Chapter 3 Material and Methodology

This chapter discusses the process of preparing biodiesel, the properties of the fuel blends, the measuring instruments used to measure various parameters of the test rig during the experiment, the methodology followed for the experiment, and the uncertainty involved in the experiment.

3.1 Madhuca longifolia (Mahua)- a biodiesel feedstock

India is home to five distinct varieties of mahua, out of the approximately 84 varieties that exist. These varieties can be differentiated based on their leaf structure.[110][111]. Madhuca longifolia, latifolia, butyracea, bourdillonii, and neriiolia are the 5 scientific names for Indian species. [111][112]. Indian forests are home to the well-known Mahua tree, which is a member of the Sapotaceae family. It is a multi-use tree known by different names in different geographical areas of the country. People in India call it Mahua, Mohua, Mahula, Mowrah, Moha, Mova, Mahuda, Dodi, and so on. These trees thrive in a variety of soils, but none more so than on alluvial soil. A sandy-loam, deep loamy soil with good drainage is best suited for increased development and productivity. The tree has a wide, spreading, strong root system that catches the soil lump together and prevents soil erosion.[111]

The components, like roots, bark, fruits, and seeds, of the mohua are medicinal. The wood of mohua is very strong, hefty, and brown. The bark of mahua is rough and grayish, with cracks and wrinkles. The leaves of mahua are thick and oblong; when split, they release a milky sap. The flowers of Mahua are cream-colored and cluster at the ends of the branches. Mahua flowers, which are eaten fresh, are high in carbs, proteins, minerals, and vitamins.[113] Figure 3-1[111] also depicts mahua blooms and dried flowers. Fruits are elliptical and around 1.19–1.95 inches long, with fleshy greenish flesh. As seen in Figure 3-1 a fruit of mahua bears 1-4 sparkling elliptical-shaped brown-colored seeds. The biodiesel of mahua minimizes dependency on fossil fuels.

The global warming potential (GWP) was determined to be 7 times lower than the Petro-diesel value, and it was reported that the acidification and eutrophication potential of the Mahua system were negligible.[114]. Diesel vehicles release 11 pm per MJ, while biodiesel releases less than 0.01 pm per MJ, potentially contributing significantly to pollution-free air. [111][115].

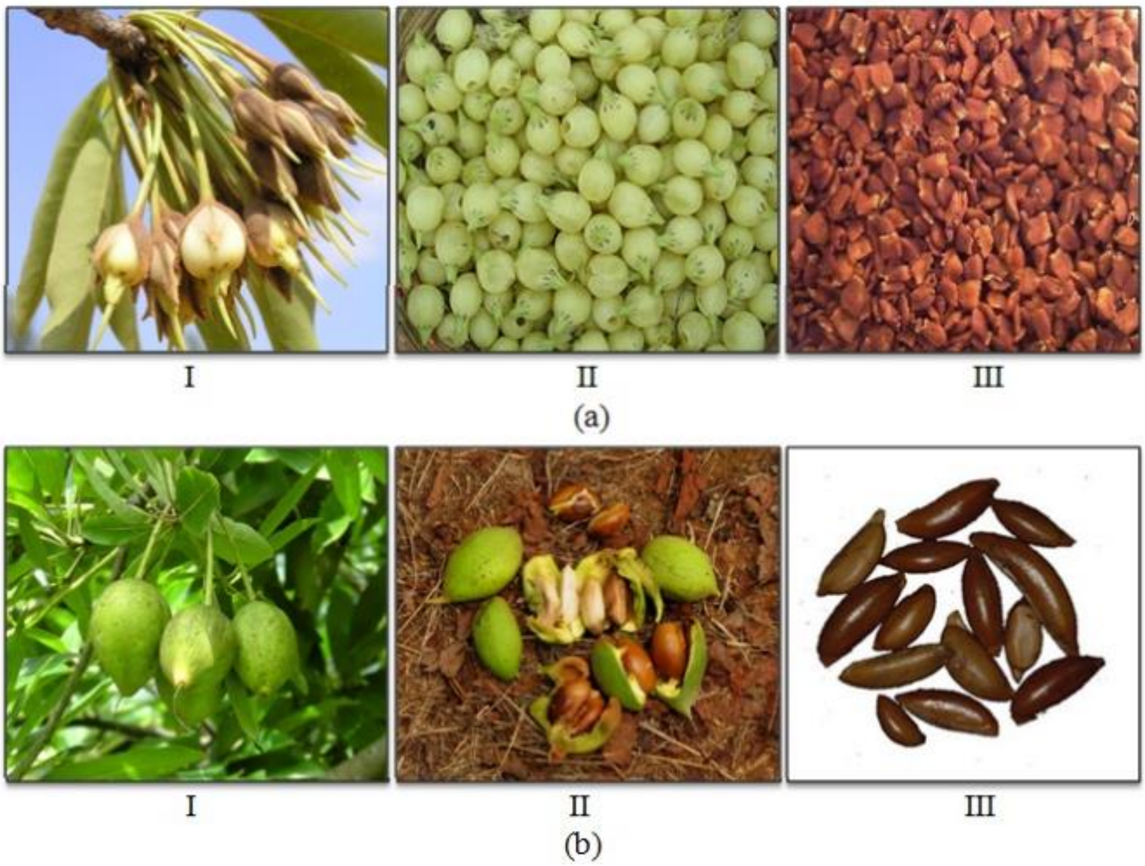

Figure 3-1: (a) Mahua flowers and (b) Mahua fruits with seeds

Table 3-1:Madhuca longifolia (A year cycle)

	February	March	April	May	Jun	July	August	September
Blossom	■	■	■	■				
Fruits		■	■	■				
Leaf Fall		■	■					
Pods				■	■	■	■	
New leaf				■	■	■	■	
Seeds					■	■	■	■

The biodiesel of mahua minimizes dependency on fossil fuels. Researchers determined the. Furthermore, from this process, mahua seed cake is obtained, and it is used as fertilizer, detergent, pesticide compost for earthworms, organic shampoos, burns of seed cakes for mice and insects, and so on. Alternatively, it finds application in the production of biogas and activated charcoal. The mahua system's NEG is 17.17 MJ/working unit. When compared to Jatropha and the Pongamia biodiesel system, the Mahua plant has a higher CO_2 sequestration potential (from 0.2 to 5.8 t CO_2/hectare).[111] Mahua seed output ranges from 10–225 kilograms per tree. The age and size of the tree primarily determine the output of mahua seeds. The projection for mahua seed oil extraction in India is 18 lakh metric tons per year.[116]. Mahua seed has 315.51ppb of total aflatoxin, while mahua oil contains 220.66ppb.[111][117]. It also contains saponins and tannins that are harmful to humans, and as a result, Madhuca Longifolia oil is classified as non-edible.[111][118]

3.1.1 Preparation of Biodiesel Fuel

Madhuca longifolia oil has been collected from the local wander at village Kavant in the Chhotaudepur district of Gujarat. The transesterification process is used to produce biodiesel from the oil. Transesterification, in essence, is the chemical conversion of triglycerides with alcohol into alkyl esters with the help of a catalyst. Methanol and ethanol are the most commonly used alcohols in this process due to their low cost and easy availability. The Figure 3-2 illustrates the transesterification process.

1. **Material**: 1-liter oil sample, methanol, KOH solution, methanol, three-neck glass flask, heating mental, separating funnel with bottom-side valve.
2. **Pre-treatment:** 1 liter of Madhuca longifolia oil is cleaned and heated for 2–5 minutes at 60 °C. It was poured into a flask with three necks. This 3-neck glass container is heated mentally and has the magnetic stirring capability. Figure 3-3 depicts the setup. A thermocouple was installed to measure temperature. For dehydration and impurity filtration, the oil is heated for 10 minutes between 60°C to 65°C. It is then allowed to return to room temperature.[119]
3. **Transesterification:** A base catalyst is used for this process. 15 gm potassium hydroxide (KOH) blended with 300 ml of methanol (CH_3OH). The solution derived was placed in the oil for 60 minutes at 60 °C. [119]
4. **Separation:** Glycerin and fatty acid methyl ester (FAME) separated after an hour of transesterification reactions. The settling and separation process takes approximately 8–10 hours. The separation unit is shown in Figure 3-4. The bottom layer of glycerine separated, and biodiesel in the form of FAME was derived. To condense ethanol, a condenser was utilized.

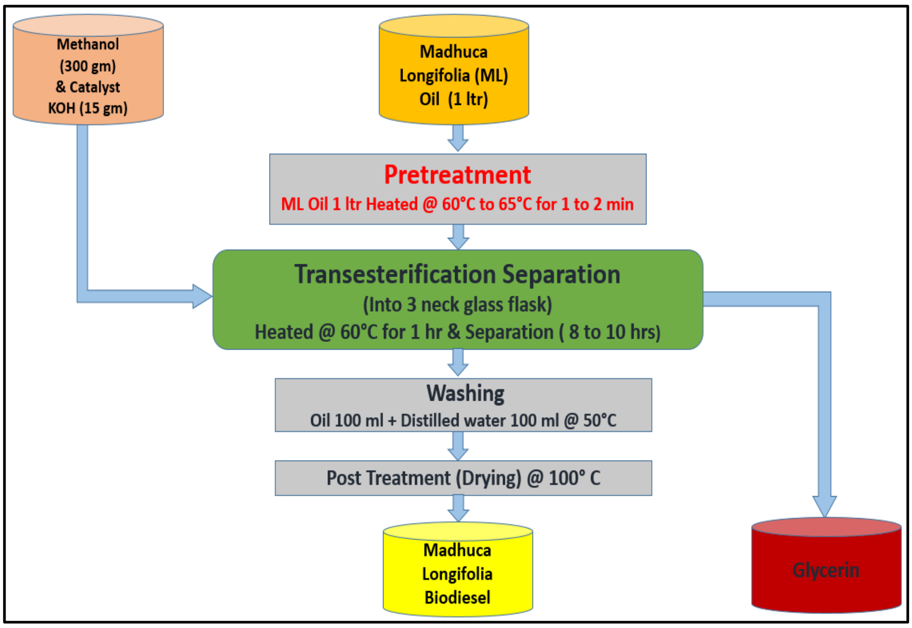

Figure 3-2:Transesterification Process

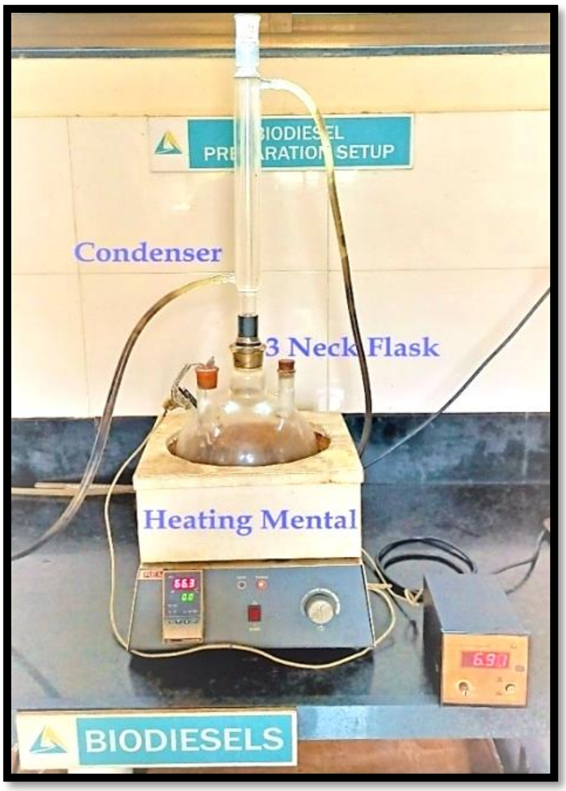

Figure 3-3:Biodiesel Preparation Setup

For water washing, 100 ml of distilled water at 50 degrees Celsius was blended with 100 ml of oil. Methanol and associated impurities are rinsed away in water. Water, on the other hand, can be added to oil. We obtained a yield of 85% to 90%. in the production of Madhuca longifolia methyl ester (MLME).

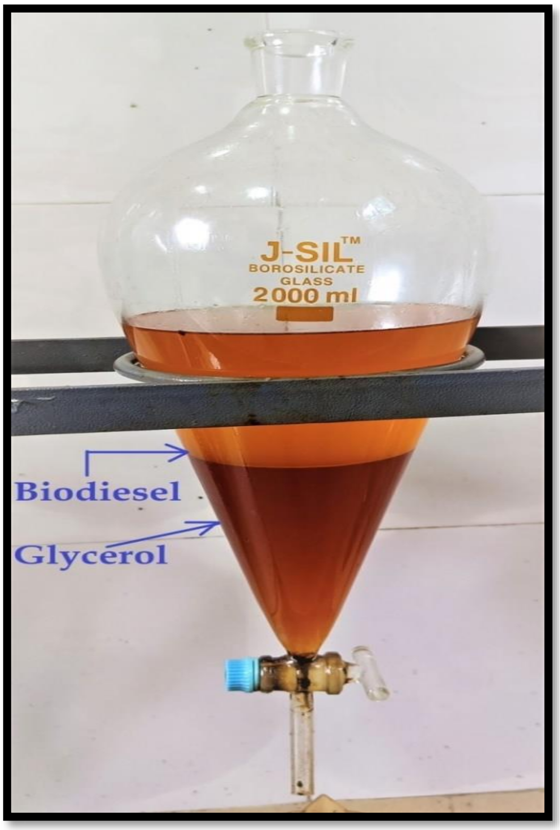

Figure 3-4:Biodiesel and glycerol separation

3.1.2 Madhuca Longifolia Biodiesel Blends Properties:

For the experimentation, four types of fuels are used. i.e. B0, B10, B20, B30. Table 3-2 shows the notation for Madhuca Longifolia biodiesel and diesel blends. For example, in a B10 biodiesel blend, the volume percentage of ML biodiesel is 10%, and the remaining percentage of volume is diesel fuel, i.e., 90%.

Table 3-2:Notations for Madhuca Longifolia biodiesel and diesel blends

SR. NO	NOTATIONS	DESCRIPTION
1	B0	Madhuca Longifolia biodiesel 00 % + Diesel fuel 100%
2	B10	Madhuca Longifolia biodiesel 10% + Diesel fuel 90%
3	B20	Madhuca Longifolia biodiesel 20% + Diesel fuel 80%
4	B30	Madhuca Longifolia biodiesel 30% + Diesel fuel 70%

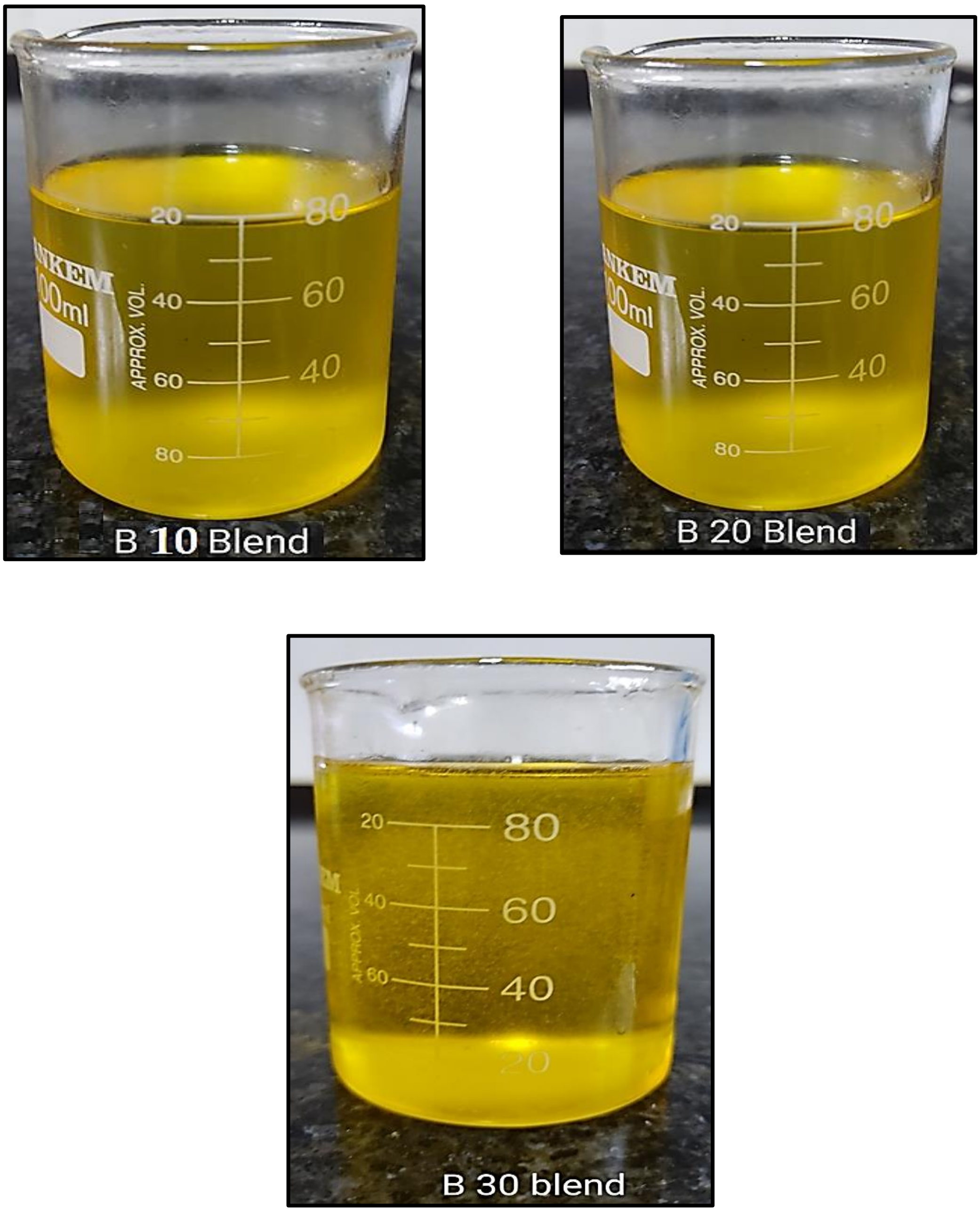

Figure 3-5: B10, B20, and B30 Sample of ML biodiesel blends

3.1.3 Properties of ML Biodiesel Blends

Understanding the various qualities of biodiesel is essential in order to compare them to the properties of traditional Petro-diesel. The various properties of Madhuca longifolia biodiesel are tested in laboratories as per ASTM standards.

The Table 3-3 shows properties of B10, B20, and B30 blends compared with standard diesel, Madhuca longifolia oil (raw oil), and Madhuca longifolia biodiesel. The fuel laboratory test report is attached in Appendix B.

Table 3-3:Properties of standard diesel and Madhuca Longifolia biodiesel blends

Sample/ Properties	**ASTM Standard**	**St. Diesel**	**B10**	**B20**	**B30**	**B100**	**Raw Oil**
Calorific value (KJ/kg**)**	D4809	45236	44074	42941	42256	42034	39932
Density (Kg/m^3**)**	D287	816	826	828	832	871	910
Acid Value (Mg of KOH/ gm of oil**)**	D6751	0.6	0.73	0.79	0.89	1.31	2.2
Flash Point (°C**)**	D9358T	53	61	68	71	101	256
Fire Point (°C**)**	D9358T	56	67	74	77	110	270
Kinematic Viscosity(cSt**)**	D445	2.09	2.79	2.93	3.08	4.98	39.6
Dynamic Viscosity (cP**)**	D445	1.73	2.3	2.43	2.56	4.34	36

ML biodiesel is blended with diesel in 10%–90%, 20%–80%, and 30%–70% by volume to reduce its viscosity. The important chemical and physical properties of the blend are determined by standard methods and equipment and compared with diesel. The analytical findings are displayed in Table 3-3. The results imply that the densities of the raw oil and biodiesel blends are somewhat greater than those of diesel fuel. The calorific value of biodiesel is less than that of diesel. However, oxygen in biodiesel facilitates the complete combustion of the fuel in a diesel engine.[120][121]. Biodiesel's high flash point made it safer than diesel in terms of handling and storing the fuel. However, the higher flash point also indicates lower fuel volatility[122]. which can influence the evaporation characteristics. Pure diesel has a flash point of 53 °C, while ML oil has a flash point of 256 °C, which is several times higher than that of pure diesel. The values listed in Table 3-3 clearly show that blending with diesel significantly reduces the flash point value of ML oil.

3.2 Experimental Set Up

Various fuels were tested on a single-cylinder, four-stroke, and CRDI VCR engine test rig to evaluate their exhaust gas emissions and performance parameters. We employed a fuel injection system of the common rail direct injection (CRDI) variety to ensure a consistent pressure within the rail.

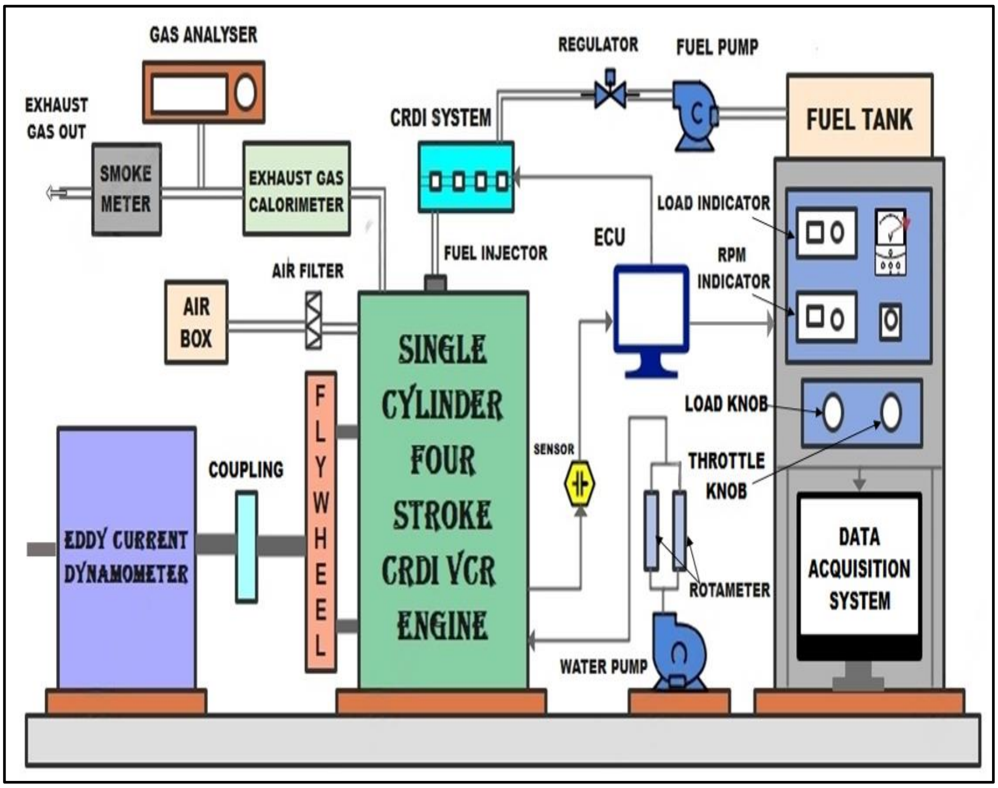

Figure 3-6:Schematic diagram of Experimental test setup

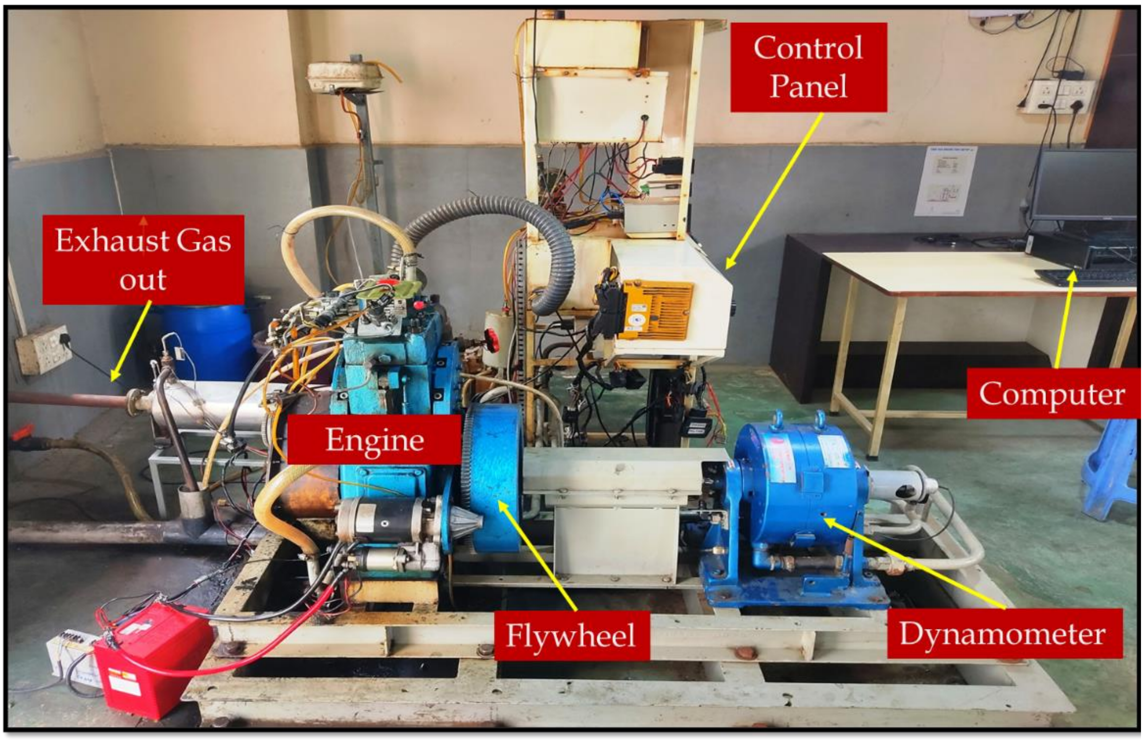

Figure 3-7: Test rig

Table 3-4: Technical specification of a test rig

Make and Model	**Kirloskar, TV1**
Number of cylinders	Single
Stroke	Four
Stroke length	110 mm
Bore	87.5 mm,
Cubic Capacity	661 cc
Power	3.5 KW,
Speed	1500 rpm,
Compression Ratio Range	12-18
Cooling system	Water-cooled
Dynamometer	Type eddy current, water-cooled with loading unit
Common rail	With pressure sensor and pressure regulating valve

Figure 3-6 provides the schematic diagram of the test rig, while Figure 3-7, displays the experimental engine test rig. The technical features of the engine described in Table 3-4 The setup is linked to an eddy current-type dynamometer to provide a load.

The engine features a developed tilting cylinder block configuration that enables the adjustment of the compression ratio without the need to stop the engine or modify the geometry of the combustion chamber. The setup comprises the essential equipment for measuring combustion pressure and crank angle. The configuration includes an independent control panel comprising an air box, two fuel tanks for conducting dual fuel tests, a manometer, a fuel measuring device, transmitters for measuring air and fuel flow, a process indicator, and a hardware interface. Rotameters are installed to measure the flow of engine cooling water and calorimeter water. The engine's electric start system comprises a battery, starter, and battery charger. The software package "Engine Soft" is a LabVIEW-based tool designed for real-time examination of engine performance.

RTD sensors are employed to measure the temperatures at the intake and outflow of the engine jacket cooling water, as well as the exhaust gas calorimeter cooling water. K-type thermocouples are used to measure the temperature of the engine exhaust gas, as well as the temperatures of the gas at the input and exit of the calorimeter. A piezoelectric pressure sensor (Kistler Instruments, Switzerland, model :6613CQ09), is employed for the purpose of detecting pressure within the cylinder.

3.2.1 Variation in Compression Ratio

The engine incorporates a unique tilting cylinder block layout that enables the adjustment of the compression ratio without the need to halt the engine or modify the combustion chamber's geometry. To modify the compression ratio, just loosen the six Allen bolts that secure the tilting block. Next, loosen the lock nut and lock the adjuster to achieve the required compression ratios of 15, 16, 17, and 18. Lastly, tighten the lock nut and all six Allen bolts. Figure 3-8 shows the compression ratio adjustor

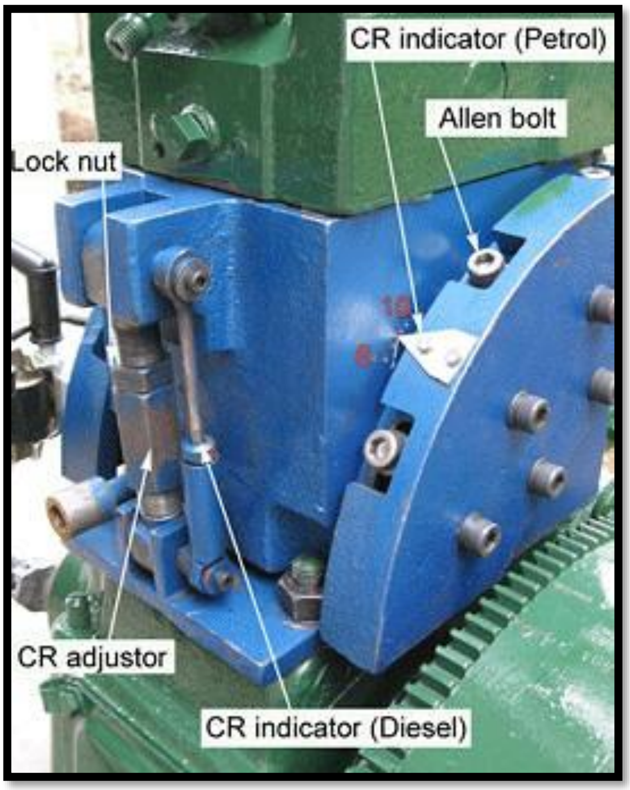

Figure 3-8: The compression ratio adjustor

3.2.2 Eddy Current Dynamometer

A 7.5 kW water-cooled eddy current dynamometer is used to apply a load to the diesel engine. The dynamometer allows for the operation of the engine across its complete load and speed range. A dynamometer that utilizes eddy currents is linked to an S-type load cell in order to quantify the torque produced by the engine. A rotary encoder is attached to the dynamometer in order to measure the engine speed. The dynamometer controller, comprising a control panel and a throttle actuator, governs the speed and load of the engine.Figure 3-9 depicts the water-cooled eddy current dynamometer, while Table 3-5. provides the specifications of the dynamometer. The cooling water feed line circuit links a flow switch to the dynamometer in order to monitor the flow of water. The controller utilizes digital technology to precisely regulate the load and speed of the engine. The dynamometer controller consists of the computer, control panel, instrumentation box, and throttle actuator. The instrument box is linked to the engine wiring system, which encompasses the battery, ignition, starter motor, fuel supply, throttle actuator, and temperature and pressure sensors. The controller establishes communication with the dynamometer using the automation software.

Figure 3-9:Eddy current dynamometer

Table 3-5:Specification of Eddy current dynamometer

Make	TECHNOMECH,
Model	TMEC-10
Capacity	7.5 KW
RPM	1500-6000

3.2.3 Exhaust Gas Analyzer

VL DIGAS 444N Exhaust Gas Analyzer (EGA) can identify the constituents in exhaust gases such as carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UBHC), and oxygen (O_2). For measuring HC, CO, and CO_2, the non-dispersive infrared sensor (NDIR) concept is employed. Measurements of NOx and O_2

are made using the chemiluminescent analyzer (CLA) principle. The fundamental idea behind NDIR analyzers is that certain gases absorb specific wavelengths of infrared light while transmitting other wavelengths. Figure 3-10. displays the exhaust gas analyzer. Table 3-6 gives the gas analyzer's specifications along with its resolution.

Figure 3-10: Exhaust Gas Analyzer

Table 3-6:Specifications of Exhaust Gas Analyser

Parameter	**Unit**	**Measurement**	**Resolution**
CO	% Vol	0 to 15% Vol	0.01% Vol
HC	ppm Vol	0 to 20,000	1 ppm /10 ppm <2000 RPM / >2000RPM
CO_2	% Vol	0 to 20	0.1 % Vol
O_2	% Vol	0 to 25	0.01 % Vol
NO	ppm Vol	0 to 5000	1 ppm Vol
Speed	RPM	400 to 6000 RPM	1 RPM
Oil Temp	^0C	0 to 125	1^0C
Lambda (λ)	-	0 to 9.999	0.001

3.2.4 Smoke Meter

Figure 3-11 shows the smoke meter, which is used to measure the opacity of exhaust gas. This smoke meter utilizes the light-extinction principle.

Table 3-7 provides the smoke meter's specification.

Figure 3-11: Smoke Meter

Table 3-7:Specifications of Smoke Meter

AVL437 Standard	**Smoke Opacity measurement**	
Measurement range	430 mm ±5 mm	
Measurement	Range	Resolution/Accuracy
Absorption (K Value)	0 to 99.99 m^{-1}	0.01 m^{-1}
Opacity	0 to 100%	0.1 %
Engine speed (RPM)	400 to 6000 min^{-1}	1 min^{-1}
Oil temperature	0 to 150 ^{0}C	1 ^{0}C
Linearity check	≈ 50% of the measured range	

3.2.5 Water Injector

The port fuel injector (PFI) of Maruti Suzuki was used for the water injection Figure 3-12. displays the injector.[123] Table 3-8 provides the instrument's specifications.

Figure 3-12: Water Injector

Table 3-8: Technical Specifications of the Injector

Parameters	**Details**
System Pressure	Max 8 bar
Weight	55g
Fuel Input	Top feed injector
Operating Temperature	-40 to 110 °C
Permissible fuel temperature	70°C
Flow rate	963 cc/min

3.2.6 Water Pump

The Yokohama water pump was used to supply the water to the injector. The pump has a 6.8 bar pressure rating, and the discharge rate is 4.5 LPM. The Figure 3-13 shows the pump.

Figure 3-13: Water Pump

Software Interface

ICEngineSoft is used to collect and manage the data. It is a LabVIEW-based software engine performance monitoring system. It establishes a link between the computer and the sensor to gather data from the DAQ. This program collects and averages pressure signals for analysis. Figure 3-14 displays the software's interface.

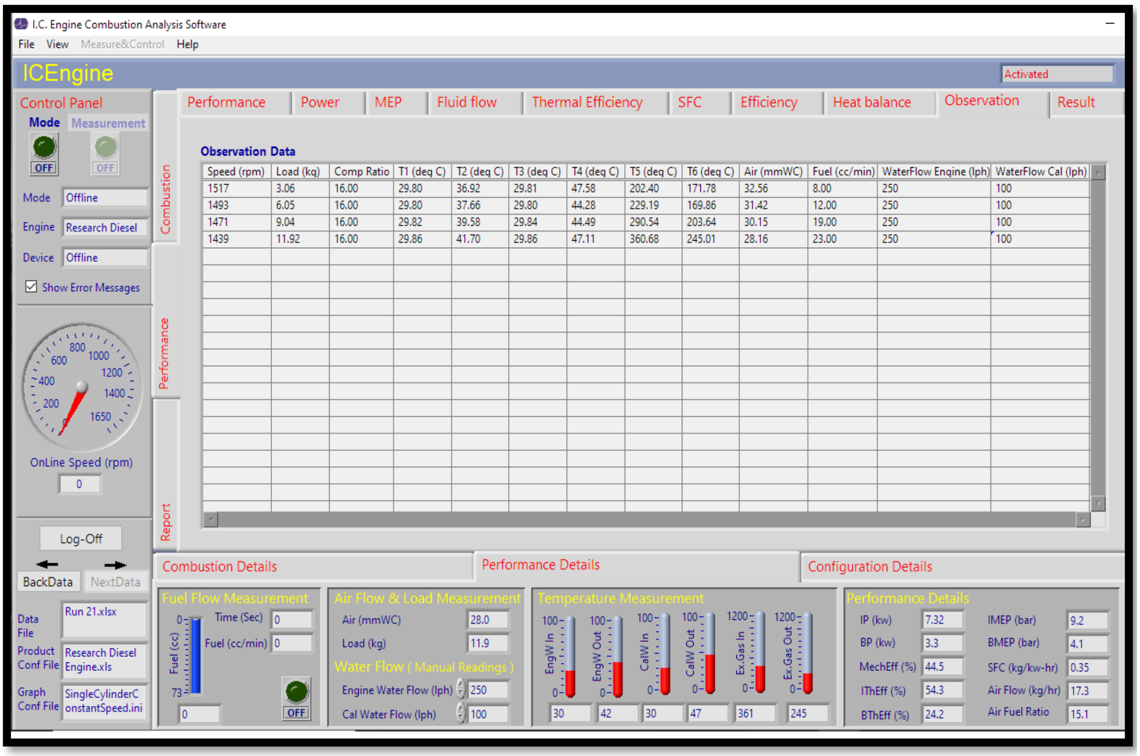

Figure 3-14: IC Engine Software interface

3.3 Experimental Methodology

3.3.1 Test procedure

The experimentation is divided into two phases. The first phase of experimentation was conducted to investigate the effect of various parameters on NOx emissions. The experimentation was carried out by varying four compression ratios (15, 16, 17, and 18), four injection pressures (300, 400, 500, and 600 bar), and four fuel blends (diesel, B10, B20, and B30) at a constant speed of 1500 RPM for 25, 50, 75, and 100% engine loading conditions.

The NOx emission values were recorded and quantified for all the combinations, along with the specific fuel consumption and brake thermal efficiency. Table 3-9 shows the test matrix for phase I experimentation. The phase II experimentation was conducted to investigate the effect of water injection on NOx emissions by injecting the water downstream of the engine. The based on the phase I. The distilled water was used for the injection, as shown in Figure 3-15. Many researchers are starting their experiments with identical fuel and water flow rates via the injector. The average fuel flow rate for the first part of the experiment was 16 cc/min.

The first NOx reduction is observed for 10 ms (38.7 CC/min). Furthermore, the test runs are then conducted for 20 ms, 30 ms, and 35 ms. cycle times.

Table 3-9:Test Matrix Phase-I Experimentation

Test Fuel	Operating Conditions			
	Compression Ratio	Injection Pressure (bar)	Load (%)	Speed (rpm)
Diesel	15	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	16	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	17	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	18	300, 400, 500, 600	25%, 50%, 75% 100%	1500
B10	15	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	16	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	17	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	18	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	15	300, 400, 500, 600	25%, 50%, 75% 100%	1500
B20	15	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	16	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	17	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	18	300, 400, 500, 600	25%, 50%, 75% 100%	1500
B30	15	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	16	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	17	300, 400, 500, 600	25%, 50%, 75% 100%	1500
	18	300, 400, 500, 600	25%, 50%, 75% 100%	1500

Table 3-10: Flow rate of Injector

Cycle time of Injector (ms)	Water injector flow rate (CC/min)
0	0
10	38.7
20	82.7
30	130.4
35	166.7

By varying the cycle time of the injector opening, the ECU and software that regulate the

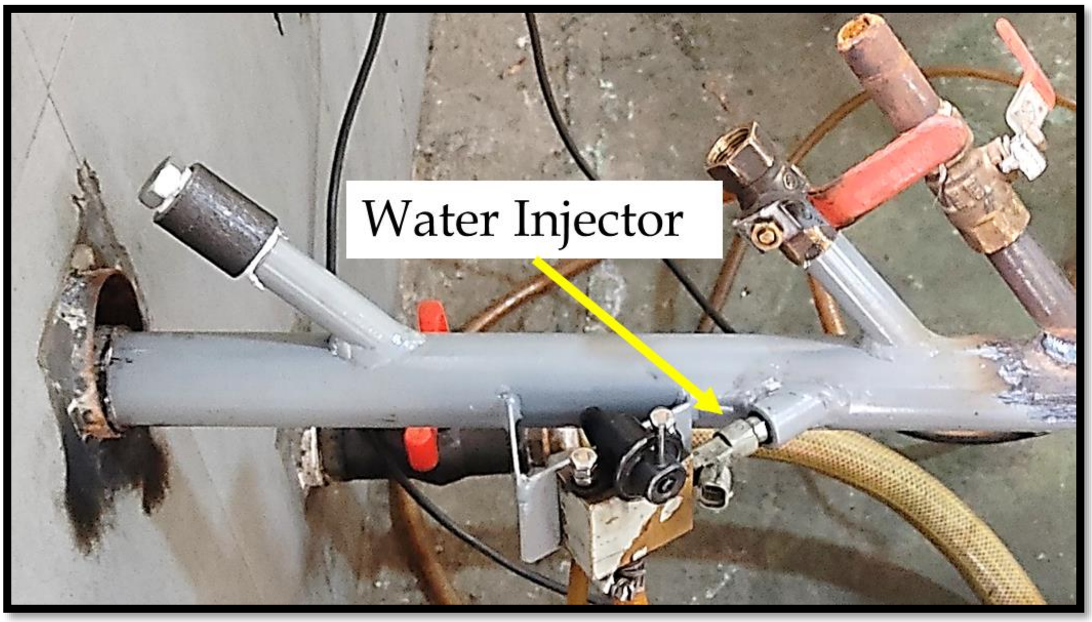

Figure 3-15: water injection at the downstream side of the engine

injector allow for the adjustment of the water flow rate. Table 3-10 shows the flow rate for each time lap. The test matrix of the phase II experimentation is shown in Table 3-11

Table 3-11:Test Matrix Phase-II Experimentation

Test Fuel	Operating Conditions			
	Compression Ratio	Water Injection flow rate CC/min	Load (%)	Speed (rpm)
B10	15	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	16	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	17	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	18	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
B20	15	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	16	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	17	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	18	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
B30	15	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	16	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	17	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500
	18	0, 38.7, 82.7, 130.4, 166.7	75% 100%	1500

3.3.2 Operating Instructions

The experimentation is first performed with diesel as fuel and then with blends of Madhuca Longifolia Methyl Ester (10%, 20%, and 30%).

1. Fill the diesel in the fuel tank.
2. At first, we established the compression ratio to be 18.
3. Initiate the water supply. Establish the appropriate flow rate of cooling water for the dynamometer cooling and engine jacket, namely 250 liters per hour, and for the exhaust gas calorimeter, 100 liters per hour.
4. Inspect any electrical connections. Initiate the electrical power transmission to the computer via the uninterruptible power supply (UPS).
5. Launch the lab view-based software package "I.C.Engine soft" designed for analyzing engine performance. Use it to assess the performance displayed on the screen.
6. Provide the diesel fuel to the engine by activating the valve located on the burette.
7. Initiate the engine by engaging the battery, starter, and decompressor lever.
8. Choose the "run" function of the software and allow it to operate for a few minutes without any external load.
9. Select the logging option within the software. Activate the gasoline supply knob. After a duration of one minute, the display transitions into input mode. Proceed by inputting the values of water flows in the cooling jacket, followed by entering the file name in the software.
10. Obtain the measurement of exhaust gas emissions using an exhaust gas analyzer, and measure the smoke opacity using a smoke meter.
11. Conduct the experiment again with various loads by adjusting the load knob at different injection pressures. The monitor will display all of the readings.
12. Record the measurements for a specific compression ratio.
13. Adjust the compression ratio while the engine is running by loosening the Allen bolt on the tilting block and the lock nut. Then, use the compressor adjuster to select the desired compression ratio.
14. Conduct the experiment again using various compression ratios and injection pressures.
15. Record the measurements for each compression ratio.

16. Likewise, modify the type of gasoline in the fuel tank and adjust the fuel's calorific value and specific gravity inside the software.
17. Conduct the experiment again using a specific fuel, varying the compression ratios.
18. Conclude the experiment by bringing the engine to a state where it is not carrying any load, and then proceed to turn off both the engine and the computer to halt the experiment.
19. Subsequently, deactivate the water supply after a brief interval.

During phase II testing, data is acquired for all four water injection flow rates for each load.

3.3.3 Uncertainty Analysis

Appendix A explains the uncertainty analysis of performance and emission parameters. Table 3-12 summarizes all the calculated uncertainties of the various parameters.

Table 3-12; summery of estimated uncertainty

Sr	Parameter	Uncertainty	Unit
1	Brake Power	±0.050	kW
2	Brake Thermal Efficiency	±1.49%	BTHE (%)
3	Brake Specific Fuel Consumption	±1.11%	kg/kWhr
4	Hydrocarbons emissions	±2.16	ppm
5	Carbon monoxide	±0.01	% Vol
6	Nitric Oxide	±68.49	ppm
7	Smoke	±1.48	% Volume

All the calibration reports are attached in Appendix C