

## AN IMPACT OF INJECTION PRESSURE ON OPERATING CHARACTERISTICS OF A DIESEL ENGINE FUELED WITH GARCINIA GUMMI-GUTTA BIODIESEL

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**Abstract.** *The current study assesses the effect of injection pressure on the performance of a single-cylinder direct injection diesel engine running on biodiesel extracted from Garcinia gummi-gutta. The experiments were carried out on diesel, B20 (20% biodiesel and 80% diesel), B20 with Hemispherical Combustion Chamber (HCC), and B20 with Toroidal Re-entrant Combustion Chamber (TRCC) at standard injection pressure of 200 bar. At full load, the brake thermal efficiency (BTE) of diesel was found to be 32.8%, whereas that of B20 was 30.9%. The use of HCC increased BTE to 31.6%, whereas B20+TRCC at standard pressure increased BTE to 33.4%, which is a clear indication of better air-fuel mixing and turbulence. Further change in injection pressure for TRCC configuration showed that at 180 bar, BTE was 32.1% with brake specific fuel consumption (BSFC) of 0.282 kg/kWh; at 200 bar, BTE increased to 33.4% with 0.268 kg/kWh; at 220 bar, maximum efficiency was attained with 34.6% BTE and 0.254 kg/kWh; and at 240 bar, BTE slightly dropped to 34.2% with 0.259 kg/kWh. Analysis of the emission revealed that CO emission reduced from 0.42% (diesel) and 0.38% (B20) to 0.24% at 220 bar, while HC emission reduced from 54 ppm to 38 ppm and smoke opacity reduced from 58 HSU to 44 HSU. But NOx emission increased from 842 ppm (diesel) to 910 ppm at 220 bar due to increased peak temperatures. Maximum cylinder pressure also increased from 67 bar (B20 standard) to 72 bar at 220 bar injection pressure. Thus, the B20+TRCC combination at 220 bar had the optimal trade-off between efficiency enhancement and emission control, thereby establishing the suitability of Garcinia gummi-gutta biodiesel in compression ignition engines.*

**Key words:** Diesel engine, Garcinia Gummi-Gutta, High-pressure injection, Performance, Emissions, combustion.

## ВПЛИВ ТИСКУ ВПОРСКУВАННЯ НА РОБОЧІ ХАРАКТЕРИСТИКИ ДИЗЕЛЬНОГО ДВИГУНА, ЩО ПРАЦЮЄ НА БІОДИЗЕЛІ З ГАРЦІНІЇ ГУММІ-ГУТТА

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**Анотація.** У цьому дослідженні оцінюється вплив тиску впорскування на робочі характеристики одноциліндрового дизельного двигуна, що працює на біодизелі з гарцинії гуммі-гутта.

вого дизельного двигуна з безпосереднім впорскуванням, що працює на біодизелі, отриманому з гарцинії гуммі-гутта. Експерименти проводили з використанням дизельного палива, суміші B20 (20% біодизеля та 80% дизельного палива), суміші B20 у двигуні з напівсферичною камерою згоряння (HCC) та суміші B20 у двигуні з тороїдальною камерою згоряння з повторним входом (TRCC) за стандартного тиску впорскування 200 бар. За повного навантаження ефективний термічний ККД (BTE) дизельного палива становив 32,8%, суміші B20 — 30,9%. При застосуванні двигуна з напівсферичною камерою згоряння показник BTE підвищився до 31,6%, в експерименті із застосуванням B20+TRCC за стандартного тиску показник BTE зріс до 33,4%, що свідчить про краще змішування паливно-повітряної суміші та підвищення турбулентності. При подальшій зміні тиску впорскування у експериментах із двигуном з тороїдальною камерою згоряння за тиску 180 бар ККД становив 32,1% за питомої ефективної витрати палива (BSFC) 0,282 кг/кВт·год; при 200 бар ККД зріс до 33,4% при BSFC на рівні 0,268 кг/кВт·год; при 220 бар було досягнуто максимальної ефективності — ККД дорівнював 34,6%, BSFC — 0,254 кг/кВт·год, відповідно; тоді як при 240 бар ККД дещо зменшився до 34,2% при BSFC на рівні 0,259 кг/кВт·год. За результатами аналізу викидів, обсяги викидів CO зменшилися з 0,42% (у експериментах із дизельним паливом) та 0,38% (B20) до 0,24% при тиску 220 бар, тоді як обсяг викидів незгорілих вуглеводнів зменшився з 54 ppm до 38 ppm, а димність знизилася з 58 HSU до 44 HSU. Втім, обсяг викидів оксидів азоту зріс з 842 ppm (дизельне паливо) до 910 ppm при 220 бар унаслідок підвищення пікових температур. Максимальний тиск у циліндрі також зріс з 67 бар (B20 за стандартних умов) до 72 бар при тиску впорскування 220 бар. Таким чином, в експерименті з комбінацією B20+TRCC при тиску 220 бар забезпечується оптимальний баланс між підвищенням ефективності та контролем викидів, що підтверджує придатність біодизеля з гарцинії гуммі-гутта до використання в двигунах із запалюванням від стиснення.

**Ключові слова:** дизельний двигун, гарцинія гуммі-гутта, високий тиск впорскування, робочі характеристики, викиди, згоряння.

## Abbreviations

CI - Compression Ignition engines

TRCC - Toroidal Re-entrant Combustion Chamber

BP - Brake power, kW

D MDF - Diesel/Methanol Dual Fuel

CO - Carbon monoxide, % vol.

BSFC - Brake-specific fuel consumption

HC - Hydrocarbon, ppm

IMEP - Indicated mean effective pressure

NOx - Nitrogen oxides

ORG - Original Injection Pressure

DI - Direct Injection

FIP - inline Fuel Injection Pump

HRR - Heat Release Rate

ROHR - simulation of the Rate of Heat Release

CN - Cetane Numbers

PM - Particulate Matter

IP - Injection Pressure

CR - compression ratio

## 1. Introduction

The rising depletion of fossil fuel resources and the stricter emission standards set globally have accelerated the search for alternative fuels for compression ignition engines that are renewable and sustainable [1]. Diesel engines are extensively used in transportation, agriculture, and power production because of their higher fuel efficiency and longer engine life; nevertheless, they are also one of the largest sources of air pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx),

and particulate matter. Biodiesel has been identified as a promising alternative fuel to conventional diesel fuel due to its renewability, biodegradability, oxygen content, and compatibility with existing diesel engines [2]. Among the different non-edible materials, biodiesel produced from *Garcinia gummi-gutta* has been explored because of its high oil content, desirable fatty acid profile, and accessibility in tropical areas. The biodiesel produced from *Garcinia gummi-gutta* oil has a desirable cetane number and oxygen content, which result in better combustion and lower CO

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and HC emissions. However, its slightly higher viscosity and lower calorific value may impact spray formation, atomization, and engine performance. Hence, proper engine operating conditions are required to ensure better efficiency and emission control [3]. Injection pressure is a significant parameter in diesel engine combustion, which affects fuel spray atomization, penetration, droplet size distribution, and air-fuel mixture. Higher injection pressures tend to produce smaller fuel droplets, leading to better mixing and complete combustion. But higher injection pressures can also lead to higher peak combustion temperature and NO<sub>x</sub> emissions. Therefore, it is essential to find an optimal injection pressure to ensure performance and emission trade-offs [4]. Besides the injection conditions, the geometry of the combustion chamber also plays a major role in turbulence intensity and mixture formation. Modern combustion chamber designs like the Hemispherical Combustion Chamber (HCC) and Toroidal Re-entrant Combustion Chamber (TRCC) promote swirl and squish processes, thus improving the efficiency of combustion. The TRCC design, in particular, is recognized for its ability to create high turbulence levels within the combustion chamber, thus ensuring better mixing of biodiesel blends with air [5]. Many research studies have been conducted on alternative fuels for compression ignition (CI) engines to decrease dependence on fossil fuels, reduce environmental effects, and meet the stringent emission norms. Biodiesel, derived from various edible and non-edible oils, has been extensively researched due to its renewability, high lubricity, and oxygen content, which helps to improve combustion efficiency. As per Knothe et al., biodiesel has a higher cetane number and better combustion properties than conventional diesel fuel, which leads to a reduction in CO, HC, and particulate matter emissions, but slightly increases NO<sub>x</sub> emissions because of the higher combustion temperatures [6]. Various researchers have also investigated the impact of different blends of biodiesel on engine performance and emissions. For example, investigations on B20 blends, which contain 20% biodiesel and 80% diesel fuel, have indicated that B20 has similar brake thermal efficiency (BTE) to diesel fuel and lower CO and HC emissions because of increased oxygen availability, but slightly higher NO<sub>x</sub> emissions because of earlier combustion timing. However, studies conducted by Agarwal et al. have indicated that B20 blends have similar torque and power to diesel fuel, but reduce smoke and unburned hydrocarbons [7]. The choice of feedstock is a major factor in determining biodiesel properties and engine performance. Non-edible oils like *Jatropha*, *Karanja*, and *Neem* have been explored in depth; however, studies on *Garcinia gummi-gutta* biodiesel are relatively rare. Studies by Shankar et al. showed that *Garcinia* oil biodiesel has desirable fatty acid methyl ester (FAME) properties, with a suitable cetane number and oxygen content, resulting in improved combustion and reduced CO and HC emissions. However, its higher viscosity and lower calorific value than diesel may impact atomization and combustion efficiency, requiring optimization of engine operating conditions like injection pressure and combustion chamber design [8]. Injection pressure is a critical parameter in the combustion mechanism of diesel engines. Higher injection pressures result in increased atomization, reduced droplet size, and improved

spray penetration, resulting in better air-fuel mixing and combustion efficiency [9]. Observed that an increase in injection pressure led to a decrease in brake specific fuel consumption (BSFC) and an improvement in brake thermal efficiency (BTE) for biodiesel blends up to a certain optimal point, beyond which the improvement tended to decrease [10]. Also, Kannan and Anand observed that an increase in injection pressure could potentially increase the peak cylinder pressure and heat release rate, thus improving combustion but sometimes at the expense of higher NO<sub>x</sub> emissions. Combustion chamber geometry is also an important factor in in-cylinder flow and mixture formation. Conventional combustion chambers, such as the Hemispherical Combustion Chamber (HCC), are known to have good volumetric efficiency and fair swirl values. More advanced geometries, such as the Toroidal Re-entrant Combustion Chamber (TRCC), have been found to produce higher turbulence levels and to favor rapid air-fuel mixing, leading to a reduction in ignition delay and improved combustion efficiency [11]. Research conducted by [12]. show that TRCC configurations are capable of providing improved combustion stability and lower smoke emissions compared to conventional chamber designs. Although a lot of research work has been conducted on biodiesel blends, injection pressure, and combustion chamber geometry separately, the effect of varying injection pressures along with modern combustion chamber designs on *Garcinia gummi-gutta* biodiesel, specifically B20 blends, has not been well investigated yet. The aim of this research work is to fill this research gap by comprehensively analyzing the performance and emission behavior of a diesel engine fueled with B20+HCC and B20+TRCC fueling systems at varying injection pressures (180-240 bar). The current research work tends to explore the joint effect of injection pressure variation and combustion chamber modification on the performance characteristics of a CI engine running on *Garcinia gummi-gutta* biodiesel (B20 blend). Performance aspects like brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), and emission aspects like CO, HC, NO<sub>x</sub>, and smoke opacity are taken into consideration. The scope of this research work is to identify the optimal injection pressure and combustion chamber design that ensures maximum efficiency and minimum emissions, thus increasing the applicability of *Garcinia gummi-gutta* biodiesel in CI engines.

## 2. *Garcinia gummi-gutta* Biodiesel Oil Preparation

The biodiesel derived from *Garcinia gummi-gutta* is obtained from the oil extracted from the seeds of *Garcinia gummi-gutta* (Malabar tamarind). Ripe fruits are harvested, and the seeds are separated, washed, and dried in the sun to evaporate the moisture. The dried seeds are crushed, and the oil is extracted either by expeller or solvent extraction using n-hexane. The extracted oil is filtered and heated to evaporate the remaining moisture. The raw oil has high viscosity; hence, it is converted to biodiesel through a transesterification reaction. In this reaction, the raw oil is heated to 55-60°C and mixed with methanol in the presence of a catalyst such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). The mixture is stirred for 60-90 minutes and left to settle, separating into two distinct

layers: biodiesel (top layer) and glycerol (bottom layer). The biodiesel is separated, washed with warm distilled water to remove contaminants, and dried to produce clear FAME, which can be used in diesel engines or blended with conventional diesel fuel (Table 1).

**Table 1. Physical Properties of Garcinia gummi-gutta Biodiesel**

Property	Diesel	Garcinia Biodiesel (Typical)	Effect on Engine
Density (kg/m <sup>3</sup> )	820–840	870–890	Higher density increases injected fuel mass
Kinematic Viscosity (mm <sup>2</sup> /s at 40°C)	2–4	4.5–5.8	Higher viscosity affects atomization
Calorific Value (MJ/kg)	42–45	36–39	Slightly lower → higher fuel consumption
Flash Point (°C)	50–70	150–170	Safer storage and handling
Cetane Number	45–50	50–55	Better ignition quality
Cloud Point (°C)	-5 to 5	8–15	Poor cold flow properties
Pour Point (°C)	-15 to 0	5–10	May cause cold-start issues

### 3. Experimental setup

The experimental work was conducted on a single-cylinder, four-stroke, water-cooled, direct injection diesel engine equipped with an eddy current dynamometer. The engine was run at a constant speed of 1500 rpm with a compression ratio of 17.5:1 and a rated power output of 5.2 kW. Biodiesel fuel was prepared from Garcinia gummi-gutta oil using the transesterification method and mixed with diesel fuel in a 20:80 proportion (B20). Two types of combustion chamber designs, namely Hemispherical Combustion Chamber (HCC) and Toroidal Re-entrant Combustion Chamber (TRCC), were used by changing the piston bowl design with the same compression ratio. The injection timing was set at 23° bTDC, and the injection pressure was changed at 180, 200 (standard), 220, and 240 bar by adjusting the spring tension of the injector. The performance aspects of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were determined using fuel consumption and brake power measurements. The combustion parameters like maximum cylinder pressure were measured by a piezoelectric pressure transducer along with a crank angle encoder. Emission-related parameters like CO, HC, and NOx were measured by a five-gas analyzer, and the smoke opacity was measured by an AVL smoke meter. The test was repeated three times to get accurate results, and the uncertainty of measurement was maintained within ±2% for performance and ±3% for emission parameters (Fig. 1).

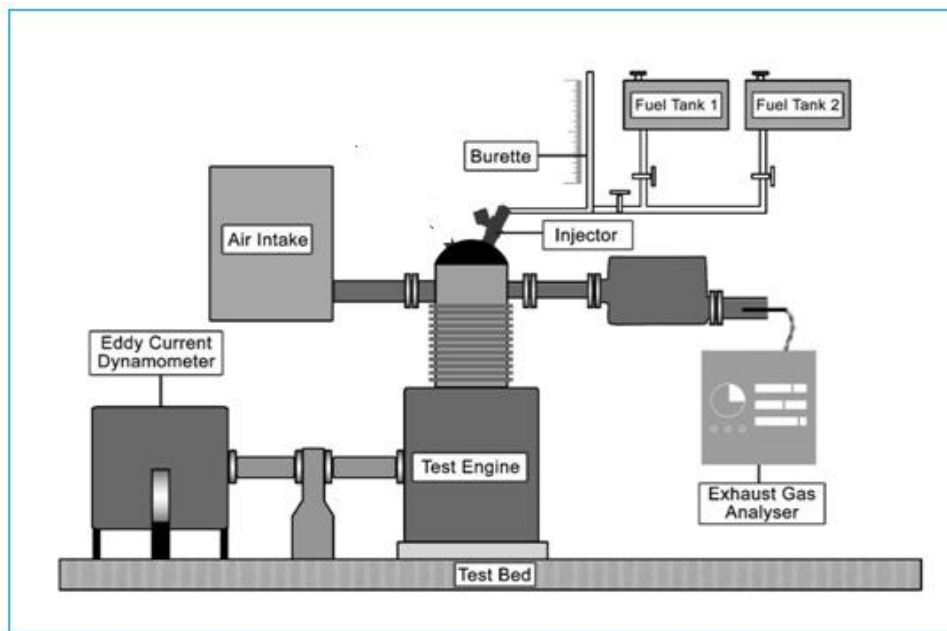


Fig. 1. Layout of experimental setup

### 4. Result and Discussions

The use of alternative fuels like biodiesel in diesel engines causes a loss of efficiency, increased fuel consumption, and NOx emissions. These problems have been resolved by the application of different measures so far. In addition, an injection pressure strategy was also applied as the final stage

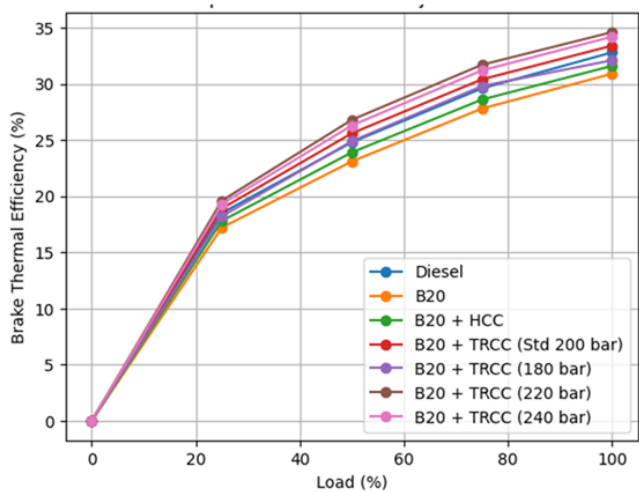
of the experiment. Injection pressure is also an important factor in improving engine performance, combustion, and reducing emissions. It improves fuel spray quality and promotes a high rate of mixing. Larger droplet sizes, lack of mixing, and low penetration are some of the drawbacks of lower-pressure fuels used for operation. These problems are removed by increasing the injection pressure. The rate

of evaporation was increased by reducing the fuel core size and increasing the penetration rate. From the literature review, different injection pressures of 180 bar, 200 bar, 220 bar, and 240 bar were used with a fixed amount of fuel injected into the engine (Table 2).

**Table 2. Annotations for TRCC engine operated with various injection pressure**

Sl. No.	Annotations	Descriptions
1.	Diesel	100% Diesel fuel
2.	B20	20% Garcinia Gummi-Gutta (GGG)+80% diesel
3.	B20+HCC	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in default hemispherical combustion chamber.
4.	B20+TRCC	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in TRCC
5.	B20+TRCC +180	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in TRCC with 180 bar injection pressure
6.	B20+TRCC +200	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in TRCC with 200 bar injection pressure
7.	B20+TRCC +220	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in TRCC with 220 bar injection pressure
8.	B20+TRCC +240	20% Garcinia Gummi-Gutta (GGG)+80% diesel operated in TRCC with 240 bar injection pressure

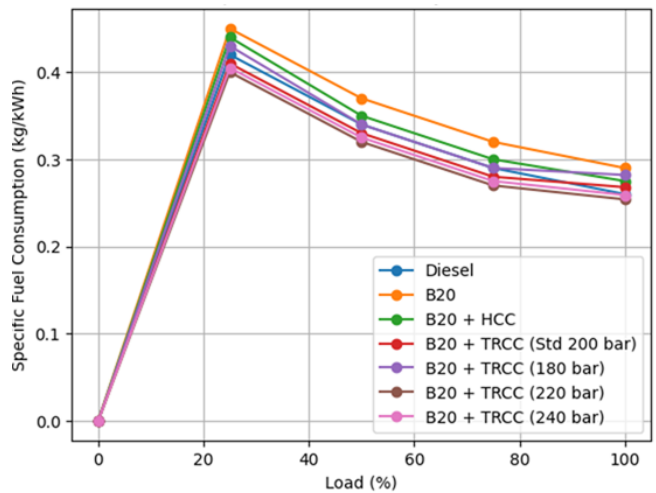
**4.1 Performance Characteristics**



*Fig. 2. Variation of brake thermal efficiency with engine load*

The effect of engine brake thermal efficiency with respect to engine load for diesel and Garcinia gummi-gutta

blended under various combustion chamber geometries and injection pressures shows a prominent effect of both in-cylinder turbulence and fuel atomization quality (Fig. 2). For all test fuels, BTE increases with load because of decreased relative heat losses, improved combustion stability, and better fuel-air interaction at higher cylinder temperatures [13]. Compared to diesel (32.8% at full load), B20 has a lower BTE (30.9%) mainly because of its lower calorific value and slightly higher viscosity, which impacts spray breakup and evaporation. However, with the inclusion of the hemispherical combustion chamber (HCC), BTE increases to 31.6%, which indicates better swirl and mixing. The Toroidal Re-entrant Combustion Chamber (TRCC) at standard pressure (200 bar) further increases BTE to 33.4%, which exceeds that of diesel. This is because of increased turbulence and better squish motion, which hastens combustion [14]. Variation of injection pressure shows that 220 bar gives the maximum BTE of 34.6%. At this pressure, atomization is optimal, which gives smaller droplet sizes and faster evaporation rates, resulting in better premixed combustion. At 180 bar, the lack of atomization leads to a lower efficiency of 32.1%, and at 240 bar, a slight over-penetration of the spray and wall impingement could result in a marginal decrease of 34.2%. Hence, 220 bar is recognized as the optimal injection pressure [15].



*Fig. 3. Variation of BSFC with engine load*

Specific fuel consumption reduces with the increase in load for all test conditions because higher loads enhance the ratio of useful work to fuel energy input (Fig. 3). B20 fuel has a higher SFEC than diesel fuel because of its lower heating value and higher density. At full load, the SFEC of diesel fuel is 0.26 kg/kWh, whereas for B20 fuel, it is 0.29 kg/kWh. The addition of HCC reduces SFEC to 0.275 kg/kWh. TRCC at standard pressure further reduces SFEC to 0.268 kg/kWh because of better in-cylinder mixing. Injection pressure is a very important factor, and at 220 bar, the lowest SFEC of 0.254 kg/kWh is obtained, thus confirming better combustion efficiency and less fuel wastage. At 180 bar, the fuel is not fully atomized, resulting in higher fuel consumption, whereas 240 bar results in a slight increase in SFEC compared to 220 bar, possibly due to increased pumping work and spray-wall interaction [16].

### 4.2 Combustion Characteristics

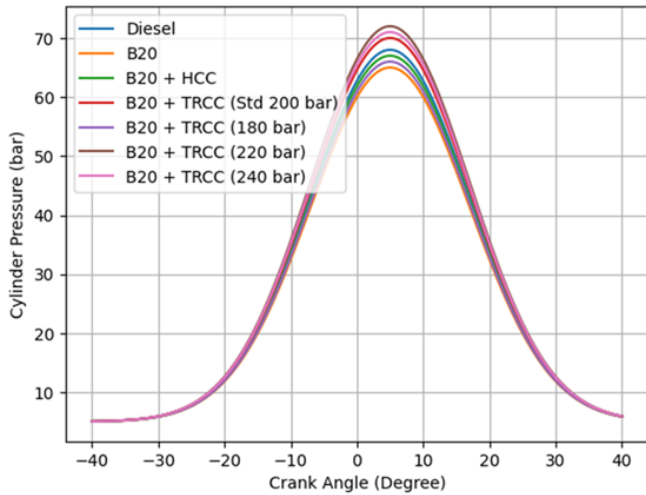


Fig. 4. Pressure vs crank angle

Peak cylinder pressure is an important parameter that shows the intensity of combustion (Fig. 4). Diesel fuel has a peak pressure of about 68 bar. B20 fuel has a slightly lower pressure of 67 bar because of its lower energy density. HCC has a slightly higher pressure due to enhanced turbulence. TRCC with 200 bar pressure has a 70 bar peak pressure, which shows more intense premixed combustion. With 220 bar injection pressure, the maximum peak pressure of 72 bar is attained, which is a result of fast heat release and efficient combustion. With 180 bar pressure, the pressure is lower because of late combustion, and with 240 bar, there is a slight decrease in pressure compared to 220 bar [17].

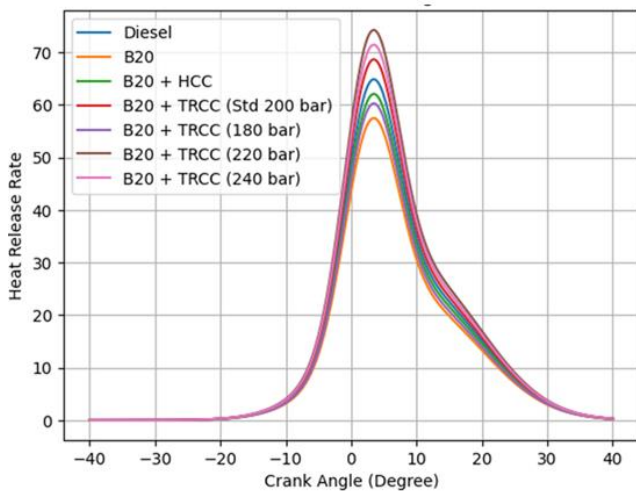


Fig. 5. HRR vs Crank angle

The HRR curve indicates a distinct premixed combustion peak and diffusion combustion phase. Diesel fuel has a moderate premixed peak (Fig. 5). B20 fuel has a slightly lower HRR due to reduced evaporation and mixing rates. HCC has a marginal increase in premixed combustion. TRCC has a substantial increase in premixed combustion due to improved atomization and turbulence. The HRR peak is highest at 220 bar, indicating lower ignition delay and faster

combustion. At 180 bar, the premixed peak is lower due to poor spray atomization. At 240 bar, a slight decrease is noticed compared to 220 bar, which indicates that 220 bar is the optimal injection pressure [18].

### 4.3 Emission Characteristics

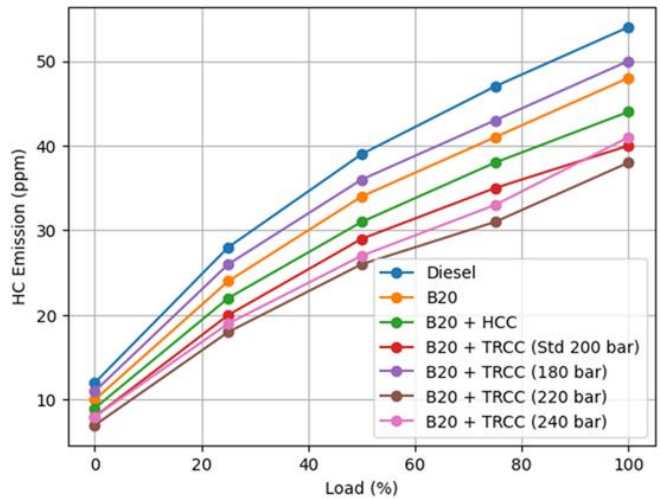


Fig. 6. Variation of HC with engine load

Unburned hydrocarbon emissions are affected by flame quenching in the vicinity of the cylinder walls, incomplete combustion, and fuel trapped in crevice volumes (Fig. 6). Diesel fuel has 54 ppm HC at full load. B20 decreases HC to 48 ppm because of the oxygen content, which enhances oxidation. The HCC arrangement further decreases HC (44 ppm), which indicates better flame propagation. TRCC at 200 bar decreases HC to 40 ppm because of increased swirl and faster combustion. At 220 bar injection pressure, HC emission is lowest (38 ppm), which indicates better vaporization and lower ignition delay. At 180 bar, spray atomization is poor, which increases HC because of incomplete combustion. At 240 bar, there is a slight increase compared to 220 bar [19].

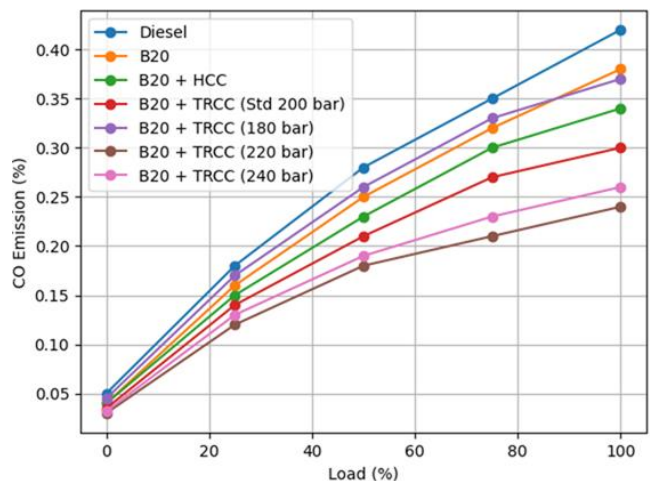


Fig. 7. Variation of CO with engine load

CO emissions rise with load due to higher mixture richness and lower oxygen availability at higher fuel injection rates

(Fig. 7). Diesel fuel has the highest CO emission (0.42% at full load) because of incomplete combustion in locally rich regions. B20 fuel lowers CO emission (0.38%) because of its oxygenated molecular composition, which favors complete combustion. HCC lowers CO emissions slightly (0.34%) because of better air-fuel mixing. TRCC arrangement lowers CO emissions substantially (0.30%) at standard pressure because of increased turbulence and oxidation rates. The lowest CO emission (0.24%) is at 220 bar because of higher spray atomization and faster mixing, which favor complete combustion of carbon species. At 180 bar, lower atomization raises CO emissions, while 240 bar is slightly higher than 220 bar [20].

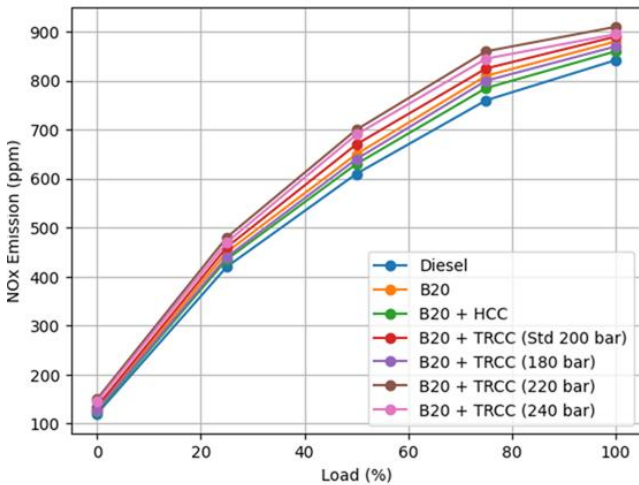


Fig. 8. Oxides of Nitrogen vs engine load

NOx formation is highly sensitive to peak combustion temperature, oxygen concentration, and residence time at high temperatures (Fig. 8). Diesel fuel emits 842 ppm NOx at full load conditions. B20 fuel has a slightly higher NOx emission (880 ppm) because of higher oxygen concentration and more advanced combustion phasing. HCC has a moderate NOx increase because of improved combustion efficiency. TRCC further raises NOx emission (890 ppm at 200 bar) because of higher turbulence intensity and peak temperature. The maximum NOx emission (910 ppm) occurs at 220 bar injection pressure, which corresponds to the maximum peak cylinder pressure and maximum heat release rate. Although 240 bar injection pressure has a slightly lower NOx emission than 220 bar, it is still higher than the standard pressure because of higher combustion temperatures [21].

Smoke generation is primarily linked with the formation of soot in fuel-rich regions (Fig. 9). Diesel fuel generates the highest level of smoke opacity (58 HSU at full load). B20 reduces smoke (52 HSU) due to oxygenated fuel, which promotes soot oxidation. HCC reduces smoke (47 HSU) due to enhanced swirl. TRCC reduces smoke substantially (42 HSU at 200 bar) due to increased air-fuel mixing. The lowest level of smoke opacity (44 HSU) is obtained at 220 bar injection pressure, which verifies better atomization and soot oxidation. At 180 bar, the effect of a larger droplet size is to increase soot formation, whereas at 240 bar it is slightly higher than that at 220 bar.

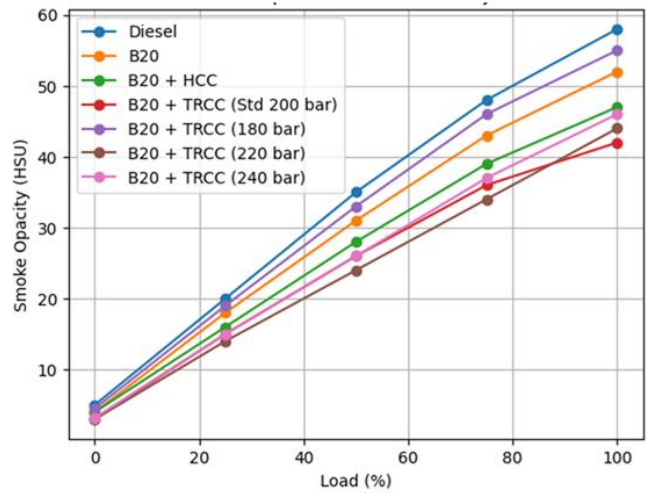


Fig. 9. Variation of Smoke with engine load

### Conclusion

The current research work was aimed at investigating the effects of injection pressure and combustion chamber geometry on the performance, emissions, and combustion properties of a single-cylinder direct injection diesel engine running on B20 biodiesel produced from *Garcinia gummi-gutta*. The experimental analysis was conducted on diesel, B20, B20 with Hemispherical Combustion Chamber (HCC), and B20 with Toroidal Re-entrant Combustion Chamber (TRCC) at different injection pressures (180, 200, 220, and 240 bar). The findings of this study clearly show that B20 biodiesel can be used successfully in a diesel engine with a slight reduction in efficiency compared to diesel. But changes in combustion chamber geometry have a remarkable effect on performance. The TRCC design at standard injection pressure (200 bar) increased brake thermal efficiency (33.4%) compared to diesel (32.8%) and B20 (30.9%), which emphasizes the need for improved turbulence and air-fuel mixing inside the combustion chamber. The effect of injection pressure on engine performance is significant. Among the four different injection pressures (180, 200, 220, and 240 bar) tested, 220 bar was found to be the best. At this pressure, the maximum brake thermal efficiency (34.6%) and lowest specific fuel consumption (0.254 kg/kWh) were obtained. In addition, a remarkable reduction in CO (0.24%), HC (38 ppm), and smoke opacity (44 HSU) was also found because of better atomization and fast combustion. Nevertheless, a slight increase in NOx emissions (910 ppm) was found at higher injection pressures because of higher peak combustion temperature. Moreover, combustion analysis also revealed that the maximum peak cylinder pressure (72 bar) and maximum heat release rate were achieved at 220 bar injection pressure, indicating better premixed combustion and shorter ignition delay. At lower injection pressure (180 bar), poor atomization resulted in lower efficiency and higher emissions, whereas at 240 bar, slight degradation was found because of possible spray over-penetration. Therefore, the optimal result, balancing performance enhancement and emission control, was achieved by the combination of TRCC

combustion chamber and 220 bar injection pressure. The results have confirmed that *Garcinia gummi-gutta* biodiesel (B20) is a technically feasible and sustainable alternative fuel for compression ignition engines if optimized combustion chamber geometry and injection conditions are used. Further research work can be conducted using higher blends of biodiesel and long-term engine tests. The injection timing and pressure can be optimized to enhance performance and minimize emissions. Methods such as EGR can be employed to manage NO<sub>x</sub> emissions. With appropriate modifications, *Garcinia gummi-gutta* biodiesel can be utilized efficiently in diesel engines.

#### Ethical Approval

Not applicable

#### Consent to Participate

Not applicable

#### Consent to Publish

Not applicable

#### Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this research work

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#### Competing Interest

There are no conflicts of interest, according to the authors.

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