively high cetane index may hinder proper mixing of the fuel with air, potentially leading to incomplete combustion and reduced engine efficiency [224]. Therefore, accurate determination of the cetane index is essential, particularly when evaluating and comparing multiple fuel samples.

In this study, the cetane index was calculated according to the ASTM D4737 standard. The calculation was based on experimentally obtained fuel density and distillation data. The equipment used for measuring the distillation temperatures is depicted in Plate 3.11. The correlation used to estimate the auto-ignition characteristics of the fuels is provided in Equation (3.2):

$$ECI = 45.2 + (0.0892)(BT10A) + [0.131 + (0.901)(X)][BT50A] + [0.0523 - (0.420)(X)][BT90A] + [0.00049][(BT10A)2 - (BT90A)2](107X + 60X2) \qquad (3.2)$$

where ECI= Estimated cetane index; X= $[e(-3.5)Z] - 1$, Z= D-0.85, D= Density of the fuel; BT10,50,90A= Recovery/Boiling temperature for obtaining 10%, 50% and 90% distilled fuel.

3.12.6 Cold Flow Properties

Cold flow properties are particularly critical when fuels are used in engines operating under low-temperature conditions. Poor cold weather performance can lead to common issues such as hard starting, fuel filter blockage, injector clogging, and white smoke emissions during ignition. To assess and compare the cold weather suitability of various fuel samples, three key parameters were evaluated: Cloud Point (CP), Pour Point (PP), and Cold Filter Plugging Point (CFPP) [225].

3.12.7 Cloud Point and Pour Point

The cloud point is the lowest temperature at which wax crystals, or a whitish haze begin to form in the fuel, signalling the start of solidification. The pour point is the temperature at which the fuel no longer flows. Both properties were measured according to ASTM D2500 and ASTM D97 standards, respectively [226]. As shown in Plate 3.9, a refrigerated bath was used for the tests. Fuel samples were placed in test tubes sealed with rubber corks that had a central opening for inserting a resistance temperature detector (RTD) sensor to monitor temperature. The test tube was periodically removed after every 3°C decrease in temperature to observe the cloud point (wax formation) and pour point (loss of flowability).

3.12.8 Cold Filter Plugging Point (CFPP)

The CFPP is the temperature at which the fuel begins to gel but can still pass through a standardized filter within a set time frame. It was determined using a CFPP apparatus from Linetronic Technologies, as shown in Plate 3.10, following ASTM D6371. The test begins by cooling the bath to -34°C, at which point a specified fuel volume is drawn into a capillary tube with vacuum assistance [227]. The sample is further cooled, and the CFPP is identified as the temperature where the fuel fails to pass through a 10-micron filter within one minute, indicating wax crystallization and filter plugging.

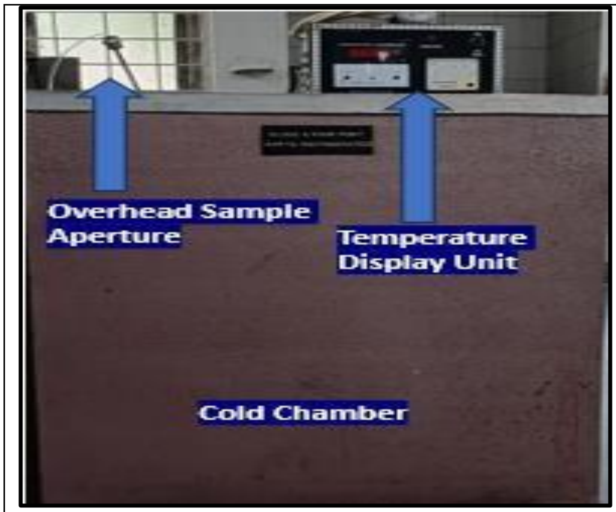

Plate 3.9. Cloud Point and Pour Point Apparatus

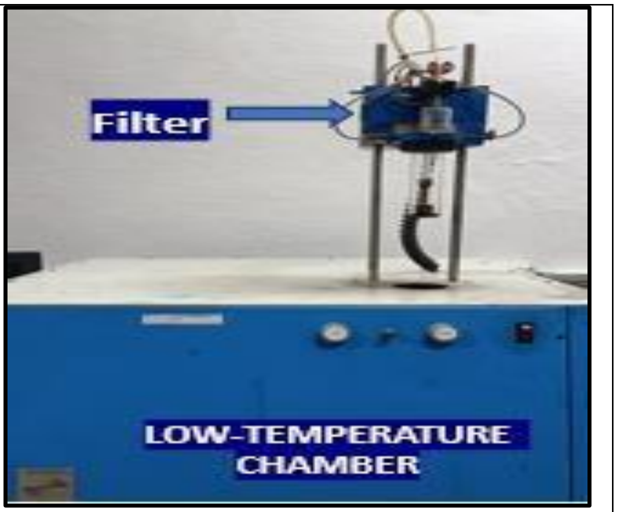

Plate 3.10: Cold Flow Plugging Point Apparatus

3.13 Experimental Setup for Conducting Engine Trials

This study aims to evaluate the potential of a multipurpose additive blended with ultra-low sulfur diesel (ULSD) for application in compression ignition (CI) engines. The investigation begins with the selection of a suitable diesel engine, followed by a comprehensive analysis of its performance, combustion characteristics, and emission output under various operating conditions

3.13.1 Selection of I C Engine

Agriculture has long been recognized as a key driver of economic growth, playing a vital role in the development of both advanced and developing nations. In industrialized countries, the agricultural sector has already made significant contributions to economic progress, while in developing regions, its role in fostering growth remains equally important. Since the conclusion of World War II, millions of diesel engines have transformed agricultural operations by providing reliable power for various farm activities. Although diesel engines are known to contribute to environmental pollution, they continue to be widely used in agriculture and rural economies due to their efficiency and reliability. In countries like India and across the African continent, agriculture is a primary source of livelihood, and over five million light- and medium-duty diesel engines are in active use. Likewise, in developed nations such as the United States, approximately two-thirds of the energy required for farm machinery is still provided by diesel-powered engines.

While recent advancements in electric vehicles and fuel cell technologies have begun to influence global transportation trends, their adoption in rural and agricultural settings is limited due to the high costs associated with infrastructure upgrades and equipment replacement. A sudden shift away from diesel technology in these sectors could have adverse economic impacts on a global scale.

For this purpose, a Kirloskar DAF8 direct injection diesel engine was utilized. It is a single-cylinder, four-stroke, air-cooled engine with a rated power of 3.5 kW at 1500 rpm. The engine specifications are listed in Table 3.5, and the experimental setup is illustrated in Figure 3.10.

Table 3.6. Specification of Air-Cooled Diesel Engine setup

Make	**Kirloskar (Shakti)/ CAF-8**
Type	4 Stroke, DI Engine
Model	KSA-2057-P-1170
No. of Cylinder	01
Compression ratio	17.5:1
Fuel injection timing	23°bTDC
Bore (mm)	87.5
Stroke (mm)	110
Cubic Capacity (ltr.)	0.661
Fuel Tank Capacity	6.5
Cooling	Air cooled
Piston movement	Vertical

The engine's cylinder block is manufactured from cast iron, while the removable cylinder liner, also referred to as the sleeve, is made from high phosphorus cast iron to withstand wear and provide a smooth surface for piston movement. The camshaft is responsible for synchronizing the timing of the intake and exhaust valve operations. The fuel injection system includes components such as the high-pressure fuel pump, fuel injector, and fuel lines, all of which are critical for precise fuel delivery into the combustion chamber. To improve thermal efficiency, the engine's cylinder head and block are equipped with cooling fins that increase surface area for better heat dissipation. Additional fins are present on components such as the pistons and crankcase. Lubrication is ensured by engine oil, which minimizes friction among moving parts and aids in heat transfer, thereby supporting the engine’s cooling mechanism. A thermostat is also integrated into the system to control airflow and maintain optimal engine temperature. Plate 3.11 presents the actual engine used during the experimental phase of this investigation.

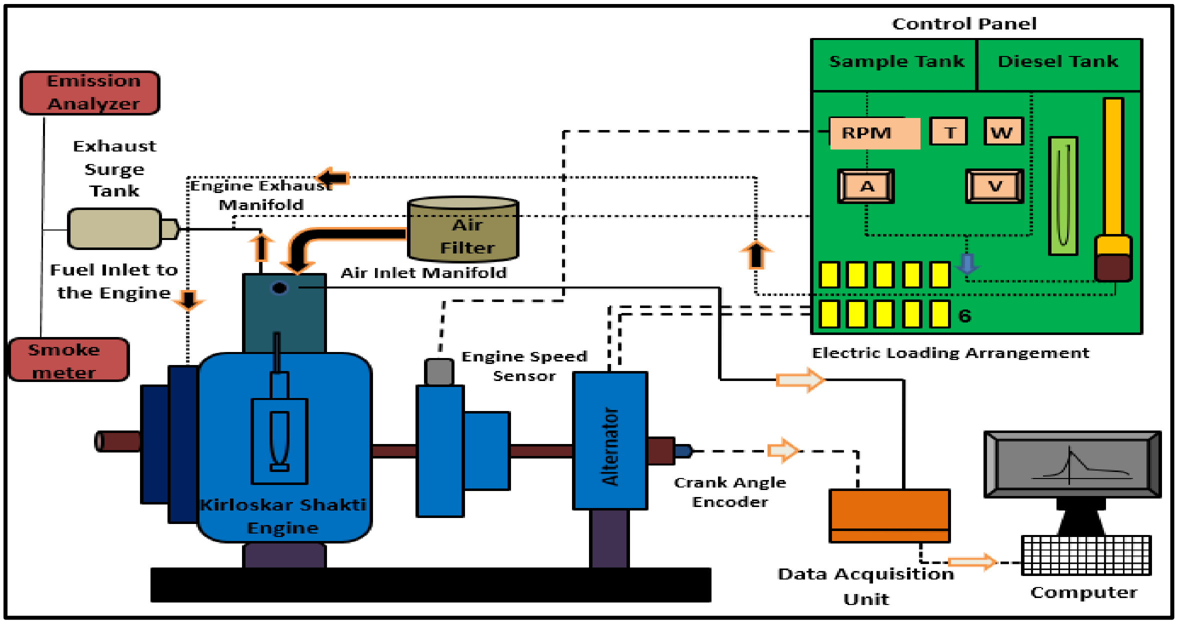

Figure 3.10: Engine Test Rig for Performance Parameters

Alternators are widely used to impose an electrical load on air-cooled engines during testing. In this study, an alternator functioning as AC generator was utilized, with its rated specifications being 230 volts, 21.7 amperes, and a speed of 1500 revolutions per minute. The engine test setup was interfaced with a personal computer to facilitate data acquisition during the experiments. The complete arrangement of the test rig and data monitoring system is illustrated in Plate 3.12.

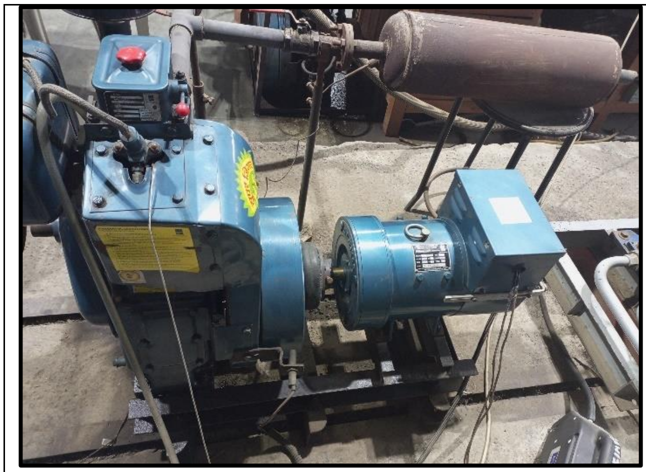	
Plate 3.11. Engine Test Setup	Plate 3.12. Personal Computer system

3.13.2 Selection of Engine Test Parameter

Some parameters must be observed during experimental trials, and some must be calculated by input conditions. These parameters are represented in Table 3.6.

Table 3.7. Observed and calculated parameters of the engine

Observed Parameter	**Calculated Parameter**
Engine load	Brake Power (BP)
Engine speed	BTE
Fuel consumption rate	BSEC
Temperature	BMEP
In-cylinder pressure	HRR, Heat release rate
Emissions C O , H C , N O x , Smoke opacity	

3.14 Assessment of Observed and Calculated Engine Test Parameters

3.14.1 Engine Load

Engine power output is directly influenced by the applied load, with the load generally acting as a resisting force against engine performance. Engines are typically designed to run at a specific speed corresponding to their rated or maximum load. For laboratory testing, especially under varying load conditions, a straightforward method for load estimation is essential. To assess engine power in such setups, dynamometers are commonly used. In this study, an air-cooled AC dynamometer was employed, which enables quick adjustments to the load, making it suitable for dynamic testing scenarios. The dynamometer unit consists of several key components, including a rotor, shaft, bearings, casing, and a base plate. The rotor is mounted on the shaft with the help of bearings to ensure smooth rotation. When a direct current flows through the stator windings, it creates a magnetic field across the air gaps on both sides of the rotor, allowing the rotor to turn within this magnetic field.

The dynamometer system also includes a load resistance unit and an AC generator to simulate different loading conditions. The control panel is equipped with an ammeter, voltmeter, and switch fuse carrier, which assists in monitoring and managing the electrical parameters during testing. This setup is integrated with the engine testing apparatus to measure the power absorbed under various loads. Plate 3.13 illustrates the electrical loading bulbs used in the testing process.

3.14.2 Engine Speed Measurement

Engine speed was measured using a magnetic pick-up RPM sensor placed near a toothed gear. As the gear rotated, each passing tooth generated an alternating voltage pulse, producing a signal sequence proportional to the rotational speed. An increase in gear speed resulted in a higher pulse frequency. These signals were digitized and sent to the data acquisition system, which processed them to determine the engine's revolutions per minute (RPM). The calculated RPM was then displayed on the control panel for real-time monitoring. The RPM sensor used in the setup is shown in Plate 3.14.

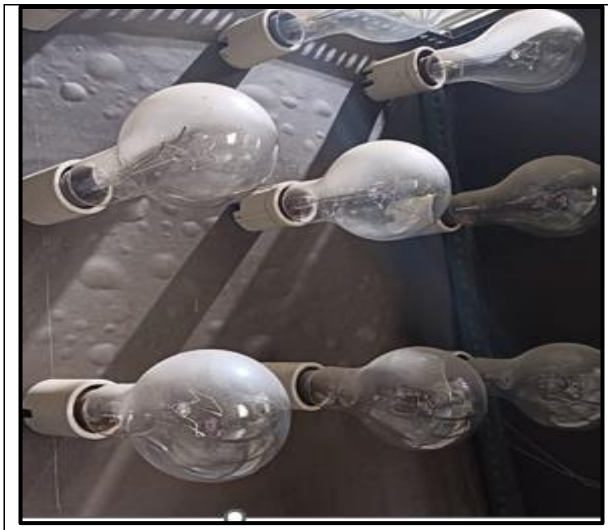	
Plate 3.13 Electric Loading Bulbs	**Plate 3.14 RPM Sensor**

3.14.3 Measurement of Fuel Consumption Rate

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

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

$$M_f\,(kg/s) = M_f\,(kg) / t\,(sec) \qquad [3.3]$$

$$M_f\,(kg/s) = (Ycc * \rho) / t$$

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

3.14.4 Measurement of Temperature

K-type thermocouples are widely used for temperature measurement in various applications, including thermal monitoring of diesel engines, as illustrated in Plate 3.15. They are well-suited for tracking temperatures of components such as exhaust gases, cylinder walls, and cooling systems due to their broad operating range of approximately -200°C to +1350°C, making them ideal for demanding engine environments. A major benefit of K-type thermocouples is their quick response time, enabling real-time temperature monitoring and control—crucial for maintaining engine efficiency and safety. The sensor operates by joining two dissimilar metal wires, typically nickel and aluminum, at a sensing junction. A temperature difference between this junction and the wire ends generates a voltage, which is proportional to the temperature and used to determine the thermal state at the junction.

Plate 3.15 K-Type Thermocouple

3.14.5 In-Cylinder Pressure Measurement

A piezoelectric pressure transducer, typically mounted on the cylinder head (Plate 3.16), is employed in diesel engines to measure in-cylinder pressure. It functions based on the piezoelectric effect, where pressure-induced mechanical stress generates an electrical charge. As the engine operates, the transducer converts combustion chamber pressure fluctuations into electrical signals, which are transmitted to a data acquisition system for real-time recording and analysis throughout the engine cycle. Its fast response and resilience to extreme temperatures and pressures make it ideal for monitoring dynamic pressure changes during combustion.

Plate 3.16. Piezoelectric Pressure Sensor

3.14.6 Exhaust Emissions Measurements

Exhaust emissions, including carbon monoxide (CO), carbon dioxide (CO_2), unburnt hydrocarbons (UBHC), and nitrogen oxides (NO_x), were analyzed using an AVL DITEST 1000 gas analyzer. Smoke opacity was measured with an AVL DISMOKE 480 BT smokemeter. Plate 3.17 shows both instruments along with their sampling probes, while technical specifications are detailed in Appendix II.

(i) **Operating Principle of AVL DITEST 1000 Gas Analyzer**

The AVL DITEST 1000 employs two main measurement principles. For CO, HC, and CO_2, it uses Non-Dispersive Infrared (NDIR) spectroscopy, which relies on the unique IR absorption characteristics of each gas. An IR beam passes through a sample cell containing exhaust gas and a reference cell with inert gas. By comparing the absorbed IR radiation, gas concentrations are determined. For oxygen (O_2) and nitrogen oxides (NO_x), the analyzer utilizes electrochemical sensors. In the case of NO_x, the gas diffuses through a permeable membrane into an electrolyte, where it undergoes oxidation at electrodes made of silver (Ag) and silver chloride (AgCl). The redox reaction generates a current proportional to the NO_x concentration, which is then amplified and recorded by the system.

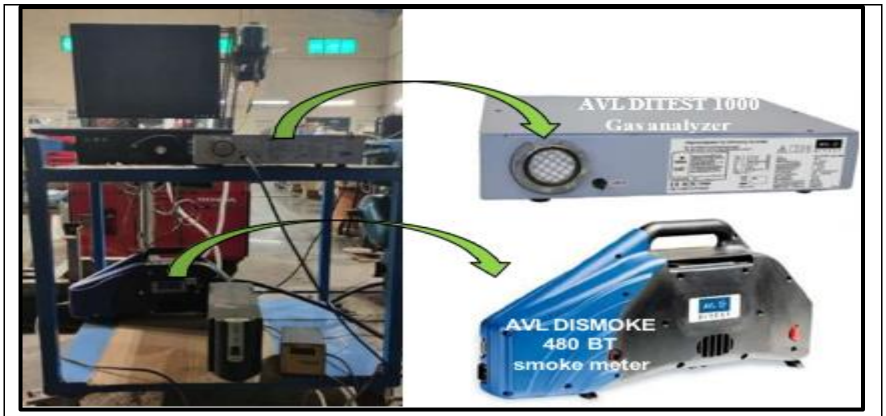

Plate 3.17. AVL Exhaust Gas Analyzer and Smoke Meter

ii. Operating Principle of AVL DISMOKE 480 BT Smoke Meter

The AVL DISMOKE 480 BT smoke meter functions on the principle of light absorption and scattering. A section of filter paper is exposed to a sample of engine exhaust gas, allowing soot and particulate matter to accumulate on the paper. After this sampling, a beam of light is directed at the darkened filter area. Soot particles absorb and scatter a portion of this light, and the amount of light scattered is detected by a photocell system. The photocell compares the transmitted light against a reference value using photoelectric detection. The resulting electrical signal—generated due to the photoelectric effect—correlates to the density of soot on the filter. This signal is then interpreted as the smoke opacity or soot concentration in the exhaust stream.

3.14.7 Brake Power

Brake power refers to the actual power output of an engine measured at the crankshaft or flywheel, excluding any mechanical losses due to components such as the gearbox, alternator, or other accessories [228]. It is the usable mechanical power that can be harnessed for external work, such as driving a vehicle or powering machinery. Brake power can be calculated by given below equation 3.4.

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

Where:

BP = Brake Power (W, kW, or hp)

π = Pi (approximately 3.14159)

N = Engine speed (revolutions per minute, RPM)

T = Torque (Newton-meters, Nm)

V = Voltage (Volts)

I = Current (Amperes)

η_9 = Generator efficiency (unitless)

3.14.8 Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) is a key parameter for assessing how effectively an internal combustion engine converts the chemical energy of the fuel into mechanical output at the crankshaft [229]. It reflects the ratio of useful work produced to the total energy input from the fuel. The BTE is calculated by given equation 3.5.

$$\text{BTE (\%)} = \text{BP (KW)} * 100 / M_f * CV \qquad [3.5]$$

M_f = Mass flow rate measured in kg/s

CV = Calorific value measured in kJ/kg

3.14.9 Brake-Specific Fuel Consumption

BSFC is an important performance metric that quantifies how much fuel is consumed to produce a unit of brake power. It is typically expressed in grams per kilowatt-hour (g/kWh) and is a direct indicator of an engine's fuel efficiency [211].

Brake-Specific Energy Consumption (BSEC) refers to the energy content of the fuel consumed per unit of power output and is given in equation 3.6:

$$\text{BSEC (MJ/kWh)} = [(M_f * CV) * 3600] / \text{BP (kW)} \qquad [3.6]$$

M_f = Mass flow rate calculated in kg/s

CV = Calorific value calculated in kJ/ kg

3.14.10 Brake Mean Effective Pressure

Brake Mean Effective Pressure (BMEP) represents the average pressure exerted on the piston during the power stroke. It serves as an indicator of how efficiently the engine converts combustion pressure into rotational work. The equation utilized for the computation of Brake Mean Effective Pressure is as follows in equation 3.7:

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

BP = Brake power measured in KW

L= Stroke length

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

L= Stoke length of stroke in mete

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

3.14.11 Heat Release Rate

The Heat Release Rate (HRR) in diesel engines represents the rate at which thermal energy is liberated during the combustion process. It quantifies the amount of heat generated within a defined time frame as fuel undergoes combustion inside the engine cylinders. HRR plays a vital role in analyzing combustion behavior, engine efficiency, and emission characteristics in compression ignition engines [179].

A widely adopted method for determining the HRR in diesel engines involves analyzing cylinder pressure data collected via in-cylinder pressure transducers. This pressure data is typically recorded throughout the combustion cycle. By evaluating the rate of change in cylinder pressure with respect to crank angle (dp/dθ), insights into the combustion dynamics can be derived.

The variation in pressure over different crank angles provides the basis for calculating HRR. The application of the first law of thermodynamics serves as the fundamental principle for determining the rate at which heat is released during the engine's operation.

According to the law

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

Where:

$Q(cyl+wall)$ = Combined engine cylinder heat release and heat exchange across the walls; U= Combust gases internal energy (J/kg)

W= System work done

The representation of the HRR is given by equation 3.9:

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

Where:

$dQ/d\theta$ = Net rate of HRR (J/°CA)
$dQw/d\theta$ = Heat transfer rate executed from wall (J/°CA)
γ = Specific heat ratio
P = pressure inside the cylinder (bar)
V = Volume of the gases (m^3)
θ = Crank angle (°)

3.15 Engine Trials Methodology

The engine testing procedure was carefully structured to ensure accurate and consistent data collection for evaluating the performance, combustion behavior, and emissions of different fuel blends. The process began with a thorough inspection and calibration of the engine test rig and all related equipment to confirm proper functionality. Initial checks were carried out to verify sufficient fuel levels and eliminate air from the fuel lines. The engine was first operated on pure diesel under no-load conditions for 20 to 30 minutes. This warm-up period allowed the engine to reach a stable thermal condition and ensured uniform exhaust temperatures across various load levels. Once thermal equilibrium was achieved, the data acquisition system (DAS) was activated. Inputs from pressure sensors and other transducers were recorded, with in-cylinder pressure data captured over 60 consecutive combustion cycles to support combustion analysis. Simultaneously, exhaust emissions—including carbon monoxide (CO), unburnt hydrocarbons (UBHC), nitrogen oxides (NO_x), and other pollutants—were measured using gas analyzers. Engine trials were conducted at a constant power output of 3.5 kW and a fixed speed of 1500 rpm, in accordance with manufacturer calibration and IS:10000 standards. Data was collected at 20% load increments, ranging from no load to full load. Before testing each fuel blend, key engine parameters were rechecked to ensure uniformity. To improve result reliability, each test was repeated multiple times. Baseline tests were performed using pure diesel from a dedicated tank. After these initial runs, fuel supply was switched to biodiesel blends using a rotary valve. In all cases, the engine was started on diesel and operated for at least 20 to 30 minutes before transitioning to biodiesel to ensure consistency across trials.

3.16 Accuracies and Uncertainties of Measurements

The systematic assessment of potential errors in physical measurements is referred to as uncertainty analysis. In this study, the Holman method was employed to evaluate the uncertainties arising from various sources such as human error, inaccurate data recording, outdated instrument calibration, and fluctuating environmental conditions during testing. The accuracy of each measuring instrument and the corresponding uncertainty values are summarized in Table 4. Based on the uncertainty analysis conducted, the total experimental uncertainty was determined to be 2.96%. The method used to calculate this combined uncertainty is outlined below.

$$= \left[(\text{Uncertainty of BMEP})^2 + (\text{Uncertainty of BTE})^2 + (\text{Uncertainty of BSEC})^2 + (\text{Uncertainty of HC})^2 + (\text{Uncertainty of CO})^2 + (\text{Uncertainty of NOx})^2 + (\text{Uncertainty of Smoke})^2 + (\text{Uncertainty of Pressure transducer})^2 + (\text{Uncertainty of Crank Angle encoder})^2 + (\text{Uncertainty of Speed sensor})^2 + (\text{Uncertainty of burette})^2 + (\text{Uncertainty of stopwatch})^2 + (\text{Uncertainty of EGT})^2\right]^{(1/2)}$$

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides a structured overview of the experimental results, beginning with a comparative analysis of Bharat Stage IV (BS IV) and Bharat Stage VI (BS VI) diesel fuels using an unmodified compression ignition engine. The study identifies key issues associated with BS VI diesel, particularly those arising from the desulfurization process, such as reduced lubricity, lower combustion efficiency, and poorer emission performance.

To address these limitations, a novel multifunctional additive was formulated and tested with two fuel types: standard BS VI diesel and biodiesel–diesel blends in line with the National Biofuel Policy. The additive was designed to target specific performance deficiencies and comprised surfactants, cetane improvers, lubricity enhancers, antioxidants, and combustion catalysts.

Both untreated and treated fuels were analyzed for physicochemical properties, including density, viscosity, flash point, calorific value, and cetane number. Lubricity was assessed using a High-Frequency Reciprocating Rig (HFRR) by measuring the Wear Scar Diameter (WSD) at different additive concentrations.

Performance evaluation was carried out on a single-cylinder, four-stroke diesel engine, focusing on Brake Thermal Efficiency (BTE), Brake Specific Energy Consumption (BSEC), and Exhaust Gas Temperature (EGT). Emission measurements included nitrogen oxides (NO_x), carbon monoxide (CO), unburnt hydrocarbons (HC), and smoke opacity.

Combustion characteristics were analyzed using in-cylinder pressure data to generate Pressure–Crank Angle (P–θ) diagrams and Heat Release Rate (HRR) curves. The combined findings, presented through graphs and tables, demonstrate that the multifunctional additive effectively improves fuel quality, enhances engine performance, and reduces emissions in both BS VI diesel and biodiesel–diesel blends, all without requiring engine modifications.

4.2 GC-MS Analysis of Waste Oil Cooking Biodiesel

Gas chromatography-mass spectrometry (GC-MS) is employed to analyze the individual components of essential oils or biodiesel samples, providing both identification and quantitative composition data for each compound. This technique integrates the separation capabilities of gas chromatography with the detection specificity of mass spectrometry, enabling precise characterization of complex mixtures such as fatty acid profiles. Fatty acids (FAs) are categorized into two primary groups based on their chemical structure: saturated fatty acids (SFAs), which contain no double bonds, and unsaturated fatty acids (UFAs), which feature one or more double bonds. UFAs are further subdivided into:

- Monounsaturated fatty acids (MUFAs): One double bond.
- Polyunsaturated fatty acids (PUFAs): Two to six double bonds.

The spatial arrangement of double bonds distinguishes cis and trans isomers, while PUFAs are classified as n-3 or n-6 based on the position of the first double bond relative to the methyl end of the molecule [213].

Figure 4.1 displays the GC-MS chromatographic profile of WCB, while Table 4.1 summarizes its compositional breakdown, listing saturated and unsaturated compounds with their respective percentage areas (28.33% saturated vs. 71.67% unsaturated fatty acids). The elevated unsaturated fatty acid (UFA) content in biodiesel directly correlates with increased oxidative degradation potential due to double-bond reactivity [230]. Biodiesel formulations with greater unsaturation demonstrate heightened vulnerability to autoxidation during storage, as double bonds readily interact with atmospheric oxygen to form peroxides, hydroperoxides, and secondary oxidation products [231][230]. These reactive compounds degrade fuel quality by altering viscosity, accelerating sediment formation, and causing undesirable changes in color and chemical purity [230].

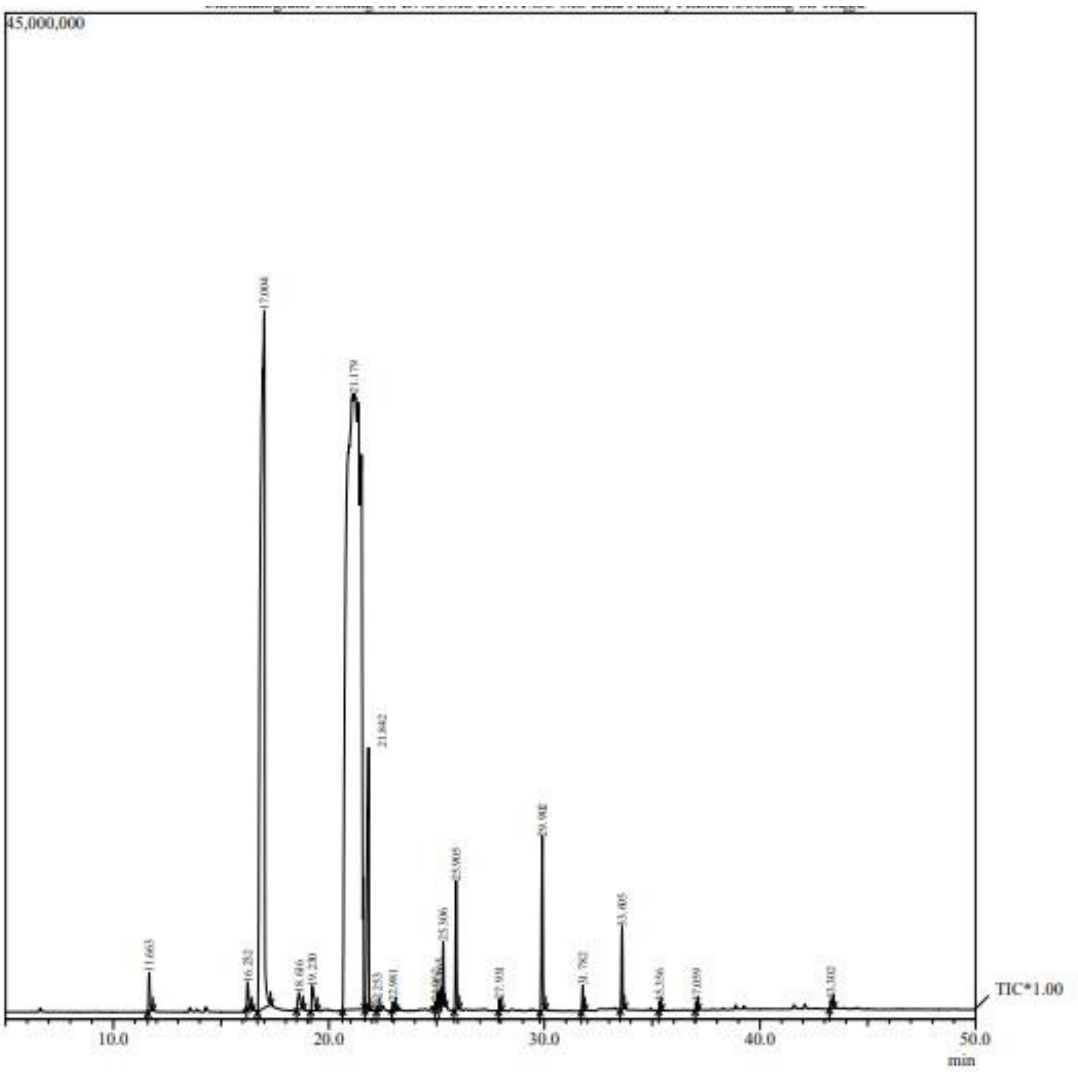

Figure 4.1: Represents a Gas-Chromatograph of Waste Cooking Oil Biodiesel

Table 4.1: List of saturated and unsaturated compounds present in WCB

Constituents type	Type	Chemical Formula	Amount (% area)
Docosanoic acid, methyl ester	Saturated	$C_{23}H_{46}O_2$	1.63
Tricosanoic acid, methyl ester	Saturated	$C_{24}H_{48}O_2$	0.22
9,12-Octadecadienoic chloride, (Z, Z)-	Unsaturated	$C_{18}H_{32}O_2$	0.04
Hexacosanoic acid, methyl ester	Saturated	$C_{27}H_{54}O_2$	0.07
Pentacosanoic acid, methyl ester	Saturated	$C_{26}H_{52}O_2$	0.07
Hexadecatrienoic acid, methyl ester	Saturated	$C_{17}H_{28}O_2$	0.03
Tetracosanoic acid, methyl ester	Saturated	$C_{25}H_{50}O_2$	0.74
9,12-Octadecadienoic acid, methyl ester	Unsaturated	$C_{19}H_{34}O_2$	0.09
Methyl Tetradecanoate	Saturated	$C_{15}H_{30}O_2$	0.41
9,11-Octadecadienoic acid, methyl ester, (E, E)-	Unsaturated	$C_{19}H_{34}O_2$	0.07
Eicosanoic acid, methyl ester	saturated	$C_{21}H_{42}O_2$	1.17
(Z)-Methyl heptadec-9-enoate	Saturated	$C_{18}H_{34}O_2$	0.35
Hexadecanoic acid, methyl ester	saturated	$C_{16}H_{32}O_2$	22.1
gamma-Sitosterol	Saturated	$C_{29}H_{52}O_2$	0.11
Heneicosanoic acid, methyl ester	Saturated	$C_{22}H_{44}O_2$	0.1
Heptadecanoic acid, methyl ester	Saturated	$C_{19}H_{38}O_2$	0.48
9-Hexadecenoic acid, mthyl ester, (Z)-	Saturated	$C_{16}H_{30}O_2$	0.35
Cis-Methyl 11-eicosenoate	Saturated	$C_{21}H_{40}O_2$	0.5
Methyl stearate	Unsaturated	$C_{19}H_{38}O_2$	3.72
9,12-Octadecadienoic acid, methyl ester	Unsaturated	$C_{19}H_{34}O_2$	67.72
Unsaturated fatty acid			**71.67**
Saturated fatty acid			**28.33**

4.3 Phase Stability Analysis of Prepared Blends

Phase stability assessment of fuel blends is critical for ensuring reliable performance in engine applications, particularly when testing formulations with varying compositions. The experimental protocol first established optimal surfactant concentrations for additive compatibility across temperature thresholds (10°C, 25°C, 40°C) through systematic measurements. Subsequent phase stability verification employed long-term visual monitoring under controlled storage conditions simulating real-world scenarios. Samples underwent six-month observational studies at three temperature setpoints selected to reflect typical Indian climatic variations.

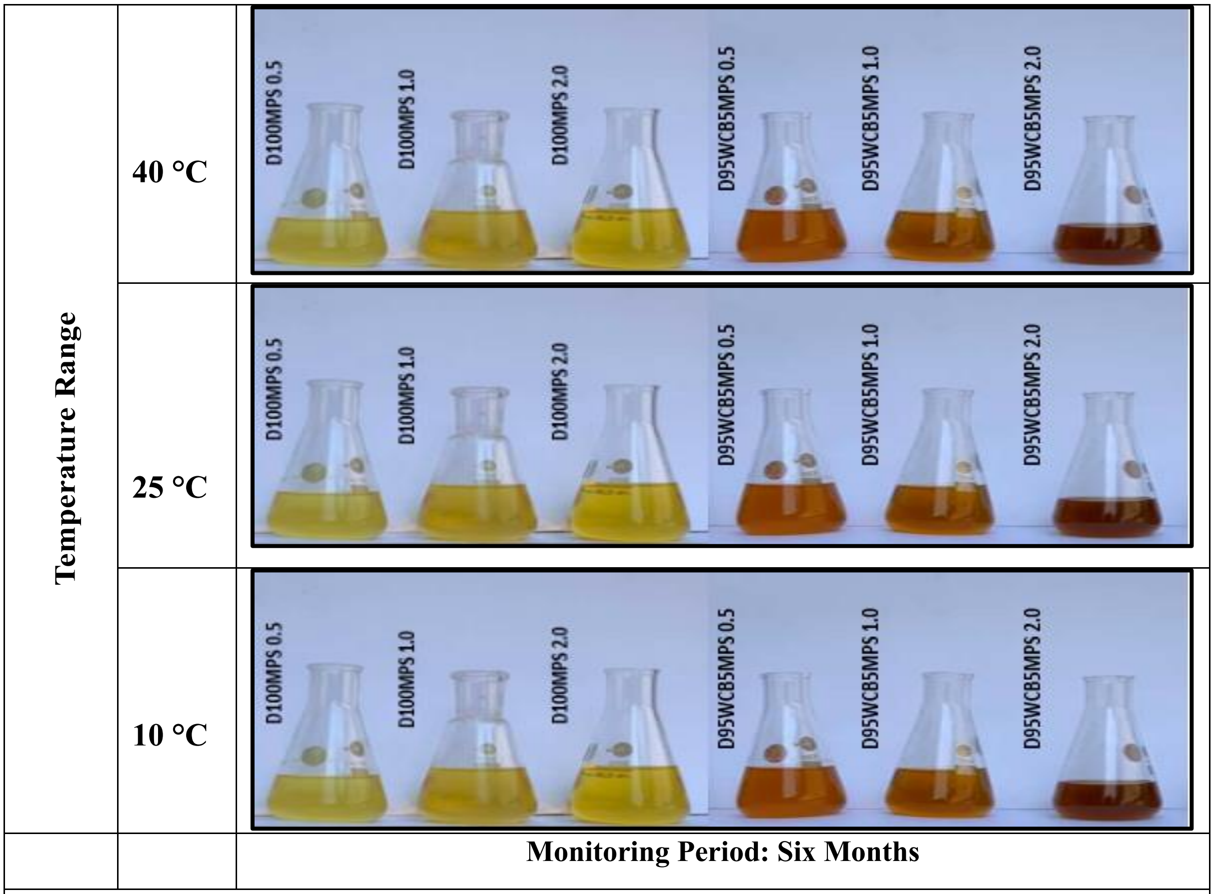

Plate 4.1. Visual Inspection of Prepared Samples at Different Temperature Ranges

Maintained undisturbed in clinical chambers, the fuel blends were visually inspected and photographically documented at bimonthly intervals to track phase separation dynamics. This dual-axis evaluation (temporal + thermal) revealed temperature-dependent stability patterns through comparative image analysis. Plate 4.1 chronologically illustrates sample conditions, providing empirical evidence of phase behavior under accelerated storage simulations.

4.4 Physio-Chemical Characteristics of Biodiesel and their Blends

Fuel quality and performance assessment fundamentally relies on comprehensive physicochemical property analysis. As detailed in Section 3, specialized equipment was utilized to measure these characteristics following ASTM D standard protocols to maintain methodological rigor and accuracy [232]. The chemical property estimations specifically adhered to ASTM D testing frameworks. This section systematically examines key fuel parameters across all tested formulations. Table 4.2 catalogs physicochemical properties of test fuel blends with Bharat Stage VI Diesel with Multi-Purpose Solution, while Table 4.3 documents test fuel blends with Diesel-Biodiesel Blend (D95WCB5) with Multi-Purpose Solution. Both tables present critical performance metrics including viscosity, cetane Index, sulfur content, and flash point measured under standardized conditions.

Table 4.2: Physiochemical characteristics test fuel blends with Bharat Stage VI Diesel with Multi-Purpose Solution

Fuel Properties	**Kinematic Viscosity (cSt)@40 °C**	**Density @15 °C (Kg/m3)**	**Lower Heating Value (MJ/kg)**	**Flash Point (°C)**	**Cetane Index**	**Sulfur Content (ppm)**
Diesel (D100)/BSIV	2.56	834.62	46.272	66	46	40.39
Diesel (D100)/BSVI	2.47	832.37	43.198	63.8	51.5	3.45
D100MPS0.5	2.468	826.52	37.62	63.3	52.2	3.41
D100MPS1.0	2.462	821.36	36.89	62.9	52.5	3.43
D100MPS2.0	2.455	819.24	35.41	62.5	52.8	3.46

Table 4.3: Physiochemical characteristics of test fuel blends with Diesel-Biodiesel Blend (D95WCB5) with Multi-Purpose Solution

Fuel Properties	Kinematic Viscosity (cSt)@40 °C	Density @15 °C (Kg/m3)	Lower Heating Value (MJ/kg)	Flash Point (°C)	Cetane Index	Sulfur Content (ppm)
Diesel (D100)/BSVI	2.47	832.37	43.198	63.8	51.5	3.45
Waste Cooking Oil Biodiesel (WCB)	5.97	879.82	39.083	129	62.7	6.3
D95WCB5	3.389	852.29	42.78	66	54.6	3.76
D95WCB5MPS0.5	3.375	847.63	39.36	65.7	55.2	3.79
D95WCB5MPS1.0	3.367	841.27	38.65	64.8	55.5	3.74
D95WCB5MPS2.0	3.355	835.21	37.72	64.1	56	3.77

4.4.1 Variation in Kinematic Viscosity for Prepared Samples

Viscosity is a critical fuel property that significantly influences the spray characteristics such as droplet size and air-fuel mixing during injection. Elevated viscosity can hinder proper atomization, resulting in larger fuel droplets, incomplete combustion, increased fuel consumption, reduced efficiency, and higher levels of soot and deposit formation within the engine. According to ASTM D6751 and EN 14214 standards, the acceptable viscosity range for diesel-like fuels is 2–6 cSt at 40 °C.

The addition of MPS to neat diesel (BS VI) results in a slight decrement in kinematic viscosity, as observed across various concentration levels. The measured kinematic viscosity of D100 (BS IV) is 2.56 cSt at 40 °C, while D100 (BS VI) shows a reduced value of 2.47 cSt, likely due to changes in refining processes such as increased desulfurization. Upon blending MPS with D100 (BS VI), a gradual reduction in viscosity is noted: D100MPS 0.5 records a viscosity of 2.468 cSt, D100MPS 1.0 shows 2.462 cSt, and D100MPS 2.0 records 2.455 cSt.

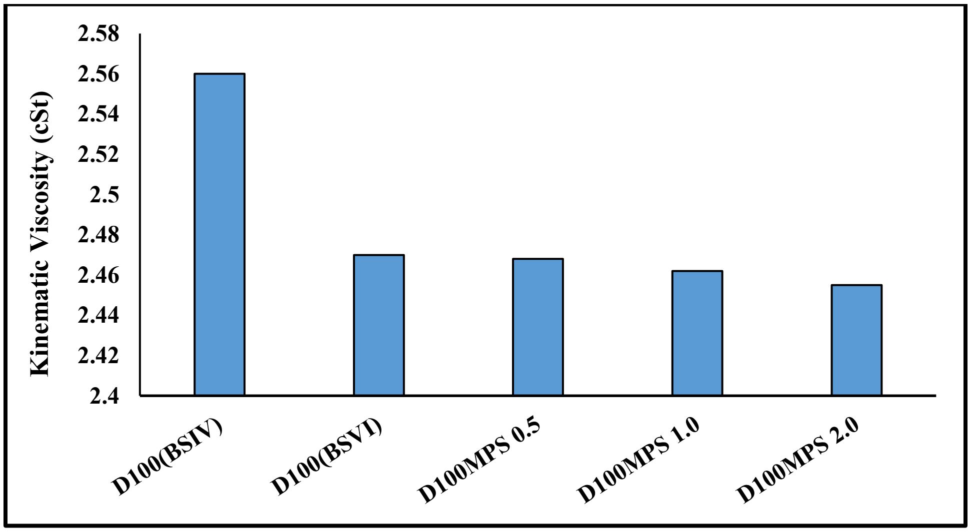

Figure 4.2: Kinematic viscosity variation for Diesel

This slight decrease in viscosity can be attributed to the chemical nature of MPS, shown in Figure 4.2. The additive likely contains low-molecular-weight hydrocarbons or solvent-like compounds with inherently lower viscosities. When mixed with diesel, these components reduce the overall molecular interaction forces within the fuel, thereby enhancing fluidity. MPS may also interfere with the cohesive van der Waals forces among diesel molecules, resulting in a lower resistance to flow.

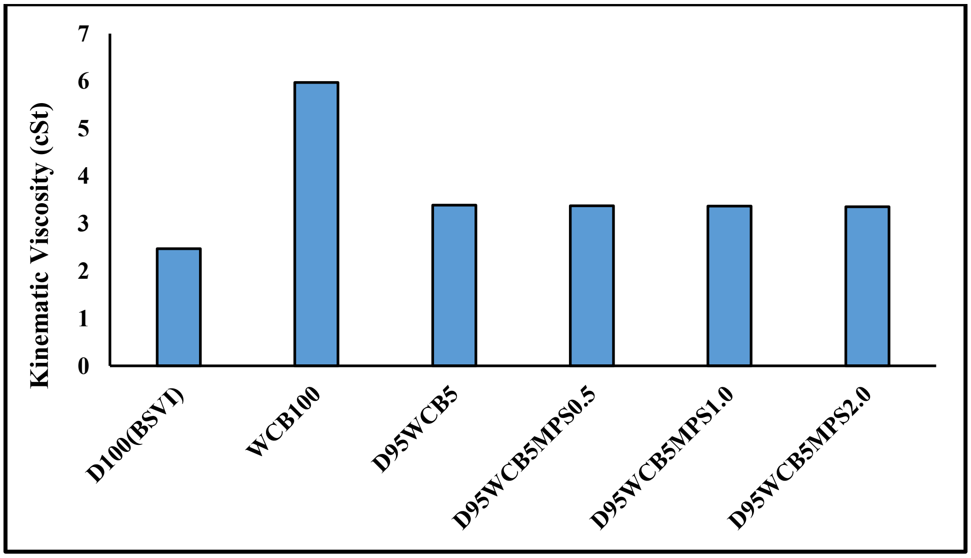

Figure 4.3. Kinematic viscosity variation for Diesel-Biodiesel Blend (D95WCB5)

Biodiesel generally increases the viscosity of diesel due to the presence of long-chain fatty acid methyl esters. However, MPS likely contains lighter, solvent-like compounds that dilute the heavier biodiesel molecules and disrupt intermolecular interactions, resulting in reduced internal friction and improved fluidity.

4.4.2 Variation in Density for Prepared Samples

Density becomes a critical parameter, particularly when blending two or more fuels to form a homogeneous and stable mixture. To ensure compatibility and proper mixing, the density difference between the fuels should be minimal. Moreover, density significantly influences the combustion process. According to diesel fuel standards ASTM D6751 and EN 14214, the density of any fuel intended for blending with diesel should fall within the range of 0.820 to 0.900 g/cc. Deviations from this range can lead to inadequate fuel atomization, resulting in inadequate combustion and increased carbon deposits within the engine cylinder.

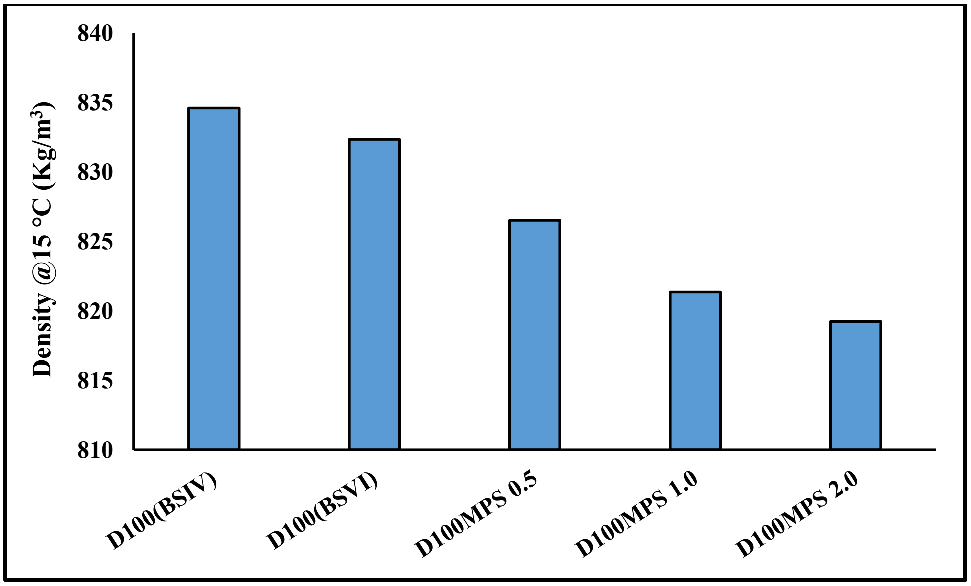

Figure 4.4 Density variation for Diesel

The addition of MPS to neat diesel (BS VI) results in a consistent decrease in fuel density with increasing concentration levels of the additive. The density of D100 (BS IV) is 834.62 kg/m³, while that of D100 (BS VI) is slightly lower at 832.37 kg/m³, due to stricter refining processes such as desulfurization. Upon blending MPS, the density drops further: 826.52 kg/m³ for D100MPS 0.5, 821.36 kg/m³ for D100MPS 1.0, and 819.24 kg/m³ for D100MPS 2.0. This decrement is attributed to the intrinsic physical properties of MPS, which likely contain low-density hydrocarbon compounds or oxygenated solvents. These components, when blended with diesel, dilute the heavier hydrocarbon chains present in diesel fuel, leading to a net reduction in bulk density.

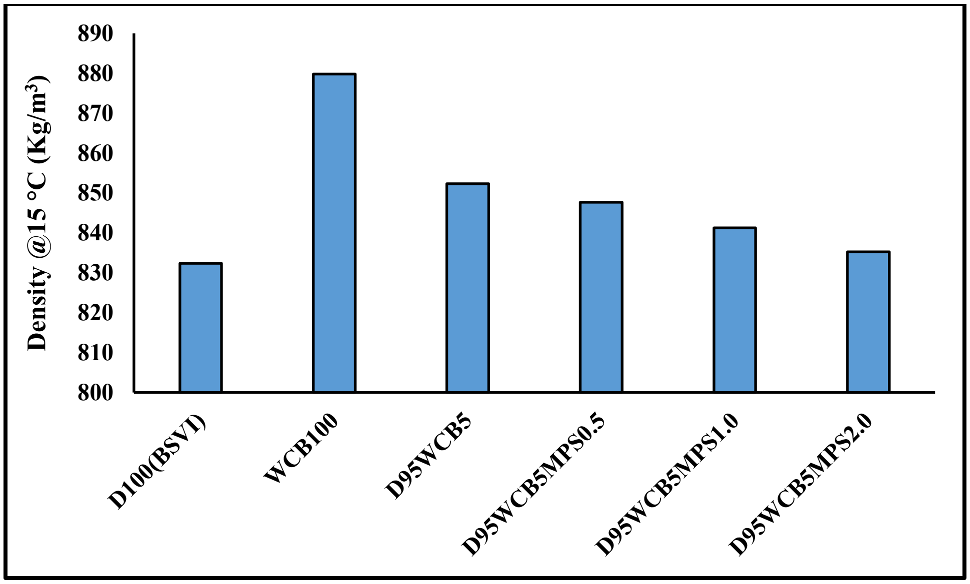

Figure 4.5. Density variation for Diesel-Biodiesel Blend (D95WCB5)

For diesel–biodiesel blend (D95WCB5) leads to a noticeable decrease in density as the concentration of the additive increases from 0.5 to 2.0 mL. The base blend D95WCB5, which contains 5% waste cooking biodiesel (WCB), has a density of 852.29 kg/m³. With the addition of MPS, the density reduces to 847.63 kg/m³ at 0.5 mL, 841.27 kg/m³ at 1.0 mL, and 835.21 kg/m³ at 2.0 mL. This reduction is primarily due to the low-density nature of MPS, which contains lighter hydrocarbon or oxygenated compounds.

4.4.3 Variation in Calorific Value for Prepared Samples

The calorific value, also known as the lower heating value (LHV), indicates the energy content of a fuel. As per EN 14213, the LHV should not fall below 35,000 kJ/kg to ensure efficient engine operation. Higher LHV generally leads to better brake thermal efficiency and reduced fuel consumption. Biodiesel, however, typically has a lower LHV than conventional diesel due to its higher oxygen content, resulting in less energy released per unit volume during combustion.

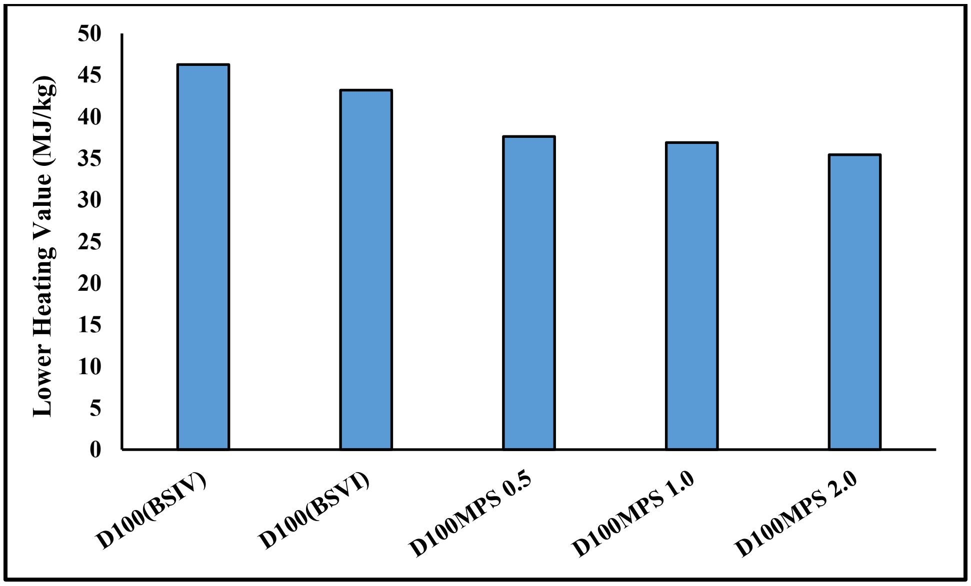

Figure 4.6 Calorific value variation for Diesel

In this study, adding the multipurpose solution (MPS) to pure BS VI diesel (D100) led to a gradual reduction in LHV with increasing additive concentration. The LHV of base diesel was 43.198 MJ/kg, which decreased to 37.62 MJ/kg at 0.5 mL, 36.89 MJ/kg at 1.0 mL, and 35.41 MJ/kg at 2.0 mL of MPS. This decline is attributed to the lower energy content of MPS compared to diesel, likely due to the presence of oxygenated or light hydrocarbon compounds. While these compounds can enhance combustion properties, they contribute less energy per unit mass. Moreover, the oxygen content in the additive may promote partial oxidation during combustion, further reducing the heat release.

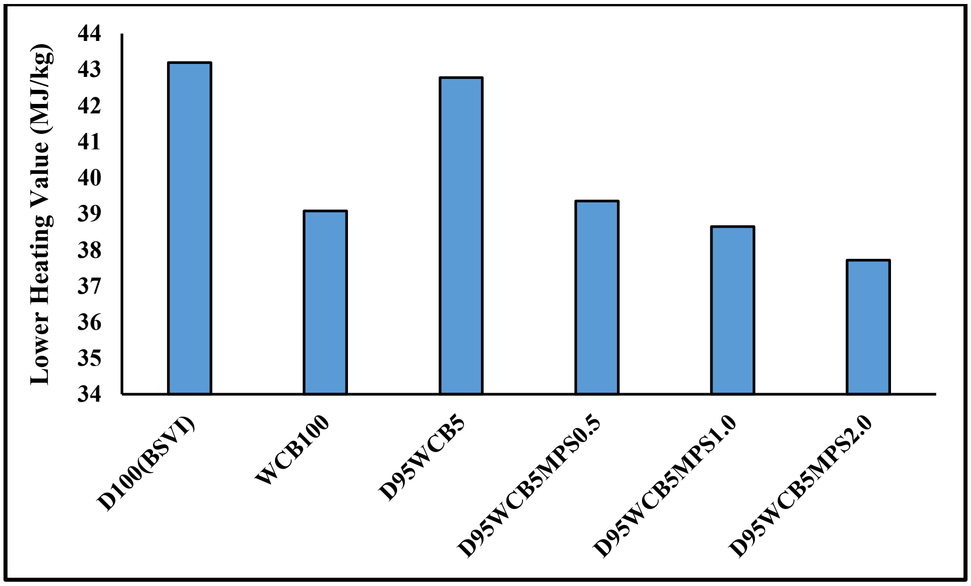

Figure 4.7 Calorific value variation for Diesel-Biodiesel Blend (D95WCB5)

4.4.4 Variation in Cetane Index for Prepared Samples

The cetane index reflects fuel's ignition quality, indicating how easily it ignites after injection into the combustion chamber. A higher cetane index corresponds to a shorter ignition delay. It typically increases with longer carbon chains but decreases with a higher number of carbon–carbon double bonds.

The increase in cetane index observed when MPS is added to neat diesel (D100) at concentrations of 0.5, 1.0, and 2.0 mL/L can be attributed to the cetane-enhancing properties of the additive. MPS likely contains oxygenated or nitrate-based compounds that are known to promote shorter ignition delay and improve combustion quality, which directly increases the cetane index. As the concentration of MPS increases, more ignition-promoting molecules are present in the fuel, leading to a progressive rise in the cetane index from 51.5 (BSVI diesel) to 52.8 at 2.0 mL/L additive level. This enhancement improves engine startability, reduces knock, and leads to smoother combustion.

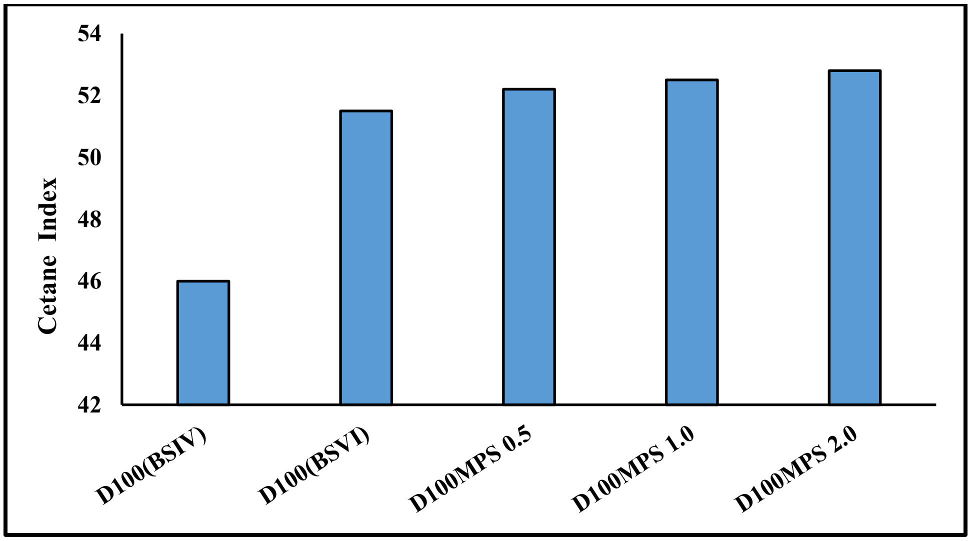

Figure 4.8 Cetane Index variation for Diesel

The increase in cetane index observed when MPS is added to a diesel–biodiesel blend (D95WCB5) at concentrations of 0.5, 1.0, and 2.0 mL/L is due to the cetane-boosting effect of the additive. MPS likely contains ignition-promoting compounds that shorten ignition delay and improve combustion quality. As concentration increases, these effects become more prominent, raising the cetane index from 54.6 (base blend) to 56 at the highest additive level. This improvement enhances engine performance, particularly in cold starts and underload, and supports more complete combustion with reduced knocking.

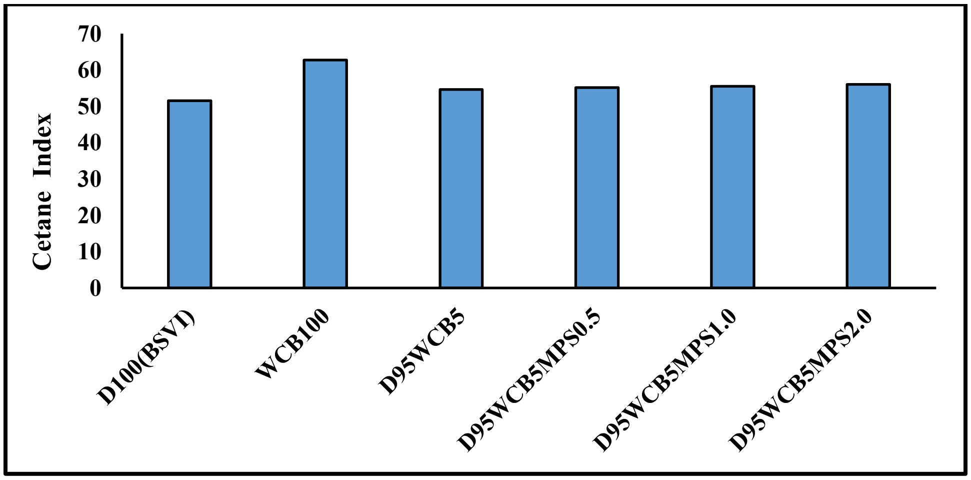

Figure 4.9 Cetane Index variation for Diesel-Biodiesel Blend (D95WCB5)

4.4.5 Variation in Flash Point for Prepared Samples

The flash point is a key parameter for ensuring the safe handling and storage of fuels, as it indicates the temperature at which fuel vapors can ignite. It is inversely related to volatility—more volatile fuels have lower flash points. As per ASTM specifications, biodiesel (ASTM D6751) should have a flash point between 100°C and 185°C, while diesel (ASTM D975) typically ranges from 55°C to 66°C

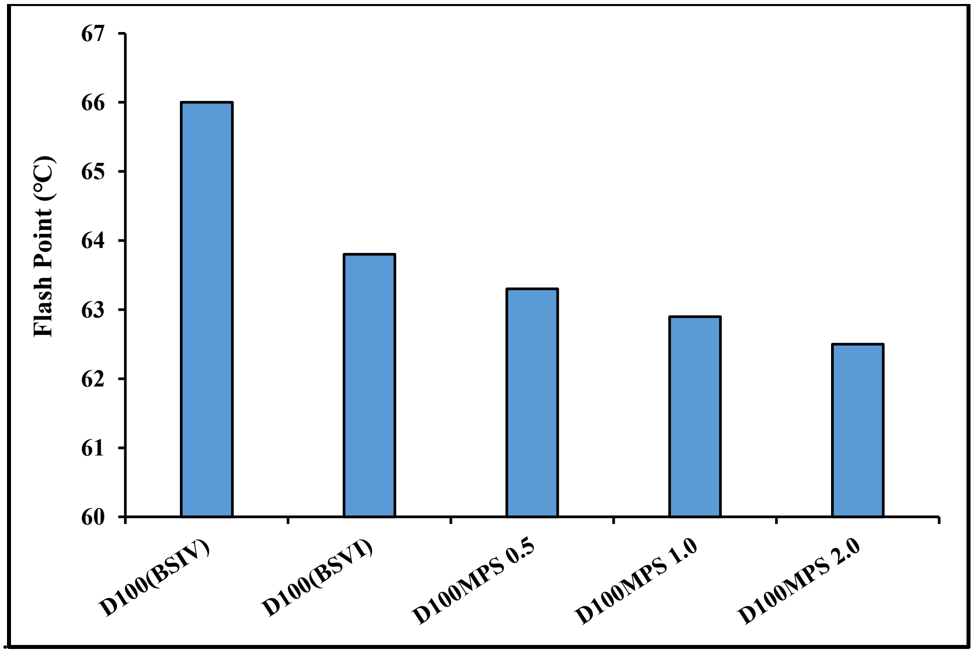

Figure 4.10 Flash Point variation for Diesel

The slight decrease in flash point observed with the adding of MPS to diesel fuel at concentrations of 0.5, 1.0, and 2.0 mL/L can be attributed to the presence of more volatile and lighter components in the additive. MPS likely contains compounds with lower boiling points, which increases the vapor pressure of the fuel blend. As a result, the mixture becomes slightly more flammable at lower temperatures. However, this change remains within the acceptable ASTM D975 range for diesel fuel safety.

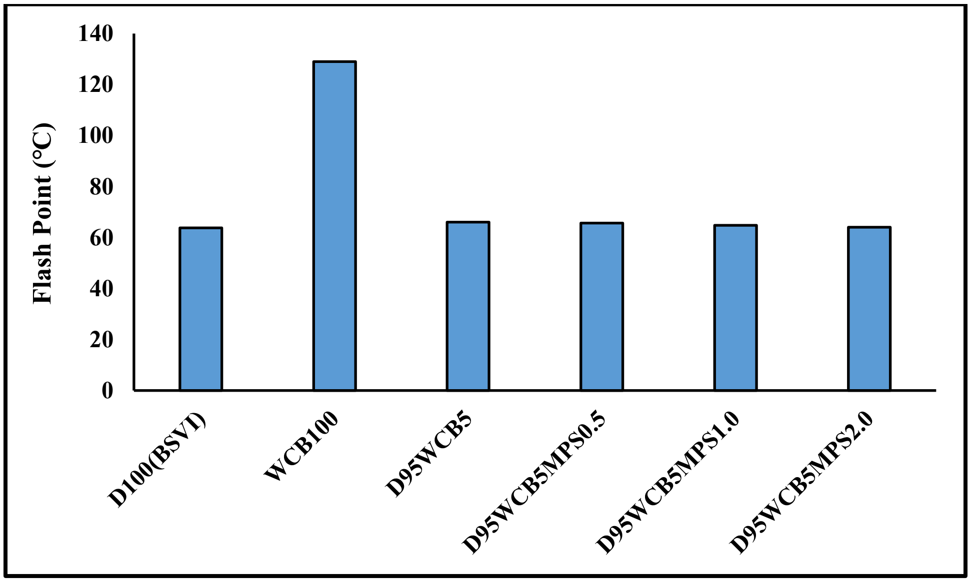

Figure 4.11 Flash Point variation for Diesel-Biodiesel Blend (D95WCB5)

The slight decrease in flash point observed with the addition of MPS to the D95WCB5 at concentrations of 0.5, 1.0, and 2.0 mL/L is due to the presence of light, volatile compounds in the additive. MPS likely contains low-boiling organic components that increase the volatility of the overall blend.

4.5 Tribological Characteristics

4.5.1 Evaluation of Tribological Characteristics for Bharat Stage IV and Bharat Stage VI

A comparative tribological study was conducted on Bharat Stage IV (BS-IV) and Bharat Stage VI (BS-VI) commercial diesel fuels using a High-Frequency Reciprocating Rig (HFRR) to assess their friction and wear characteristics under boundary lubrication conditions. Wear performance was measured by the Mean Wear Scar Diameter (MWSD). BS-IV diesel exhibited a lower MWSD of 196 µm, while BS-VI diesel showed a larger scar of 345 µm, indicating higher wear potential. This increase in wear scar size for BS-VI diesel suggests reduced boundary lubrication, which could lead to faster wear of critical engine components like injectors and high-pressure pumps.

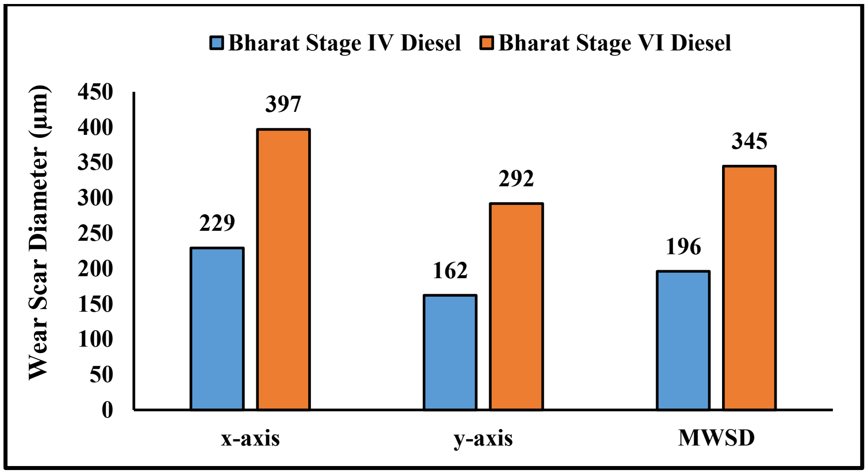

Figure 4.12. Wear Scar Diameter for BS IV and BS VI Diesel

Figure 4.13. Wear Scar Image for BS IV

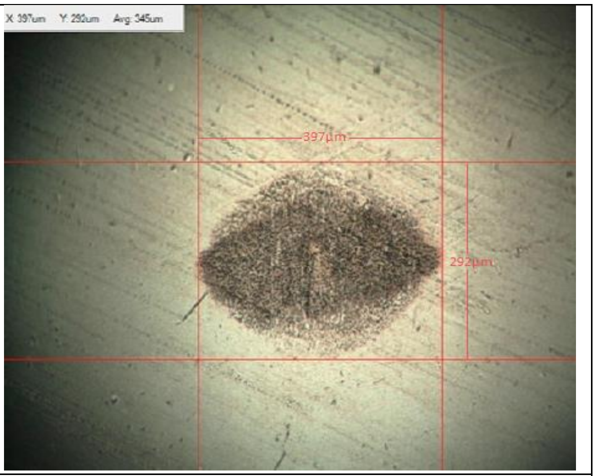

Figure 4.14. Wear Scar Image for BS VI

The frictional performance was assessed based on measured frictional force and coefficient of friction (COF). BS-IV diesel exhibited superior lubricity, with a frictional force of 0.03378 N and a COF of 0.01723, compared to 0.06624 N and 0.03375 for BS-VI diesel. The enhanced performance of BS-IV fuel is primarily due to its higher sulfur content (~50 ppm), which promotes the formation of boundary films that reduce metal-to-metal contact. In contrast, BS-VI diesel, containing less than 10 ppm sulfur to meet stringent emission standards, showed higher friction despite the presence of lubricity additives. This suggests limited effectiveness of additives in replicating the natural lubricity provided by sulfur compounds, especially in engines not optimized for ultra-low sulfur diesel.

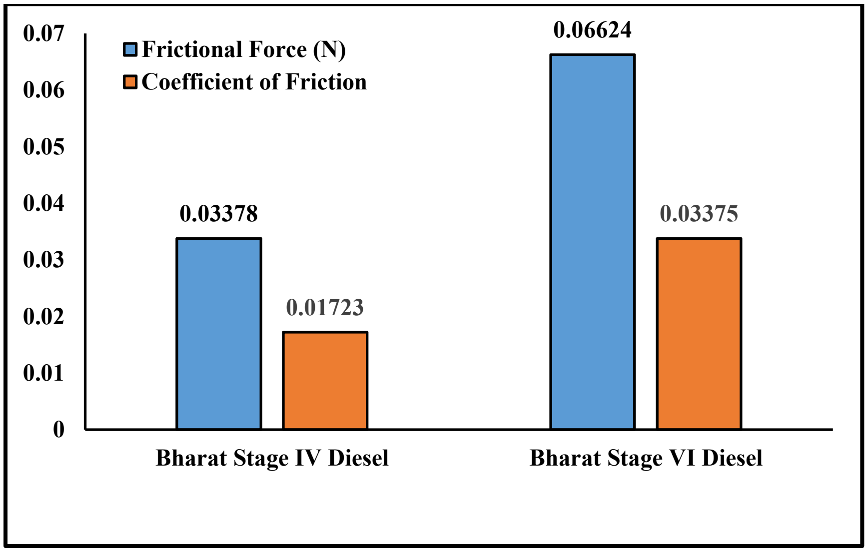

Figure 4.15. Friction Attributes for BS IV and BS VI Diesel

BS-IV diesel demonstrates better tribological performance than BS-VI diesel in terms of both friction reduction and wear resistance. While BS-VI diesel supports cleaner emissions, its lower inherent lubricity may pose durability concerns in legacy engines not designed for ultra-low sulfur fuels.

4.5.2 Effect of Sulfur Doping on Tribological Parameters of Bharat Stage VI Diesel

A tribological evaluation was conducted to assess the effect of sulfur doping in Bharat Stage VI (BS6) diesel using dibutyl sulfide as a doping agent, with the HFRR method employed to analyze frictional and wear behavior. Compared to Bharat Stage IV (BS4) diesel, which has approximately 50 ppm sulfur, BS6 diesel showed significantly inferior lubricity characteristics. BS4 diesel exhibited a low frictional force of 0.03378 N and a coefficient of friction (CoF) of 0.01723, while BS6 diesel recorded substantially higher values of 0.06624 N and 0.03375 respectively, indicating nearly double the friction under identical test conditions [233].

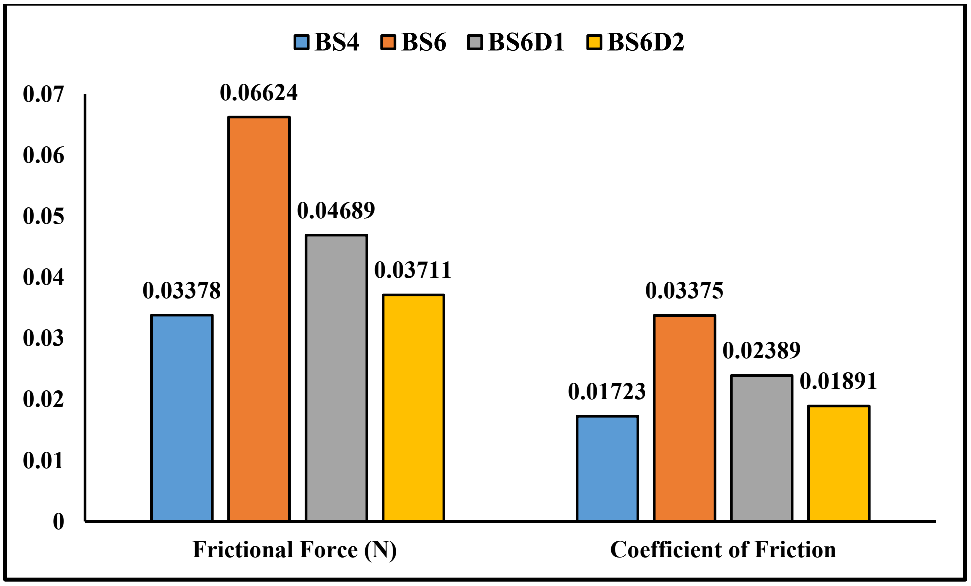

Figure 4.16. Effect of Sulfur doping on Friction Attributes of BS VI Diesel

This is attributed to the loss of natural lubricity from sulfur compounds, which typically form protective boundary films that reduce metal-to-metal contact. With sulfur doping, the tribological performance of BS6 improved significantly. BS6D1 (moderate doping) reduced the frictional force to 0.04689 N and CoF to 0.02389, while BS6D2 (higher doping) brought the values down further to 0.03711 N and 0.01891—close to BS4 levels. These reductions confirm that sulfur additives like dibutyl sulfide restore boundary lubrication, enhancing fuel-film formation and decreasing shear resistance.

The wear scar analysis also reinforced these findings. BS4 diesel showed a Mean Wear Scar Diameter (MWSD) of 196 µm, indicating minimal wear due to effective surface protection. In contrast, BS6 diesel exhibited a MWSD of 345 µm—an increase of over 75%—highlighting the adverse impact of ultra-low sulfur content on wear resistance. Upon doping, the wear performance of BS6 improved markedly: BS6D1 showed a MWSD of 253 µm, and BS6D2 recorded 231 µm, reflecting 27% and 33% reductions in wear compared to BS6, respectively.

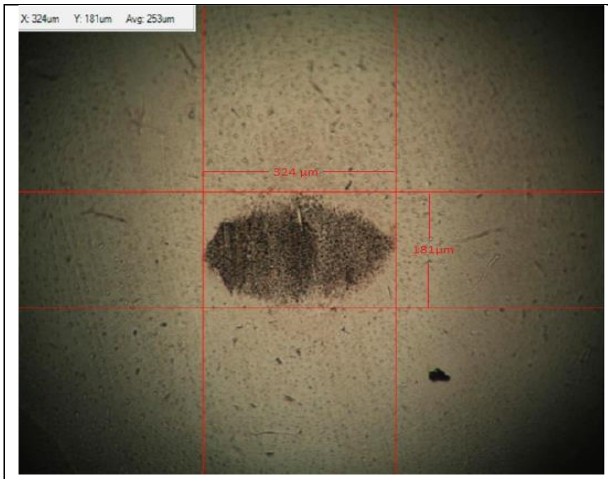

Figure 4.17. Wear Scar Image for BS6D1

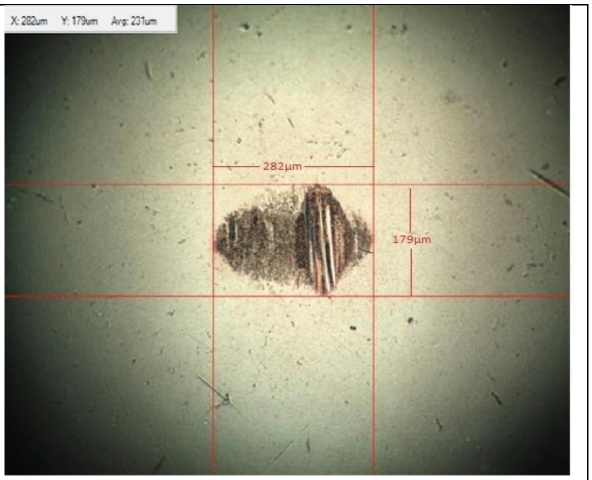

Figure 4.18. Wear Scar Image for BS6D2

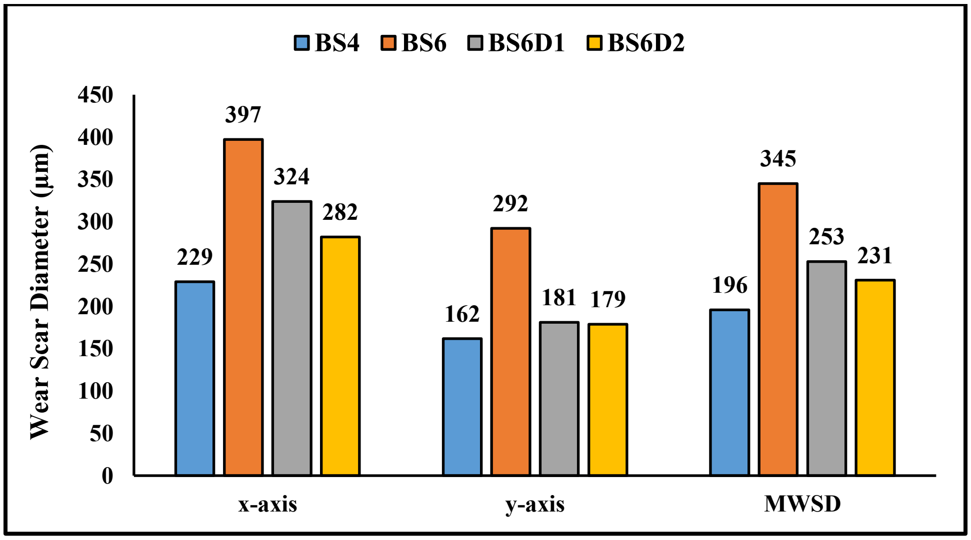

Figure 4.19. Wear Scar Diameter for Doped BS6D1 and BS6D2

The improvement is justified by the ability of dibutyl sulfide to adsorb on metal surfaces and form thermally stable tribofilms that resist abrasion and scuffing during reciprocating motion. These results underline that while BS6 fuels meet environmental standards, their lubricity-related shortcomings can be substantially mitigated through targeted sulfur doping—particularly relevant for protecting fuel injection and high-pressure components in legacy diesel engines that lack compatibility with ultra-low sulfur fuels.

4.5.3 Evaluation of Tribological Characteristics for Bharat Stage VI Diesel with additive

The Mean Wear Scar Diameter (MWSD) results for the D100, D100MPS 0.5, D100MPS 1.0, and D100MPS 2.0 samples are shown in Figures 4.14, 4.20, 4.21, and 4.22. A notable reduction in wear scar diameter was observed as the multipurpose solution (MPS) concentration increased from 0% to 2% (v/v). Specifically, the WSD decreased by 25.79% for D100MPS 0.5, 46.08% for D100MPS 1.0, and 56.23% for D100MPS 2.0 compared to the base D100 diesel. This improvement is attributed to the higher concentration of aromatic compounds in the MPS, which function as surface-active agents [234]. These agents help form protective films on sliding contacts during lubrication, reducing both wear and friction. The enhanced surface adhesion and better boundary lubrication provided by these films contribute to the improved tribological performance observed [233]. Figure 4.23 offers a comprehensive graphical summary of the WSD variations across the different samples, highlighting the effectiveness of the multipurpose solution in significantly reducing wear scar diameter and enhancing diesel fuel's lubricity.

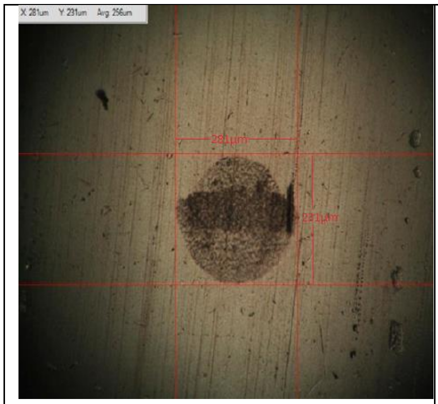 	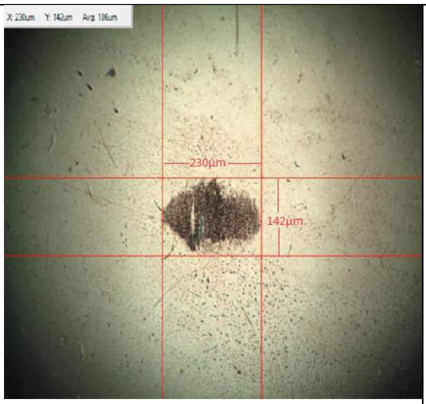 	
Figure 4.20. Wear Scar Image for D100MPS 0.5	**Figure 4.21. Wear Scar Image for D100MPS 1.0**	**Figure 4.22. Wear Scar Image for D100MPS 2.0**

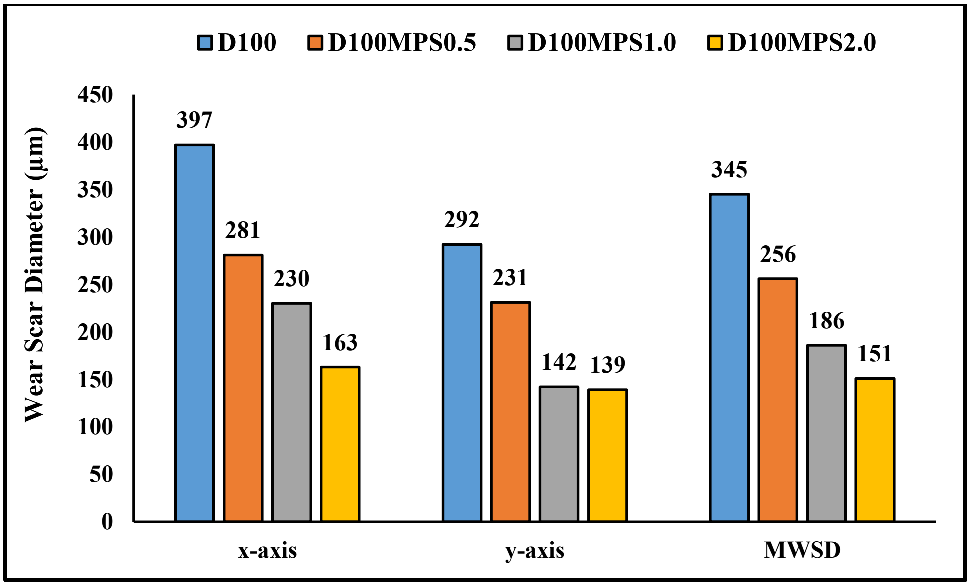

Figure 4.23. Wear Scar Diameter for Bharat Stage VI Diesel with additive

Effect of Multi-Purpose Solution on Friction Characteristics

In figure 4.24 presents a detailed analysis of the coefficient of friction (COF) for various diesel samples treated with different concentrations of the multipurpose solution (MPS). The results highlight a notable reduction in COF with the addition of MPS, confirming its effectiveness in enhancing frictional behavior. This improvement can be attributed to the presence of anti-wear and surface-active agents in the solution that adsorb onto the metal surfaces within the friction pair. These additives form a protective boundary layer that minimizes direct metal-to-metal contact, thereby reducing friction and improving overall lubricity. Without such additives, elevated temperatures at the contact interface can degrade the lubricant film, causing it to collapse and allowing direct surface interaction, which in turn increases the COF [235]. However, the polar functional groups in MPS additives counteract this effect by strengthening the film's resilience to thermal and mechanical stress. When blended with BS6 diesel, the multipurpose solution enhances the formation and stability of this lubricating film, improving diesel's tribological performance and contributing to reduced component wear and potentially longer engine life.

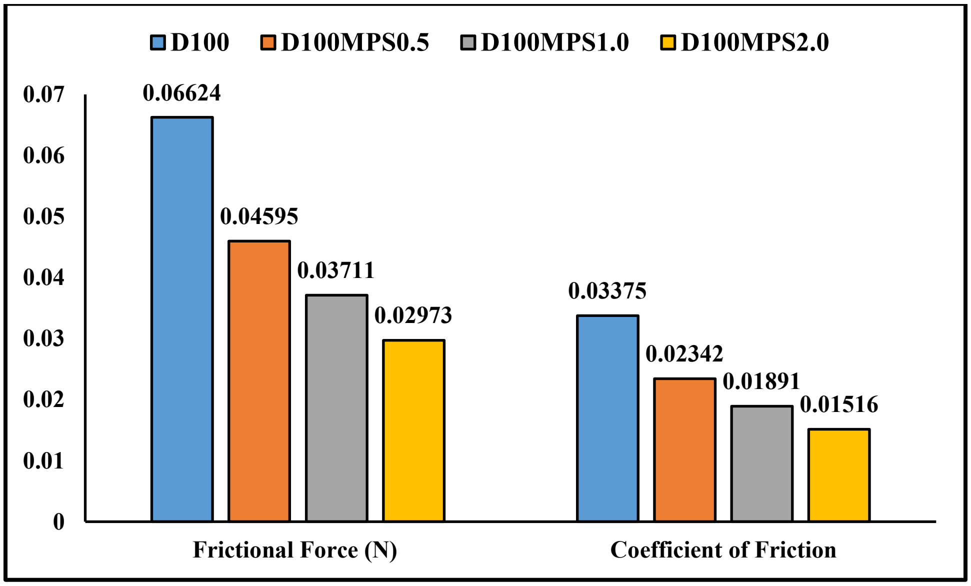

Figure 4.24. Friction Attributes for Bharat Stage VI Diesel with additive

4.5.4 Evaluation of Tribological Characteristics for Diesel-Biodiesel Blend with additive

The tribological behavior of various fuel samples, including pure diesel (D100), a 5% waste cooking oil biodiesel blend (D95WCB5), and D95WCB5 further doped with increasing concentrations of the MPS additive (0.5%, 1.0%, and 2.0% by volume), was evaluated using an HFRR setup. The primary indicators considered were frictional force, coefficient of friction (CoF), and Mean Wear Scar Diameter (MWSD). The baseline diesel fuel (D100) exhibited a frictional force of 0.066 N, CoF of 0.0337, and MWSD of 345 µm, reflecting poor lubricity due to the removal of sulfur compounds in ultra-low sulfur diesel (ULSD). Upon blending with 5% WCO biodiesel (D95WCB5), a significant improvement in tribological behavior was observed. The frictional force decreased to 0.0391 N, CoF dropped to 0.0199, and MWSD was reduced to 196 µm. This enhancement is attributed to the natural oxygenates and polar compounds in biodiesel that contribute to boundary lubrication.

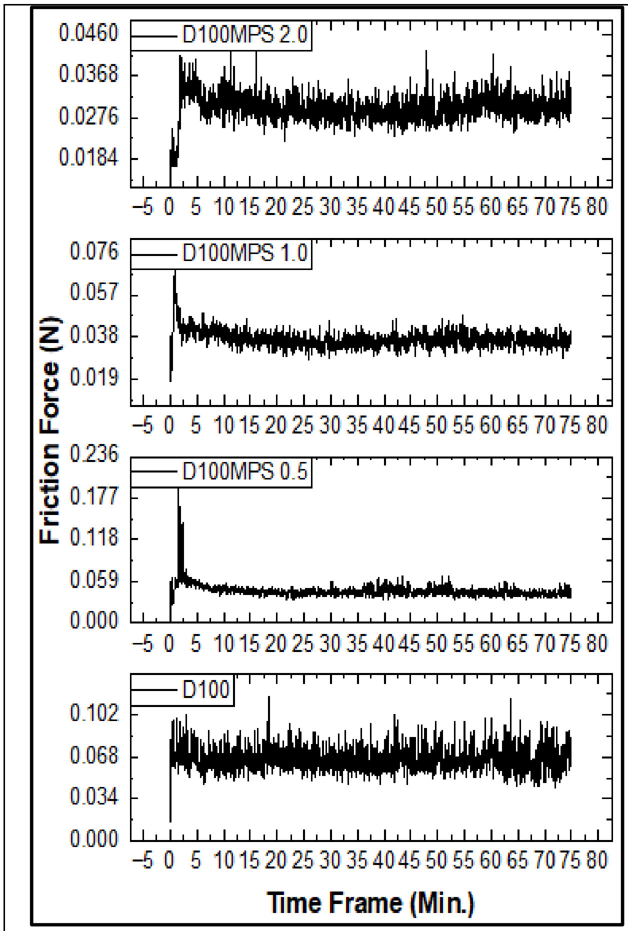

Figure 4.25. Frictional Force V/s Test Duration for Commercial Diesel (D100) with Additive

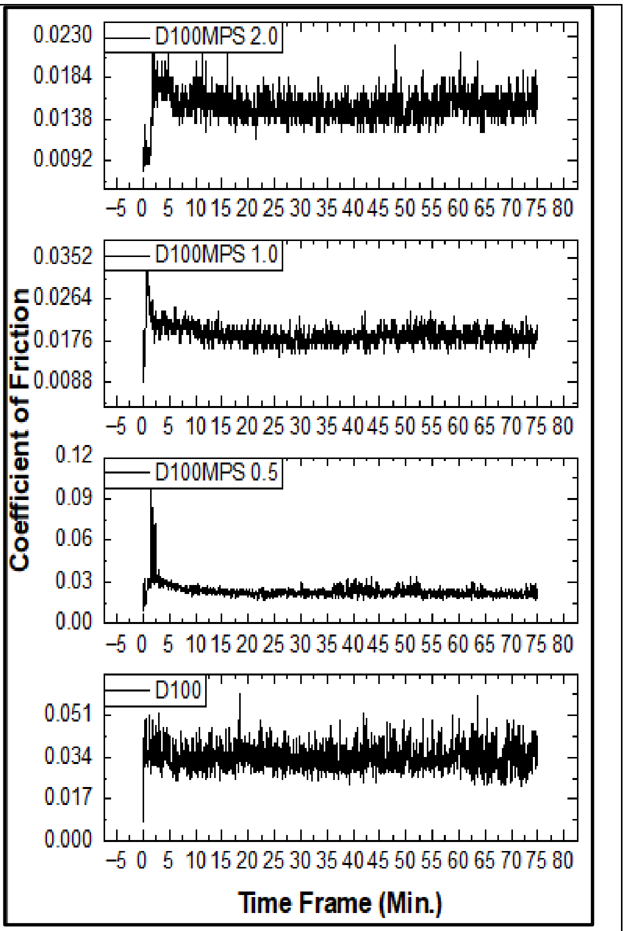

Figure 4.26. Coeff. of Friction V/s Test Duration for Commercial Diesel (D100) with Additive

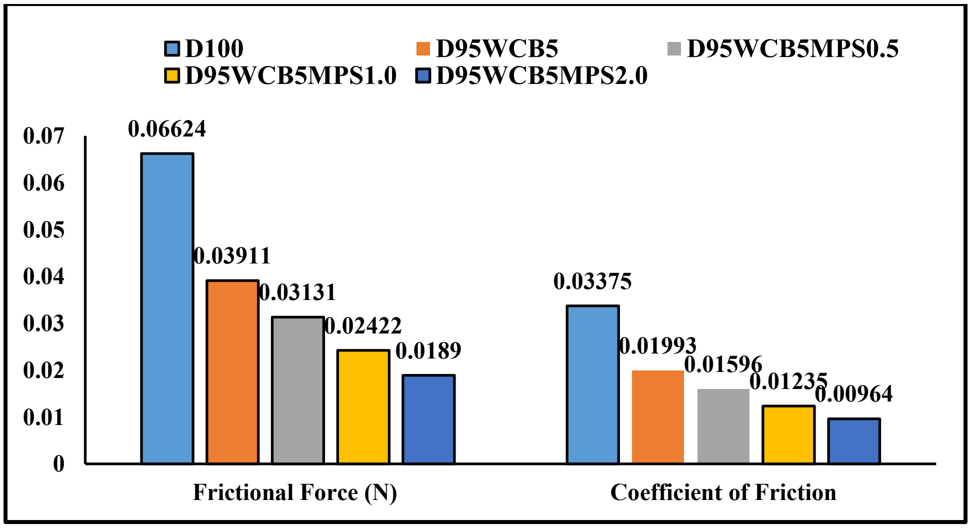

Figure 4.27. Friction Attributes for Diesel-Biodiesel Blend (D95WCB5) Diesel with additive

The incorporation of the MPS additive further enhanced lubricity in a dose-dependent manner. At 0.5% concentration (D95WCB5MPS0.5), the frictional force reduced to 0.0313 N, COF to 0.0159, and MWSD to 159 µm. With 1.0% additive (D95WCB5MPS1.0), these values improved further to 0.0242 N, 0.0124, and 123 µm, respectively. The best performance was achieved at 2.0% additive (D95WCB5MPS2.0), which recorded the lowest frictional force (0.0189 N), COF (0.0096), and MWSD (96 µm).

These results clearly indicate that the MPS additive significantly improves the lubricity of diesel-biodiesel blends. The progressive reduction in MWSD aligns with the observed decrease in both frictional force and coefficient of friction, confirming enhanced anti-wear properties. This can be attributed to the film-forming ability and polar nature of the additive, which enhances surface protection by forming a boundary lubrication layer between moving parts.

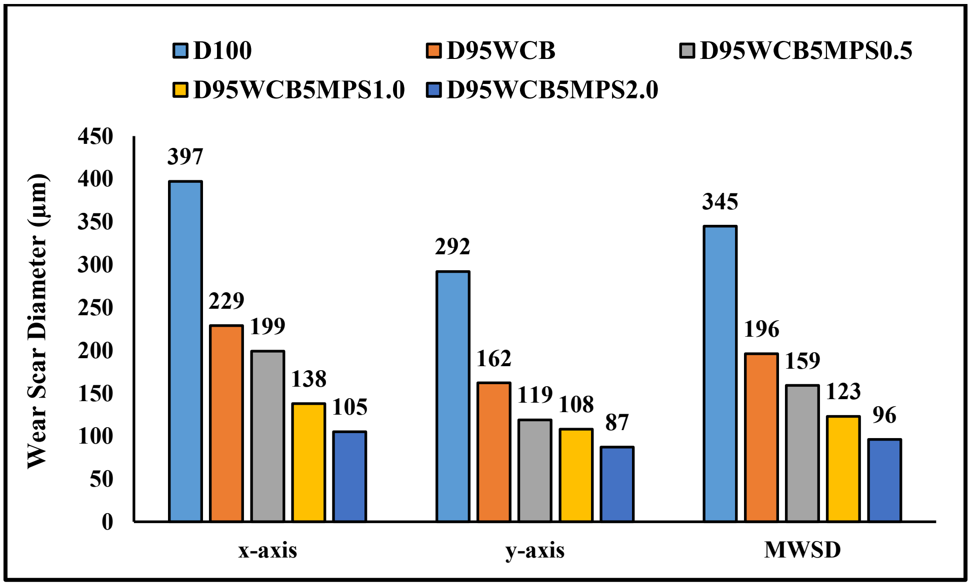

Figure 4.28. Wear Scar Diameter for Diesel-Biodiesel Blend (D95WCB5) Diesel with additive

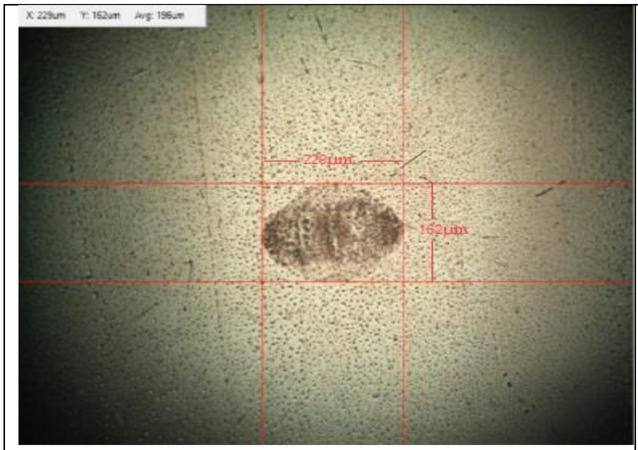

Figure 4.29. Wear Scar Image for D95WCB5

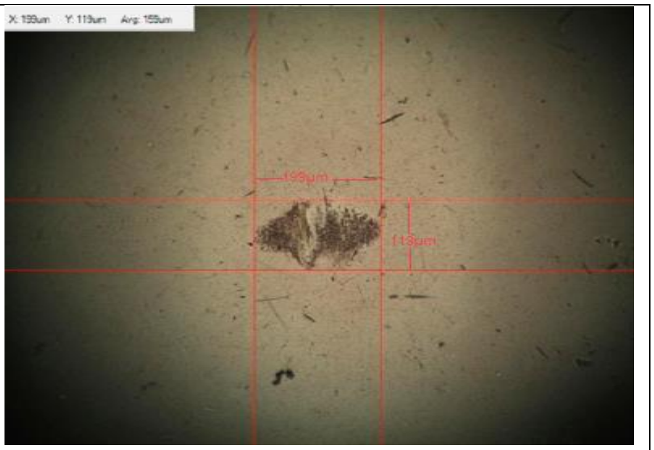

Figure 4.30. Wear Scar Image for D95WCB5MPS0.5

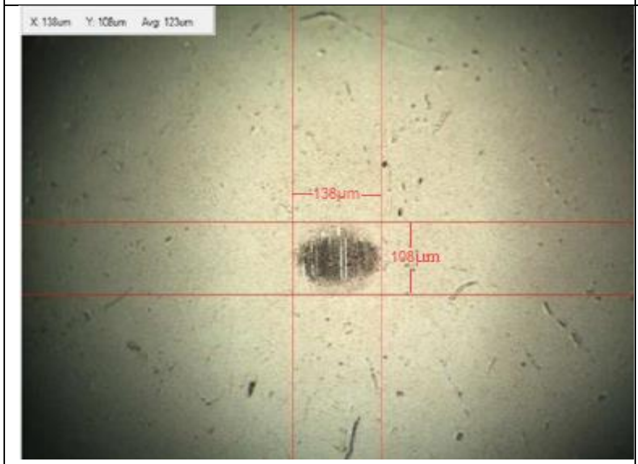

Figure 4.31. Wear Scar Image for D95WCB5MPS1.0

Figure 4.32. Wear Scar Image for D95WCB5MPS2.0

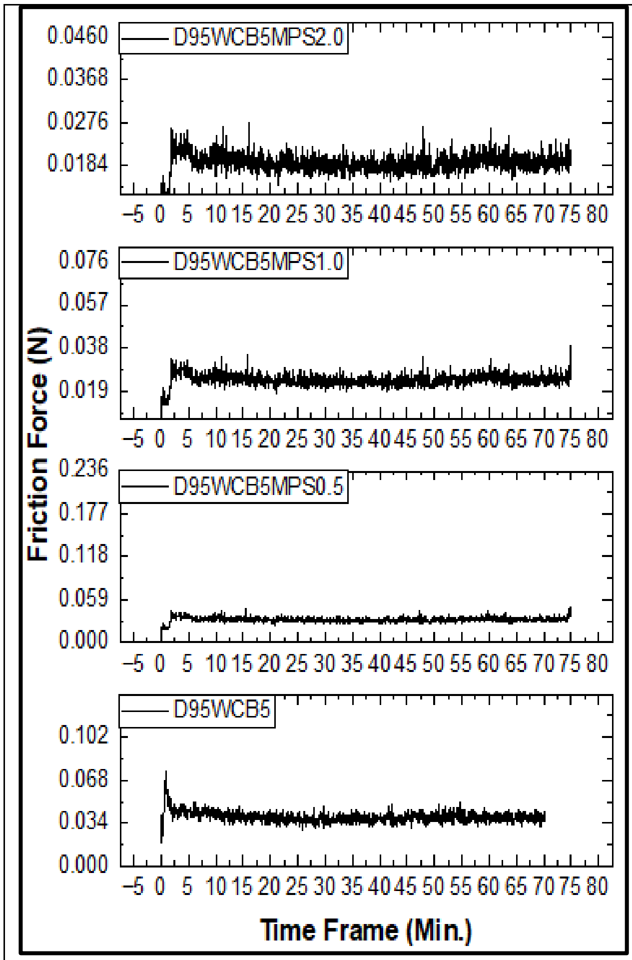

Figure 4.33. Frictional Force V/s Test Duration Diesel-Biodiesel Blend (D95WCB5) with Additive

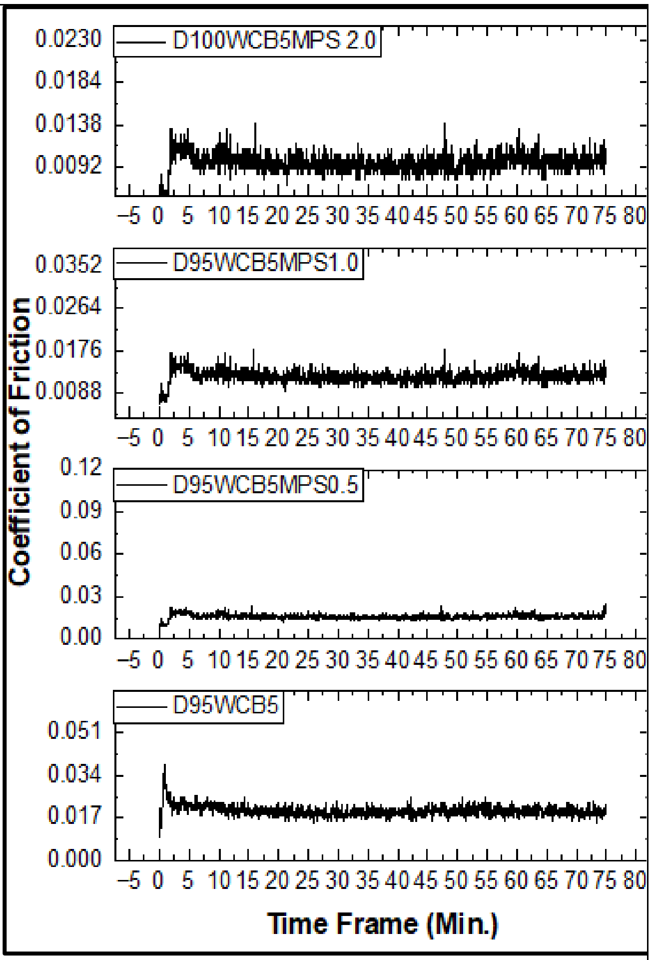

Figure 4.34. Coeff. of Friction V/s Test Duration for Diesel-Biodiesel Blend (D95WCB5) with Additive

Thus, the combined analysis of frictional and wear data validates the synergistic effect of biodiesel and MPS additive, making D95WCB5MPS2.0 a highly promising formulation for improving the tribological performance of diesel fuels without compromising engine component longevity.

4.6 Engine Performance Characteristics of Test Fuel Blends

4.6.1 Comparative Study Between Bharat Stage IV and Bharat Stage VI

A comparative evaluation of BS-IV and BS-VI diesel fuels in an unmodified CI engine reveals notable differences in BTE and BSEC. BS-IV diesel demonstrated slightly higher BTE compared to BS-VI diesel under identical operating conditions. This can be attributed to the higher sulfur content in BS-IV fuel (less than 50 ppm), which enhances lubricity and reduces frictional losses, an advantage particularly significant in engines not designed for low-sulfur fuels. Although BS-VI fuel has a higher cetane number, which theoretically promotes better ignition quality, the benefits are not fully realized in non-BS-VI-compliant engines due to their injection systems not being optimized for this fuel. As a result, BS-VI diesel yield a BTE that is 5.45% lower than that of BS-IV diesel in such engines [236].

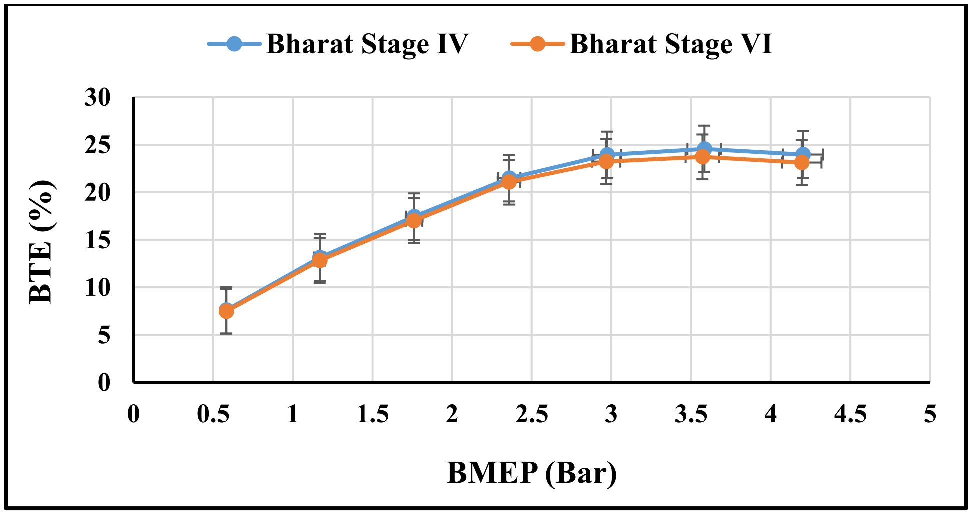

Figure 4.35. Variation in BTE for BS IV and BS VI Diesel

In terms of BSEC, the experimental results showed that BS-VI diesel exhibited 4.23 % higher BSEC [236]. This increase was attributed to the lower combustion efficiency of BS-VI fuel when used in the unmodified diesel engine, where injection timing and pressure were not optimized for the fuel's properties. Additionally, the presence of lubricity-enhancing additives in BS-VI diesel was observed to affect fuel spray characteristics and atomization, which may have contributed to incomplete combustion. As a result, a greater amount of energy was required to produce the same power output, thereby increasing BSEC.

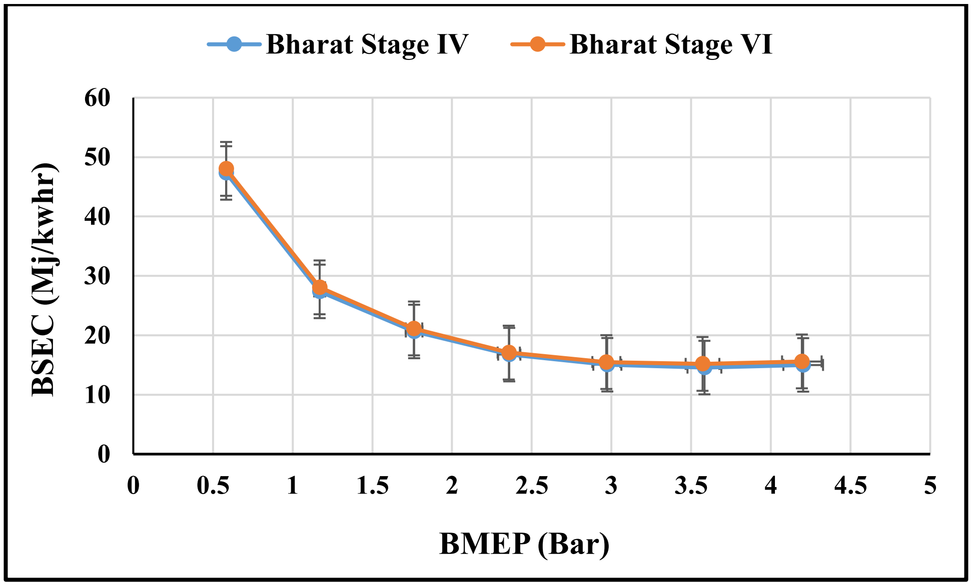

Figure 4.36. Variation in BSEC for BS IV and BS VI Diesel

4.6.2 Variation of Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) represents the ratio of engine power output to the heat supplied by the fuel. As shown in Figure 4.37, BTE increases with engine load for all tested fuels, reaching 23.01% for pure D100 diesel at full load. The addition of the multipurpose solution (MPS) to D100 enhances BTE at all load levels. At full load, BTE improves to 23.67% with D100MPS 0.5, 24.13% with D100MPS 1.0, and 26.51% with D100MPS 2.0 [221]. This increase in efficiency is attributed to the homolytic fission triggered by MPS, which promotes the breakdown of long-chain hydrocarbons and improves combustion.

The presence of 2-Ethyl-Hexyl Nitrate (EHN) accelerates ignition, while cetane improver and combustion catalysts further enhance the combustion process. Additionally, lubricity enhancers in MPS reduce frictional losses by improving sealing and maintaining an adequate lubrication film, contributing to overall performance gains.

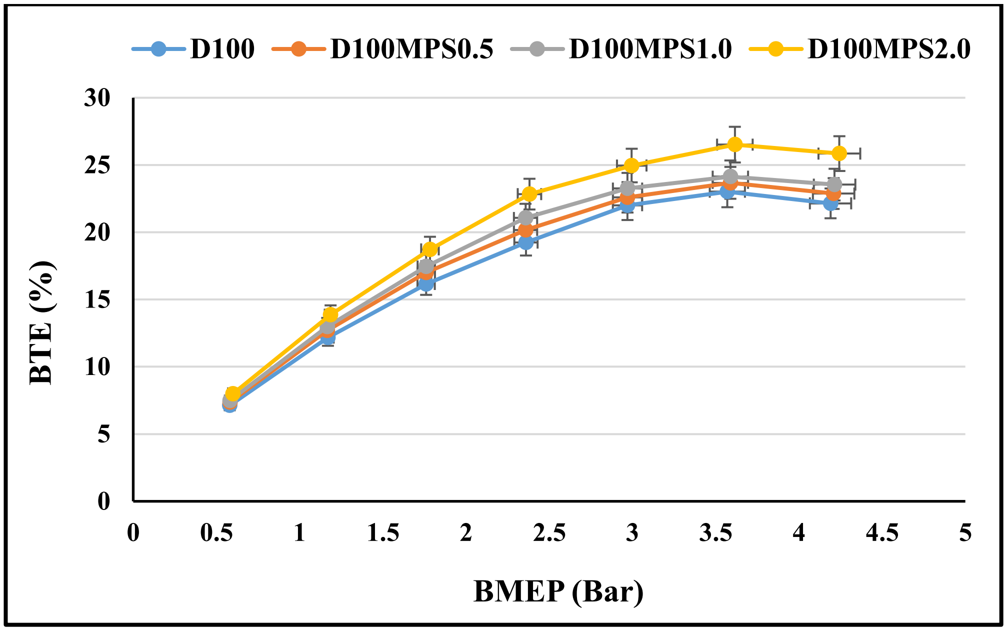

Figure 4.37: Variation in the BTE for Diesel with additive

The impact of multipurpose solution as an additive on Brake Thermal Efficiency (BTE) in diesel blends containing 5% waste cooking oil (WCO) reveals a consistent improvement in combustion performance with increasing additive concentration. The base blend (Diesel + 5% WCO) typically shows slightly reduced BTE compared to pure diesel due to the higher viscosity and lower volatility of WCO as shown in figure 4.37. However, the inclusion of multipurpose solution at concentrations of 0.5 ml, 1.0 ml, and 2.0 ml progressively enhances BTE across engine loads. With 2.0 ml multipurpose solution, BTE reaches its highest value among the tested samples, attributed to the synergistic effects of combustion catalysts and ignition improvers present in multipurpose solutions, which ensure more complete combustion and reduced energy losses. The enhancement in BTE is primarily due to improved cetane number, better mixing of fuel-air, and optimized combustion phasing, all facilitated by the chemical composition of multipurpose solution, which includes ignition accelerators and combustion enhancers.

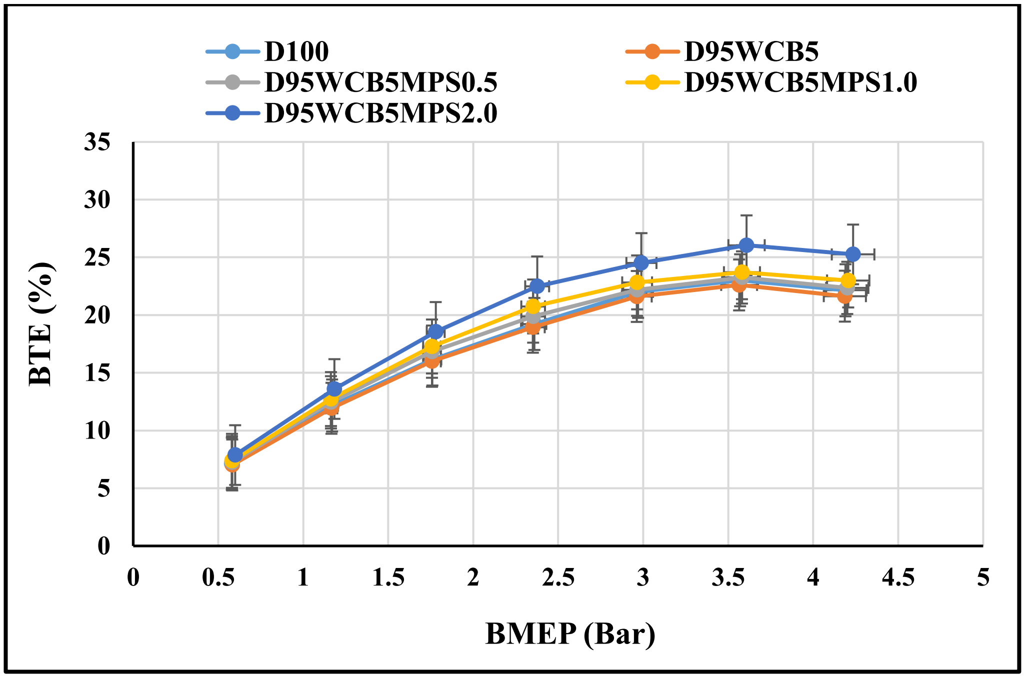

Figure 4.38. Variation in the BTE for Diesel-Biodiesel Blend with additive

4.6.3 Variation of Brake-Specific Energy Consumption

Brake Specific Energy Consumption (BSEC) is a key indicator of engine energy efficiency, as it measures the actual energy required to produce one unit of output power, unlike Brake Specific Fuel Consumption (BSFC), which focuses solely on fuel quantity. Figure 4.39 illustrates the variation of BSEC with Brake Mean Effective Pressure (BMEP) for the tested fuel samples. The BSEC values for D100 blended with MPS are 14.24 MJ/kW-hr (0.5%), 12.95 MJ/kW-hr (1.0%), and 12.17 MJ/kW-hr (2.0%).

Across all engine loads, BS VI diesel shows higher BSEC than the MPS-enhanced blends, indicating improved energy efficiency with the additive. This improvement occurs despite the slight reduction in calorific value caused by the presence of MPS. The reduction in BSEC is primarily due to better momentum exchange between burned and unburned gases, which enhances heat transfer within the combustion chamber [237]. Catalysts and cetane improvers in MPS promote faster and more complete combustion, reducing energy losses, while surfactants improve atomization and air-fuel mixing, resulting in more uniform combustion. Overall, the incorporation of MPS effectively lowers BSEC, signaling enhanced engine performance.

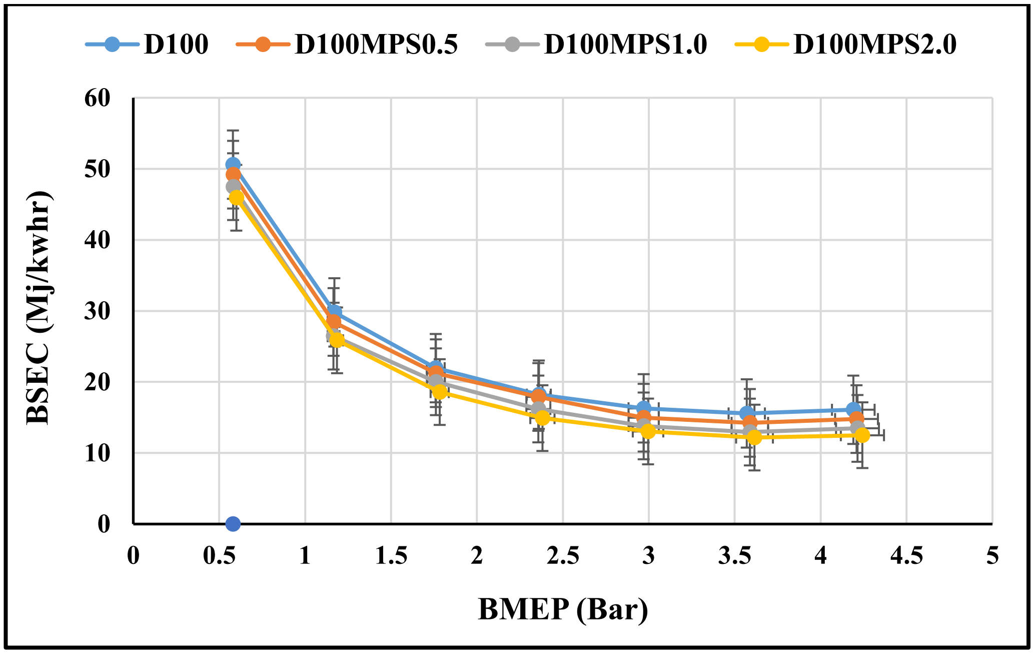

Figure 4.39. Variation in the BSEC for Diesel with additive

Initially, BSEC for D95WCB5 is higher than D100, after addition of multipurpose solution it decreases by 25.79 % The addition of multi-purpose solution at 0.5 ml reduces BSEC slightly, indicating improved combustion efficiency. At 1.0 ml concentration, the BSEC decreases further as the multi-purpose solution's ignition accelerators and combustion catalysts enhance fuel ignition and promote more complete combustion. At 2.0 ml, the lowest BSEC is recorded, reflecting optimal utilization of fuel energy despite the presence of the WCO.

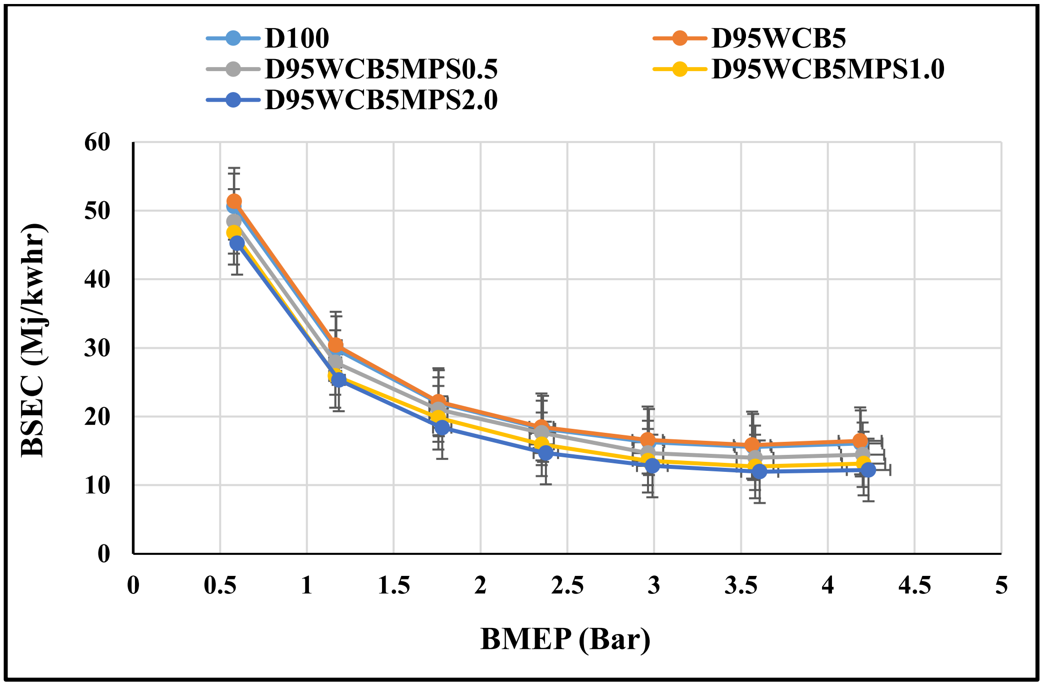

Figure 4.40. Variation in the BSEC for Diesel-Biodiesel Blend with additive

This reduction in BSEC is primarily due to improved cetane number, better fuel atomization, and enhanced air-fuel mixing facilitated by the active components in the multi-purpose solution. The additive's effect compensates for the slight calorific value reduction from WCO, demonstrating its effectiveness in improving energy efficiency through better combustion characteristics.

4.6.4 Variation of Exhaust Gas Temperature

The integration of the multi-purpose solution (MPS) additive into diesel fuel significantly affects Exhaust Gas Temperature (EGT) by improving combustion efficiency. EGT shows a gradual increase with rising MPS concentration. At 0.5 mL, a modest rise in EGT compared to pure diesel suggests quicker ignition and enhanced combustion onset. Increasing the dosage to 1.0 mL results in a further rise, attributed to improved fuel atomization and a higher cetane index, which support faster and more complete combustion. The highest EGT is recorded at 2.0 mL, indicating optimal combustion efficiency driven by the active ingredients in MPS—particularly combustion catalysts and cetane enhancers—that accelerate ignition and ensure thorough fuel burning. This upward trend in EGT with additive concentration confirms that MPS boosts the combustion process, contributing to better heat release and enhanced engine performance.

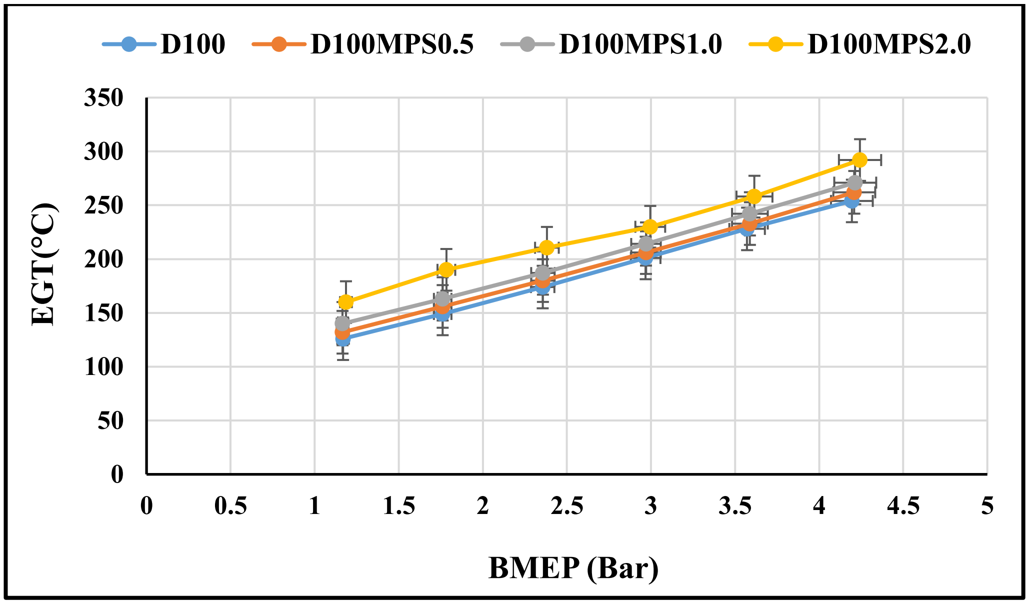

Figure 4.41. Variation in the EGT for Diesel with additive

The impact of multi-purpose solution additive on Exhaust Gas Temperature (EGT) in diesel blended with 5% waste cooking oil (WCO) reveals a consistent increase in EGT with higher additive concentrations, indicating enhanced combustion efficiency. The base blend of diesel with 5% WCO generally shows slightly lower EGT due to the higher viscosity and lower volatility of WCO, which hinder complete combustion. With the addition of 0.5 ml multi-purpose solution, a moderate rise in EGT is observed, suggesting improved ignition and partial enhancement in combustion quality. At 1.0 ml concentration, EGT increases further as the additive's cetane improver and combustion catalysts contribute to more efficient and quicker combustion. At 2.0 ml, the highest EGT is recorded, indicating the most complete combustion among the tested blends. The presence of surfactants in multi-purpose solution also aids in better fuel-air mixing and atomization, which promotes uniform burning.

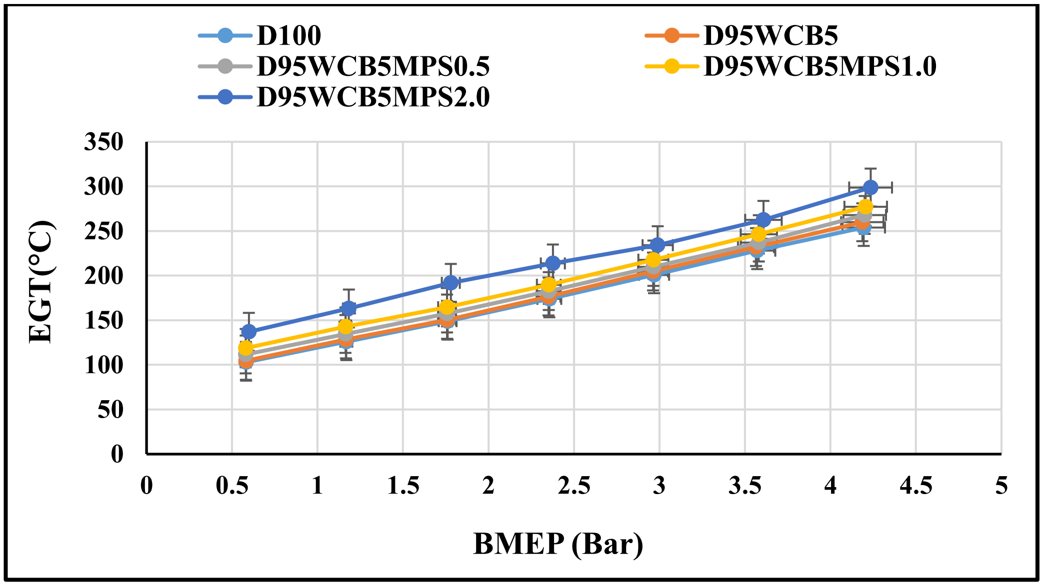

Figure 4.42. Variation in the EGT for Diesel-Biodiesel Blend with additive

Overall, the rising trend in EGT with increasing multi-purpose solution concentration confirms improved combustion behavior despite the challenges posed by WCO in the blend.

4.6.5 Variation of NOx Emission

Diesel engine exhaust primarily contains nitrogen oxides (NOx), mainly nitric oxide (NO) and nitrogen dioxide (NO_2), formed via the Zeldovich mechanism during high-temperature combustion. Factors such as injection timing, ignition delay, combustion chamber geometry, flame temperature, fuel composition, and air–fuel ratio influence NOx formation. Figure 4.43 presents the NOx emissions for standard BS6 diesel and its blends with the Multipurpose Solution (MPS). At full load, commercial diesel records the highest NOx level at 1196 ppm, while D100MPS 2.0 exhibits the lowest at 1154 ppm. Compared to neat diesel, NOx emissions decreased by 1.33% for D100MPS 0.5, 2.32% for D100MPS 1.0, and 3.51% for D100MPS 2.0. This reduction is mainly due to the antioxidant Tert-butylhydroquinone (TBHQ) in MPS (0.5–1.5%), which inhibits free radical formation, thereby limiting NOx generation. [238]. Although antioxidants may slightly lower the fuel's calorific value, they increase the flash point and cetane number. Additionally, cetane improvers in MPS contribute by altering the combustion chemistry, encouraging early hydrogen atom separation and limiting nitrogen and hydrocarbon oxidation, thereby suppressing NO formation [239]. Moreover, despite containing nitrogen, the cetane booster 2-EHN helps reduce NOx by shortening ignition delay and lowering peak combustion temperatures, leading to disrupted nitrite formation and overall lower NOx emissions.

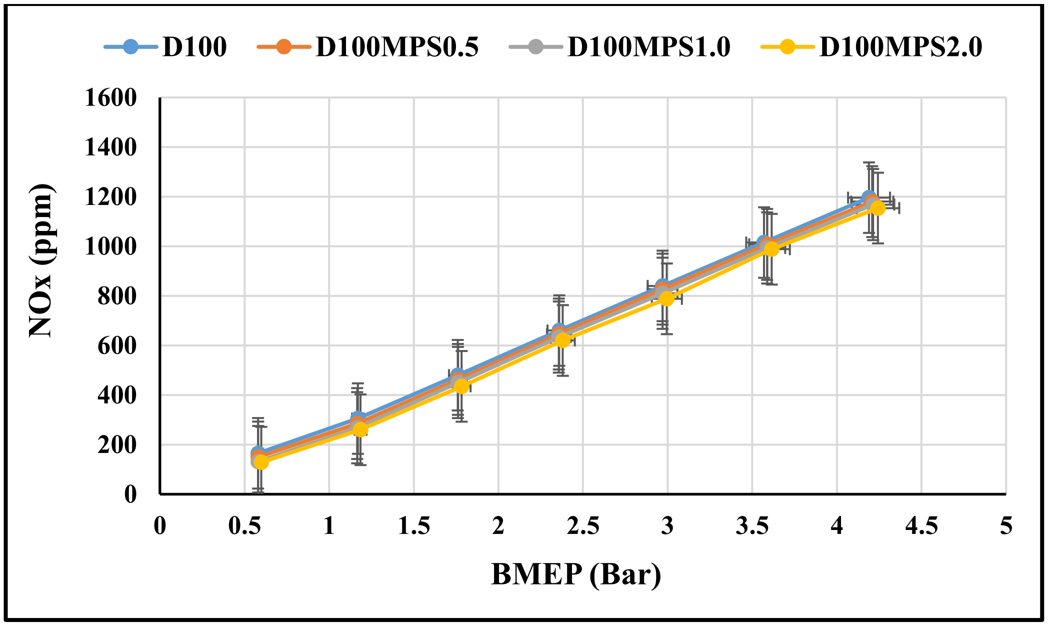

Figure 4.43. Variation in the NOx for Diesel with additive

Figure 4.44 illustrates a consistent decrease in NOx emissions with rising concentrations of the multipurpose solution (MPS) additive. The baseline diesel–5% WCO blend shows relatively high NOx levels due to incomplete combustion and the elevated viscosity of WCO, which hampers atomization and air–fuel mixing. Introducing 0.5 ml of MPS leads to a slight reduction in NOx, suggesting marginal improvement in combustion behavior. At 1.0 ml, NOx emissions decrease further as the additive's combustion catalysts and cetane improver enhance ignition quality, shorten ignition delay, and promote more efficient combustion, resulting in lower peak temperatures. The most notable reduction occurs at 2.0 ml, indicating maximum effectiveness of MPS in minimizing NOx formation.

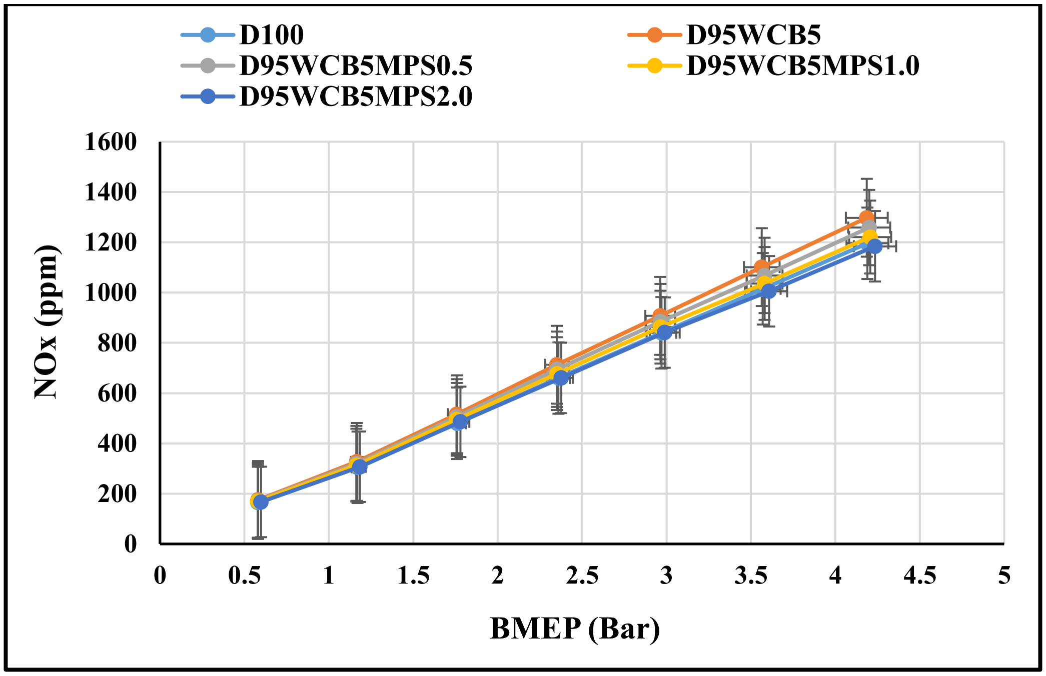

Figure 4.44. Variation in the NOx for Diesel-Biodiesel Blend with additive

This is due to the synergistic effects of multi-purpose solution's active components, which optimize the combustion process, shorten the ignition delay, and minimize the formation of high-temperature zones that lead to NOx production.

4.6.6 Variation of Unburnt Hydrocarbon Emission

Fuel combustion, ideally, converts hydrocarbons into carbon dioxide and water vapor, releasing heat. However, incomplete combustion—often due to poor air–fuel mixing—leads to unburnt hydrocarbon (HC) emissions. More than the overall air–fuel ratio, the uniformity of air–fuel mixing plays a key role in HC formation.

Figure 4.45 shows that diesel blended with MPS (at 0.5, 1.0, and 2.0-mL concentrations) produces lower HC emissions compared to standard BS6 diesel. At 2% MPS concentration under peak load conditions, HC emissions drop by 7.5%. This reduction is primarily due to the catalytic action of MPS components and the increased oxygen availability in the blend. Cetane enhancers in MPS shorten ignition delay, improving combustion completeness [240]. Simultaneously, surfactants reduce fuel viscosity, leading to finer atomization and better air–fuel mixing. These improvements help eliminate fuel-rich zones within the cylinder, thereby reducing HC emissions. Overall, the higher cetane index, better atomization, and oxygen-enriched blend achieved through MPS contribute to a significant decrease in unburnt hydrocarbons [241].

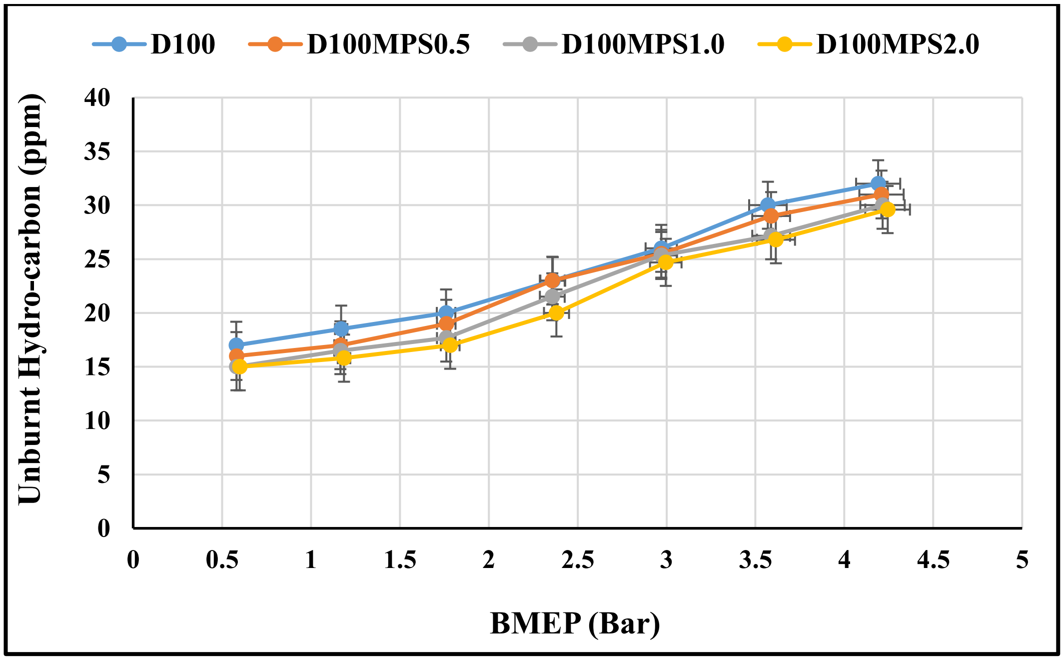

Figure 4.45. Variation in the UBHC for Diesel with additive

The impact of multi-purpose solution on UBHC emissions in diesel blended with 5% waste cooking oil (WCO) reveals a reduction in HC emissions with increasing additive concentration. The base diesel-WCO blend typically shows higher HC emissions due to the increased viscosity and lower volatility of WCO, which affects fuel atomization and combustion efficiency [242].

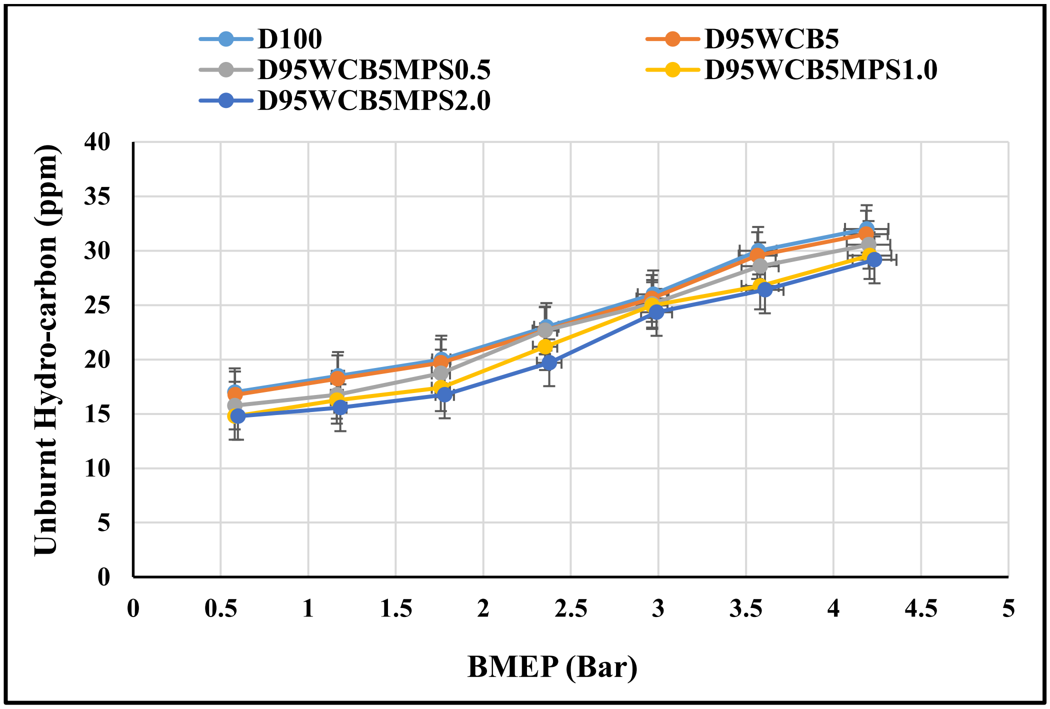

Figure 4.46. Variation in the UBHC for Diesel-Biodiesel Blend with additive

4.6.7 Variation of Carbon Monoxide Emission

Carbon monoxide (CO) emissions result from incomplete combustion, often caused by limited oxygen availability or low combustion temperatures. As shown in Figure 4.47, the addition of the multipurpose solution (MPS) to BS6 diesel significantly reduces CO emissions across all engine loads. The improved combustion efficiency from MPS is mainly due to its ability to shorten ignition delay and accelerate the combustion process. At full load, CO emissions decrease by 8.4%, 15.7%, and 18.07% for MPS concentrations of 0.5%, 1.0%, and 2.0% (v/v), respectively, compared to standard BS6 diesel. These reductions are primarily attributed to the dispersant-detergent components in MPS, which help maintain cleaner combustion chambers and reduce deposit formation in the fuel system. This leads to more complete combustion and, consequently, lower CO emissions. [243]. These additives also enhance the oxidation stability of the fuel by neutralizing acidic compounds, raising the base number of additives, and releasing protons that generate carboxylic acid and peroxide free radicals. This results in significantly lower CO emissions by improving the oxidation stability of the diesel fuel blends [244] . In conclusion, additives like MPS help reduce CO emissions by improving oxidation stability and promoting cleaner combustion.

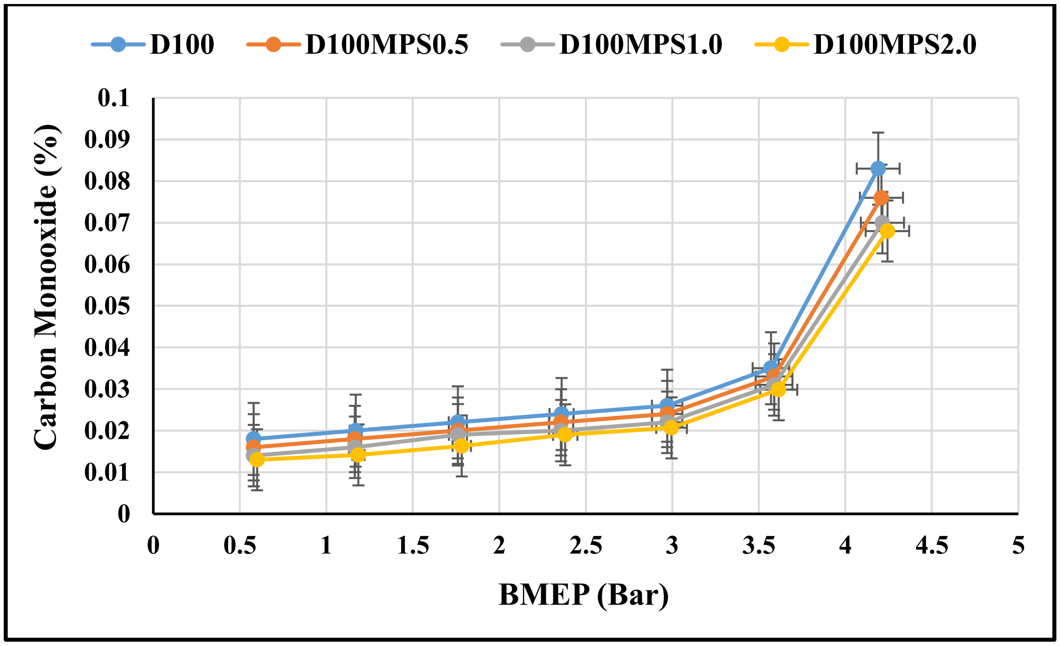

Figure 4.47. Variation in the Carbon Monoxide for Diesel with additive

Additives like MPS enhance the oxidation stability of diesel by neutralizing acidic compounds, increasing the base number, and promoting the formation of free radicals that support cleaner combustion. This leads to a notable reduction in CO emissions, particularly at a 2.0 ml concentration, where combustion efficiency is maximized. MPS's surfactant properties improve fuel atomization and air–fuel mixing, reducing fuel-rich zones that typically produce CO. Additionally, cetane improvers shorten ignition delay, enabling more complete combustion even in blends containing 5% waste cooking oil. Overall, MPS significantly lowers CO emissions by improving combustion quality and oxidation stability.

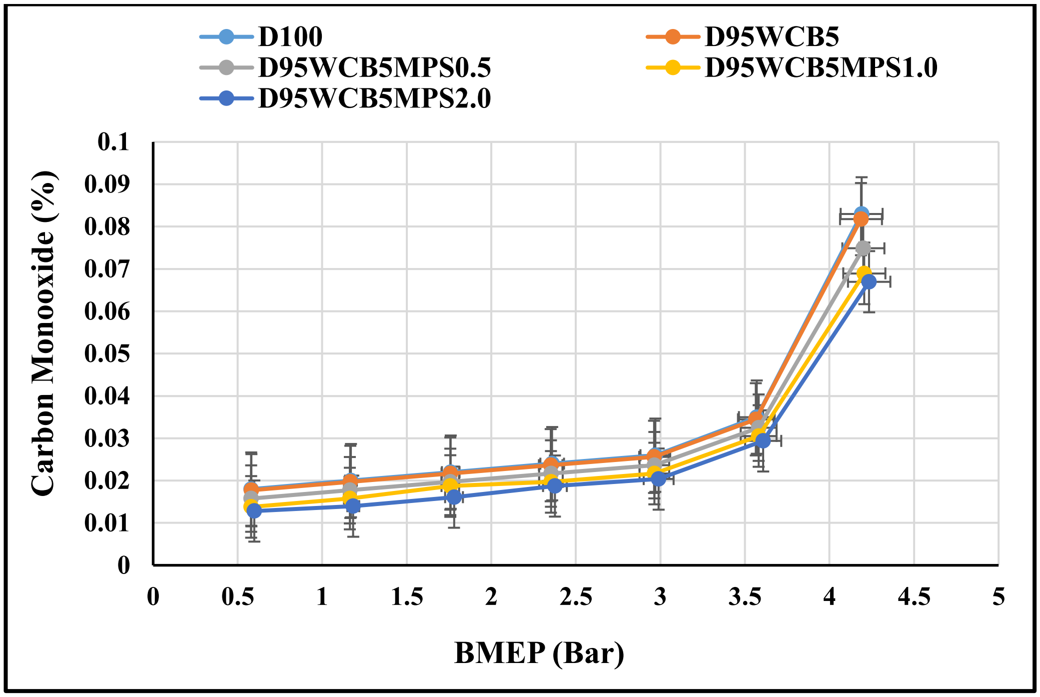

Figure 4.48. Variation in the Carbon Monoxide for Diesel-Biodiesel Blend with additive

4.6.8 Variation of Smoke Opacity

The combustion process in compression-ignition (CI) engines generates carbonaceous particulates that can adsorb organic compounds, contributing to smoke emissions when combustion is incomplete [245]. As shown in Figure 4.49, conventional diesel produces higher smoke opacity than diesel blended with multipurpose solutions (MPS). At full load, smoke opacity is reduced by 0.78%, 0.96%, and 1.56% for D100MPS 0.5, D100MPS 1.0, and D100MPS 2.0, respectively. MPS acts as a smoke suppressant [249], and its increasing concentration leads to greater reductions in smoke emissions. This effect is attributed to the combined action of cetane improvers, combustion catalysts, detergents, and surfactants in MPS. Surfactants enhance fuel atomization and evaporation by lowering surface tension [246], while cetane improvers and catalysts reduce ignition delay and promote more complete combustion, allowing more carbon particles to oxidize and thereby decreasing soot formation.

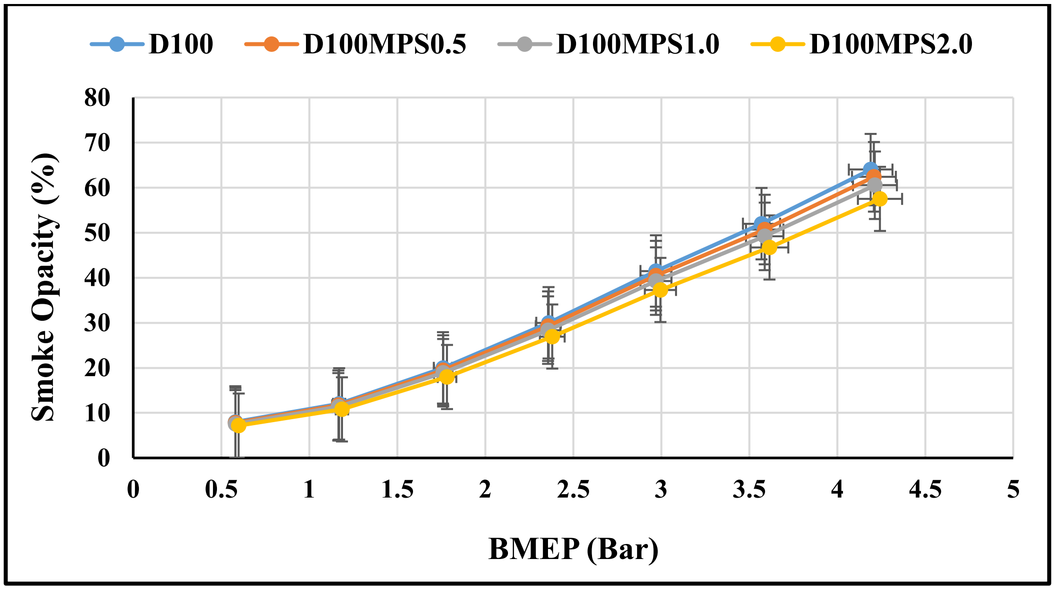

Figure 4.49. Variation in the Smoke Opacity for Diesel with additive

The addition of MPS to diesel-biodiesel blend fuel led to a reduction in smoke emissions. At maximum load, smoke opacity values D95WCB5 from 58.56% to 53.99%, with increasing concentrations of multi-purpose solution. This reduction is attributed to the combined effects of the multifunctional components in MPS, including a cetane improver, combustion catalyst, detergent, and surfactant.

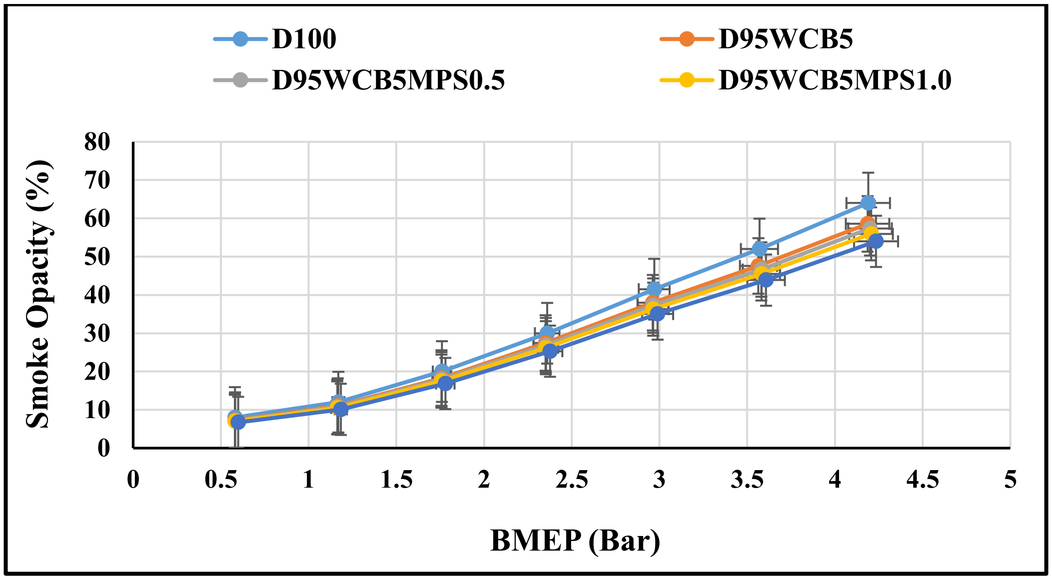

Figure 4.50. Variation in the Smoke Opacity for Diesel-Biodiesel Blend with additive

The surfactant contributes to fuel emulsification, reducing surface tension and the Sauter Mean Diameter (SMD), which enhances atomization and evaporation rates, thereby shortening ignition delay. Furthermore, the presence of a combustion catalyst and cetane enhancer within MPS promotes more efficient combustion. These improvements allow for an extended diffusion combustion phase, during which a greater number of carbon particles could react with oxygen, ultimately resulting in reduced soot formation.

4.7 Engine Combustion Characteristics of Test Fuel Blends

4.7.1 Heat Release Rate

Combustion is a complex phenomenon involving the simultaneous ignition and oxidation of the fuel–air mixture. The heat release rate (HRR) is a crucial parameter for understanding combustion characteristics [247]. Figures 4.51 and 4.52 illustrate HRR variations with crank angle degrees for pure diesel and diesel–biodiesel blends, both with and without the multipurpose additive solution (MPS). Across all test fuels—diesel, biodiesel blends, and MPS-enhanced samples—HRR profiles followed a similar trend under different engine loads. Under full load (100%), biodiesel showed a reduced HRR compared to diesel, mainly due to a shorter premixed combustion phase. This behavior is consistent with previous findings, which associate it with biodiesel's higher cetane number and oxygen content (10–15%). The addition of the MPS additive to both diesel and biodiesel further enhanced combustion by reducing the ignition delay. This effect was observed across all tested fuels, with ignition delay decreasing as the concentration of MPS increased. Notably, the HRR curves for all fuel types were smooth and stable at both partial and full load conditions. This consistent behavior is attributed to the presence of combustion catalysts and cetane improvers in the MPS, which facilitate a more controlled combustion process. The premixed combustion stage was found to be less intense, while the controlled (diffusion) combustion stage became more prominent, indicating that combustion was more evenly distributed over the entire combustion stroke.

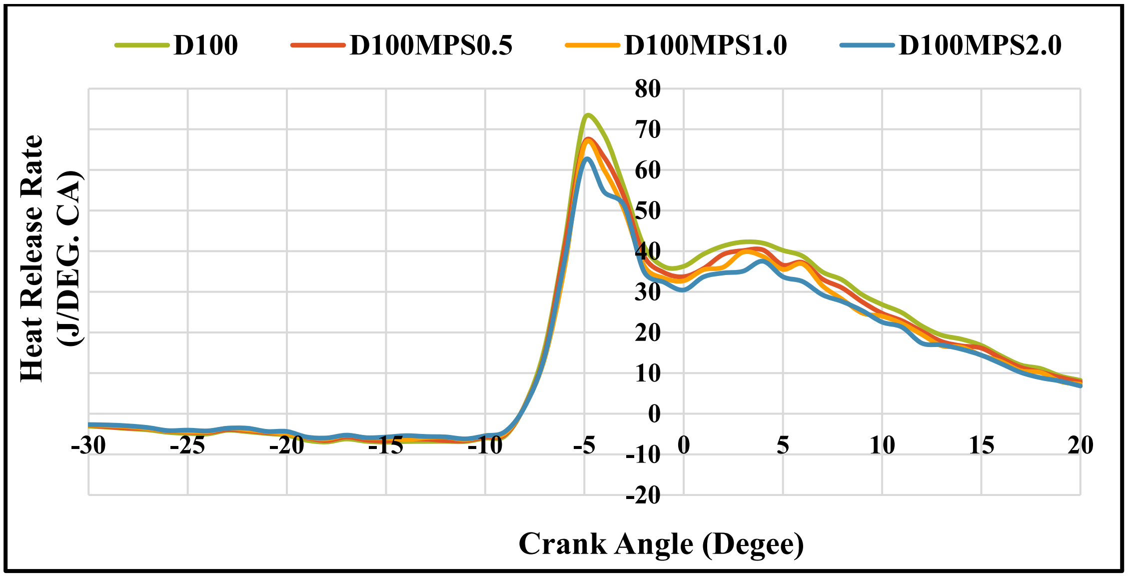

Figure 4.51. HRR Vs Crank Angle for Diesel with additive

Additionally, the antioxidant component in the MPS contributed to a reduction in peak HRR by limiting the available oxygen concentration—an effect observed in both diesel and diesel–biodiesel blends [248].

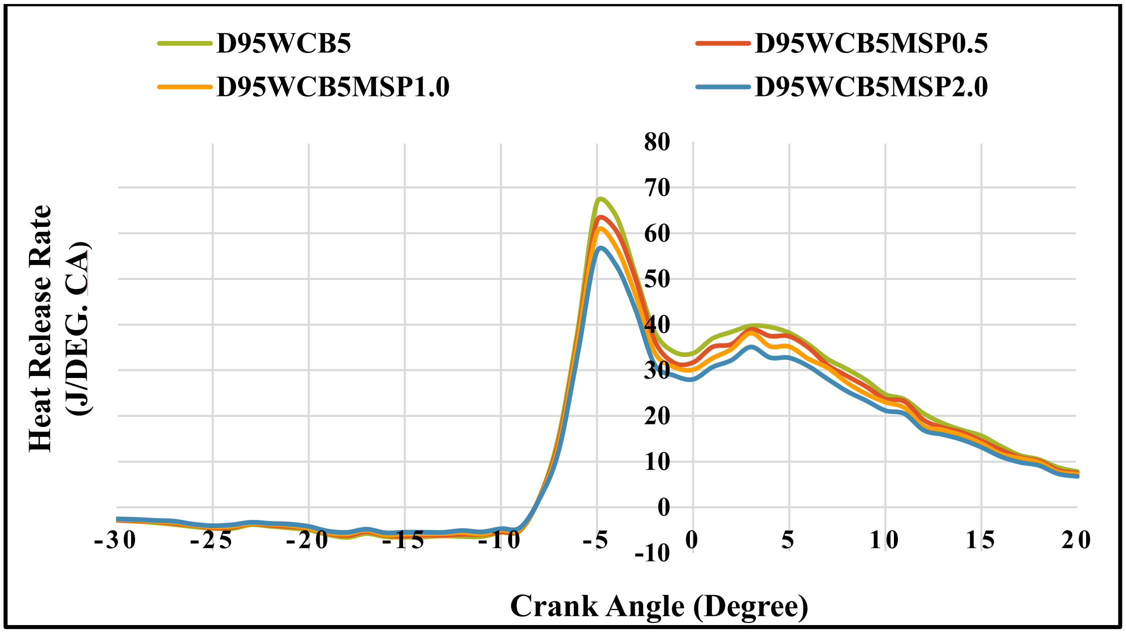

Figure 4.52. HRR Vs Crank Angle for Diesel-Biodiesel Blend with additive

4.7.2 Variation of In-Cylinder pressure with Crank Angle

The pressure–crank angle diagram offers essential insights into combustion behavior by illustrating in-cylinder pressure across crank angles over multiple cycles. Figures 4.53 and 4.54 depict in-cylinder pressure variations under full load (100%) conditions. Pure diesel demonstrates slightly higher peak pressure than the diesel–biodiesel blend, primarily due to its greater calorific value. The addition of the multipurpose solution (MPS) results in a noticeable decline in peak cylinder pressure for both diesel and biodiesel blends. This reduction is likely attributed to the antioxidant content in MPS, which may suppress pressure buildup. As shown in Figure 14, peak pressure generally occurs a few degrees after top dead center (TDC), significantly influenced by the combustion rate and timing during the premixed combustion phase. As shown in the figures, peak in-cylinder pressure rises with increasing engine load due to enhanced fuel combustion rates. However, incorporating MPS into both fuel types results in a consistent decline in peak pressure, with the reduction proportional to the additive concentration.

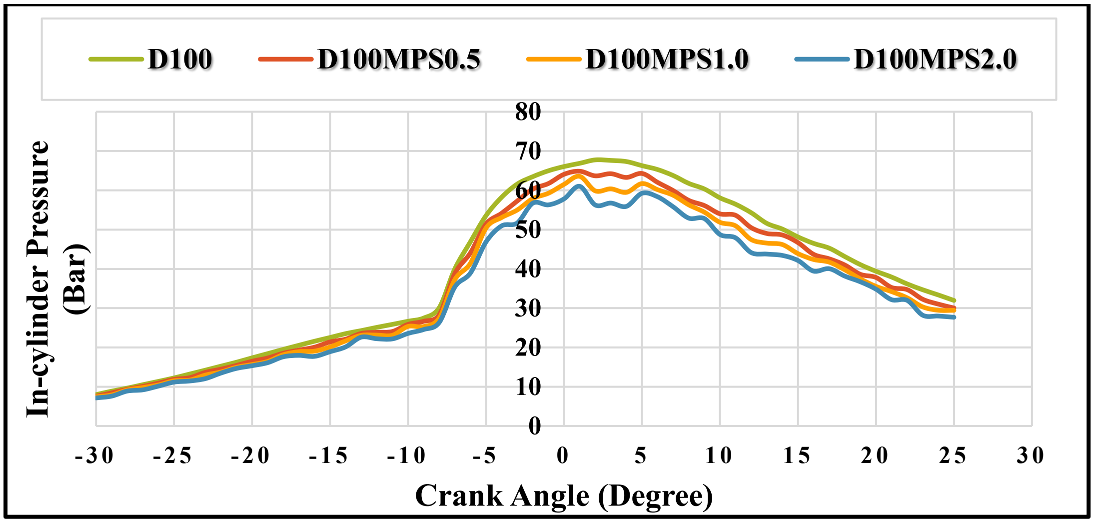

Figure 4.53. Cylinder Pressure Vs Crank Angle for Diesel with additive

For pure diesel, peak pressure dropped by 4.68%, 6.16%, and 9.93% for D100MPS0.5, D100MPS1.0, and D100MPS2.0, respectively. Likewise, adding 2% (v/v) MPS to the D95WCB5 blend led to a 10.72% decrease in pressure [250]. This reduction is attributed to the combined effects of antioxidants, cetane enhancers, and combustion catalysts in MPS, which optimize combustion by shortening ignition delay and advancing peak pressure timing toward TDC.

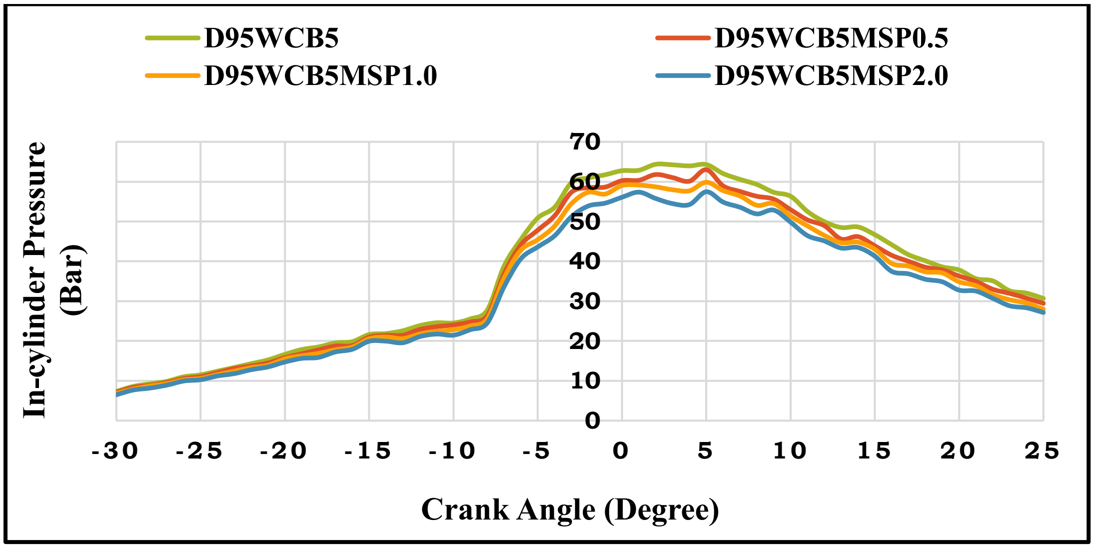

Figure 4.54. Cylinder Pressure Vs Crank Angle for Diesel-Biodiesel Blend with additive

Chapter 5

CONCLUSION AND FUTURE SCOPE

5.1.Conclusions

This study explores the feasibility and effectiveness of a novel multipurpose solution (MPS) as an additive for Bharat Stage VI (BS-VI) diesel and diesel–biodiesel blends, in accordance with the National Biofuel Policy. The key aim is to mitigate issues associated with ultra-low sulfur diesel, particularly its compromised lubricity and energy content. Fuel blends were prepared by incorporating MPS at 0.5%, 1.0%, and 2.0% (v/v) concentrations into neat diesel and a D95B5 blend. These were evaluated against standard BS-VI diesel (D100). The MPS was synthesized using cost-effective methods, characterized as per ASTM standards, and assessed for long-term stability and physico-chemical properties. Its tribological, combustion, performance, and emission characteristics were analyzed using a single-cylinder farmland diesel engine. Results were benchmarked against D100, B100, and D95B5 blends.

The following conclusions are derived from the comprehensive research undertaken:

1. BS-VI diesel exhibited a 95.8% higher coefficient of friction (COF) and a 73.5% greater mean wear scar diameter (MWSD) compared to BS-IV diesel, indicating significantly reduced lubricating properties due to desulfurization processes in BS-VI formulations.
2. BS-IV diesel demonstrated 5.45% higher (BTE) and 4.23% lower brake-specific fuel consumption (BSFC) at peak load relative to BS-VI diesel. These enhancements are attributed to the higher heating value and superior lubricity of BS-IV fuel.

3. The addition of a novel multipurpose solution (MPS) at concentrations of 0.5%, 1.0%, and 2.0% v/v to commercial BS-VI diesel significantly improved its tribological and performance characteristics.
4. The aromatic-rich composition of the MPS acted as surface-active agents forming protective tribofilms. As a result, reductions in MWSD were observed as follows: 25.79% for D100MPS 0.5, 46.08% for D100MPS 1.0, and 56.23% for D100MPS 2.0. Additionally, D100MPS 2.0 achieved a 55.08% reduction in COF compared to untreated BS-VI diesel.
5. The incorporation of MPS improved brake thermal efficiency across all engine loads for both neat diesel and biodiesel-diesel blends, with observed improvements in the range of 10% to 15%.
6. A notable decrease in brake-specific energy consumption (BSEC) was observed for all MPS-treated diesel and biodiesel-diesel blends, indicating enhanced fuel economy.
7. The use of MPS, formulated with antioxidants and cetane improvers, resulted in a reduction in NOx emissions from 1196 ppm to 1154 ppm for neat diesel and from 1298 ppm to 1185 ppm for the D95WCB5 blend at maximum brake mean effective pressure (BMEP).
8. All MPS-treated fuel samples consistently exhibited reduced hydrocarbon (HC), carbon monoxide (CO), and smoke emissions in comparison to neat BS-VI diesel, underscoring the effectiveness of the additive in lowering overall emissions.
9. A reduction in peak cylinder pressure and heat release rate (HRR) was observed upon the addition of MPS, with the maximum reduction ranging between 6% and 10% for both diesel and diesel-biodiesel blends, suggesting a smoother and more controlled combustion process.

5.2. Scope of Future Work

1. Future work should focus on refining the chemical composition of the multipurpose solution (MPS) by adjusting concentrations of aromatic compounds, antioxidants, and cetane improvers to achieve targeted improvements in both tribological and combustion characteristics.
2. Long-term investigations are necessary to evaluate the impact of MPS-treated fuels on engine durability, component wear, injector deposits, and after-treatment systems. Studies involving accelerated aging tests and real-world engine simulations will provide valuable insights into the stability, corrosion potential, and material compatibility of MPS formulations.
3. Future research should focus on evaluating additives with biocidal or anti-microbial properties that are compatible with existing MPS formulations. Investigating biofilm formation, fuel degradation, and filter clogging in storage tanks and vehicle fuel systems will be vital to ensuring fuel stability and cleanliness.
4. In the present work, biodiesel's blending ratio is limited to 5% by volume in the diesel. Further research is needed to explore the effect of the novel MPS on diesel blends containing higher proportions of waste cooking oil biodiesel.
5. The release of hybrid additives into the environment, either through combustion or accidental spillage, may pose ecological risks. Comprehensive environmental impact assessments (EIA) and life-cycle analysis (LCA) should be conducted to determine the toxicity, biodegradability, and regulatory alignment of the MPS components.
6. The behavior of MPS-treated fuels under advanced combustion modes such as Homogeneous Charge Compression Ignition (HCCI), Reactivity Controlled Compression Ignition (RCCI), and Partially Premixed Combustion (PPC) remains an open research area.

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APPENDICES

Appendix 1: Measured Parameters with their Accuracy and Uncertainty

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

Appendix 2: AVL Dismoke 480 BT Smoke Meter Technical Specifications

Description	**Data**
Make	AVL
Model	AVL DITEST MDS 205 (Modular Diagnostic system)
Weight	3.2 Kg
Dimensions	395 x 285 x 136 (W x H x D)
Humidity	max. < 90 %, non-condensing
Interfaces	RS232; Bluetooth Class1
Power Consumption	approx. 78 VA (incl. heating)
Chamber Heating	100°C
Measuring principle	Light Extinction Measurement
Light source	Halogen bulb 12 V / 5W
Detector	Selenium Photocell, diameter 45mm
Range	0-99%
Accuracy	0.1%
Max. Emission Temperature	200 °C
Measurement Length	215 mm ± 2 mm

Appendix 3: AVL Ditest 1000 Gas Analyzer Technical Specifications

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

LIST OF PUBLICATIONS

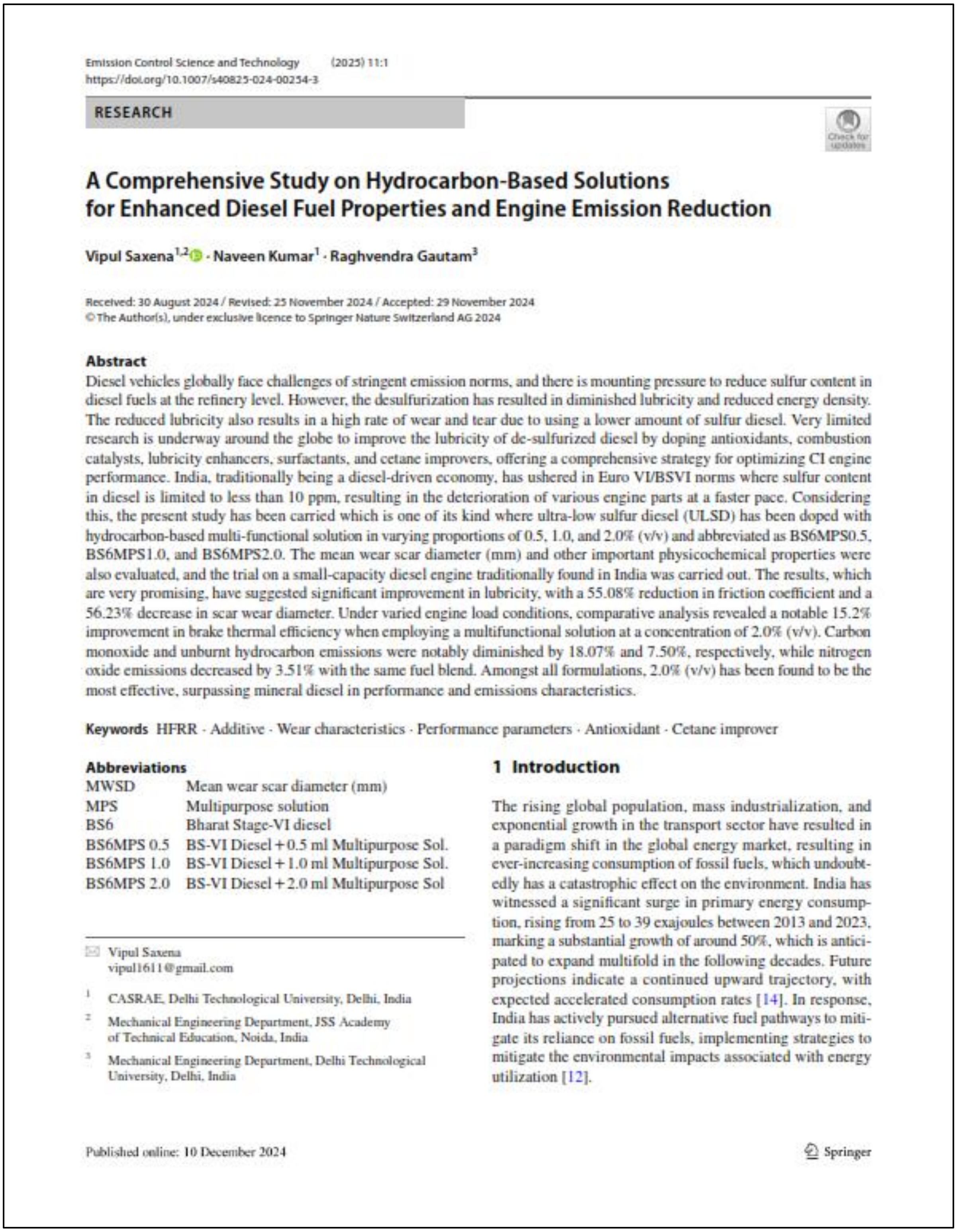
International Journals

1. **Saxena, V.,** Kumar, N. & Gautam, R. (2024) **A Comprehensive Study on Hydrocarbon-Based Solutions for Enhanced Diesel Fuel Properties and Engine Emission Reduction**. Emiss. Control Sci. Technol. 11, 1 (2025). https://doi.org/10.1007/s40825-024-00254-3 **Publisher- Springer, Impact Factor- 1.3 (Q2)**
2. **Saxena, V**., Kumar, N., & Gautam, R. (2022). **Experimental Investigation on the Effectiveness of Biodiesel Based Sulfur as an Additive in Ultra Low Sulfur Diesel on the Unmodified Engine.** Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(2), 2697–2714. https://doi.org/10.1080/15567036.2022.2059596 **Publisher: Taylor & Francis, Impact Factor- 2.3 (Q2)**

International Conferences

1. **Vipul Saxena**, Naveen Kumar, and Raghvendra Gautam, "**Improvement in Tribological Characteristics of commercial Diesel by using Fuel Additives**", International Symposium on Fusion of Science & Technology (ISFT-2024), January 4-8, 2024, JC Bose University of Science & Technology, YMCA, Faridabad, Haryana, India.
2. **Vipul Saxena**, Naveen Kumar, and Raghvendra Gautam, **"An Experimental Assessment of Diesel Engine Characteristics using Diesel/Argemone/Corn Biodiesel Blends"**, International Symposium on Fusion of Science & Technology (ISFT-2022) & 2nd RUSiCON, August 16-19, 2022, Rajamangala University of Technology Suvarnabhumi Thailand.
3. **Vipul Saxena,** Naveen Kumar, and Raghvendra Gautam, **"Comparative assessment of unmodified diesel engine characteristics with commercial diesels",** International Conference on mechanical engineering (INCOME-2021), 25-26 November 2021, Netaji Subhas University of Technology, New Delhi. **Lecture Notes in Mechanical Engineering Recent Trends in Thermal and Fluid Sciences, 2022, p. 209-217 https://doi.org/10.1007/978-981-19-3498-8_19 [Scopus]**

First Page of Publication



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RESEARCH

A Comprehensive Study on Hydrocarbon-Based Solutions for Enhanced Diesel Fuel Properties and Engine Emission Reduction

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Abstract

Diesel vehicles globally face challenges of stringent emission norms, and there is mounting pressure to reduce sulfur content in diesel fuels at the refinery level. However, the desulfurization has resulted in diminished lubricity and reduced energy density. The reduced lubricity also results in a high rate of wear and tear due to using a lower amount of sulfur diesel. Very limited research is underway around the globe to improve the lubricity of de-sulfurized diesel by doping antioxidants, combustion catalysts, lubricity enhancers, surfactants, and cetane improvers, offering a comprehensive strategy for optimizing CI engine performance. India, traditionally being a diesel-driven economy, has ushered in Euro VI/BSVI norms where sulfur content in diesel is limited to less than 10 ppm, resulting in the deterioration of various engine parts at a faster pace. Considering this, the present study has been carried which is one of its kind where ultra-low sulfur diesel (ULSD) has been doped with hydrocarbon-based multi-functional solution in varying proportions of 0.5, 1.0, and 2.0% (v/v) and abbreviated as BS6MPS0.5, BS6MPS1.0, and BS6MPS2.0. The mean wear scar diameter (mm) and other important physicochemical properties were also evaluated, and the trial on a small-capacity diesel engine traditionally found in India was carried out. The results, which are very promising, have suggested significant improvement in lubricity, with a 55.08% reduction in friction coefficient and a 56.23% decrease in scar wear diameter. Under varied engine load conditions, comparative analysis revealed a notable 15.2% improvement in brake thermal efficiency when employing a multifunctional solution at a concentration of 2.0% (v/v). Carbon monoxide and unburnt hydrocarbon emissions were notably diminished by 18.07% and 7.50%, respectively, while nitrogen oxide emissions decreased by 3.51% with the same fuel blend. Amongst all formulations, 2.0% (v/v) has been found to be the most effective, surpassing mineral diesel in performance and emissions characteristics.

Keywords HFRR · Additive · Wear characteristics · Performance parameters · Antioxidant · Cetane improver

Abbreviations

MWSD	Mean wear scar diameter (mm)
MPS	Multipurpose solution
BS6	Bharat Stage-VI diesel
BS6MPS 0.5	BS-VI Diesel + 0.5 ml Multipurpose Sol.
BS6MPS 1.0	BS-VI Diesel + 1.0 ml Multipurpose Sol.
BS6MPS 2.0	BS-VI Diesel + 2.0 ml Multipurpose Sol

1 Introduction

The rising global population, mass industrialization, and exponential growth in the transport sector have resulted in a paradigm shift in the global energy market, resulting in ever-increasing consumption of fossil fuels, which undoubtedly has a catastrophic effect on the environment. India has witnessed a significant surge in primary energy consumption, rising from 25 to 39 exajoules between 2013 and 2023, marking a substantial growth of around 50%, which is anticipated to expand multifold in the following decades. Future projections indicate a continued upward trajectory, with expected accelerated consumption rates [14]. In response, India has actively pursued alternative fuel pathways to mitigate its reliance on fossil fuels, implementing strategies to mitigate the environmental impacts associated with energy utilization [12].

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Experimental Investigation on the Effectiveness of Biodiesel Based Sulfur as an Additive in Ultra Low Sulfur Diesel on the Unmodified Engine

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ABSTRACT

Adequate lubricity and energy content play a significant role in fuel injection and performance in the diesel engine. The major challenge with ultra-low sulfur diesel (ULSD) is lower lubricity. This study aims to perform experimental analysis to investigate the wear behavior of commercial diesel with biodiesel-based sulfur (BBS) solution as an additive and examine the engine characteristics. BBS is a novel solution with higher ester and sulfur content (500 ppm). By doping this novel solution, two test fuels, BS6D1 and BS6D2 were prepared with a sulfur concentration between BS4 and BS6 commercial diesels. Compared to BS6 commercial diesel, the BS6D2 sample showed a significant reduction in mean wear scar diameter (MWSD) and coefficient of friction (COF) by 43.97% and 33%, respectively. At peak load, BS6D2 had 4.13% higher brake thermal efficiency than BS6 diesel. Due to enhanced ignition quality, the brake-specific energy consumption (BSEC) for the BS6D2 sample was found to be the lowest, i.e., 3.85% less than BS6 diesel. Furthermore, a significant reduction in exhaust pollutants for BS6D2 sample compared to BS6 diesel at maximum loads, such as smoke opacity (14.06%), unburnt hydrocarbon (8.82%), and carbon monoxide (20.45%). In conclusion, the BS6D2 sample produces the best results of all the tested fuel samples evaluated on the unmodified diesel engine.

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KEYWORDS
Commercial diesel; high-frequency reciprocating rig (HFRR); performance; emissions; sulfur doping

Introduction

According to the statistical analysis of the world's energy report 2020, the contribution of fossil fuel was around 84% of the total energy demand in the year 2019 (BP 2020). Diesel is the most dependable fuel in power efficiency and robustness (Khalife et al. 2017). Diesel engines contribute significantly to hazardous emissions like CO, NO_x, PM, CO2, and UBHC. Vehicle emissions adversely affect human health and air quality (Panda and Ramesh 2021). As pollution levels in the environment continue to rise, strict emission regulations have been enacted. So, there are three ways that several researchers have established to implement them successfully stringent emission norms; modification in operating parameters, after-treatment devices, and fuel chemistry (Kang et al. 2018).

(Nayak et al. 2022) analyzed the influence of advancement in injection timing with 24°bTDC in CI engine with biogas and waste oil methyl ester as a dual fuel system. At peak load, higher BTE (2.40%) and lower EGT (15.77%) were observed along with a significant reduction in UBHC (44.5%), CO (61.72%), NO_x (64.13%), and smoke intensity (47.42%) compared to diesel fuel. To achieve improved characteristics of diesel engines, another study was performed by (Rajesh Kumar et al. 2016) to establish the collective impact of exhaust gas recirculation and infusion timing with the advanced

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First Page of Conference Paper

Comparative Assessment of Unmodified Diesel Engine Characteristics with Commercial Diesels

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Abstract As a result of the current ecological situation, it has become necessary to change the nature of fuel to limit the harmful effects of sulfur, which directly leads to SO_2 emissions and reduces the engine's life due to corrosion. In light of the recent mandate, the amount of sulfur in diesel was reduced from 50 to 10 ppm or even less to comply with green climate conditions. However, diesel desulfurization promotes a loss in lubricity due to the low level of aromatic and polar compounds in diesel. Diesel's low lubricity affects the chemical lubrication process of injectors, engine performance, and combustion. The purpose of this research was to compare engine characteristics between commercial Bharat Stage IV and Bharat Stage VI diesel. According to the results of the tests, Bharat Stage IV diesel has 3.52% better brake thermal efficiency and 4.23% less brake-specific fuel consumption at peak load than Bharat Stage VI diesel. As a part of the combustion process, in-chamber pressure, the pace of pressure rises, and the pace of dissipation of heat were measured, and it was discovered that Bharat Stage IV diesel has better combustion characteristics than Bharat Stage VI diesel on an unmodified diesel engine due to its better lubricity.

Keywords Performance · Combustion · Bharat stage · Desulfurization

1 Introduction

In modern times, the development of any nation is dependent on the availability and utilization of energy. Crude oil is a significant source of energy, accounting for more than one-third of global primary energy demand. Crude oil consumption is increasing day by day as the economy's prime mover, primarily in developing countries such

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A BRIEF BIOGRAPHICAL SKETCH

Mr. Vipul Saxena is an accomplished academician and researcher in the field of **Mechanical Engineering**. He holds a **Master of Technology (M.Tech.)** with **First Division and Honors** from **MNNIT, Prayagraj**, and a Bachelor of Technology (B.Tech.) in Mechanical Engineering from **BSA College of Engineering & Technology, Mathura**, affiliated with UPTU, Lucknow. Currently, he is pursuing a **Ph.D**. from **Delhi Technological University (DTU),** where he is associated with the **Centre for Advanced Studies and Research in Automotive Engineering (CASRAE).** His doctoral research focuses on the role of fuel additives in enhancing the performance of commercial diesel.

Since **August 2010**, Mr. Saxena has been serving as an Assistant Professor in the Department of Mechanical Engineering at **JSS Academy of Technical Education (JSSATE), Noida**. He has consistently demonstrated excellence in teaching, mentoring, and curriculum development. In addition to his academic responsibilities, he has been actively contributing as the **Assistant Training & Placement Officer** since **August 2022**. In this role, he has successfully coordinated student training, facilitated industry collaboration, and played a vital part in improving the placement outcomes for students. Prior to joining JSSATE, he served as an Assistant Professor at the **GLA Group of Institutions, Mathura**, where he gained early experience in teaching and academic mentorship.

Mr. Saxena is also a dedicated researcher, having authored **two** SCI-indexed research papers and **twelve** more in reputed peer-reviewed journals and conferences, including those by **Springer and Taylor & Francis**. His research primarily explores alternative fuels, diesel engine performance, and emissions, contributing meaningfully to the advancement of sustainable automotive technologies.

In addition to his academic pursuits, he actively participates in sports and extracurricular activities. He has been part of winning teams in **football, volleyball, and tug of war** at the college level. A **three-time GATE qualifier (2007, 2013, and 2014)**, Mr. Saxena's strong technical foundation reflects his commitment to continuous learning and professional development.

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2007 Bachelor of Technology (B.Tech.) **(Mechanical Engineering)** with **1st Division** from **BSA College of Engineering & Technology,** Mathura **(Uttar Pradesh Technical University, Lucknow)**.

2003 Higher Secondary Certificate with **1st Division** from VPIC, Panki, Kanpur (**UP Board**).

2001 Senior Secondary Certificate with **1st Division** from VPIC, Panki, Kanpur (**UP Board**).

Academia Projects

During M. Tech.: The topic of MTech. The dissertation was **"Deformation Analysis of Human Musco-skeletal System During Gait Cycle"** Here an attempt has been made to study the Mechanical Behavior of Human Leg Skeletal Muscle for gait cycle. The model describes the mechanical behavior with an explicit strain-energy function associated with the active response of skeletal muscle tissue during gait cycle. A strain energy density function that relates the strain energy density of a material to the deformation gradient. In the present model, the formulation is done in longitudinal extension, transverse extension, longitudinal shear, and transverse shear cases after application of load (body weight) for the upper leg and lower leg muscle.

During B. Tech.: During the final year of graduation (B.Tech.), I have done a project on the topic of **"Hybrid Chimney"**. This project aim was to design and fabricate a model to generate electricity with the help of wind energy as well as solar energy. This model is most suitable for coastal areas.

Industrial Training/Summer Internship

Organization: Hindustan Aeronautics Limited, Lucknow (2006).

Training: Hands on Training on various Machines in **Machine Shop (Mechanical).**

One month Certification course in "Foundation in Mechanical CADD" from CADD Centre, Lucknow (2006).
Organization : Panki Thermal Power Station, Panki, Kanpur (2005).

Area of Training: Attain Knowledge of Electricity production through various operations (like Pulverization of coal, coal handling, Demineralized water treatment plant, boiler division, turbine division, ESP, Control room functioning etc. through **Operation General Division -1**.

Research Publications

- ☑ **Saxena, V**., Kumar, N. & Gautam, R. (2024) **"A Comprehensive Study on Hydrocarbon-Based Solutions for Enhanced Diesel Fuel Properties and Engine Emission Reduction".** Emiss. Control Sci. Technol. 11, 1 (2025). https://doi.org/10.1007/s40825-024-00254-3. Publisher- Springer, Impact Factor- 1.3 (Q2)
- ☑ Shivam Singh, Shivangi Rupam, Vaibhaw Raj, Abhishek Kumar Shukla, **Vipul Saxena**, **"Shape Variation Effects on Performance of Closed Loop Wind Tunnel: A CFD Analysis"**, The 4th Biennial International Conference on Future Learning Aspects of Mechanical Engineering, 31st July to 2nd August 2024, Amity University, Noida, Uttar Pradesh, India.
- ☑ Pranav Kushwaha, Pratham Bhatt, Prakher Saxena, Nandini Agarwal, **Vipul Saxena**, **"Comparative Analysis of a Flat Plate Solar Collector with Different Glazing Materials"**, The 4th Biennial International Conference on Future Learning Aspects of Mechanical Engineering, 31st July to 2nd August 2024, Amity University, Noida, Uttar Pradesh, India.
- ☑ **Vipul Saxena**, Naveen Kumar, and Raghvendra Gautam, **"Improvement in Tribological Characteristics of commercial Diesel by using Fuel Additives"**, International Symposium on Fusion of Science & Technology (ISFT-2024), January 4-8, 2024**,** JC Bose University of Science & Technology, YMCA, Faridabad, Haryana, India.
- ☑ Shivam Singh, Shivangi Rupam, Vaibhaw Raj, Abhishek Kumar Shukla, **Vipul Saxena**, **"CFD Analysis of Close Loop Wind Tunnel with Shape Variation in Loop"**, International Symposium on Fusion of Science & Technology (ISFT-2024), January 4-8, 2024**,** JC Bose University of Science & Technology, YMCA, Faridabad, Haryana, India.
- ☑ **Vipul Saxena**, Naveen Kumar, and Raghvendra Gautam, **"An Experimental Assessment of Diesel Engine Characteristics using Diesel/Argemone/Corn Biodiesel Blends"**, International Symposium on Fusion of Science & Technology (ISFT-2022) & 2nd RUSiCON, August 16-19, 2022**,** Rajamangala University of Technology Suvarnabhumi Thailand.
- ☑ Saxena, V., Kumar, N., & Gautam, R. (2022). **"Experimental Investigation on the Effectiveness of Biodiesel Based Sulfur as an Additive in Ultra Low Sulfur Diesel on the Unmodified Engine".** Energy Sources, Part A: Recovery, Utilization, and

Environmental Effects, 44(2), 2697–2714. https://doi.org/10.1080/15567036.2022.2059596 . Publisher: Taylor & Francis, Impact Factor- 2.3 (Q2)

☑ **Vipul Saxena**, Naveen Kumar, and Raghvendra Gautam, **“Comparative assessment of unmodified diesel engine characteristics with commercial diesels”**, International Conference on mechanical engineering (INCOME-2021), **Lecture Notes in Mechanical Engineering (Springer Nature) [Scopus].**

☑ Abhishek Chauhan, Ankit Prakash, Anand Mani, Anmol Kumar, **Vipul Saxena, “A Review of Physical Properties, Emission and Performance Improvement Analysis of Biodiesel-Diesel Blends Obtained from Different Feedstocks”**, International Research Journal of Engineering and Technology (IRJET), Volume: 08 Issue: 06 | June 2021

☑ **Vipul Saxena, “A Study on Enhancement of the Oxidation Stability and Wear Behavior of Edible & Non-Edible Oil Methyl Esters using Partial Hydrogenation Method”,** Journal of Biofuels, 0976-3015. Online ISSN: 0976-4763. Published online: 2020 09.

☑ Rishabh Chaudhary, Srishti Singh, Vaibhav Kumar Pathak, **Vipul Saxena, “Design Optimization of Torque Link of an Aircraft Landing Gear Assembly”,** International Conference on Future Trends in Materials and Mechanical Engineering (ICFTMME-2020), November 6-7, 2020, SRM Institute of Science and Technology, Delhi-NCR Campus, Ghaziabad, U.P., India, **Lecture Notes in Mechanical Engineering (Springer Nature) doi.org/10.1007/978-981-16-0673-1_12 [Scopus]**.

☑ **Vipul Saxena**, Prem Shankar Yadav, **“Parametric Study of Deep Drawing Process”,** Intelligent Control and Computation for Smart Energy and Mechatronics Systems (ICCSEMS–2020), JSSATE, NOIDA.

☑ **Vipul Saxena**, H.S Pali, **“Structural and Magnetic Analysis of Electro Magnetic Suspension Spring”**, International Symposium on Fusion of Science & Technology (ISFT-2020), January 6-10, 2020, JC Bose University of Science & Technology, YMCA, Faridabad, Haryana, India. **IOP Conf. Series: Materials Science and Engineering** 804 (2020) 012022 IOP Publishing doi:10.1088/1757-899X/804/1/012022 **[Scopus]**.

☑ Shivam Singh, Sulabh Upadhyay, Swapnil Mishra, Vasu Agarwal, **Vipul Saxena, “Water Cooler Integrated with Dual Axis Solar Tracker”,** IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 17, Issue 3 Ser. IV (May - June 2020), PP 10-17.

☑ Rishabh Chaudhary, Srishti Singh, **Vipul Saxena, “Static Structural Analysis of Landing Gear for Different Titanium Alloys”,** International Research Journal of Engineering and Technology (IRJET), ISSN: 2395 – 0056, Volume-06 Issue-7, July 2019.

☑ Rishabh Chaudhary, Srishti Singh, **Vipul Saxena, “Linear Buckling Analysis of Landing Gear”,** International Journal of Engineering and Advanced Technology (IJEAT), ISSN: 2249 – 8958, Volume-8 Issue-6, August 2019 **[Scopus]**.

☑ **Vipul Saxena**, P S Yadav, H.S Pali, **“Effect of Magnetic Abrasive Machining Process Parameters on Internal Surface Finish”,** 2nd International Conference on Computational & Experimental methods in Mechanical Engineering (ICCEMME-2019), May 3-5, 2019, G.L. Bajaj Institute of Technology & Management, Greater Noida, Materials Today: Proceedings 25 (2020) 842–847 **[Web of Science]**.

☑ **Vipul Saxena,** Anupam Tripathi, Anurag Mishra, Amod Kumar, Abhinav Kumar Yadav, **“Power generation using speed bumps”,** SSRN electronic journal, June-2019, http://dx.doi.org/10.2139/ssrn.3387562.

☑ **V Saxena,** P S Yadav, H S Pali, N Kumar, S N Singh, “**Effect of Mast Modification in Ingress Problem in Gas Turbine of Naval Ship”,** 2nd International conference on New Frontiers in Engineering, Science & Technology (**NFEST-2019,** February 18-22, 2019**,** National Institute of Technology Kurukshetra. **IOP Conf. Series: Journal of Physics:** Conf. Series 1240 (2019) 012076, IOP Publishing doi:10.1088/1742-6596/1240/1/012076 **[Scopus]**.

☑ **Vipul Saxena,** Kalash Singhal, Gaurav Prajapati, “**Solar Powered Seed Sowing Machine”,** International Journal of Applied Engineering Research, ISSN 0973-4562 Volume 13, Number 6 (2018) pp. 259-262.

☑ **Vipul Saxena**, Rohit Singh, Shyam Kishor Sharma, Shivendra Singh, Shubham Tyagi, **“Effect of blade thickness on the natural frequency of H-rotor Vertical Axis Wind Turbine”**, International Conference on Advances in Dynamics, Vibration and Control (ICADVC-2018), June 6-8, 2018. National Institute of Technology Durgapur West Bengal, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) **[Scopus]**.

☑ **Vipul Saxena,** Rajesha S., **“Development of Aluminum Based Metal Matrix Composite and its Characterization”** International Conference on Advances in Business and Engineering Sustainability (ABES-2018), March 27-28, 2018, ABES Engineering collage, Ghaziabad.

☑ **Vipul Saxena,** Binit Kumar Jha, Neelam Khandelwal, Prateek Singh **“Design and Fabrication of Solar Powered Water Dispenser”** International Conference on Sustainable Development in Design & Manufacturing (ICSDDM-2017), January 12-13, 2017, Saraswati Engineering college, Mumbai.

☑ **Vipul Saxena,** Ravi Prakash Tewari, Rakesh Mathur**, “Mechanical Behaviour of Human Leg Skeletal Muscle for Gait Studies”** International Conference on Biomechanics (WCB-2010), Singapore, IFMBE proceeding, Springer **[Scopus]**.

☑ **Vipul Saxena,** Ravi Prakash Tewari, **Large Deformation of Human Skeletal Muscle System”**, Indian Journal of Bio-Mechanics. Special Issue NCBM-2009 ISSN 0974-0783.

☑ **Vipul Saxena,** Ravi Prakash Tewari, “**Mathematical Modelling of Human Skeleton Muscle System”** National Conference of Biomechanics (NCBM-2009) at IIT Roorkee.

☑ **Vipul Saxena,** S J Pawar, “**High Temperature Super Conducting Ceramic Magnets and Its Effect on The Societal Development**” in a National Conference CMP degree College at Allahabad (2008).

Training/Workshop/FDP/e-Symposium

☑ Certificate of participation in one day workshop on **“Navigating India’s Energy Landscape: Challenges, Potential and Solutions in 2050”** held on 25th April 2024 organized by Mechanical Engineering Department Delhi Technological University, Delhi.

☑ Certificate of participation in Faculty development Program on **“NEP2020 Orientation & Sensitization Program”** under Malaviya Mission Teacher Training Program (MM-TTP) of

University Grants Commission (UGC) organized by UGC-MMTTC Shri Mata Vaishno Devi University, Katra, Jammu from 12th February to 22nd February 2024.

☑ Certificate of participation in one day workshop on **“Innovative ways to Optimize your LinkedIn Profile for better visibility, outreach and Career Prospects”** organized by SEMS Welfare Foundation in collaboration with JSS Academy of Technical Education, Noida held on 22nd December 2023.

☑ Certificate of participation in Faculty development Program on **“Industry 4.0 Skill Development using AICTE IDEA LAB”** AICTE-ATAL Academy, organized by Electrical & Electronics Engineering Department, JSS Academy of Technical Education, Noida held on 20th November to 25th November 2023.

☑ Certificate of participation in Two days Workshop as part of **National Event: Sustainable India 2023** at JSS Academy of Technical Education, Noida held on 21st &22nd November 2023.

☑ Certificate of participation in Two days Workshop on **“Capacity Building”** organized by Mechanical Engineering Department, JSS Academy of Technical Education, Noida held on 05th &06th September 2023.

☑ Certificate of participation in one day workshop on **“Frugal Engineering & innovation: a Roadmap for Engineering students”** held on 22nd August 2023 organized by Mechanical Engineering Department Delhi Technological University, Delhi.

☑ Certificate of participation in one day workshop on **“Use of Robotics & New Technology for Engineering Faculty & Students”** held on 29th July 2022 organized by Mechanical Engineering Department Delhi Technological University, Delhi.

☑ Certificate of participation in professional development Program on **“Recent Developments in Renewable Energy”** organized by Mechanical Engineering Department, Amity School of Engineering and Technology, NOIDA held on 20th June to 24th June 2022.

☑ Certificate of participation in webinar on **“Simple ways to improve student’s classroom performance and experience”** collaboration with CASRAE-DTU-IMechE chapter by Prof. Autar Kaw, professor at University of South Florida, USA held on to 11th April 2022.

☑ Certificate of participation in Faculty development Program on **“AICTE Student Learning Assessment – STTP- PARAKH”** AICTE & Construction Industry Development Council (CIDC) held on 22nd Nov to 19th December 2021.

☑ Certificate of participation in Faculty development Program on **“Opportunity and Challenges for Electric Vehicles in the Automotive Industry”** AICTE-ATAL Academy, organized by Mechanical Engineering Department, National Institute of Technology, Srinagar held on 26th July to 30th July 2021.

☑ Certificate of participation in Faculty development Program on **“Green Technology & Sustainability Engineering- Advanced Computational Fluid Dynamics”** AICTE-ATAL Academy, organized by Mechanical Engineering Department, Institute of Engineering & Technology, Lucknow held on 23rd to 27th November 2020.

☑ Certificate of participation in Faculty development Program on **“Mathematical Modelling & its Applications in Engineering”** AKTU-AICTE Short Term Training Program organized by Applied Sciences & Humanities Department, Institute of Engineering & Technology, Lucknow held on 06th to 10th July 2020.

- ☑ Certificate of participation in Faculty development Program on **“Biofuels & Its Applications in I C Engines”** organized by Department of Mechanical Engineering, MEA Engineering College, Perinthalmanna held on 01st to 05th June 2020 **[ONLINE]**.
- ☑ Certificate of participation in Faculty development Program on **“Mechanical Design Techniques for Academic and Industrial Environment”** sponsored by AICTE, organized by JSSATE, NOIDA held on 08th to 20th July 2019.
- ☑ Certificate of participation in Faculty development Program on **“Instructional Design Delivery System Embedded with Useful/State of the Art Software Tools”** sponsored by AKTU, Lucknow organized by JSSATE, NOIDA held on 27th to 01st September 2018.
- ☑ Certificate of participation in Faculty development Program on “**Manufacturing World and Its Future**” sponsored by AKTU, Lucknow organized by JSSATE, NOIDA held on 23rd April 2018 to 28th April 2018.
- ☑ Certificate of participation in Faculty development Program on “**Universal Human Values & Professional Ethics**”, organized by TEQIP-III and conducted by Value Education Cell, AKTU, Lucknow held on 19 December 2017 to 26 December 2017 at NIET, Gautam Budh Nagar.
- ☑ Certificate of participation in Faculty development Program on “**Innovative Approach to Skill Development and Employment Generation in India**”, through ICT conducted by NITTTR, Chandigarh held on 24 July 2017 to 28 July 2017 at JSSATE NOIDA.
- ☑ Certificate of participation in Faculty development Program on “**Research Methodology**”, through ICT conducted by NITTTR, Chandigarh held on 28 December 2015 to 08 January 2016 at JSSATE NOIDA.
- ☑ Certificate of participation in one day workshop on “**Industrial Robotics**” held on 23rd September 2015 at TIFAC, Centre of Relevance and Excellence, AKGEC, Ghaziabad.
- ☑ Certificate of participation in Faculty development Program on “**Instructional Planning & Delivery (module-II- Instructional delivery)**”, through ICT conducted by NITTTR, Chandigarh held on 11 May 2015 to 15 May 2015 at JSSATE NOIDA.
- ☑ Certificate of participation in one week training program on “**CNC Turning and Milling-Hands on Experience**” organized by department of Manufacturing Technology, held on 09th June 2014 to 14th June 2014 at JSSATE, NOIDA.
- ☑ Certificate of participation in “**NBA Workshop one day webinar and three days personal training”** conducted by NBA, New Delhi with Nodal & Training Centre JSSATE, NOIDA held on 22nd February 2014 to 24 February 2014 at JSSATE NOIDA.
- ☑ Certificate of participation in National workshop on **“Deployment & Use of NPTEL Courses”,** organized by IIT, Kanpur in collaboration with JSSATE, NOIDA held on 30-31st October, JSSATEN.

Webinar/Workshop/Conferences organized

- ☑ Organized a webinar on **“Simple ways to improve student’s classroom performance and experience”** collaboration with CASRAE-DTU-IMechE chapter by Prof. Autar Kaw, professor at University of South Florida, USA held on to 11th April 2022.

- ☑ Organized an online workshop on **"Beyond Petroleum-The Strategies for Future Energy Needs"** collaboration with CASRAE-DTU-IMechE chapter held on 27th March 2022.

Computer Proficiency

IT FORTE: BRG.LifeMod-7.1, ANSYS-10, AUTOCAD, Pro-E, CATIA, Conversant with Windows, MS Office, and Internet Applications

Beyond Curriculum Activities & Achievements

- ☑ Reviewer in Energy Sources, Part A: Recovery, Utilization, and Environmental Effects
- ☑ Reviewer in the International Conference (FLAME-2024) at Amity University, NOIDA
- ☑ Received Best Faculty Award at Department Level in year 2020-21
- ☑ Received Best Paper Award in the session in INCOME-2021 at NSUT, New Delhi
- ☑ Reviewer in the International Conference (FLAME-2019) at Amity University, NOIDA
- ☑ Received Best Faculty Award at Department Level in the year 2016-17
- ☑ Member of winning team TUG of War at college level (2015,2016)
- ☑ Qualified in GATE 2014 Examination, GATE Score: 474
- ☑ Qualified in GATE 2013 Examination, GATE Score: 400
- ☑ Member of the winning Volleyball team at college level (2008).
- ☑ Qualified in GATE 2007 Examination, GATE Score: 329
- ☑ Member of the winning football team at college level (2006).

Personal Dossier

Date of Birth : 16th November 1986

Marital Status : Married

Gender : Male

Nationality : Indian

Permanent Address : Flat No. 058, H-Tower, 16th Avenue, Gaur City-2, Gr. NOIDA (West),
Gautam Buddha Nagar, UP- 201009.

Contact Number : 09599200739

Declaration: All the above information provided is correct to the best of my knowledge.

(Vipul Saxena)