COMPARATIVE INVESTIGATION OF CRUDE AND WASTE SOYABEAN OIL BIODIESEL BLENDS IN A VCR ENGINE

A Thesis Submitted in Partial Fulfilment of the Requirements

forAwarding the Degree of

Master of Engineering in Automobile Engineering

under

Faculty of Engineering and Technology

Submitted

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ACKNOWLEDGEMENT

This acknowledgement is to express the gratitude of the author to all those individuals who guided him in every aspect to make the thesis work successful.

*I would like to convey my sincere gratitude to my thesis advisor, **Dr. Prokash Chandra Roy**, Professor, Department of Mechanical Engineering, Jadavpur University, Kolkata, for his insightful advice and necessary direction in various facets of this project work. It was an honour to work under their supervision.*

*I am thankful to **Prof. Amit Karmakar**, Head of Mechanical Engineering Department, Jadavpur University, and **Prof. Saswati Mazumdar**, Dean of Faculty Council of Engineering & Technology, Jadavpur University, for their support in academic matters.I would like to thank all the faculty of the Heat Power Lab for their assistance with my thesis work.*

*I would also like to thank **Mr. Anindya Adhikary** and **Dr. Abhishek Samanta** for their consistent assistance and motivation in my thesis work. My sincere thanks also go to **Mr. Sampad Kumar Das** (PHD Scholar, ME department. Jadavpur University) and my friends who helped me during this project work.*

I want to extend my heartfelt appreciation to my family for their constant and unwavering support. Additionally, I would like to express my gratitude to all those who, whether through direct or indirect contributions, assisted me in successfully completing this endeavor.

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ABSTRACT

Biodiesel presents itself as a promising and environmentally friendly alternative fuel source, derived from both edible and non-edible oils, attainable through the process of transesterification. This fuel source exhibits the potential for integration into diesel engines, whether with modifications or in their existing state. The impending scarcity of conventional diesel fuel, which carries significant implications, propels biodiesel into a role as a feasible remedy that can offset the adverse impacts on our lifestyle. The creation of biodiesel entails the transformation of waste soybean oil (WSOBD) and crude soybean oil (CSOBD) into a practical fuel solution. The density and viscosity attributes of the resulting biodiesel hold considerable importance, aligning with industry standards. The density and viscosity values for WSOBD fall within the prescribed parameters, whereas those for CSOBD slightly surpass those of WSOBD while maintaining acceptable levels. The evaluation of biodiesel's combustion characteristics involves an analysis of two blends—5% and 10% biodiesel—in conjunction with traditional diesel fuel. This assessment takes place within a four-stroke VCR Diesel engine, under varying load conditions (zero and full). Experiments are conducted at different compression ratios (15 to 18). The investigation focuses on comparing the highest pressures reached during combustion and the values of Net Heat Release. Notably, WSOBD5 displays a slight enhancement in peak pressure when compared to the CSOBD blend under no load conditions. Meanwhile, WSOBD10 surpasses the CSOBD blend in full load conditions. A scrutiny of NHR values between crude and waste biodiesel reveals minor variations. The duration of combustion displays negligible differences between the biodiesel blends, with WSOBD demonstrating a tendency toward superior performance relative to CSOBD. At distinct load points— Zero, 25%, 50%, 75%, and full load—CSOBD5 consistently presents the highest NHR_{max} values within the realm of crude biodiesel blends, showcasing its robust combustion characteristics. Nevertheless, in multiple scenarios, WSOBD10 maintains a competitive stance by exhibiting commendable NHR_{max} values. The recorded cylinder pressure for biodiesel blends in relation to crank angle is consistently lower than that of diesel fuel under all load conditions. Particularly noteworthy is the observation that at a compression ratio (CR) of 17, both CSOBD and WSOBD exhibit maximum pressures that closely approach those of diesel. Moreover, at a load condition of 75%, the biodiesel blends demonstrate their most favorable results in this regard. Minor variations in Net Heat Release (NHR) become apparent when

comparing the two biodiesel types, crude (CSOBD) and waste (WSOBD). There's an observable pattern of fluctuations as the compression ratio (CR) increases, with some decreases followed by increases in NHR. Notably, at a compression ratio of 17 and under a 25% load, the maximum NHR_{max} for both CSOBD and WSOBD approaches that of diesel, highlighting their competitive performance in these conditions. The measured peak pressure of biodiesel blend is lower than diesel fuel at all load conditions and increases with at higher CRs. Throughout various compression ratios (CRs), except for CR 15, it is observed nearly identical values for cylinder pressure relative to cylinder volume. However, at CR 17 and CR 18, under a 75% load, the maximum cylinder pressure for both CSOBD and WSOBD closely matches that of diesel, signifying their comparable performance in these specific conditions. When considering Specific Fuel Consumption (SFC), the CSOBD5 blend achieves its highest value at 0.77 kg/kWhr, while at a load of 3, WSOBD5 reaches 0.67 kg/kWhr, at a load of 75%, the CSOBD10 blend records its lowest fuel consumption rate, measuring at 0.17 kg/kWhr and the WSOBD10 blend reaches its minimum fuel consumption rate of 0.05 kg/kWhr when the engine is operating at full load . In terms of Break Thermal Efficiency (BTE), the CSOBD5 blend attains its peak efficiency at 29.73, while WSOBD5 reaches 29.36 under full load and at compression ratio 17. This study underscores the potential of biodiesel, especially that derived from waste soybean oil, as an alluring option due to its promising combustion properties. While distinctions exist between crude and waste biodiesel, both exhibit the capacity to address the mounting apprehensions associated with the depleting supply of conventional diesel. It is evident from the through literature study that waste cooking oil will be a prospective feedstock for biodiesel production specifically for developing nations like India.

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Chapter 1

INTRODUCTION

1.1 General Description

The consumption of energy resources is on a relentless rise, posing a serious concern for sustainability. Fossil fuels and other non-renewable minerals are depleting rapidly, prompting extensive research in the field of alternative energy sources that are both renewable and eco-friendly. Presently, petroleum remains the predominant source of energy, with an astonishing demand of approximately 12 million tons per day, projected to escalate to a staggering 16 million tons by 2030. Petroleum-based products are deeply ingrained in modern living, yet their costs are vulnerable to global market fluctuations, and the reserves are estimated to last a more 30 years. With India heavily reliant on petroleum imports, its economy remains vulnerable to the volatile and unpredictable global oil market (India, 2004) **[1]**. The dwindling reserves of oil, soaring prices, and the detrimental environmental impacts of combustion-related emissions make renewable energy sources increasingly appealing. In a developing nation like India, the forces of modernization, urbanization, globalization, and population growth contribute to alarming daily surges in energy demands. Notably, road transportation alone accounts for 75% of diesel consumption, making it a major contributor to exhaust emissions. As fossil fuels continue to diminish, an impending crisis looms, necessitating the adoption of viable alternative fuels for energy security, environmental preservation, and socio-economic stability **[2].** Diesel engines, widely used for power generation and marine applications, boast superior fuel efficiency compared to their spark-ignition counterparts, yet suffer from significantly higher levels of pollutants and noise. This pressing need for suitable alternative fuels stems from the gradual depletion of fossil fuel reserves and the adverse environmental consequences associated with escalating exhaust emissions. Biofuels, particularly biodiesel, emerge as one of the most promising solutions to reduce reliance on petroleum derivatives. With its low sulphur content and composition of mono-alkyl esters derived from vegetable oils or animal fats, biodiesel offers a viable and sustainable alternative. In a world grappling with energy security, environmental concerns, and socio-economic implications, the development of biofuels and other sustainable energy sources holds immense promise. By embracing renewable energy alternatives like biodiesel, we can pave the way for a greener and more sustainable future, reducing our dependence on finite resources and mitigating the environmental impacts of traditional energy consumption.

The ever-increasing demand for energy resources presents a formidable challenge that calls for immediate attention. Diesel engines, despite their higher fuel efficiency compared to spark-ignition engines, suffer from elevated pollutant emissions and noise levels. This underscores the urgency of finding suitable alternative fuels as fossil fuel depletion and increasing exhaust emissions pose a crisis in the near future **[3].** Biofuels, notably biodiesel, offer one of the most promising avenues to reduce dependence on petroleum derivatives. Biodiesel, derived from vegetable oils or animal fats, contains mono-alkyl esters and boasts a low sulphur content. This renewable fuel option presents a compelling solution to the challenges of energy security and environmental sustainability. In the face of escalating energy demands, environmental considerations, and socio-economic implications, the development and widespread adoption of biofuels and other renewable energy sources are paramount. Embracing these sustainable alternatives paves the way for a greener future, reducing reliance on finite resources and mitigating the environmental impact of conventional energy consumption **[4].** To achieve this, there is an imperative need for investments in research, innovation, and policy measures to accelerate the transition to a more sustainable energy paradigm.

India annually generates a substantial amount of waste oils, which present a promising resource for biodiesel production. Various vegetable oils, such as rapeseed, soybean, sunflower, and jatropha, have been explored for their potential as biodiesel feedstocks. While biodiesel derived from these oils exhibits slightly reduced performance in internal combustion engines, they offer significant advantages as renewable and biodegradable fuels with properties comparable to conventional diesel. Experimental studies have shown that biodiesel delivers comparable power output with only a slight decrease in thermal efficiency due to its slightly lower energy content compared to diesel. In India, the practice of repeatedly using cooking oil for frying, both in households and commercial establishments, poses health risks. Repeated use of used frying oil releases harmful compounds like aldehydes and allylbenzene, which have been linked to serious illnesses including cancer, dementia, and heart problems. With India's large population, the disposal of used cooking oil presents significant ecological challenges, while its use as animal feed is also undesirable **[5].** By considering waste cooking oil as a low-cost feedstock, biodiesel emerges as a favorable alternative to diesel fuel, offering an environmentally sound option for its utilization. Biodiesel holds immense potential as a renewable fuel and as an additive to mineral fuels, presenting an attractive alternative in the energy landscape. Extensive research has been conducted on vegetable oils, both in their crude form and through various modifications. Studies have revealed that while using vegetable oils in their crude form is feasible, it is not ideal due to their high viscosity and low volatility, which can lead to challenges in atomization, incomplete combustion, carbon deposits, injector issues, and piston ring sticking **[6]**. To address these concerns, methods such as blending with diesel, emulsification, pyrolysis, and transesterification have been employed to reduce the viscosity of vegetable oils. Furthermore, the addition of appropriate additives to biodiesel blends enhances combustion by inhibiting oxidation and thermal degradation, resulting in improved fuel economy and reduced emissions of pollutants. In summary, the utilization of waste oils, especially waste cooking oil, as a feedstock for biodiesel production offers a practical and sustainable solution to reduce environmental impacts and health hazards associated with conventional cooking oil disposal. By harnessing the potential of biodiesel and implementing innovative technologies, India can make significant strides towards achieving energy security, mitigating pollution, and promoting a cleaner and greener future. The utilization of waste oils, such as used cooking oil, not only tackles the challenges of waste disposal but also offers a cost-effective and environmentally friendly alternative to traditional diesel fuel **[7]**. Through concerted efforts in research, technology development, and policy implementation, India can pave the way for a cleaner and greener energy future, ensuring a sustainable and resilient path forward.

1.2 Biodiesel as C. I. Engine Fuel

Biodiesel offers a greener solution as it is derived from sustainable sources, making it a more environmentally conscious alternative to conventional fuels sourced from finite fossil reserves. The idea of utilizing vegetable oils as a viable fuel option traces back to the late 1800s when Dr. Rudolf Diesel successfully ran an engine on peanut oil. Subsequent advancements in the 1970s brought forth the realization that vegetable oils could undergo chemical transformations, reducing their viscosity and making them compatible with diesel engines. By embracing biodiesel, nations can reduce their dependence on imported fuels, fostering greater energy independence and security. Extensive research has focused on optimizing the performance of biodiesel by blending it with petroleum diesel, enabling improved compatibility and performance in compression ignition engines. It's worth noting that directly using raw vegetable oil in unmodified diesel engines is not feasible due to inherent challenges such as high viscosity, flash point, density, and suboptimal heating value. **Kawaguchi *et al.* (2004) [8]** conducted a research project that aimed to address the challenges associated with high-viscosity waste oil in combustion processes. The team devised a custom combustion burner system that optimized oil atomization and effectively controlled emissions. The objective was to improve the efficiency and environmental impact of utilizing waste oil as a fuel source by overcoming the inherent viscosity-related limitations. The study's findings aimed to pave the way for more efficient and sustainable utilization of high-viscosity waste oil in various applications. Fig 1.1. depicts a list of leading countries of biodiesel production in Worldwide. It shows that US produced the maximum percentage compared to other nations.

Leading Countries Based on Biodiesels Production Worldwide in 2021

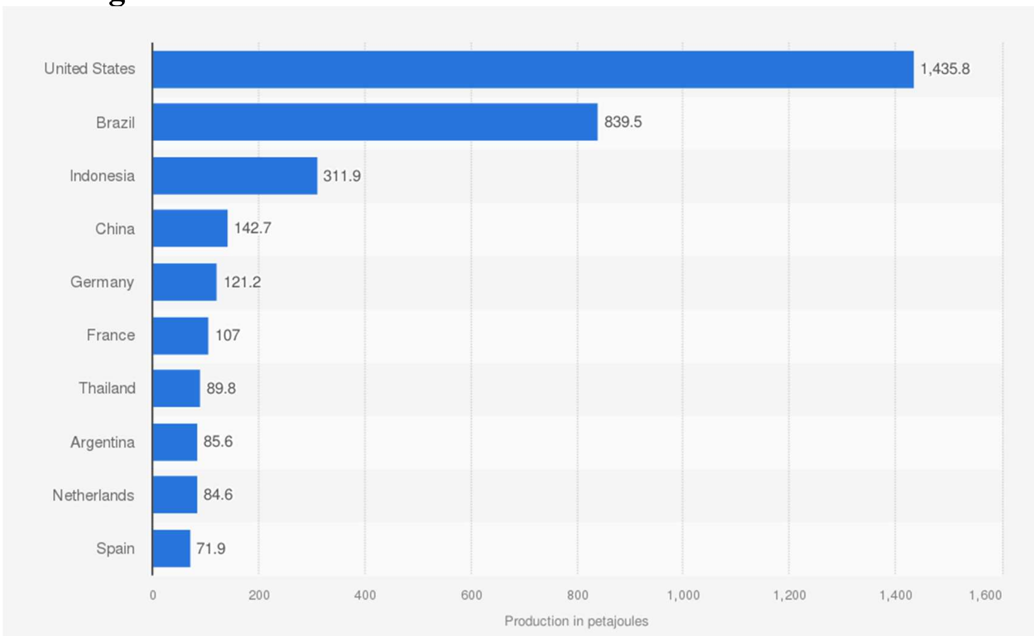

Fig 1.1 : Worldwide production of biodiesel in 2021 **[9]**

Blending biodiesel with diesel fuel at specific proportions offers the potential for improved engine efficiency and reduced emissions of harmful sulphates. Moreover, the high flash point of biodiesel enhances safety during operation. Recognizing its compatibility with diesel vehicles, many automobile manufacturers have embraced biodiesel as a viable fuel option **[10-11]**. As long as the transformed biodiesel retains desirable fuel characteristics, biodiesel derived from inedible sources like neem and waste cooking oil can be commercially utilized as a substitute for diesel fuel, meeting the standards set by organizations such as ASTM, EN, and BIS **[12]**.

India has witnessed several instances where trains have been successfully operated using bio-diesel engines. Here are a few notable cases:

1. Bandra-Bhuj Train: Railway officials in India ran the Bandra-Bhuj train on bio-diesel engines, showcasing the feasibility and effectiveness of using bio-diesel as a fuel source for train transportation. The successful operation of this train demonstrated the potential for utilizing bio-diesel in the railway sector.
2. Trials and Pilot Projects: The Indian Railways has conducted trials and pilot projects in various regions across the country to test the feasibility of bio-diesel engines in trains.

These initiatives aim to assess the performance, emissions, and efficiency of emissions running on bio-diesel, paving the way for potential future implementations.

3. Green Initiatives: As part of its sustainability and environmental conservation efforts, the Indian Railways has taken steps to reduce its carbon footprint by exploring alternative fuel options. The use of bio-diesel in train engines aligns with these green initiatives and contributes to a cleaner and greener transportation system.
4. Increasing Bio-diesel Usage: Over the years, Oil Marketing Companies (OMCs) in India have significantly increased their purchases of bio-diesel. The growing demand for bio-diesel by OMCs indicates a shift towards more sustainable fuel sources, including the use of bio-diesel in trains and other modes of transportation.

These cases illustrate the ongoing efforts in India to incorporate bio-diesel engines in trains as a means to reduce dependency on fossil fuels, minimize environmental impact, and promote sustainable practices in the railway sector.

India possesses significant untapped potential for Jatropha-based biodiesel production, offering a promising avenue for sustainable fuel development. In contrast, Western countries predominantly rely on field crops like rapeseed, sunflower, and soybean for biodiesel production. Meanwhile, Malaysia capitalizes on palm oil, while Nicaragua embraces Jatropha as their primary feedstock. Notably, the United States and Brazil emerged as dominant players in the global biofuels market, accounting for a staggering 87 percent of total production in 2018. Over the past decade, biodiesel consumption has witnessed a steady annual growth rate of 4 percent, with a projected 1 percent increase anticipated in 2019 **[13]**. However, despite these figures, the volume of biodiesel procured for blending with conventional diesel for on-road usage remains slightly above the previous year's levels, falling short of the expected market demand**.** Currently, purchasers of such blended diesel are primarily limited to select oil marketing companies, the Indian railways, State Road Transport Corporations across various states, fleet owners of transportation companies, and port authorities.

Some reasons for using biodiesel as an alternative fuel-

- Biodiesel is an oxygenated fuel hence emission of CO and soot is low in comparison to conventional diesel fuel.
- The use of biodiesel contributes to the longevity of diesel engines due to its superior lubricating properties compared to petroleum diesel fuel.
- By being produced from renewable vegetable oils and animal fat, biodiesel enhances fuel and energy security while promoting economic independence.

- Biodiesel offers a seamless transition to alternative fuel as it can be directly used in existing engines without requiring any modifications.
- Biodiesel is derived entirely from vegetable sources, ensuring it is free from sulphur, aromatic hydrocarbons, metals, or residues of crude oil.

Despite the numerous benefits of biodiesel, certain limitations need to be addressed. One such drawback is the issue of cold flow properties, which can lead to fuel thickening and clogging of fuel lines in colder climates. Additionally, biodiesel may exhibit inferior storage stability, posing challenges in long-term storage and transportation. Another concern is the unsatisfactory spray characteristics of biodiesel, which can impact fuel atomization and combustion efficiency. Furthermore, biodiesel often has a lower heating value compared to conventional diesel, potentially resulting in reduced engine performance and fuel economy.

However, it's worth noting that these drawbacks can be mitigated through appropriate improvisation and by carefully selecting biodiesel feedstock. Research and development efforts are focused on enhancing cold flow properties, stability, spray characteristics, and optimizing the energy content of biodiesel. By addressing these limitations, biodiesel can continue to evolve as a viable and sustainable alternative fuel option in the future.

1.3 Biodiesel Feedstock

The primary ingredient used for the production of biodiesel is referred to as a feedstock. Biodiesel has gained significant recognition as one of the leading contenders among alternative fuels in today's market. Various vegetable oils such as palm, jatropha, soybean, sunflower, rapeseed, safflower, and peanut oils are considered as sustainable feedstock options for large-scale biodiesel production, as outlined in **Table 1.1**. These feedstocks provide a reliable and renewable source of raw materials for the industrial manufacturing of biodiesel

Some common feedstocks are-

Animal fats: Chicken fat, lard, tallow, and by-products from fish oil production.

Vegetable oils: Edible and non-edible oils used depending on availability.

Waste or recycled oils: Obtained from mastered oil, sunflower oil, soybean oil, and used cooking oil.

Other feedstocks: Algae, halophytes such as Salicornia bigelovii, sewage sludge, and low ricin sources.

Table 1.1: Biodiesel feedstock

Edible oil	Nonedible oil	Animal fats	Other sources
Palm	Neem	Fish oil	Algae
Soybeans	Mahua	Poultry fat	bacteria
Rice bran oil	Jatropha (Jatropha curcas)	mutton tallow from sheep	fungi
Rapeseed	Pongamia	chicken fat	
Sun flower	Castor		

1.4 Waste Cooking Oil as a Feedstock

Vast reservoirs of wasted cooking oil are prevalent in hotels, restaurants, and establishments worldwide, amounting to a staggering environmental concern. This discarded oil, rendered useless after culinary use, is unfortunately disposed of in ecologically harmful ways. In certain regions, it contaminates the soil when dumped, while in others, it taints water bodies, posing severe hazards to the local ecosystem. The enormity of this issue is exemplified by the Energy Information Administration's projection that the daily global production of used cooking oil surpasses 100 million gallons, with an average individual contributing around nine pounds. Canada generates approximately 135,000 tonnes of used cooking oil annually, while EU member states collectively produce between 700,000 to 1,000,000 tonnes. The UK and India are not exempt, generating over 200,000 tonnes and finding solutions in innovative strategies, respectively **[14]**. Recognizing the urgency, India's Food Safety and Standards Authority (FSSAI) has introduced a holistic approach known as the EEE Strategy—Education, Enforcement, Ecosystem. This initiative aims to eliminate used cooking oil (UCO) from the culinary cycle, curbing the illicit practice of reusing UCO for cooking. Spearheading this transformation is the "Repurposed Used Cooking Oil" (RUCO) movement, which orchestrates the collection and conversion of UCO into biodiesel. FSSAI envisions that India could potentially yield an impressive 26 billion liters of UCO-derived biodiesel **[15].** Biodiesel, sourced from repurposed used cooking oil, emerges as an eco-friendly alternative for engines, promoting waste management and reducing environmental harm. Non-edible oils derived from plant species such as Jatropha curcas, Pongamia pinnata (Karanj), Calophyllum inophyllum (Nagchampa), Hevca brasiliensis (Rubber), etc. are the primary raw material sources for biodiesel in India **[16].** The economic aspect is equally compelling, as the readily accessible waste cooking oil, needing only collection and transport, translates into an inexpensive feedstock. Sometimes even provided at no cost, this feedstock augments the feasibility of biodiesel production, making it an economically viable and ecologically sound option. In essence, the potential of transforming discarded cooking oil into biodiesel presents a win-win scenario. Not only does it alleviate the waste problem, but it also addresses environmental concerns and offers a practical and economical avenue for biodiesel manufacturing. **Figure 1.2** illustrates the utilization of used cooking oil as a feedstock for biodiesel production in India between 2010 and 2023. A notable observation from the graph is that the biodiesel production remains relatively modest in contrast to the substantial volume of waste cooking oil generated within the country.

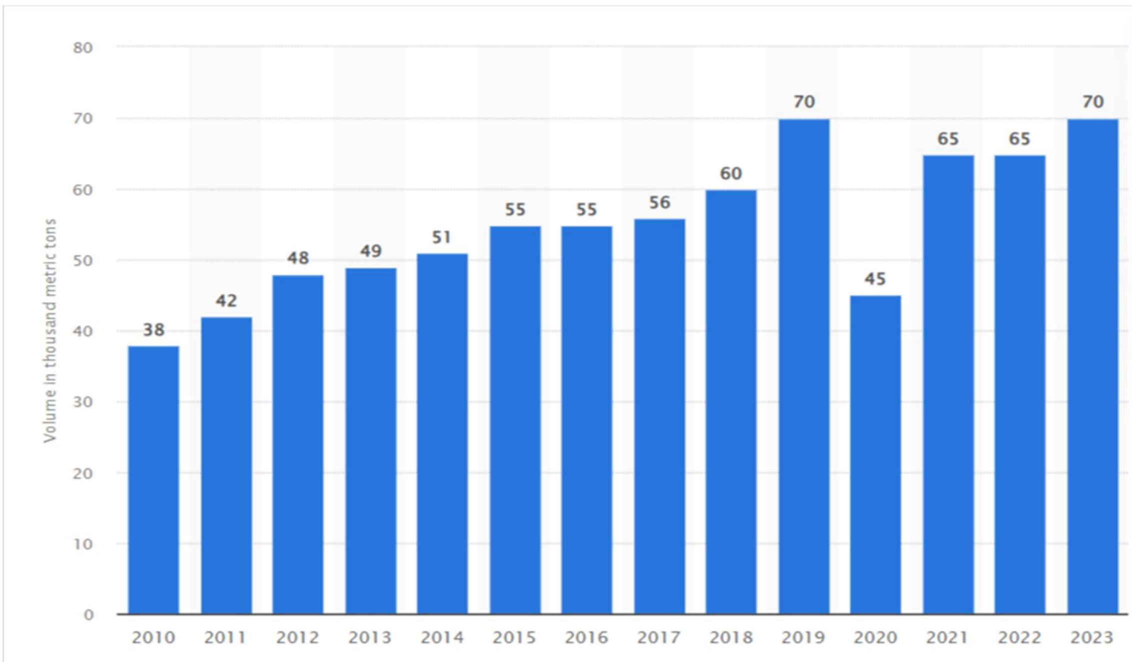

Fig 1.2: Biodiesel production from used cooking oil in India (2010 -2023) **[17]**

1.5 Availability of Biodiesel in India

Presently, India possesses the capability to fulfill approximately a quarter (25%) of its fossil fuel demand, but to bridge the remaining gap, reliance on imports is necessary, entailing a significant drain on foreign currency reserves. To effectively counteract this situation and tackle concurrent environmental and energy challenges, there is a drive to promote practical renewable energy technologies. According to findings by **Biswas and Pohit (2013) [18]**, Indian farmers explored oil seed-bearing trees within arid landscapes. Among these, Jatropha and, to a lesser extent, Pongamia were chosen as sources for biodiesel production. The overarching goal was to achieve a 20% biofuel blend by 2012. It's worth noting that India boasts around 400 oil-producing edible crops. While Jatropha oil remains a prevalent biodiesel source in India, there is an ongoing need for comprehensive exploration of alternative feedstock oils. India's approach to the biofuel initiative is distinctive, blending pragmatism, curiosity, and a formidable drive for progress. Unlike certain countries like the USA, Brazil, and Germany, which predominantly rely on food grains like rapeseed, sugarcane, and soybeans, India's approach doesn't necessitate extensive or diversification of conventional agriculture **[19].**

The burgeoning interest in biofuels is prompting various institutions, including the Indian Institute of Science, Tamil Nadu Agriculture University Coimbatore, and Kumara Guru College of Technology, to engage in the production of trans-esterified non-edible oils for biodiesel application. The Indian Oil Corporation is also actively involved in research and development efforts aimed at defining biodiesel specifications using vegetable oil derived from the Jatropha plant, notably in Faridabad. With 26 biodiesel plants operating within the country, India's commitment to biofuel production is unmistakable, signaling its increasing strides toward enhancing domestic biofuel manufacturing capabilities.

As depicted in **Figure 1.3**, India's biodiesel production demonstrates a consistent upward trajectory, with each passing year witnessing a notable increase. This escalating trend positions India favorably to potentially integrate biodiesel into a diverse array of applications as a viable fuel choice in the near future.

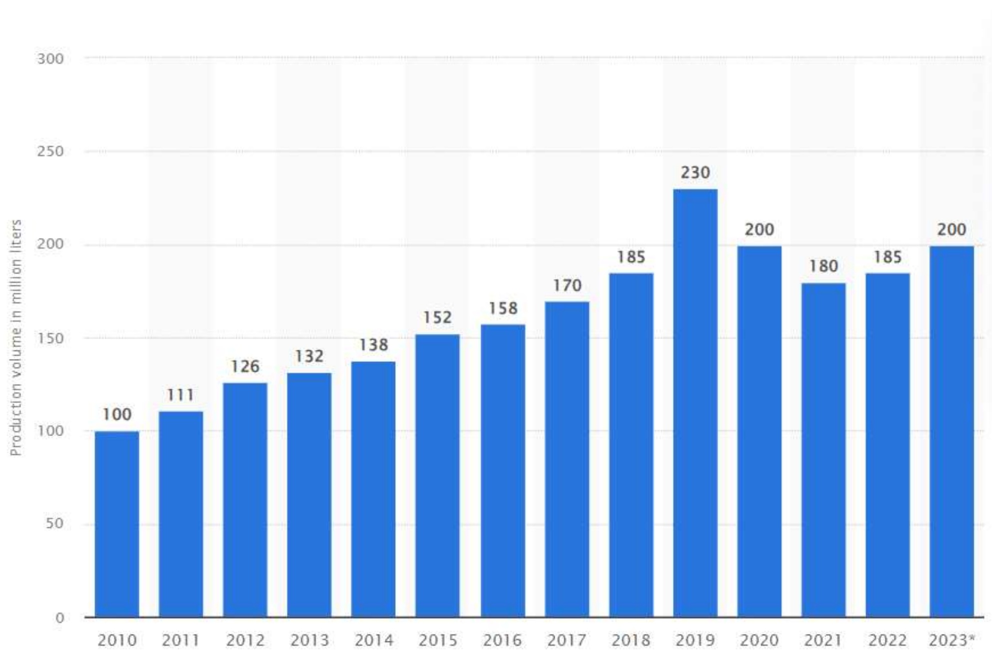

Fig 1.3: Biodiesel production in India from 2010-2023 **[20]**

Used cooking oil stands out as a highly promising biodiesel resource. Extensive research has been dedicated to the production and utilization of biodiesel derived from waste cooking oil (WCO) within the transportation sector. This strategic move to broaden the spectrum of potential feedstock options, encompassing both plant-based and waste cooking oils, has yielded insightful outcomes. While India might not have produced notably groundbreaking advancements in biodiesel creation throughout the past two decades of research, it has generated several substantial findings that possess the potential to shape the trajectory of future developments in this field.

1.6 Benefits of Biodiesel

- **Related to Engines**

• It can seamlessly power existing diesel engines with minimal or even no adjustments. This positions it as a potential future replacement for conventional fossil fuels in the hierarchy of preferred energy sources.

• Distinguished by a high cetane number, signifying a shorter interval between fuel injection and combustion, biodiesel offers a distinct edge. This characteristic translates into enhanced and more seamless engine performance, surpassing the performance of standard diesel.

• Biodiesel's elevated flash point, in comparison to regular diesel, ensures reduced volatility. This inherent safety feature renders it secure for handling, storage, and transportation.

• The implementation of biodiesel results in a tangible improvement in vehicle engine operation. The engine runs with heightened smoothness and efficiency, attributed to the augmented fuel lubrication provided by biodiesel.

• Utilizing biodiesel contributes to reduced engine wear in comparison to conventional petroleum diesel. This translates into enhanced longevity and decreased mechanical strain on the engine.

- **Social and Envoirmental**

• Diverging from finite petroleum resources, biodiesel shines as a renewable energy source. Its production can be tailored to immediate needs and it boasts lower pollution emissions compared to petroleum-based diesel, thanks to its origins in animal and vegetable fats.

• Fossil fuels, when burned, release greenhouse gases, like carbon dioxide, which contribute to global warming. Transitioning to biodiesel from traditional petroleum fuels can potentially curtail greenhouse gas emissions by an impressive 78%. The absence of sulphur content in biodiesel eliminates the emission of Sulphur oxides and sulfates post-combustion.

• The finite nature of fossil fuels raises concerns about future availability of coal, oil, and natural gas. Embracing biodiesel offers a means to alleviate reliance on foreign oil supplies, fostering greater energy independence.

• The combustion of biofuels results in significantly lower carbon dioxide emissions and reduced pollutants. Biodiesel's emission profile is marked by substantially diminished levels of soot, carbon monoxide, unburned hydrocarbons, and Sulphur dioxide in comparison to conventional petroleum diesel.

• Data from National Laboratories underscores the impactful change—shifting from petroleum to biodiesel slashes carbon dioxide emissions by an astonishing 74%. This shift aligns with a concerted effort to mitigate environmental impact and reduce carbon footprints.

1.7 Problem Statement

The daily surge in energy consumption has become a pressing concern, particularly given the dwindling reserves of fossil fuels and other unsustainable resources. A pressing need exists for exploring non-petroleum, non-depleting, and environmentally friendly fuel alternatives. Among various sectors, road transportation stands out as a substantial consumer of diesel fuel, consequently becoming a primary contributor to exhaust emissions. Biodiesel emerges as a fitting renewable substitute for petroleum-based fuels. While the biodiesel industry has achieved certain successes, significant hurdles persist. The production cost of biodiesel remains considerably higher compared to its petroleum counterpart, driven primarily by the costs of raw materials and processing **[21]**. The emission profile of diesel exhaust remains a paramount challenge, thereby underscoring biodiesel's potential as a solution to the ongoing pollution dilemma. Biodiesel exhibits distinctive fuel properties in contrast to petroleum diesel, and blending it with varying diesel proportions yields diverse fuel characteristics. However, biodiesel does encounter challenges such as viscosity, NOx emissions, and low-temperature operability. These qualities must be well-defined before integrating biodiesel into diesel engines. Research indicates that introducing additives to biodiesel blends can enhance combustion by mitigating oxidation and thermal degradation, resulting in improved fuel efficiency and reduced harmful emissions.

Considering the range of issues at hand, biodiesel emerges as a crucial alternative to address future challenges. This study seeks to comprehensively compare the production and combustion effects of crude and waste soybean oil-based biodiesel in diesel engines. Biodiesel has been synthesized from raw soybean oil, and waste cooking oil sourced from the same soybean oil for biodiesel production. Thorough testing has been conducted to assess any alterations in characteristics after cooking. Both forms of biodiesel will be tested in a VCR engine to ascertain their combustion characteristics, paving the way for informed decisions regarding their utilization.

1.8 Objectives of the Present Study

- To study the viability of biodiesel as a potential substitute for traditional diesel fuel in C.I. engines. Notably, waste cooking oil emerges as a promising and abundant resource for producing biodiesel.
- To study the experimental investigations utilizing biodiesel blends derived from waste cooking oil and raw soybean oil in a Variable Compression Ratio (VCR) diesel engine to assess combustion behaviours and other characteristics at different compression ratios..
- To compare the engine performance using different percentage of waste-based and soybean oil biodiesel blends.

1.9 Organization of the thesis

This dissertation is comprised of five chapters as organized below:

Chapter 1:	General introduction of the thesis, biodiesel as a fuel, feedstocks available for biodiesel, availability of biodiesel in India, waste cooking oil as a feedstock, advantages and issues related to biodiesel, problem statement, objectives of the present work
Chapter 2:	Literature review of the proposed work, scope of the present study
Chapter 3:	Experimental setup of the VCR diesel engine and combustion analysis
Chapter 4:	Comparison and discussion of combustion characteristics from the results obtained for both biodiesels.
Chapter 5:	General conclusion of the thesis and scope of future work

Chapter 2

LITERATURE REVIEW

2.1 Literature Survey

In the realm of biodiesel production and application, a multitude of investigations and analyses have been carried out in recent times. These studies delve into the creation of biodiesel and its subsequent utilization in diesel engines. Diverse scholarly articles present a wide array of examinations within the scope of biodiesel derived from sources like vegetable oils, discarded cooking oils, and animal fats. Numerous research contributions have been made concerning the conversion of waste cooking oil and unrefined oil into biodiesel. The quality of the resulting biodiesel is intricately tied to the initial quality of the chosen feedstock and the specific composition of fatty acids inherent in vegetable oils or animal fats. However, the application of biodiesel as a viable fuel source is not without its challenges and concerns. The utilization of biodiesel presents certain intricacies that researchers and experts have grappled with. Within this context, some notable undertakings by researchers warrant discussion. Overall, the biodiesel landscape is enriched by a diversity of studies exploring the production and utilization aspects, each contributing to our understanding of this alternative fuel's potential and limitations.

Apurba Layek *et al.* (2022) [22] conducted a study investigating the impact of incorporating waste cooking oil methyl ester (WCOME) and diesel blends with ethanol as an additive in a compression ignition (CI) engine. The primary focus was to assess the effects of these blends on engine performance and emissions. The investigation encompassed various proportions of ethanol mixed with the WCOME-diesel blend, aiming to identify the most favorable engine operating conditions. The foundational fuel for this study was a WCOME-diesel blend composed of 10% WCOME and 90% diesel. To explore the potential benefits of ethanol addition, different ethanol percentages, ranging from 5% to 20%, were incorporated into the WCOME-diesel blend to create a spectrum of blends for experimentation. The study evaluated essential performance parameters, including brake thermal efficiency, brake specific fuel consumption, heat release rate, cylinder pressure, as well as emission characteristics like nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), and smoke opacity. The research findings revealed that introducing 5% ethanol into the WCOME-diesel blends emerged as the most advantageous blend configuration. This specific blend demonstrated a reduction in emissions, particularly in terms of reduced brake specific fuel consumption (BSFC), contributing to improved environmental performance.

Kahraman *et al.* (2021) [23] conducted a comprehensive study comparing the effects of diesel-biodiesel blends (B20) and diesel-biodiesel-bioethanol blends (BE5) on combustion, performance, and emissions. The investigation encompassed parameters like brake specific fuel consumption, brake thermal efficiency, CO, CO2, HC, NOx, and smoke opacity. It also examined cylinder pressure, heat release rate, ignition delay, and combustion phases. Tests covered injection pressures of 170, 190, and 220 bar, with engine loads from 25% to 100%. Results favored BE5 at high injection pressure, showing enhanced performance, emissions, and combustion compared to B20. BE5 improved fuel consumption by 7% and thermal efficiency by 6% versus B20, while reducing NOx by 1.4% and smoke emissions by 6.4%. Notably, BE5 achieved up to a 45% smoke emission reduction compared to diesel fuel.

***Rao et al.* (2016) [24]** conducted experiments involving Diethyl Ether (DEE) as an additive to Mahua biodiesel in diesel engines, aiming to replace conventional fuels. The primary objective was to achieve low-temperature combustion while reducing NOx emissions. While biodiesel significantly reduces other emissions, NOx reduction remains a challenge due to the oxygen content in transesterified vegetable oil. DEE, with distinct properties like a higher cetane number and lower autoignition temperature, offers potential for smoother combustion initiation at lower temperatures. The study involved blending DEE with Mahua methyl ester (MME) at varying proportions—3%, 5%, and 10%—and testing under different engine loads. Results showed a substantial decrease in emission levels with a 15% DEE blend with MME at full load. Notably, thermal efficiency increased, and specific fuel consumption improved significantly with the 15% additive blend. This approach holds promise for achieving better emission levels and combustion efficiency in diesel engines.

Chaurasiya *et al.* (2019) [25] conducted an investigation focused on evaluating the viability of raw oils, specifically jatropha, soybean, and waste cooking oil, as alternative fuels for compression ignition (CI) engines. The study involved experimental analysis of blends comprising high proportions of these vegetable oils with diesel. The research process entailed blending raw oils with diesel in varying ratios, ranging from 20% to 50%, utilizing pure raw vegetable oil as the base. Two sets of experiments were carried out for each fuel blend—one for performance analysis and another for emission testing. The analysis encompassed pure diesel and different blends: Jatropha-diesel, Soybean-diesel, and waste cooking oil-diesel. All blends were evaluated at a compression ratio (CR) of 16.5. The investigation focused on examining the performance and emission characteristics of each raw oil-diesel blend, facilitating a comparative analysis. Notably, the results highlighted that B20 blends of all biodiesels exhibited closely aligned values for Brake Thermal Efficiency (BTE) across different loadings. This study contributes insights into the potential of raw oils as alternative fuels for CI engines, shedding light on their performance and emissions profiles.

Taib *et al.* (2018) [26] conducted a study to explore the potential benefits of diesel-ethanol-palm methyl ester (PME) blends in enhancing combustion characteristics. These blends combine fuels with distinct properties, aiming to optimize their performance in real engine applications. The primary goal was to identify the most suitable fuel composition through simulation and to assess its practical feasibility. The research involved using simulation to analyze the combustion characteristics of different compositions of diesel-ethanol-PME blends. Seven blends with varying percentages of PME (ranging from 10% to 40%) and ethanol were tested alongside 50% diesel fuel in a compression ignition Yanmar TF90 engine model. Operating conditions were set at 1600 RPM. Results indicated that a higher PME content led to an increase in heat release rate (HRR). However, non-uniform chemical energy release affected this trend, with the blend containing 25% PME and 25% ethanol exhibiting the highest HRR due to the reaction's characteristics. A larger ethanol fraction decreased temperature while increasing heat release. Ignition delay was observed in blends with over 15% ethanol. In summary, blending ethanol and PME with diesel elevated combustion heat release rates, contributing to improved engine efficiency. However, blends exceeding 35% ethanol were deemed unsuitable for direct injection compression ignition engines without modifications, given their low temperature and HRR. The study offers insights into optimizing fuel blends for better combustion and efficiency in engine applications.

Sahu *et al.* (2021) [27] emphasized the significance of Compression Ignition (CI) engines due to their efficiency and durability. To combat environmental pollution and resource depletion, the research explored alternative fuels like biodiesels and ethanol for CI engines. The study investigated Jatropha Biodiesel (JBD), Used Cooking Oil (UCO) Biodiesel, and Ethanol, analyzing their fuel properties. Parameters such as density, kinematic viscosity, calorific value, oxidation stability, cold weather properties (CFPP, CF, and PP), and flash point temperature were measured and compared for pure alternative fuels. Different blends (5%, 10%, 15%, and 20%) of JBD, UCO biodiesel, and ethanol were also examined. Ethanol exhibited lower density, viscosity, and improved cold weather properties compared to the other fuels and blends. Ethanol's viscosity was approximately 61.8% lower than mineral diesel. Oxidation stability tests demonstrated that mineral diesel had higher stability, while UCO biodiesel and JBD showed lower stability. The flash point of the 5% ethanol blend decreased significantly compared to mineral diesel, remaining relatively constant with higher blending ratios. The study underscores the potential of ethanol as an alternative fuel with favorable properties for CI engines.

Emiroğlu *et al.* (2018) [28] investigated the influence of adding butanol, ethanol, and methanol (at 10% blend levels) to diesel fuel on a single-cylinder diesel engine's combustion, performance, and emissions under diverse loads. These alcohol-diesel blends (B10, E10, and M10) were compared to pure diesel (D100). Results demonstrated that alcohol blends had prolonged ignition delays due to lower cetane numbers, while showing higher peak cylinder pressures across loads. The increased oxygen content and longer ignition delays led to higher maximum heat release rates in alcohol blends compared to diesel. Despite D100 exhibiting better fuel consumption and thermal efficiency due to its higher heating value, B10, E10, and M10 followed D100's trend based on heating values. Although NOx emissions slightly increased with alcohol blends, they reduced smoke and CO emissions. In summary, the study highlights the impact of alcohol-diesel blends on combustion, performance, and emissions, offering insights for engine optimization.

Felipe Fernandes Klajn *et al.* (2018) [29] conducted a study involving the production of biodiesel by blending vegetable and animal sources with diesel and diesel-ethanol. The research utilized a motor-generator setup to assess both performance and emission characteristics. The study incorporated 15% and 20% animal-vegetable biodiesel in each diesel-ethanol blend. The motor-generator tests involved subjecting samples to resistive loads ranging from 2 to 5 kW with six repetitions. The physicochemical properties of the biodiesel met national standards, and the optimal specific fuel consumption (SFC) was observed in the 15% biodiesel-1% ethanol (B15E1) blend at a 5 kW load, registering at 327.069 g kW−1 h−1. Diesel followed closely with a specific fuel consumption of 334.875 g kW−1 h−1. The exhaust gas temperature displayed varying behavior based on ethanol concentration, with higher ethanol concentrations resulting in lower temperatures. Notably, an increase in ethanol concentration led to a decrease in NO emissions but an increase in SO2 emissions.

Ashraya Gupta *et al.* (2016) [30] explored the vital role of diesel engines in medium and medium-large transport sectors due to their efficient torque generation at low RPM. Biodiesel gained attention as a promising solution for energy diversification and petroleum independence due to its high calorific value and lubricity comparable to conventional diesel. However, challenges like corrosiveness and fuel instability hindered its commercial viability. While biodiesels lower CO, HC, and PM emissions, they raise NOx emissions. Gupta's study investigated blending alcohols with biodiesel-diesel mixes to mitigate NOx emissions and enhance fuel properties. Karanja oil produced Karanja oil methyl ester (KOME) biodiesel, blended volumetrically with 70% fossil diesel, 20% KOME, and 10% alcohol (ethanol, isopropanol, or isobutanol). Evaluating engine performance and exhaust emissions, the study tested two compression ratios from no load to 20% increments to full load. The goal was finding optimal alcohol blends and compression ratios to meet diesel performance standards, emission control norms, and enhance fuel properties. Promisingly, the results suggested profitable biodiesel-alcohol utilization to address rising energy demands.

A. Silitonga's *et al.* (2018) [31] study delved into the positive impact of diminishing oil reserves on the advancement of renewable biofuels like biodiesel and bioethanol. These eco-friendly alternatives are gaining recognition for their potential to meet energy demands. The research aimed to evaluate the performance and exhaust emissions of a diesel engine using biodiesel-bioethanol-diesel blends. Biodiesel was derived from a blend of Jatropha curcas-Ceiba pentandra crude oil, with each composition at 50%. The production involved processes like degumming, acid catalyzed esterification, and alkaline-catalyzed transesterification. Various blends, including B10BE5, B20BE8, B30BE10, B40BE13, and B50BE15, were examined. Findings showed that lower concentration biodiesel-bioethanol blends closely mirrored diesel's engine performance, including torque, brake power, and thermal efficiency. Integrating biodiesel and bioethanol into diesel fuel led to reduced carbon emissions and smoke opacity. In conclusion, the study suggests that using low-concentration biodiesel-bioethanol blends could be a viable alternative fuel option for diesel engines.

Md. Saiful Islam's *et al.* (2014) [32] research unveils investigations into emissions and performance of a diesel engine using castor biodiesel and its diesel blends ranging from 0% to 40% by volume. Employing an acid-based catalyzed transesterification system, castor biodiesel was produced with a peak yield of 82.5% achieved under optimized conditions. The FTIR spectrum of castor biodiesel showcased functional groups C=O and C–O, attributed to the ester compound within biodiesel. Smoke emission tests revealed that B40 (a blend of 40% biodiesel and 60% diesel) exhibited minimal black smoke compared to conventional diesel. Performance tests on the diesel engine indicated an increase in specific fuel consumption for the biodiesel blend, with optimization of the blending ratio. Consequently, the study concludes that the blends of castor seed oil (e.g., B20) offer a viable alternative fuel for diesel engines, with potential to mitigate exhaust emissions and curb air pollution.

K. Sureshkumar *et al.* (2007) [33] addresses the escalating use of fossil fuels contributing to urban air pollution and greenhouse gas emissions, thereby driving global climate change. Biofuels, being renewable, offer an avenue to supplement hydrocarbon fuels and counteract the negative outcomes associated with fossil fuel combustion. The study primarily focuses on the creation of pongamia pinnata methyl ester (PPME) or biodiesel through transesterification of raw pongamia oil. The research further involves evaluating the properties of diesel-PPME blends at different ratios (20%, 40%, 60%, 80%, and 100%)—denoted as B20, B40, B60, B80, and B100—along with performance and exhaust emission analysis in a 3.68 kW Compression Ignition (C.I.)

engine. Experimental findings indicated that substituting 40% of biodiesel for petro diesel resulted in reduced emissions, heightened efficiency, and no compromise in engine power. This discovery holds potential to address energy crisis and environmental pollution, steering toward sustainable development.

Fitrika *et al.* (2022) [34] conducted a study involving the utilization of B15, B20, and B30 blends to power dump trucks used in coal mining operations. Employing the same type of dump truck and covering the same mileage, the investigation yielded specific fuel consumption values. For B15, the specific fuel consumption stood at 1.42 liters per ton of coal. The introduction of B20 resulted in an increase, with specific energy consumption reaching 1.43 liters per ton of coal. Intriguingly, the adoption of B30 led to a decrease in specific energy consumption, registering at 1.42 liters per ton of coal. This reduction in energy consumption can be attributed to the implementation of an energy management program that involves smart driving practices. Notably, this entails shutting off the dump truck's engine when it is not in operation. The findings underscore the potential of such practices to enhance fuel efficiency and energy utilization within coal mining operations.

S. Prabhakar *et al.* (2022) [35] conducted a study that explored the application of hybrid vegetable oil (HVO) derived from Pongamia pinnata and Madhuca indica as an alternative diesel fuel. The research involved the combination of raw pongamia oil and mahua oil in a 50:50 ratio to create the hybrid vegetable oil. Three fuel blends were formulated: a 20% blend of methyl ester of pongamia oil (MEOP), a 20% blend of methyl ester of mahua oil (MEOM), and a 20% blend of methyl ester of hybrid vegetable oil (MEHVO), all mixed with 80% neat diesel. Among these blends, the MEHVO blend exhibited competitive performance that closely approached that of diesel fuel. When utilizing the 20% MEHVO blend in conjunction with 80% diesel, the engine's performance was comparable to using pure diesel. Notably, the MEHVO blend led to reduced hydrocarbon (HC) and carbon monoxide (CO) emissions. However, there was a slight increase in carbon dioxide (CO2) and nitrogen oxides (NOx) emissions compared to using pure diesel. In essence, the study shed light on the viability of utilizing HVO derived from Pongamia pinnata and Madhuca indica as a partial substitute for diesel fuel, showcasing a balance between performance and emissions characteristics.

N. Musa's *et al.* (2016) [36] worked on the utilization of biodiesel as an alternative to mitigate the environmental, economic, and scarcity issues associated with conventional diesel use in diesel engines. Recognizing the importance of understanding the emissions resulting from biodiesel utilization, the research aimed to evaluate the emissions of particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) from diesel engines fueled by coconut oil biodiesel, its blends, and conventional diesel for comparative analysis. The evaluation outcomes unveiled distinct trends in emissions. Specifically, NOx emissions exhibited an increase corresponding to higher percentages of biodiesel in the blend, while PM, CO, and HC emissions demonstrated a decrease with the rising biodiesel content in the blend. In direct contrast, diesel fuel yielded the lowest NOx emissions while registering the highest PM, CO, and HC emissions. In summary, the study provided valuable insights into the emissions profile of biodiesel and its blends when utilized in diesel engines, offering crucial information for assessing their environmental impact in comparison to conventional diesel use. The research contributes to understanding the potential of biodiesel as a more environmentally sustainable fuel option.

Baweja et al. (2021) [37] discussed mustard oil biodiesel's effect on the performance, emission and combustion characteristics of a diesel engine. The study involved the creation of four distinct test fuels, denoted as B10, B20, B30, and B40, by blending diesel fuel with 10%, 20%, 30%, and 40% of mustard oil biodiesel, respectively. These test fuels were then subjected to comprehensive engine testing, with a focus on various combustion properties. The objective was to compare the performance of these blends with pure diesel fuel under different load conditions. Notably, at higher loads, both diesel fuel and all the blends exhibited similar cylinder peak pressure values. However, when the load was set at 75% and 100%, the B10 blend stood out by having the lowest cumulative heat release rate compared to all the other blends and pure diesel. Additionally, the B10 blend demonstrated superior brake thermal efficiency, outperforming all other blends of diesel fuel, particularly up to an 80% load. Furthermore, the B20 blend exhibited notable results in reducing NO emissions across load conditions of 0%, 25%, 50%, and 75%.

2.2 Scope of the Present Study

This thesis seeks to elucidate the potential of biodiesel as a viable substitute for conventional diesel fuel. The significance of this study stems from the inevitable depletion of petroleum resources, underscoring the urgency of transitioning to sustainable and ecologically sound energy alternatives. A multitude of feedstock options are available for biodiesel production, each catering to different regions. In Asian countries, palm oil takes precedence, while rapeseed oil dominates biodiesel production in Europe. Developing nations like India are exploring the jatropha plant as a biodiesel source. Meanwhile, the accessibility of waste cooking oil renders it a pragmatic avenue for biodiesel synthesis, contributing not only to cost reduction but also to waste management. Furthermore, waste cooking oil biodiesel with crude cooking oil biodiesel facilitates a comprehensive assessment of fuel choices. Central to this investigation is the creation of biodiesel from both crude and waste soybean oil, followed by a meticulous analysis of their combustion characteristics within a Variable Compression Ratio (VCR) diesel engine. A wealth of scholarly literature underscores the research dimensions encompassing combustion, performance, and emission attributes of diesel engines utilizing both crude and waste cooking oil. By optimizing yield and properties, the resulting biodiesels will be subjected to rigorous testing and comparison, aimed at determining their suitability as alternative fuels for diesel engines. Scrutinizing a range of combustion parameters including peak pressure, net heat release and comparative evaluations between the biodiesel blends and traditional diesel become pivotal. A comparative study has been made with convention diesel and blends of biodiesel at different compression ratio. The ultimate goal is to ascertain the viability of biodiesel as a dependable fuel source for diesel engines. This endeavor assumes importance in demarcating the differential applications of crude and waste soybean oil, thus facilitating informed decisions regarding their utilization in suitable operating conditions for better performance.

Chapter 3

EXPERIMENTAL SETUP AND METHODOLOGY

This chapter focuses on conducting a comparative analysis of performance and combustion using two different biodiesel blends, namely Waste Soyabean Oil Biodiesel (WSOBD) and Crude Soyabean Oil Biodiesel (CSOBD), on a VCR (Variable Compression Ratio) diesel engine. The biodiesel blends were prepared by mixing 5% and 10% of biodiesel with diesel fuel, resulting in CSOBD 5, CSOBD 10, WSOBD 5, and WSOBD 10. To examine the combustion characteristics of the engine, various load conditions were considered, including zero load, 25% load, 50% load, 75% load, and full load. The tests were conducted on CR 15, CR 16, CR 17, and CR 18 engine compression ratios, with nearly a constant speed of 1500 rpm. The aim of this study was to compare the performance and combustion properties of the two biodiesel blends under different load conditions, providing insights into their potential as alternative fuels for diesel engines.

3.1 Description of the experimental setup

An experimental setup is designed with a single-cylinder, four-stroke VCR diesel engine coupled to an eddy current-type dynamometer for load testing. The unique feature of this setup is the tilting cylinder block arrangement, which allows for adjusting the compression ratio without stopping the engine or modifying the combustion chamber geometry. Measurement of combustion pressure and crank-angle setup is facilitated using specialized equipment. The setup includes provisions for interfacing temperature sensors, load monitoring, fuel flow measurement, and airflow measurement. It incorporates a fuel delivery system for both diesel and biodiesel, a water-cooling system, and a lubrication system. Two fuel tanks are used for conducting blend tests. The setup also features a standalone panel box equipped with an air box, manometers, fuel metering device, process indicator, engine indicator, and fuel and air flow transmitters. Calorimeters with water flow measurement rotameters are available for heat balance analysis. The performance analysis of the VCR engine is conducted using the "Enginesoft" software, which provides real-time performance assessment. The software is connected to the electronic data acquisition system of the test engine setup, and all relevant performance and combustion data are collected and processed on a laptop. During the experiment, the engine operates at a rated speed of 1500 rpm, with constant injection pressure and timing of 210 bar and 23 degrees before top dead center (TDC), respectively. The tilting block is adjusted by loosening the allen bolts and turning the adjuster to achieve the desired compression ratio indicated on the CR indicator. Once the compression ratio is set, the lock nut and allen bolts are tightened. To facilitate data collection and analysis, the setup incorporates advanced measurement and monitoring devices. Combustion pressure and crank-angle signals are captured using engine indicators, which are connected to a computer for data processing. Additionally, temperature sensors, load monitors, fuel flow meters, and airflow measurement devices are integrated into the setup for comprehensive performance assessment. The experimental setup includes a comprehensive range of components and systems to ensure accurate testing. This includes a fuel delivery system capable of handling both diesel and biodiesel fuels, a water-cooling system to maintain optimal engine temperature, and a lubrication system for smooth operation. The setup is equipped with multiple fuel tanks for conducting blend tests and features a panel box with essential instruments for monitoring and control. Throughout the experiment, performance parameters such as braking power, indicated power, frictional power, indicated thermal efficiency, mechanical efficiency, and specific fuel consumption are measured and analysed. The data gathered provides valuable insights into the combustion behavior and overall performance of the VCR diesel engine. **Figure 3.1** illustrates the schematic diagram of the experimental setup, showcasing the arrangement and connectivity of various components. **Figure 3.2** presents a visual representation of the VCR engine setup itself, providing a clear view of the engine's physical configuration.

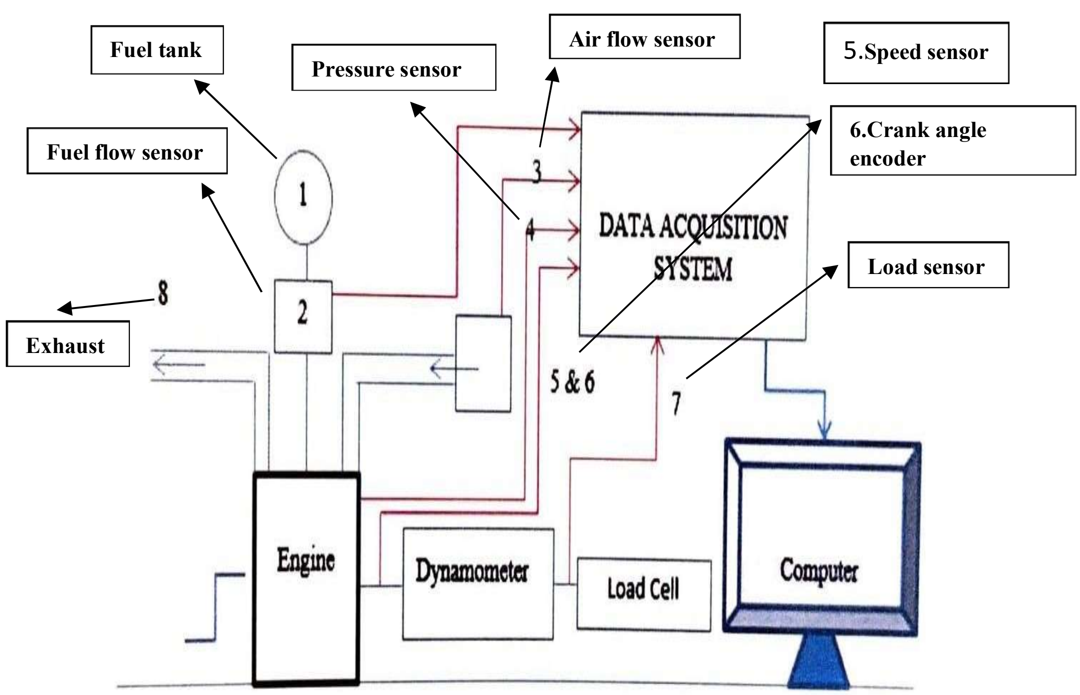

Fig 3.1 Schematic diagram of experimental engine setup

Fig 3.2: VCR Engine Set up

Table 3.1 Experimental engine setup specification **[38]**

Parameters	Specification
Make and model	Make Kirloskar, Model TV1, single cylinder, 4 stroke Diesel
Rated power	3.5 kw @1500 rpm
Compression ratio	12 to 18
Injection type and timing	Direct injection @ 23ºBTDC
Bore	87.50 mm
Stroke	110 mm
Injection pressure	210 bars
Dynamometer	Eddy current, water cooled with loading unit
Method of cooling	Water cooled
Connecting rod length	234 mm
Load sensor	Strain gauge load cell

Table 3.2 Properties of WSO and CSO **[38]**

Property	Experimentally determined value of WSO	Experimentally determined value of CSO
Density	0.935 gm/cc	0.924 gm/cc
Acid Value	0.6452 mg KOH/gm	0.589 mg KOH/gm
Free fatty acid (%)	0.3242 %	0.2959 %
Saponification value	200.557 mg KOH/gm	203.36 mg KOH/gm
Molecular weight	841.87gm/mol	830 gm/mol

Table 3.3 Properties of WSOBD and CSOBD **[38]**

Fuel Properties	Diesel		Biodiesel from WSO (WSOBD)	Biodiesel from CSO (CSOBD)	Requirement For Biodiesel ASTM D6751/EN14214	
	Min	Max			Min	Max
Density at 34ºC (gm/cc)	0.820	0.845	0.8872	0.8896	0.860	0.900
Kinematic Viscosity at 40ºC (mm^2/s)	2.15	4.6	2.83	3.87	1.9	6
Acid Value (mg KOH/gm)	–	–	0.449	0.561	0.5(max)	
Saponification Value (mg KOH/gm)	–	–	223	220.2	370(MAX)	
Iodine Value (Gm I_2/100gm oil)	–	–	107.6	126.29	120(max)	
Flash Point (^0C)	66	85	159	148	130(min)	
Fire point(^0C)			185	167	-	
Higher Heating Value (MJ/kg)	42.6	45.6	38.67	38.50		
Cetane Index	51.4		46.56	42.67	47 (min)	

3.2 Measurement systems

Various measurement systems are employed to capture experimental data during the test, including the load measurement system, fuel injection pressure measurement system, cylinder pressure measurement system, air flow measurement system, and data acquisition system. The following provides an overview of each of these systems.

3.2.1 Dynamometer load measurement system

The load measurement system within the experimental test setup is composed of an eddy current dynamometer, a strain gauge load cell, and a loading unit. This configuration enables the application and measurement of loads on the engine. The dynamometer's purpose is to assess the force, torque, or power generated by the engine, while also serving to load or exert torque on the engine. In this study, an eddy current dynamometer is employed, featuring a water-cooling mechanism. Eddy current dynamometers offer the advantage of swift load adjustments, facilitating rapid load setting changes. The VCR diesel engine is directly linked to the eddy current dynamometer through a loading device, capable of accommodating weights up to 10 kg. Load measurement is facilitated by a strain gauge load cell, and the speed is detected through a shaft equipped with a crank angle sensor. Key components of the eddy current dynamometer encompass a rotor, shaft, bearings, casing, and bed plate. The rotor is mounted on a shaft, which runs within bearings. Within the casing, two field coils are interconnected in series. Applying a direct current to these coils via a loading device generates a magnetic field in the casing across the rotor's air gap on both sides. The resultant photograph is depicted in **Figure 3.3.**

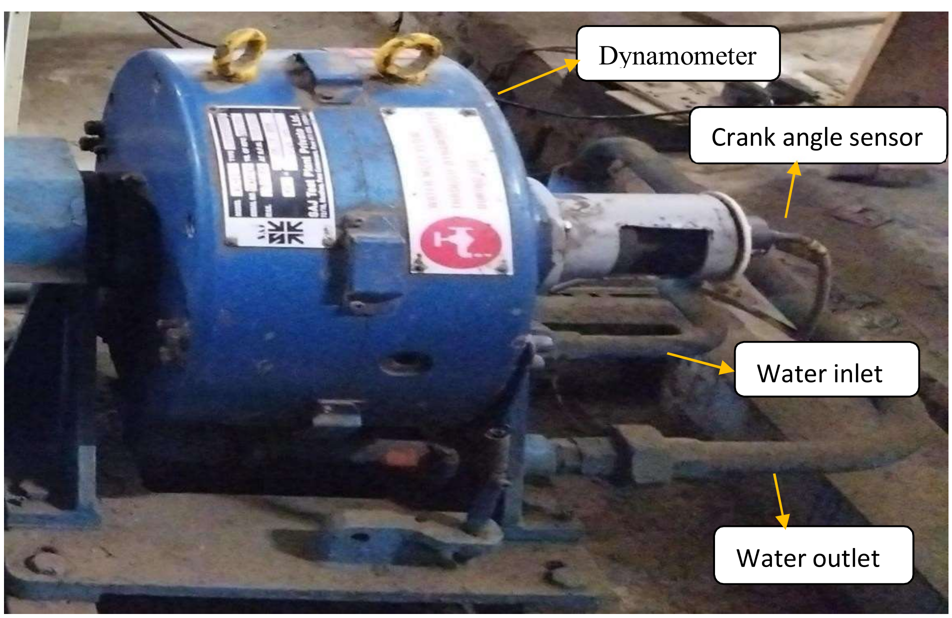

Fig 3.3 Dynamometer

3.2.2 Fuel injection pressure measurement system

The fuel injection process of an internal combustion engine involves introducing fuel through a fuel injection system. The pressure at which fuel is delivered into the engine cylinder is termed the fuel injection pressure, also known as fuel inline pressure. In the ongoing experimental study, the fuel injection pressure is monitored using a Piezo Sensor. This sensor's diaphragm is constructed from stainless steel and is hermetically sealed to ensure its integrity. The sensor is strategically positioned within a specially designed high-pressure pipeline. Adjusting the fuel injector spring tension, managed by the fuel injector itself, enables control over injection pressure. By tightening or loosening the nut, the injection pressure can be modulated to attain higher or lower levels respectively. To increase pressure, the nut is rotated clockwise, while counter-clockwise rotation reduces pressure.

3.2.3 Cylinder pressure measurement system

A Piezo sensor, equipped with a stainless steel diaphragm and designed to be hermetically sealed, is affixed to the cylinder head to meticulously monitor cylinder pressure. Positioned on the engine head, this piezo sensor interfaces with the engine's functioning components. It effectively translates the pressure within the cylinder into an electric charge output, rendering it proportionate to the prevailing pressure conditions. This sensor's functioning is reliant on a quartz crystal inherent to the piezo sensor's construction. One end of the sensor is exposed to the cylinder pressure via the diaphragm. As cylinder pressure increases, the crystal undergoes compression. This deformation prompts the piezoelectric crystal to generate an electric charge in correspondence with the pressure shift, given the inherent property of piezoelectric crystals to respond in this manner when subjected to deformation.

Due to the relatively small magnitude of the produced charge and the associated difficulty in direct measurement, the sensor integrates a charge amplifier. This amplifier translates the charge into an output voltage that directly mirrors the charge's magnitude. Visualized in **Figure 3.4,** the piezoelectric sensor stands as a crucial component in this setup.

Fig 3.4 Piezoelectric sensor

3.2.4 Air flow measurement System

An air surge tank, enhanced with an orifice meter, a manometer, and a pressure transducer (Model: SL-1-A-MQA-ND-ZA4Z-ZZZ), is strategically incorporated into the setup. Its role is to facilitate the directed passage of inducted air, enabling the measurement of flow rates and the consequential pressure drop. These measurements are pivotal for calculating the engine's volumetric efficiency across different operational scenarios. The inclusion of an air box serves to dampen any fluctuations in the airflow. To streamline the measurement process, the orifice meter, possessing a coefficient of discharge estimated at 0.65, plays a critical role. Meanwhile, the pressure transducer and the manometer collaboratively serve the purpose of quantifying the airflow. For a visual reference, the pressure transducer and manometer components responsible for airflow measurement are depicted in **Figure 3.5**. This arrangement is key to comprehensively analyzing and understanding the engine's performance under diverse conditions.

Fig 3.5 Pressure transducer

3.2.5 Data acquisition panel system

To comprehensively capture the fluctuations in-cylinder pressure concerning crank angle, a high-speed data collection system is crucial. This system serves as a pivotal tool for analyzing data derived from both injection pressure and cylinder pressure measurements. During testing, meticulous consideration is given to factors such as charge amplifier settings and transducer sensitivity. These factors come into play while converting pressure signals from pressure sensors into a digital format.

Transducers are typically employed to furnish relative pressures. However, it's imperative to establish tools for determining absolute pressures at specific cycle points, establishing a standard reference. The input manifold's pressure serves as the reference pressure. When the piston rests at bottom dead center (BDC), the mean intake manifold pressure serves as a reliable predictor of cylinder pressure.

The process involves a data acquisition system meticulously recording cylinder pressure changes concerning piston displacement in terms of both pressure and crank angle. Ensuring accurate data capture, subsequent examination and processing of the data are vital steps in the experimental analysis. Given the notable variations in cylinder pressure and injection pressure concerning crank angle from one cycle to another, a single cycle's data cannot accurately represent a specific operational scenario. To achieve accurate insights, an average of around 100 cycles of pressure versus crank angle data is often employed.

Calibration comes into play to convert voltage-based pressure signals to conventional units. The calibration factor thus obtained is applied to the average cycle, leading to computation of relative pressures. These relative pressures undergo a secondary calibration to determine absolute pressure values for the average cycle. This secondary calibration involves referencing the pressure in the intake manifold with the piston at bottom dead center. With absolute pressure values now associated with the average cycle, the process of pressure volume phasing can be conducted smoothly. The physical representation of the data acquisition card is depicted in **Figure 3.6**, illustrating its role in facilitating this complex measurement process.

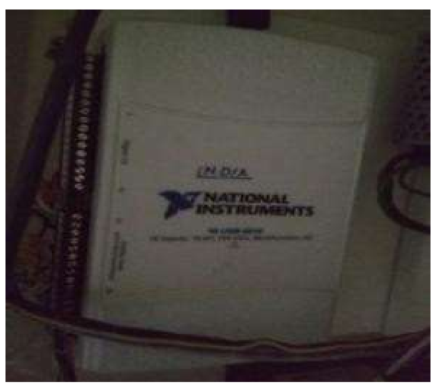

Fig 3.6 DAQ card

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this section, a comparative analysis is undertaken to explore the outcomes of studying the combustion characteristics of a Variable Compression Ratio (VCR) Diesel engine. The primary focus revolves around two types of biodiesel: Crude Soybean Oil Biodiesel (CSOBD) and Waste Soybean Oil Biodiesel (WSOBD). This investigation encompasses diverse blending ratios and compression ratios spanning from 15 to 18. The evaluation of the engine extends across a range of loads, including zero (0%) load, 25% load, 50% load, 75% load, and full (100%) load. This comprehensive analysis encompasses both diesel and biodiesel blends.

4.1.1 Combustion Characteristics at Zero load from CR 15 to CR 18

4.1.1.1 Variation of Cylinder pressure with crank angle at Zero load (0%) for CR 15 to CR 18

Figures 4.1 provides an insightful view of pressure variations concerning crank angle at zero load, focusing on compression ratios (CR) ranging from 15 to 18, with a specific emphasis on diesel-fuel blends. Across all load conditions, a consistent pattern emerges in these graphs for various blends, signifying minimal alterations. Notably, during the ignition phase at zero load, both CSOBD and WSOBD blends consistently demonstrate lower chamber pressures compared to pure diesel. This phenomenon can be attributed to several factors inherent to biodiesel. Additionally, biodiesel exhibits distinctive combustion characteristics, notably longer ignition delays, resulting in a more gradual and less forceful pressure increase during combustion. Furthermore, it tends to possess a lower cetane number, signifying poorer ignition quality and extended ignition delays, both contributing to the observed reduction in cylinder pressures. Factors such as incomplete combustion and differences in oxygen content, stemming from the molecular structure of biodiesel, further influence combustion chemistry and heat release, potentially leading to the recorded lower cylinder pressures. In summation, the comprehensive examination of various compression ratios consistently underscores the tendency of CSOBD and WSOBD blends to exhibit lower chamber pressures during the ignition delay phase in comparison to pure diesel, with this trend particularly pronounced under zero load conditions. Additionally, it's worth noting that as compression ratios increase, there is a corresponding elevation in maximum cylinder pressure as shown in **Fig. 4.2.** It is evident that better engine performance is obtained at higher CR specially for biodiesel blends.

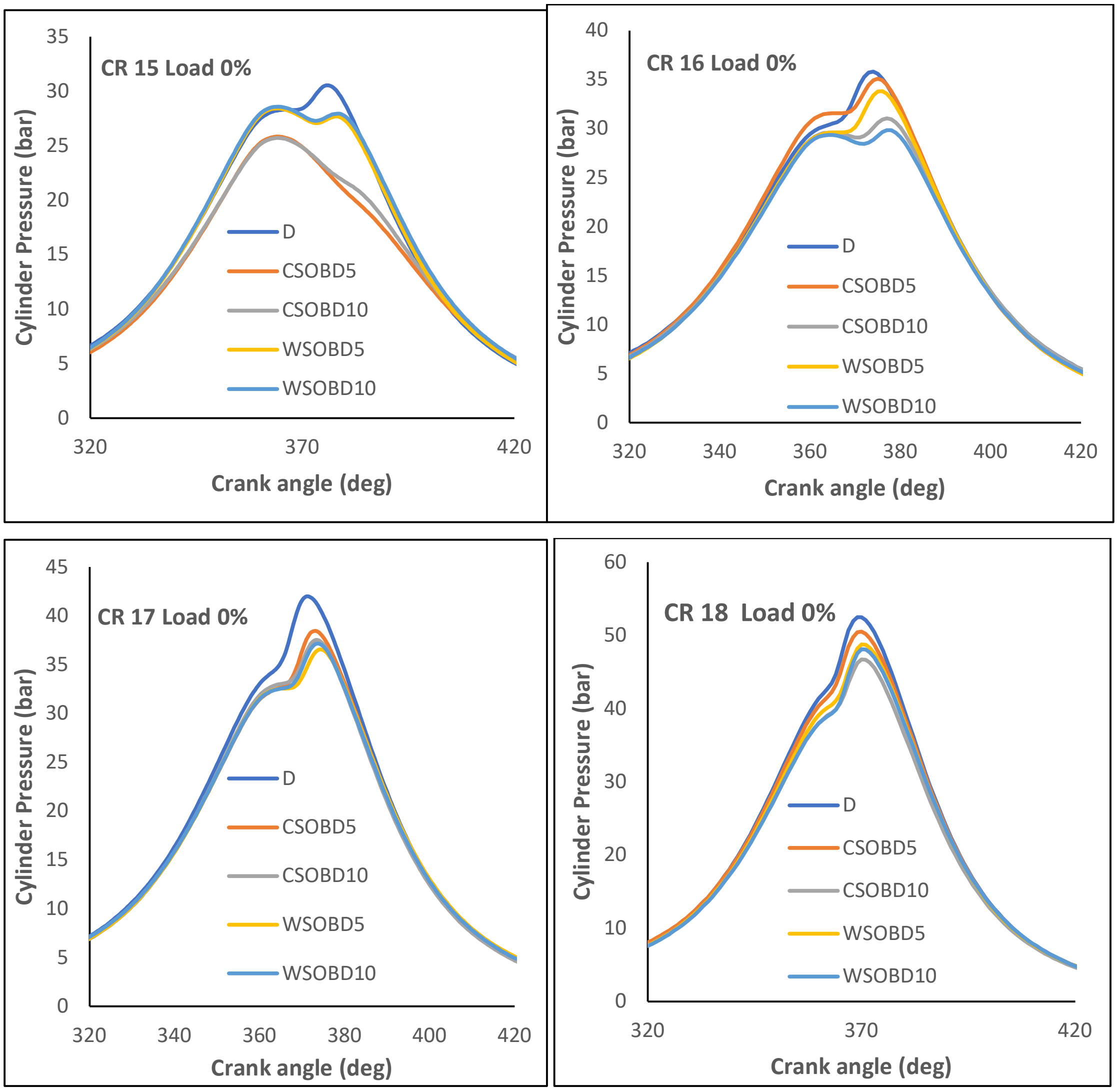

Fig 4.1: Variation of Cylinder Pressure with CA of Diesel (D), CSOBD and WSOBDblending for CR 15, CR 16, CR 17 and CR 18 at zero load (0%)

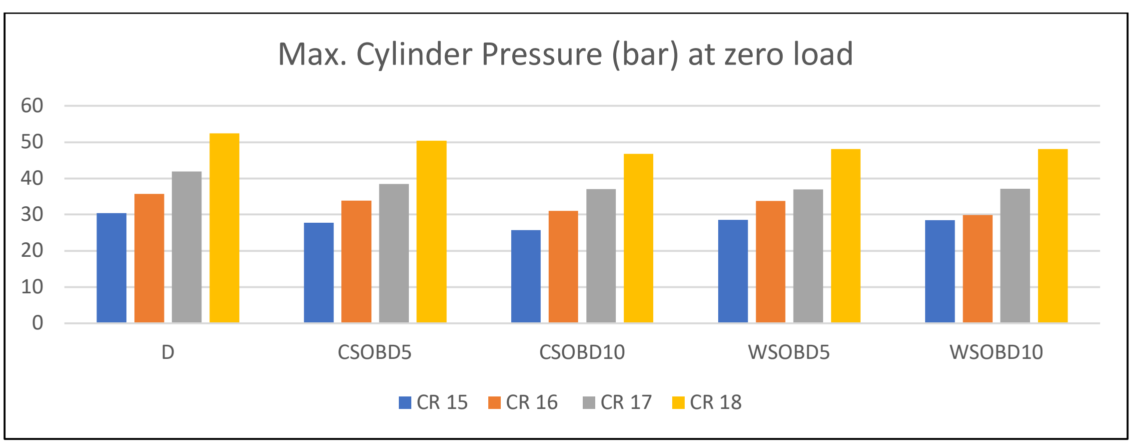

Fig 4.2: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at Zero load (0 %)

4.1.1.2 Variation of Cylinder pressure with crank angle at 25% load for CR 15 to CR 18

In **Fig. 4.3**, we delve into the dynamic world of pressure changes along the crank angle, specifically under a 25% load condition. Our focus is on compression ratios (CR) ranging from 15 to 18, encompassing both diesel and various fuel blends. When it comes to understanding combustion chamber pressure (CP), it's pivotal to consider how it's influenced. Two key factors come into play: the accumulation of fuel during the ignition delay phase and the rate of combustion during the premixed burning stage. As we scrutinize these graphs under different load conditions, a notable consistency emerges – there are no significant deviations among the various blends. What's intriguing is the persistent pattern observed in all CSOBD and WSOBD blends, both consistently showcasing lower chamber pressures in comparison to pure diesel during the ignition phase, particularly evident when operating under a 25% load. Now, let's unpack why we observe this phenomenon and why cylinder pressure tends to increase with higher compression ratios. The increase in maximum pressure with higher compression ratios can be attributed to the fundamental principles of diesel engine operation. In a diesel engine, air is compressed to a much higher pressure before fuel injection. This elevated compression ratio results in higher temperatures within the combustion chamber during compression. When fuel is injected into this highly compressed air, it rapidly ignites due to the intense heat and pressure. This quick and forceful ignition leads to a more robust and efficient combustion process, generating higher cylinder pressures. In summary, the analysis of pressure fluctuations across varying compression ratios consistently emphasizes the prevalence of lower chamber pressures in CSOBD and WSOBD blends during the ignition delay phase when compared to pure diesel, with this trend notably pronounced under a 25% load condition. Furthermore, **Fig. 4.4** shows that with increase in maximum cylinder pressure with higher compression ratios and better performance for all biodiesel blends.

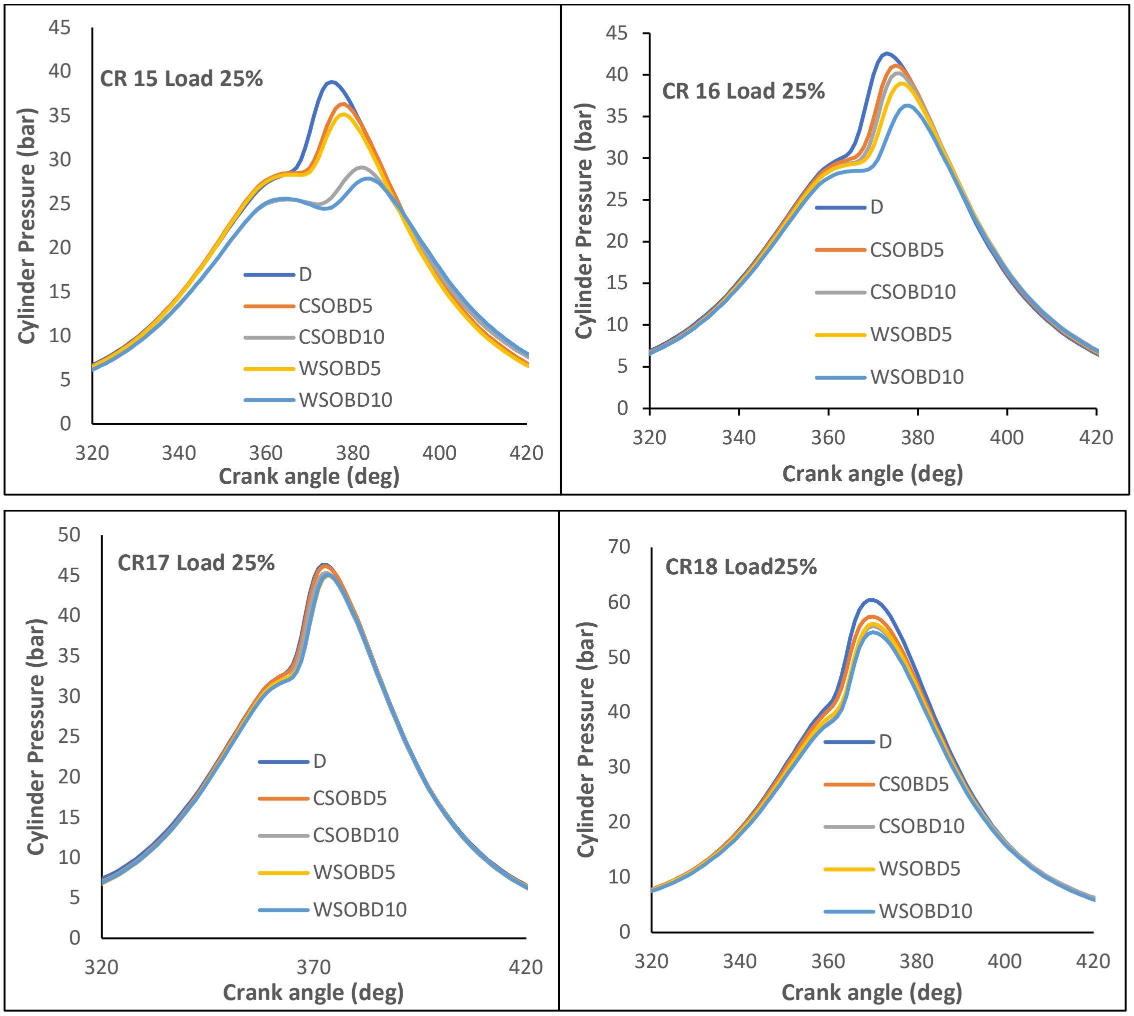

Fig 4.3: Variation of Cylinder Pressure with CA of Diesel (D), CSOBD and WSOBDblending for CR 15, CR 16, CR 17 and CR 18 at 25 % load

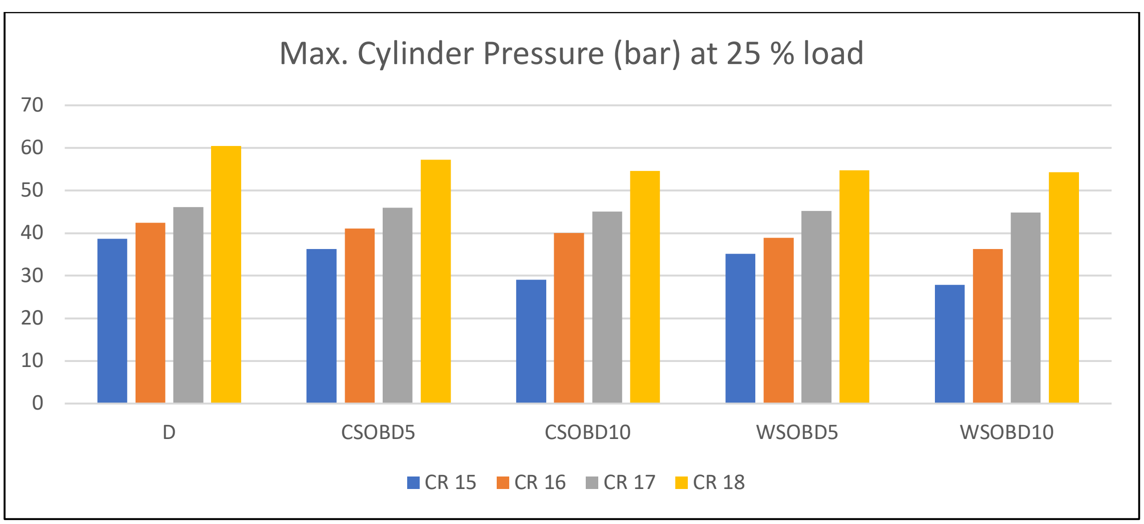

Fig 4.4: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 25 % load

4.1.1.3 Variation of Cylinder pressure with crank angle at 50 % load for CR 15 to CR 18

Fig. 4.5 gives us a visual journey into the realm of pressure dynamics under a 50% load condition. Our primary focus is on compression ratios (CR) ranging from 15 to 18, encompassing both conventional diesel and blended fuel formulations. The key player in this theater of combustion chamber pressure (CP) is the delicate balance between the fuel buildup during the ignition delay phase and the pace of combustion during the premixed burning stage. When we scrutinize these graphical representations across various load conditions, a recurring theme emerges – there are no substantial departures among the different fuel blends.

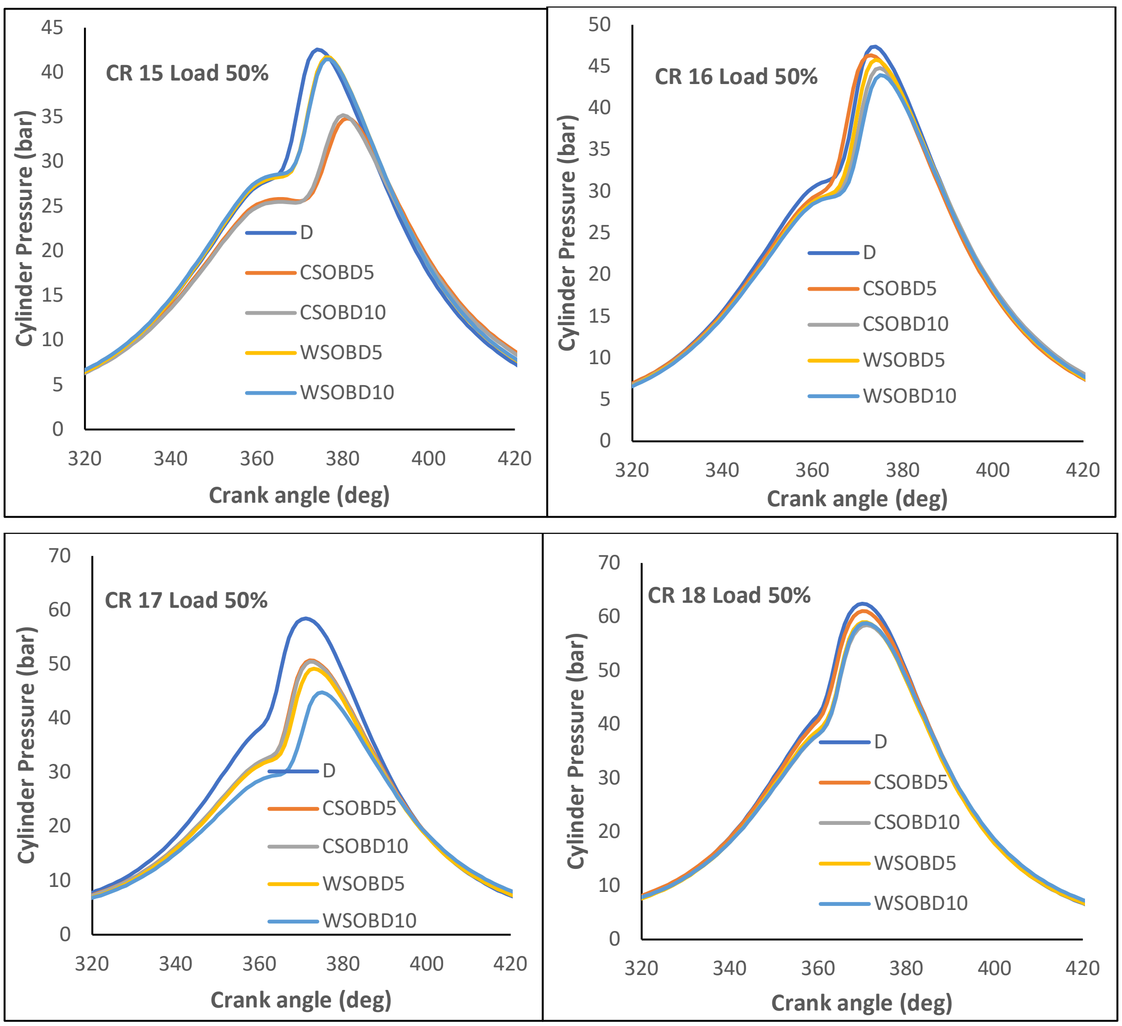

Fig 4.5: Variation of Cylinder Pressure with CA of Diesel (D), CSOBD and WSOBDblending for CR 15, CR 16, CR 17 and CR 18 at 50 % load

What's particularly intriguing is the consistent pattern seen in all permutations of CSOBD and WSOBD blends, each consistently demonstrating lower chamber pressures compared to pure diesel during the ignition phase, especially noticeable when running at half load. It's at this 50% load condition that CR 16 stands out, showcasing the most favorable cylinder pressure among CSOBD and WSOBD blends, coming remarkably close to the performance of pure diesel. Furthermore, it's essential to highlight that as we increase the compression ratio, there's a parallel increase in maximum pressure, a phenomenon that underscores the benefits of higher compression ratios in diesel engines as shown in **Fig. 4.6**. In summary, the graphical analysis across diverse compression ratios consistently highlights the prevalence of lower chamber pressures in CSOBD and WSOBD blends compared to pure diesel during the ignition delay phase, particularly when operating under a 50% load.

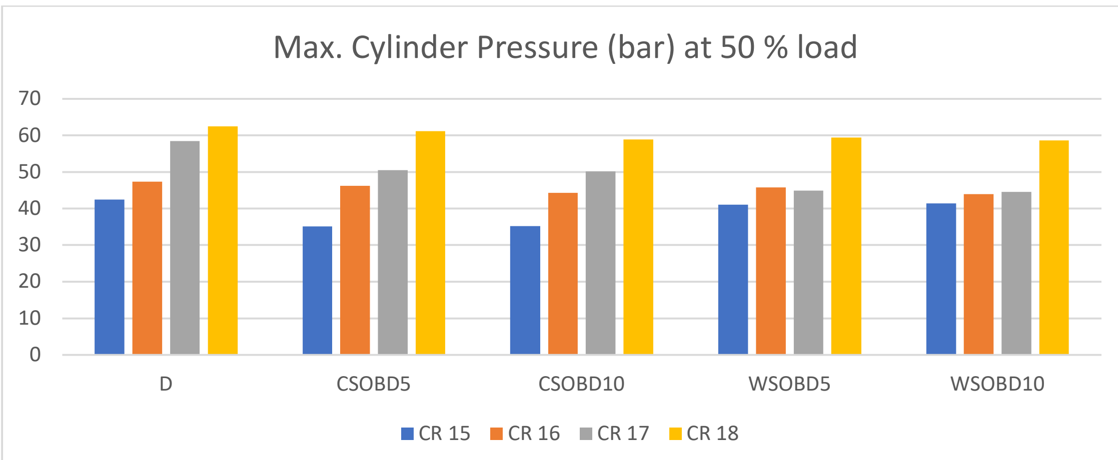

Fig 4.6: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 50 % load

4.1.1.4 Variation of Cylinder pressure with crank angle at 75 % load for CR 15 to CR 18

Fig. 4.7 provides a detailed view of pressure fluctuations during the engine's operation under a substantial 75% load. We're investigating how compression ratios (CR) ranging from 15 to 18 affect maximum cylinder pressure for both traditional diesel and its blended counterparts. In this intricate dance of combustion chamber pressure (CP), the critical interplay occurs between the fuel accumulation during the ignition delay phase and the combustion pace during the premixed burning stage. What's noteworthy is the striking consistency observed across the various load conditions – there's a noticeable absence of significant deviations among the different fuel blends. Here's the recurring theme: CSOBD and WSOBD blends consistently maintain lower chamber pressures in comparison to pure diesel during the ignition period, particularly when the engine is operating at a robust 75% load. Additionally, as we progressively increase the compression ratio, we witness a concurrent rise in maximum pressure. Notably, at a CR of 17, we identify a point where the pressure variations between Diesel, CSOBD, and WSOBD are relatively minimal, suggesting an intriguing convergence of performance at this specific compression ratio. This phenomenon highlights the significance of compression ratios in influencing engine behavior and performance. In summation, the analysis of pressure variations at varying compression ratios underscores the persistently lower chamber pressures in CSOBD and WSOBD blends during the ignition delay phase compared to pure diesel. This distinction is especially pronounced under the 75% load condition. **Fig. 4.8** depicts maximum cylinder pressure at different CR for all biodiesel blends, it is observed that almost steady performance obtained for all blends at higher CRs.

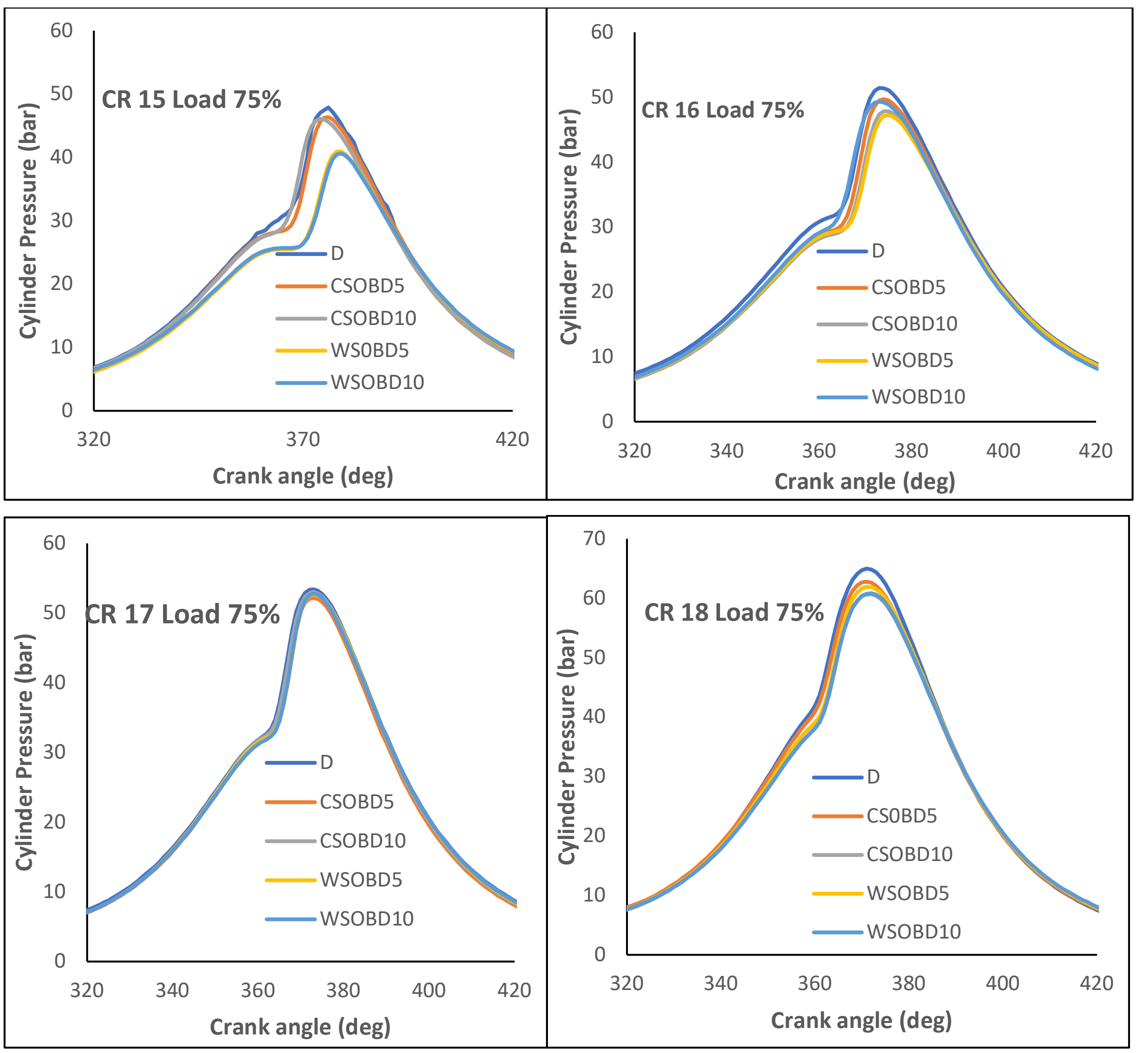

Fig 4.7: Variation of Cylinder Pressure with CA of Diesel (D), CSOBD and WSOBDblending for CR 15, CR 16, CR 17 and CR 18 at 75 % load

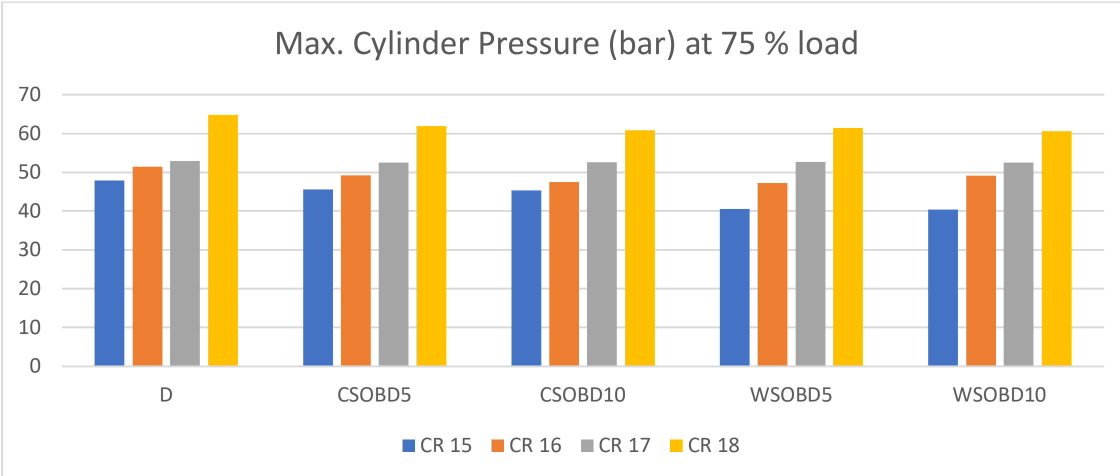

Fig 4.8: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 75 % load

4.1.1.5 Variation of Cylinder pressure with crank angle at full load (100 %) for CR 15 to CR 18

Let's dive into the insights offered by Fig. 4.9, which vividly portray the dynamic pressure changes and the maximum cylinder pressure during full-load conditions (100%). Our focus is squarely on compression ratios (CR) spanning from 15 to 18, and this scrutiny encompasses both the tried-and-true conventional diesel and its blended counterparts. In the intricate realm of combustion chamber pressure (CP), the driving forces are the intricate balance between fuel accumulation during the ignition delay phase and the combustion rate during the subsequent premixed burning stage. Here's the fascinating part: when we explore various load conditions, we encounter a striking pattern – there's a conspicuous lack of significant shifts in the graphical depictions, regardless of the specific fuel blends in use. The recurring theme asserts itself again: CSOBD and WSOBD blends consistently maintain lower chamber pressures compared to their pure diesel counterpart during the ignition phase, especially when the engine is under the demanding full load conditions. Moreover, something intriguing happens at CR 16 and CR 17 – here, we observe minuscule pressure variations among Diesel, CSOBD, and WSOBD. This observation hints at a convergence of performance at these particular compression ratios, emphasizing the pivotal role that compression ratios play in shaping engine behavior and performance. It's also noteworthy that, in line with expectations, as we increase the compression ratio, the maximum cylinder pressure follows suit, signifying the influence of compression ratios on engine performance characteristics as shown in **Fig. 4.10**. In summary, the analysis of pressure variations across varying compression ratios consistently highlights the trend of lower chamber pressures in CSOBD and WSOBD blends during the ignition delay phase compared to pure diesel. This distinction is particularly evident when operating under full load conditions.

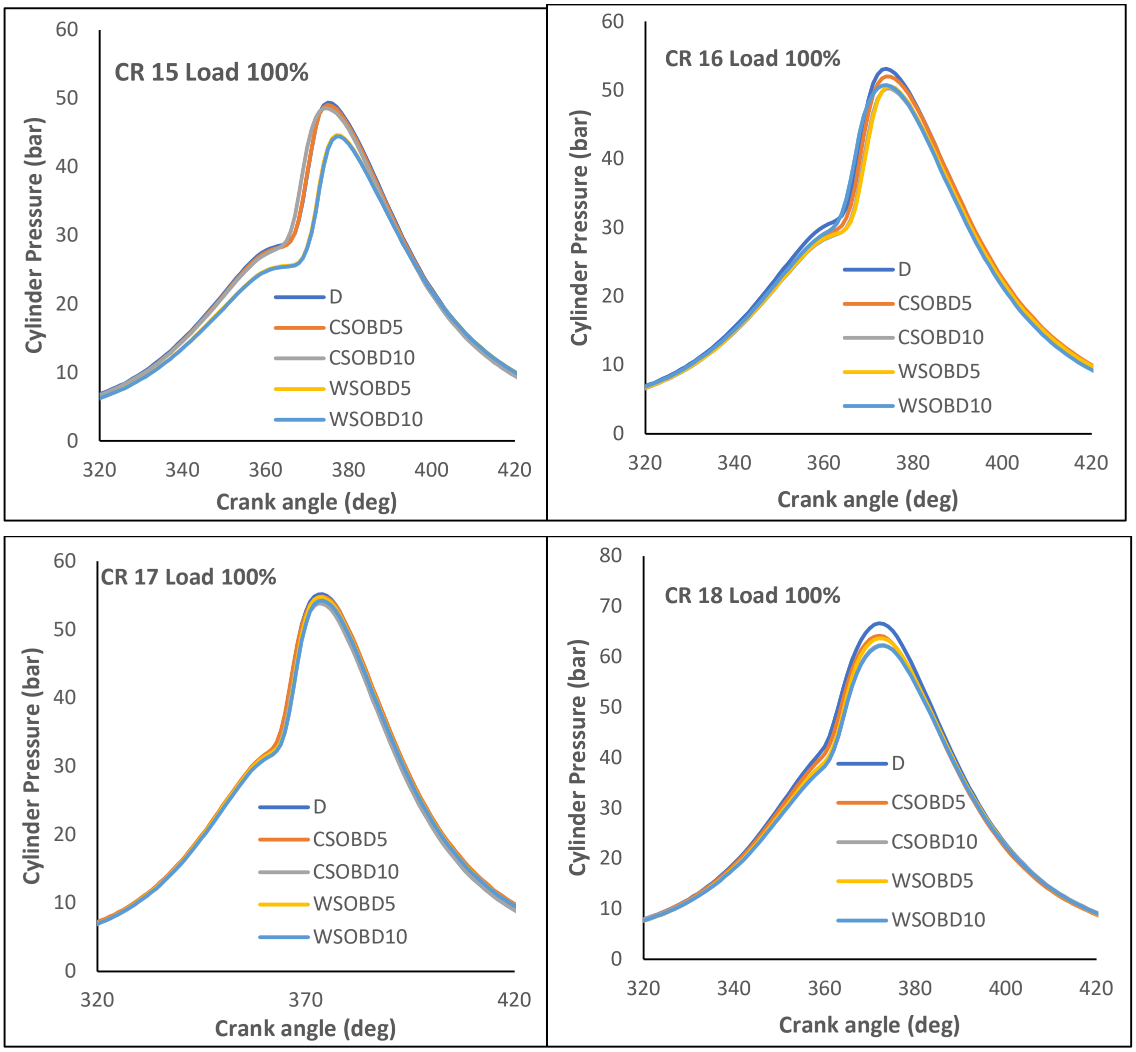

Fig 4.9: Variation of Cylinder Pressure with CA of Diesel (D), CSOBD and WSOBDblending for CR 15, CR 16, CR 17 and CR 18 at 100 % load

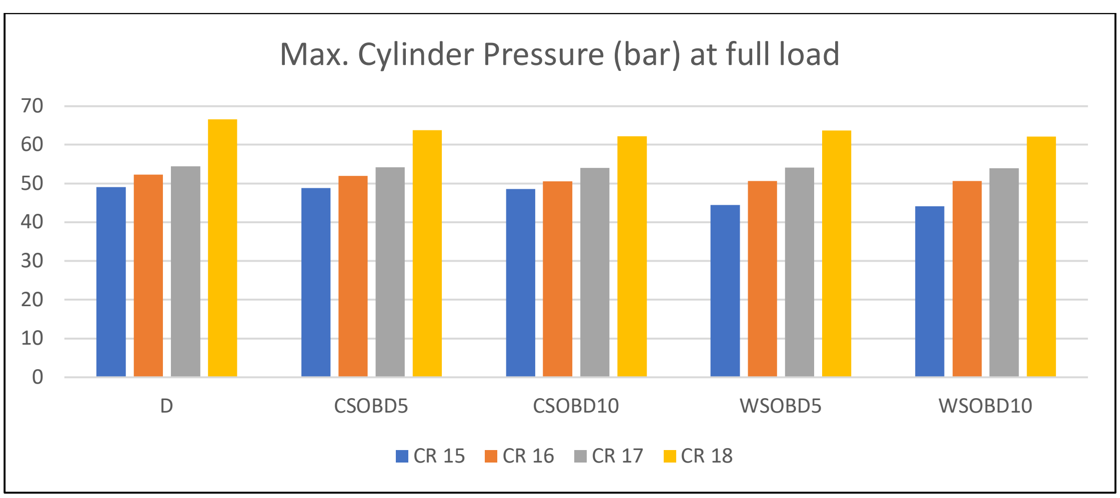

Fig 4.10: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 100 % load

4.1.2.1 Variation of Net Heat Release (NHR) with Crank angle at zero load (0%) for CR 15 to CR 18

The graphical data offers valuable insights into the dynamic alterations of the net heat release (NHR) profile and the Maximum Net Heat Release for each compression ratio (CR) ranging from 15 to 18, involving three distinct fuel categories: Diesel, CSOBD (Crude Soybean Oil Biodiesel), and WSOBD (Waste Soybean Oil Biodiesel) blends as shown in Fig. 4.11 and Fig. 4.12.

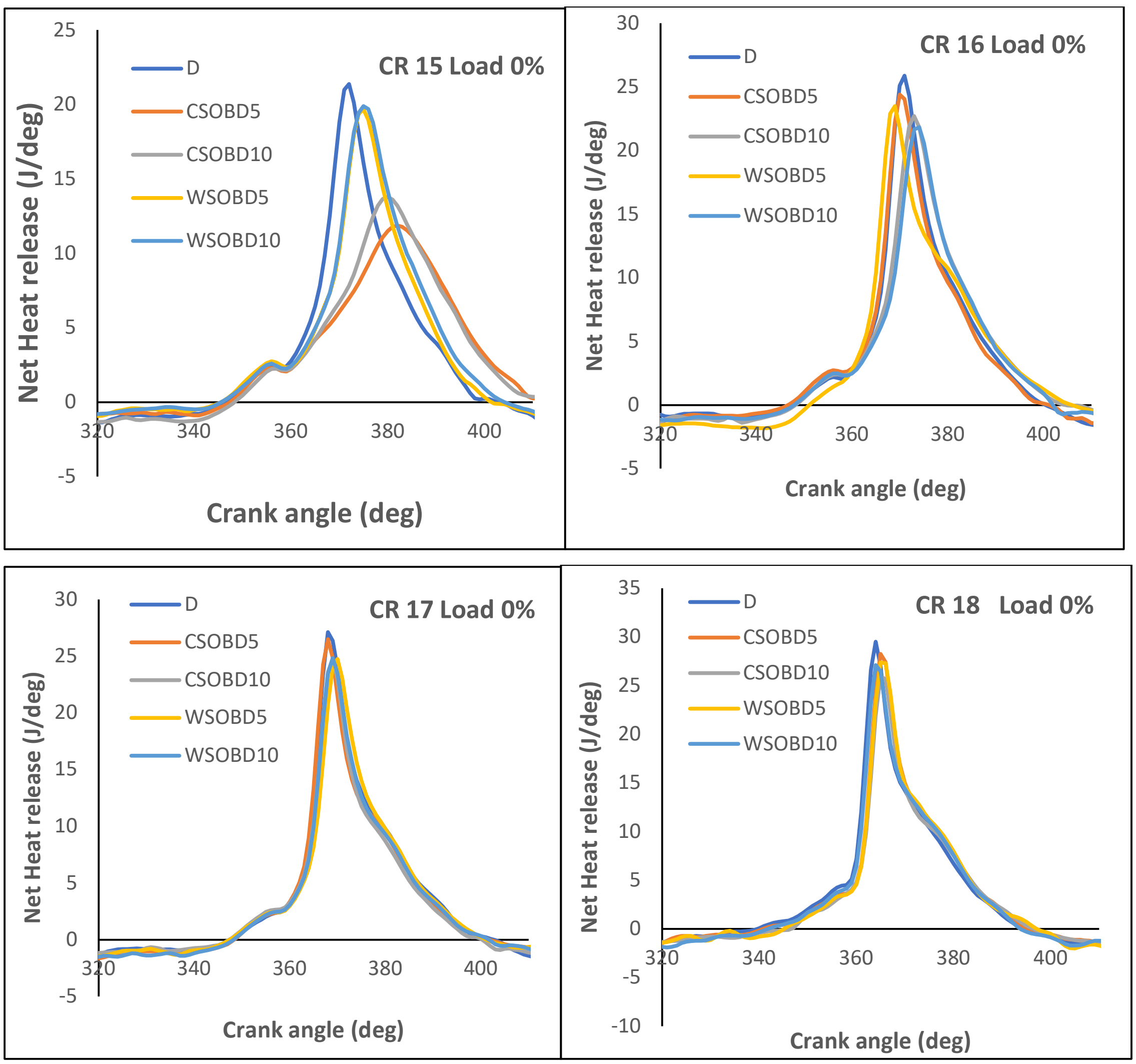

Fig 4.11 : Variation of net heat release with CA of Diesel(D), CSOBD and WSOBD blending for CR 15, CR 16, CR 17 and CR 18 at zero load (0 %)

This comprehensive assessment delves into the impact of varying compression ratios (CR) within the 15 to 18 range, with a specific focus on engine conditions characterized by zero load. The behavior of NHR is intricately governed by several pivotal factors, prominently including the start of combustion (SOC), ignition delay, and the overall volume of fuel consumed during the premixed phase. A closer examination of the data unmistakably reveals that CSOBD and WSOBD blends consistently yield lower NHR values when compared to the unadulterated diesel fuel when the engine is operating under zero load conditions. This divergence can be attributed to the inherent characteristics of biodiesel, encompassing both CSOBD and WSOBD, which typically possess a reduced energy content per unit volume or mass when juxtaposed with traditional diesel fuel. Consequently, under identical engine operating conditions, biodiesel fuels are equipped with a diminished reservoir of chemical energy available for the combustion process. Notably, at compression ratios 16 and 17, we observe minimal fluctuations in the Net Heat Release of CSOBD and WSOBD concerning Diesel. To encapsulate, this analysis underscores the intricate nexus connecting fuel compositions, compression ratios, and NHR profiles. The distinctive properties of diesel, CSOBD, and WSOBD fuels are instrumental in molding the observed disparities in peak heat release rates and ignition characteristics.

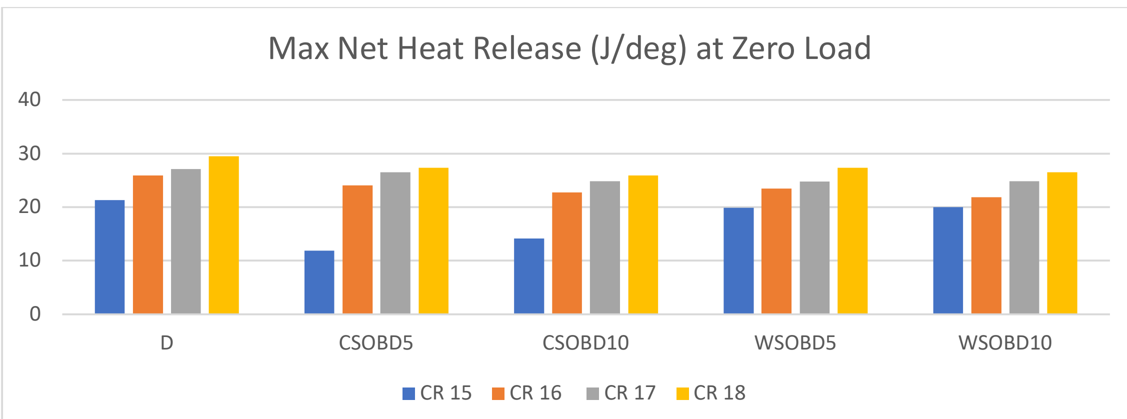

Fig 4.12: Maximum Net Heat Release obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at Zero load

4.1.2.2 Variation of Net Heat Release (NHR) with Crank angle at 25% load for CR 15 to CR 18

The graph visually demonstrates the fluctuations in net heat release (NHR) concerning crank angle and the maximum Net Heat Release, considering different Compression Ratios (CR), for three distinct fuel types: Diesel, CSOBD (Crude Soybean Oil Biodiesel), and WSOBD (Waste Soybean Oil Biodiesel) blends as shown in **Fig. 4.13 and Fig. 4.14**. This comprehensive analysis encompasses a range of compression ratios (CR) spanning from 15 to 18, conducted under a 25% load condition. The behavior of NHR is intricately influenced by various factors, with notable emphasis on the start of combustion (SOC).

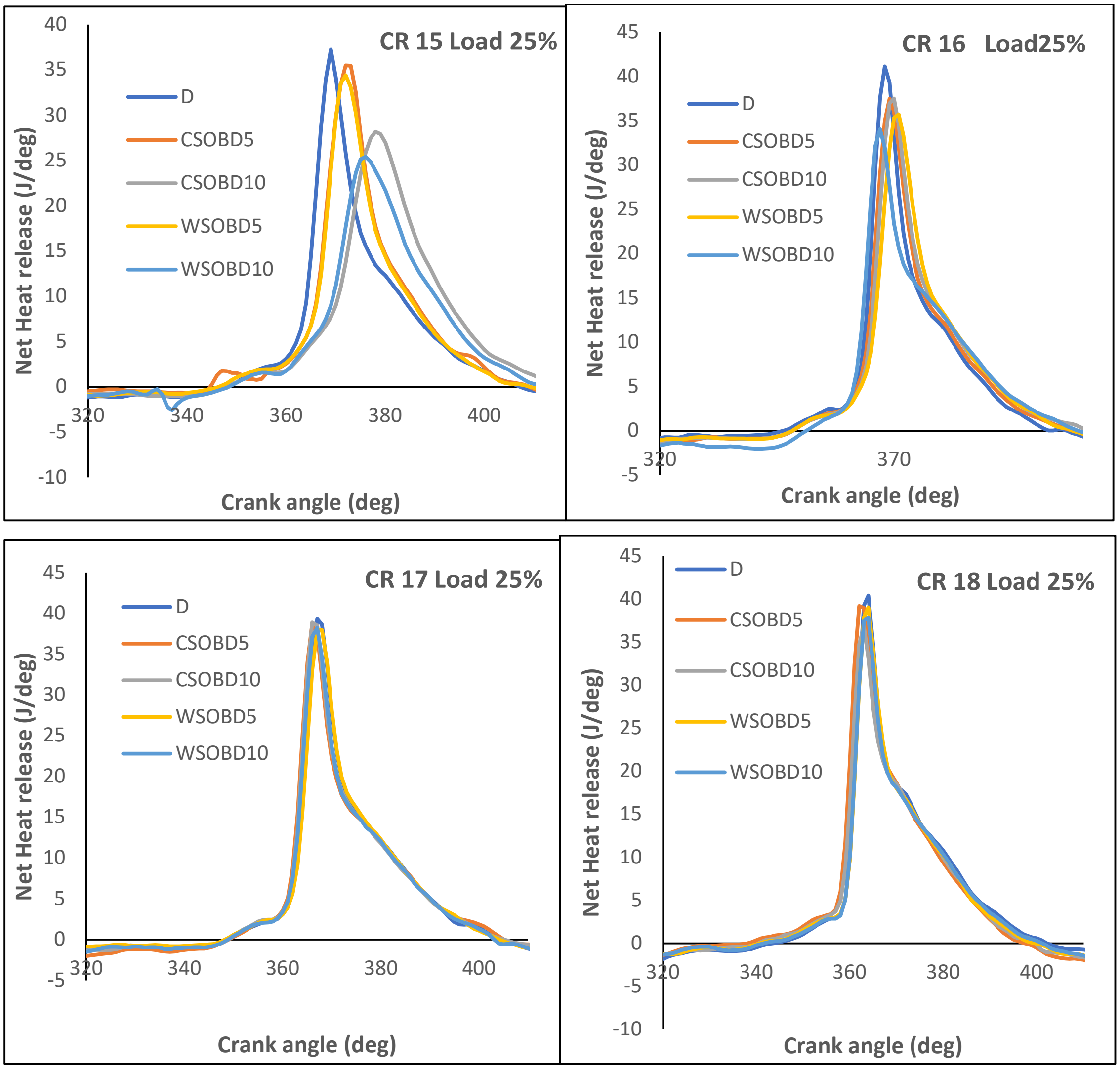

Fig 4.13 : Variation of net heat release with CA of Diesel(D), CSOBD and WSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 25 % load

It's worth noting that biodiesel fuels, such as CSOBD and WSOBD, often exhibit distinct combustion characteristics when juxtaposed with conventional diesel. One key difference is their extended ignition delay, which represents the duration between fuel injection initiation and actual combustion commencement. This prolonged ignition delay translates into a more gradual and less intense release of heat during combustion, subsequently leading to reduced peak cylinder pressures and, consequently, lower net heat release values. The graph vividly illustrates that the incorporation of CSOBD and WSOBD blends results in consistently lower NHR values in contrast to the utilization of pure diesel fuel, particularly under the 25% load conditions. This phenomenon may be attributed to diesel's higher volatility, which facilitates superior air mixing within the combustion chamber. Additionally, the increased accumulation of fuel during the premixed phase, coupled with the relatively extended ignition delay of biodiesel blends, contributes to this disparity in NHR. Examining the Max Net Heat Release chart reveals that CR 17 stands out as the point where CSOBD and WSOBD exhibit their best performance relative to Diesel.

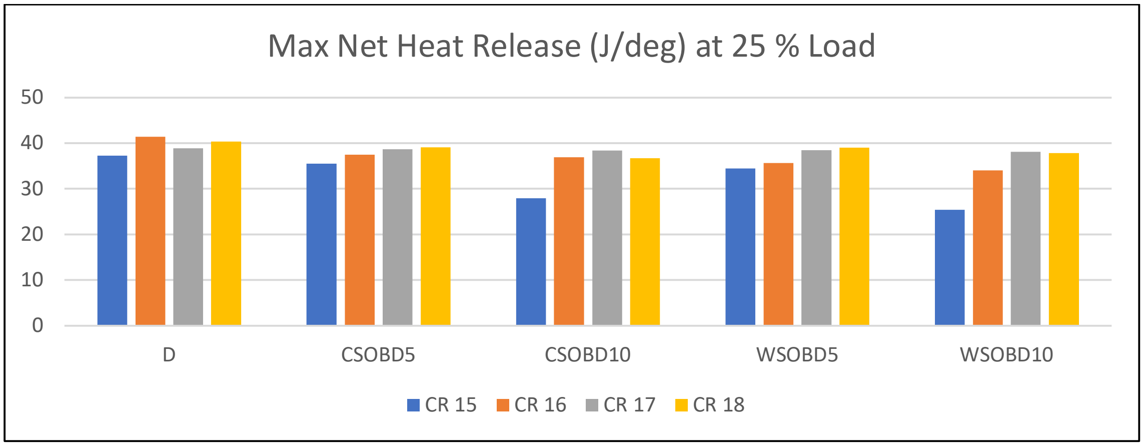

Fig 4.14: Maximum Net Heat Release obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 25 % load

4.1.2.3 Variation of Net Heat Release (NHR) with Crank angle at 50% load for CR 15 to CR 18

The figures (**Fig. 4.15 and Fig. 4.16**) provide a visual representation of how the net heat release (NHR) behaves concerning crank angle and the Maximum Net Heat Release across three distinct fuel types: Diesel, CSOBD (Crude Soybean Oil Biodiesel), and WSOBD (Waste Soybean Oil Biodiesel) blends. This comprehensive analysis encompasses a range of compression ratios (CR), spanning from 15 to 18, all conducted under a 50% load condition. NHR's performance is intricately influenced by various factors, including the crucial start of combustion (SOC), ignition delay, and the actual volume of fuel that undergoes combustion during the premixed phase. The graphical data makes it evident that the introduction of CSOBD and WSOBD blends into the mix consistently yields lower NHR values compared to the use of pure diesel fuel, especially when operating under 50% load conditions. This distinction in NHR can likely be attributed to diesel's higher volatility, which enhances its capacity for effective air mixing within the combustion chamber. Moreover, biodiesel fuels, including CSOBD and WSOBD, have a propensity for incomplete combustion, resulting in higher levels of unburned fuel. This incomplete combustion contributes to an overall reduction in heat release since not all available fuel is efficiently combusted. A noteworthy observation is made when examining the data at CR 16 and CR 17, where the Net Heat Release of CSOBD and WSOBD aligns closely with that of Diesel, signifying promising prospects for the future. In summary, the analysis underscores the complex interplay between fuel blends, compression ratios, and NHR patterns.

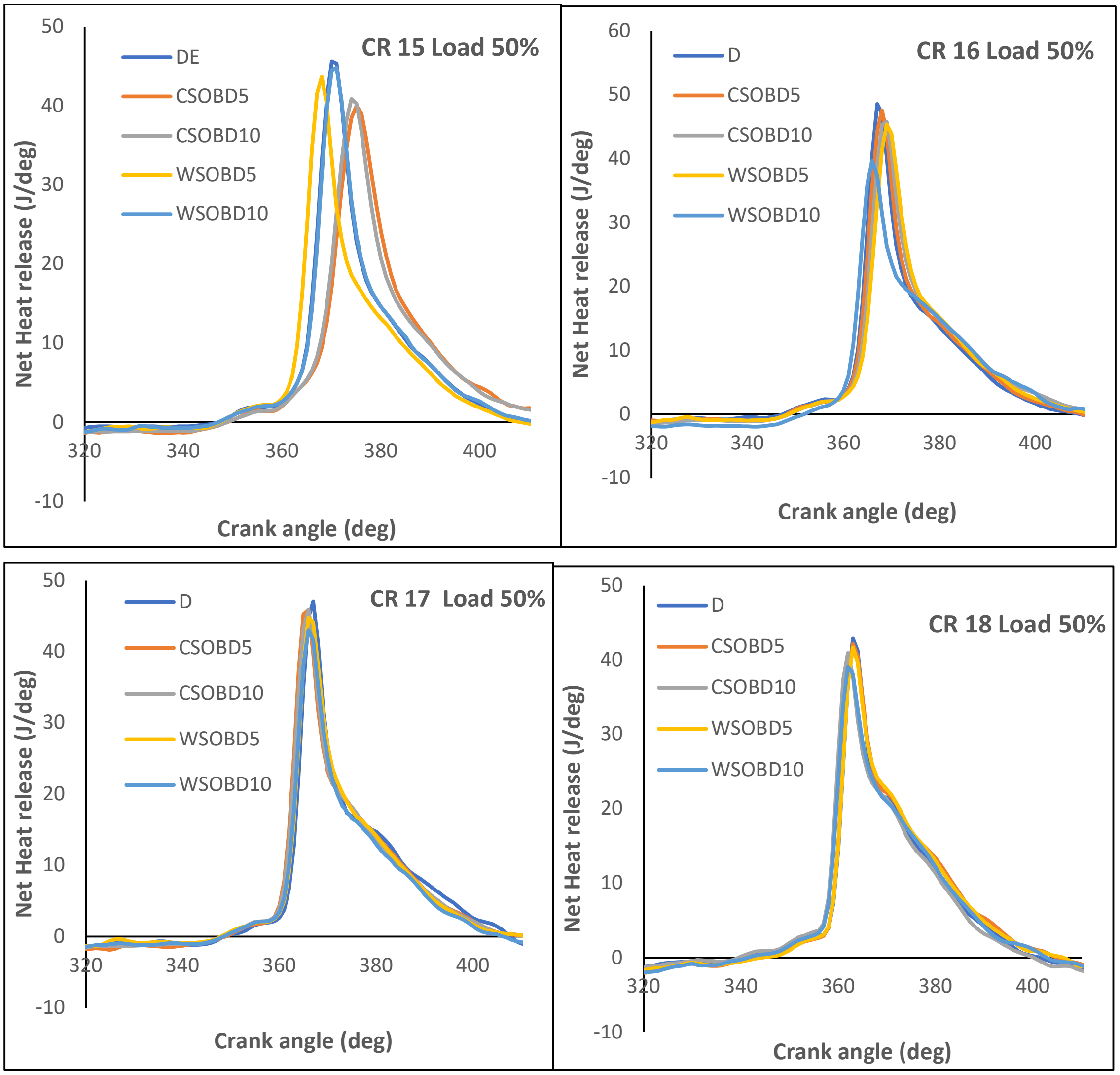

Fig 4.15: Variation of net heat release with CA of Diesel(D), CSOBD and WSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 50 % load

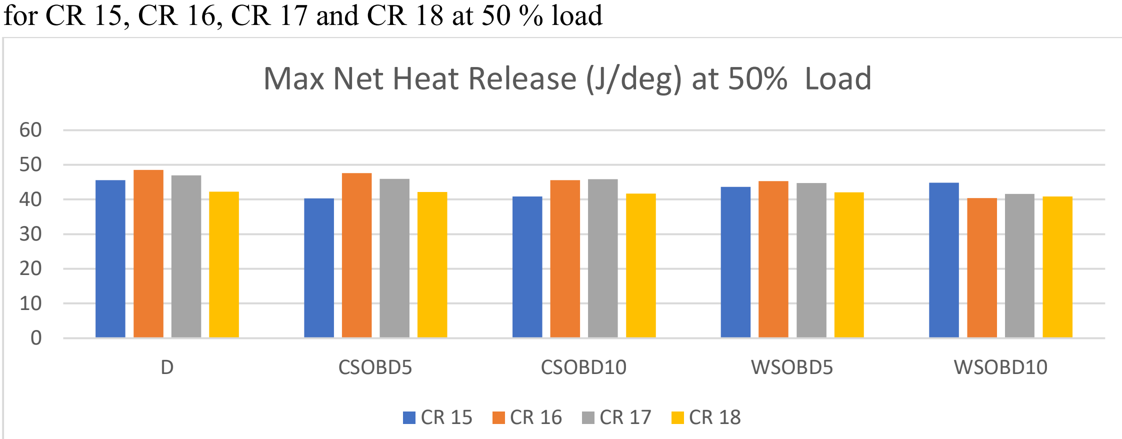

Fig 4.16: Maximum Net Heat Release obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 50 % load

4.1.2.4 Variation of Net Heat Release (NHR) with Crank angle at 75% load for CR 15 to CR 18

The provided graphs (as shown in **Fig. 4.17 and Fig. 4.18**.) offer a comprehensive view of how net heat release (NHR) behaves concerning crank angle and Maximum Net Heat Release for three distinct fuel types: Diesel, CSOBD (Crude Soybean Oil Biodiesel), and WSOBD (Waste Soybean Oil Biodiesel) blends.

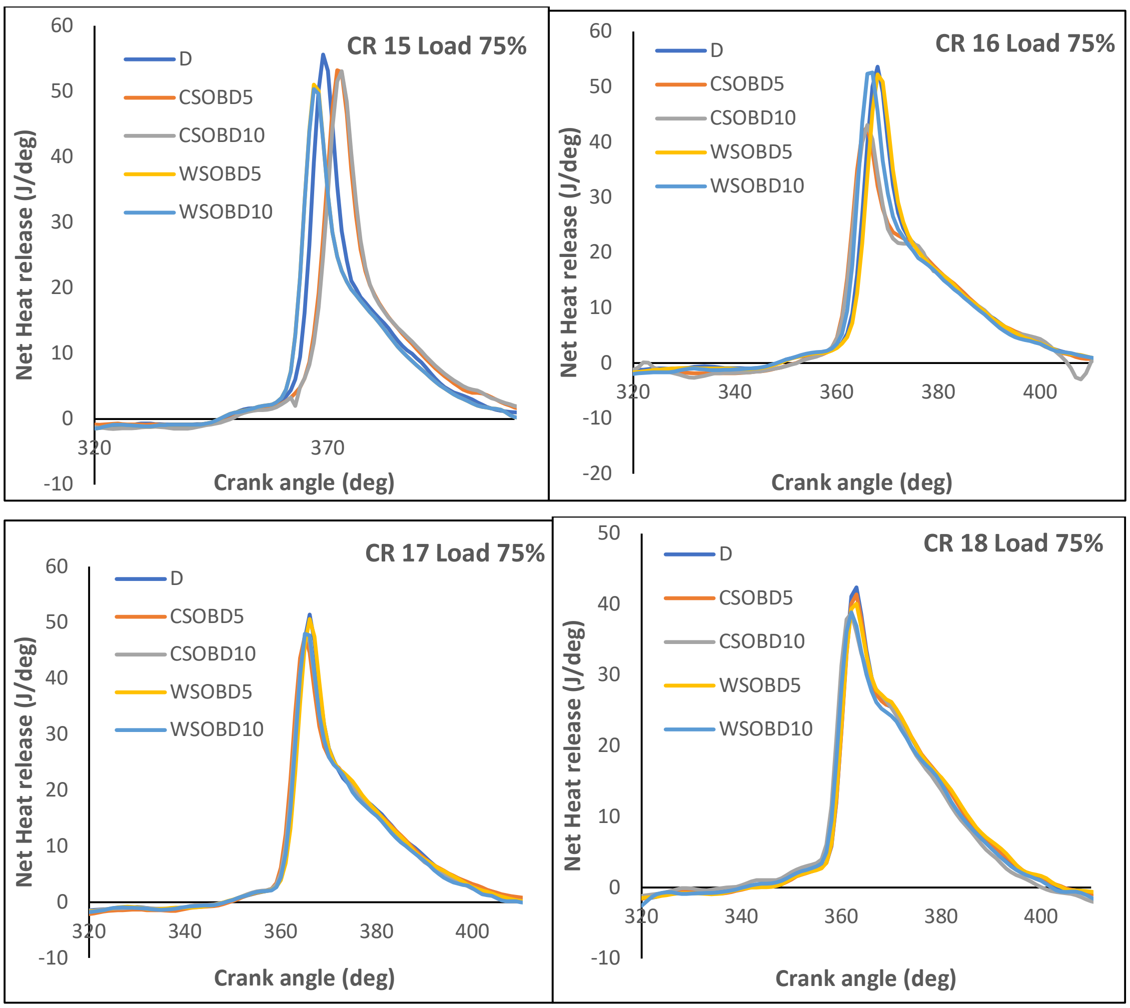

Fig 4.17: Variation of net heat release with CA of Diesel(D), CSOBD and WSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 75 % load

These analyses encompass a spectrum of compression ratios (CR), ranging from 15 to 18, all conducted under a 75% load condition. NHR tendencies are influenced by variables such as the initiation of combustion (SOC) and the unique oxygen content present in biodiesel's molecular structure, which can exert an impact on combustion chemistry and subsequent heat release characteristics, potentially resulting in lower net heat release values. Upon careful examination of the graphical data, a consistent trend emerges, indicating that the introduction of CSOBD and

WSOBD blends leads to lower NHR values when compared to the utilization of pure diesel, particularly under a 75% load condition. This noteworthy distinction in NHR can be attributed to various factors, including the presence of oxygen in biodiesel and its effect on combustion dynamics. A significant observation is made when focusing on CR 17, where CSOBD and WSOBD demonstrate the most promising NHR values in comparison to Diesel, signifying their potential as viable alternatives in the pursuit of efficient and sustainable energy sources. The distinction of highest NHR_{max} values is exhibited by CSOBD5 and WSOBD5 in this scenario.

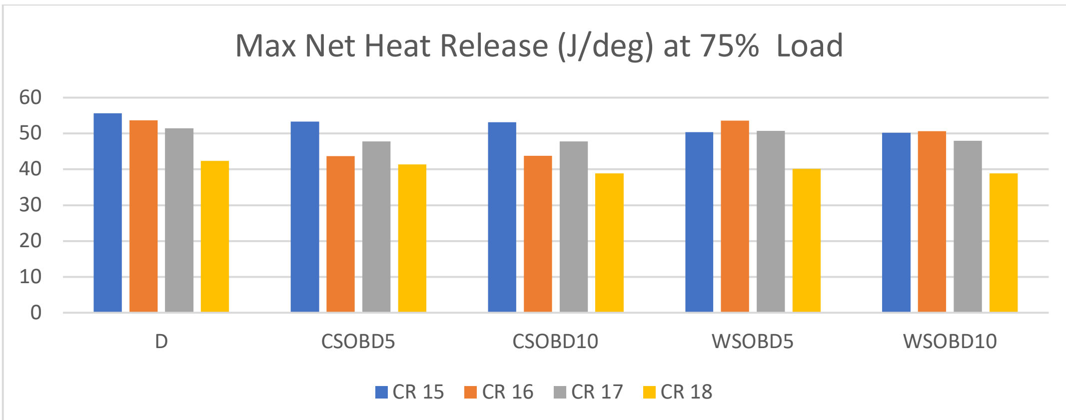

Fig 4.18: Maximum Net Heat Release obtained using Diesel (D), CSOBD AND WSOBD for CR 15, CR 16, CR 17 and CR 18 at 75 % load

4.1.2.5 Variation of Net Heat Release (NHR) with Crank angle at full load (100 %) for CR 15 to CR 18

The provided visual representations offer a comprehensive view of the dynamic changes in net heat release (NHR) concerning crank angle and Maximum Net Heat Release across three distinct fuel categories: Diesel, CSOBD (Crude Soybean Oil Biodiesel), and WSOBD (Waste Soybean Oil Biodiesel) blends as shown in **Fig. 4.19 and Fig. 4.20**. These analyses encompass a spectrum of compression ratios (CR) ranging from 15 to 18 and are conducted under full load conditions. Notably, the graphs clearly indicate that the combination of CSOBD and WSOBD results in consistently lower NHR values when compared to the use of pure diesel, particularly under full load conditions. This observation can be attributed to the fact that diesel engines are primarily calibrated and optimized for pure diesel fuel. Parameters such as compression ratio, fuel injection timing, and air-fuel ratio are fine-tuned for diesel's specific characteristics. When biodiesel blends like CSOBD and WSOBD are introduced, the engine calibration may not be perfectly suited for these fuels, leading to suboptimal combustion efficiency and consequently lower net heat release. CR 17 and CR 18 emerge as the most promising compression ratios for achieving optimal NHR values with CSOBD and WSOBD in comparison to Diesel. This emphasizes the importance of considering the distinct properties of each fuel type when aiming to achieve peak heat release rates and ignition performance.

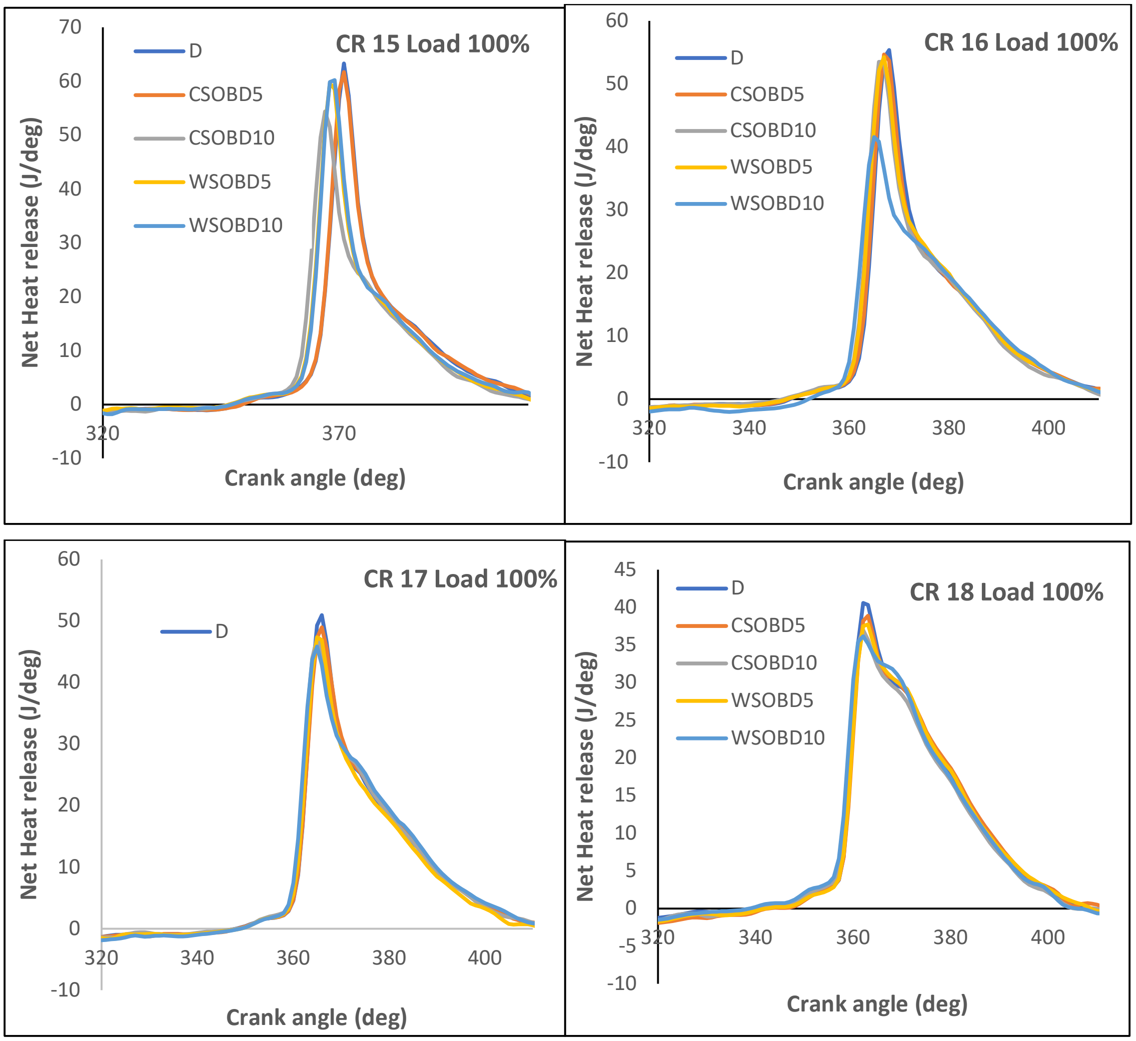

Fig 4.19: Variation of net heat release with CA of Diesel(D), CSOBD and WSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 100 % load

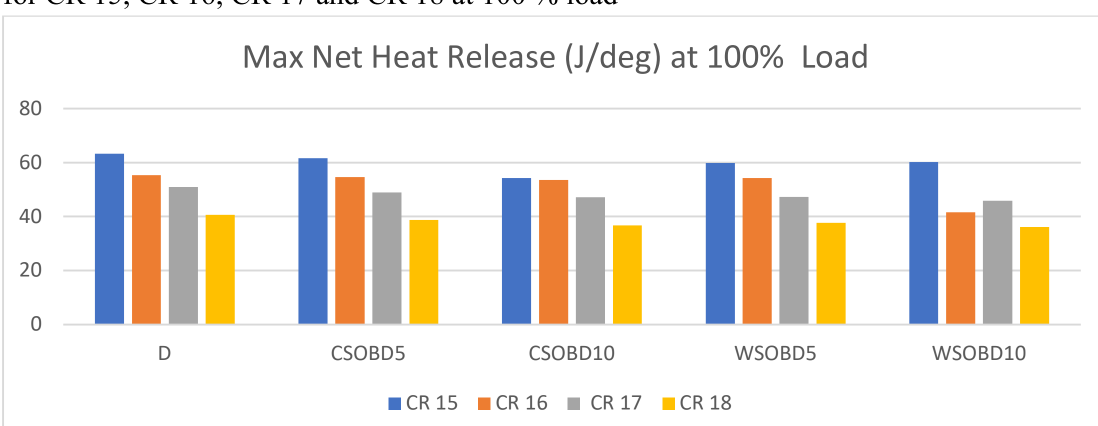

Fig 4.20: Maximum Net Heat Release obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at 100 % load.

4.1.3.1 Variation of Cylinder pressure with Cylinder volume at zero load (0%) from CR 15 to CR 18

The graph below provides a visual representation of Pressure-Volume (PV) curves for diesel fuel and various biodiesel blends, specifically under zero load conditions as shown in **Fig. 4.21 and Fig. 4.22**. When analyzing these curves, the striking observation is the remarkable similarity between biodiesel blends and pure diesel. While there might be a marginal difference in peak pressure favoring diesel at a compression ratio (CR) of 15, the broader trend remains strikingly consistent for both diesel and the blends across different compression ratios.

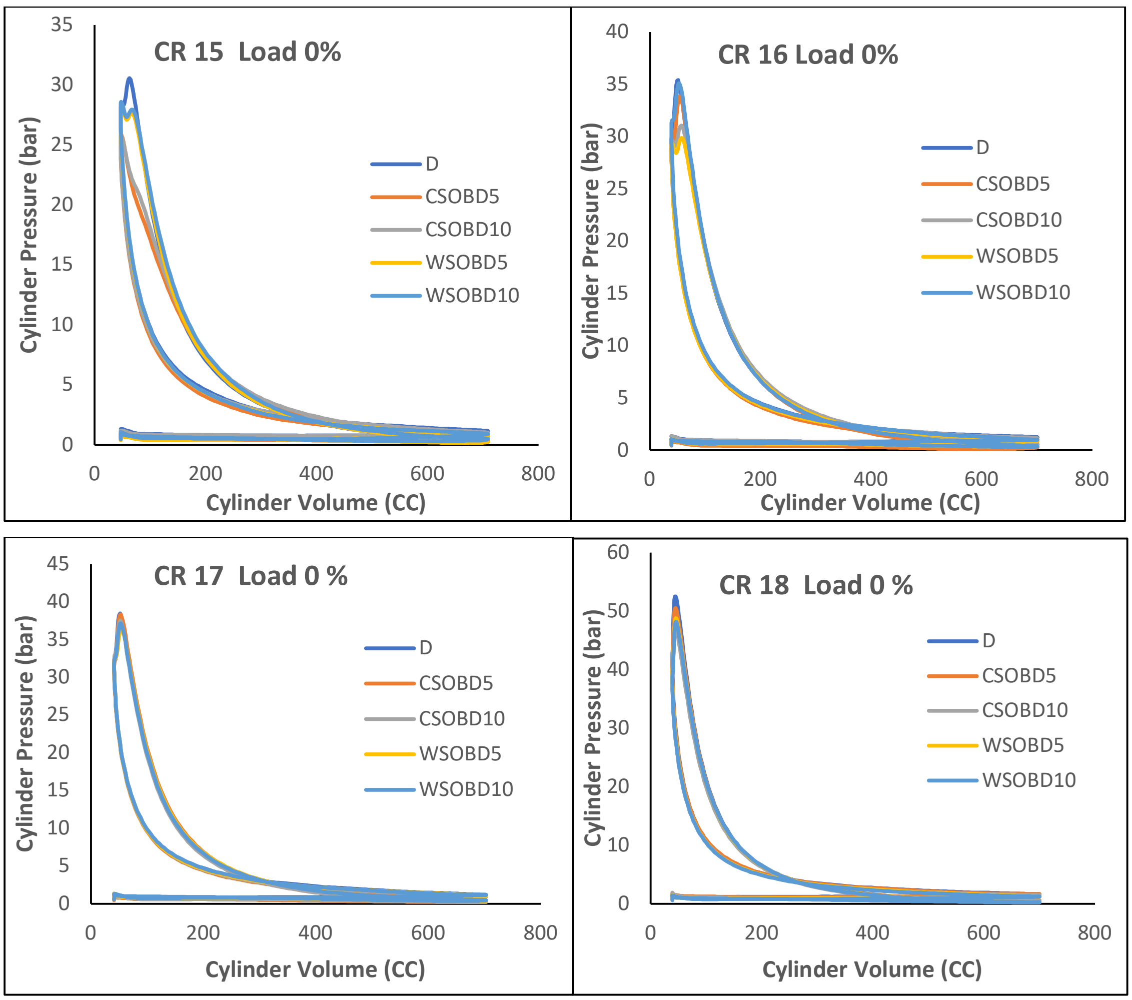

Fig 4.21: Variation of cylinder pressure with cylinder volume of Diesel(D), CSOBD andWSOBD blending for CR 15, CR 16, CR 17 and CR 18 at zero load (0%)

This coherence is primarily due to the fact that all three fuels, Diesel, CSOBD, and WSOBD, are subjected to the same range of compression ratios (CR) spanning from 15 to 18. The CR plays a pivotal role in engine design, and it exerts substantial influence over cylinder pressure. As the CR increases, the air inside the cylinder undergoes greater compression, resulting in elevated cylinder pressures across the board for all fuel types. This uniformity in trends persists across various CRs, with CR 17 being particularly noteworthy for showcasing optimal performance characteristics.

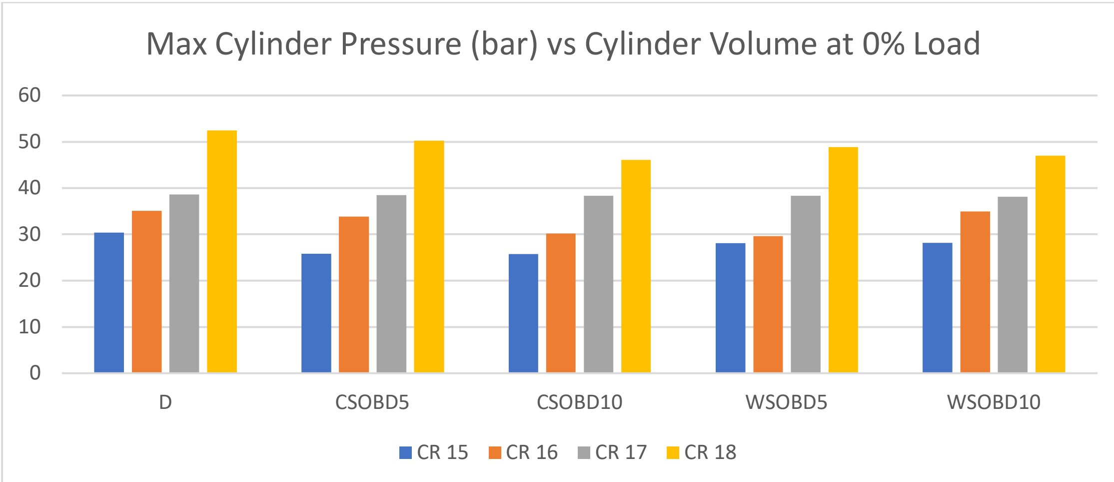

Fig 4.22: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at Zero load

4.1.3.2 Variation of Cylinder pressure with Cylinder volume at 25 % load from CR 15 to CR 18

The provided diagram (as shown in **Fig. 4.23 and Fig. 4.24)** illustrates alterations in the Pressure-Volume (PV) curve, depicting the characteristics of both traditional diesel and various biodiesel blends under a 25% load condition. Upon scrutinizing the PV curves of biodiesel blends alongside pure diesel, it becomes evident that any changes are minor and essentially inconsequential. While there is a slightly more noticeable peak pressure in the diesel PV curve at a compression ratio (CR) of 15 in comparison to the blend, the overall pattern remains nearly identical for both diesel and the blend as CR varies. This consistency in the PV curve's behavior is attributed to the engine's design, which is tailored to operate within a specific CR range. This design encompasses critical factors such as cylinder volume, piston geometry, and combustion chamber shape, all of which remain constant regardless of the fuel used. It's noteworthy that CR 17 stands out as the point where the blended fuels, CSOBD and WSOBD, exhibit their highest Maximum Cylinder Pressure, surpassing that of Diesel.

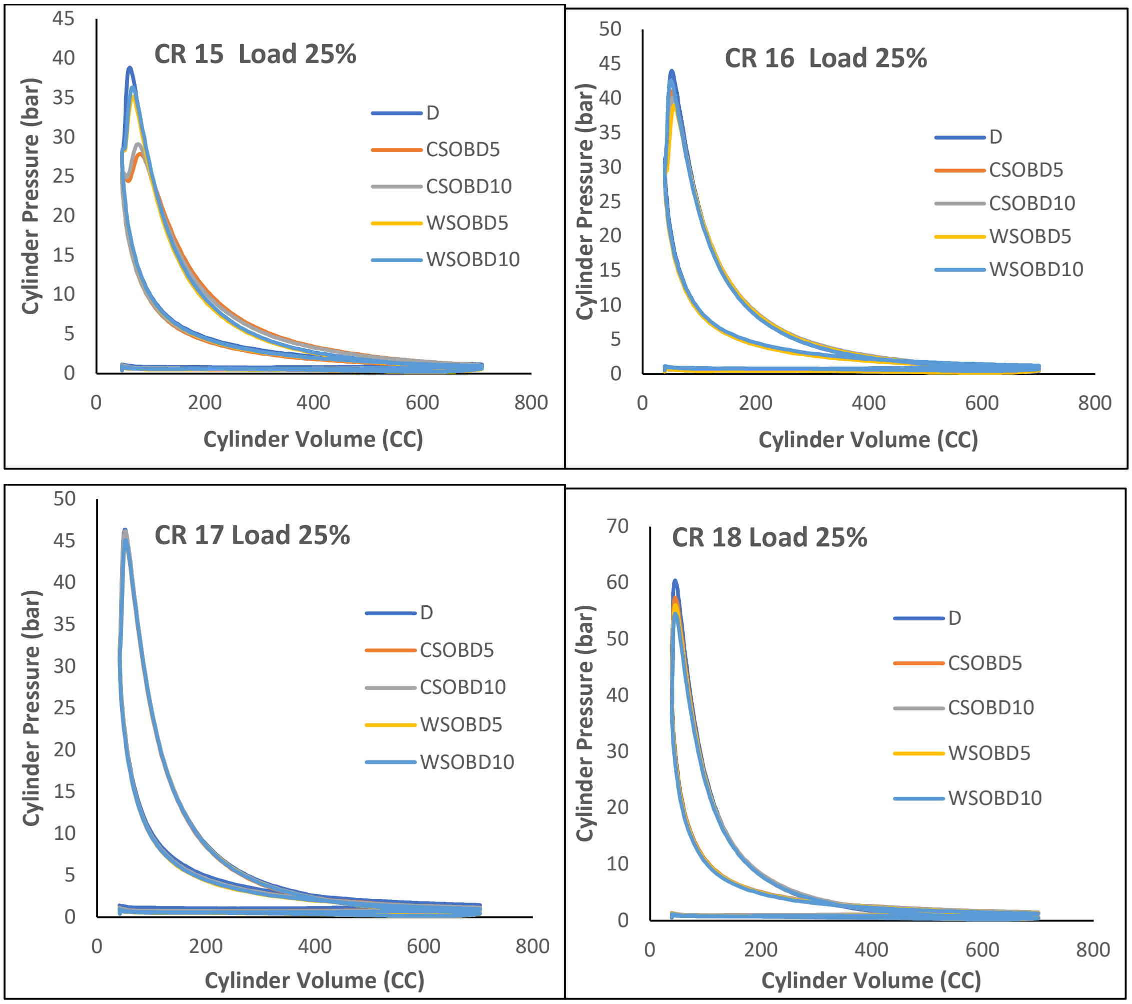

Fig 4.23: Variation of cylinder pressure with cylinder volume of Diesel(D), CSOBD andWSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 25 % load

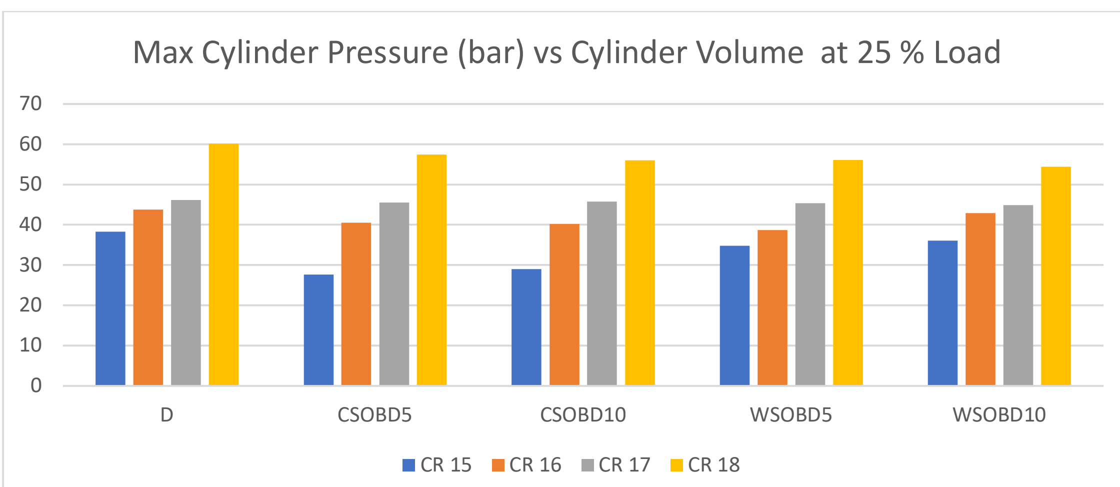

Fig 4.24: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at 25 % load

4.1.3.3 Variation of Cylinder pressure with Cylinder volume at 50 % load from CR 15 to CR 18

The provided diagram below highlights the variations observed in the Pressure-Volume (PV) curve for both traditional diesel fuel and a series of biodiesel blends while operating at a 50% load condition as shown in **Fig. 4.25 and Fig. 4.26**. Upon a close examination of the PV curves of the biodiesel blends alongside pure diesel, it becomes evident that any alterations are minor and inconsequential. Although there is a slightly more pronounced peak pressure in the diesel's PV curve at a compression ratio (CR) of 15 in comparison to the blend, the overall trend remains remarkably consistent for both diesel and the blend across a range of compression ratios.

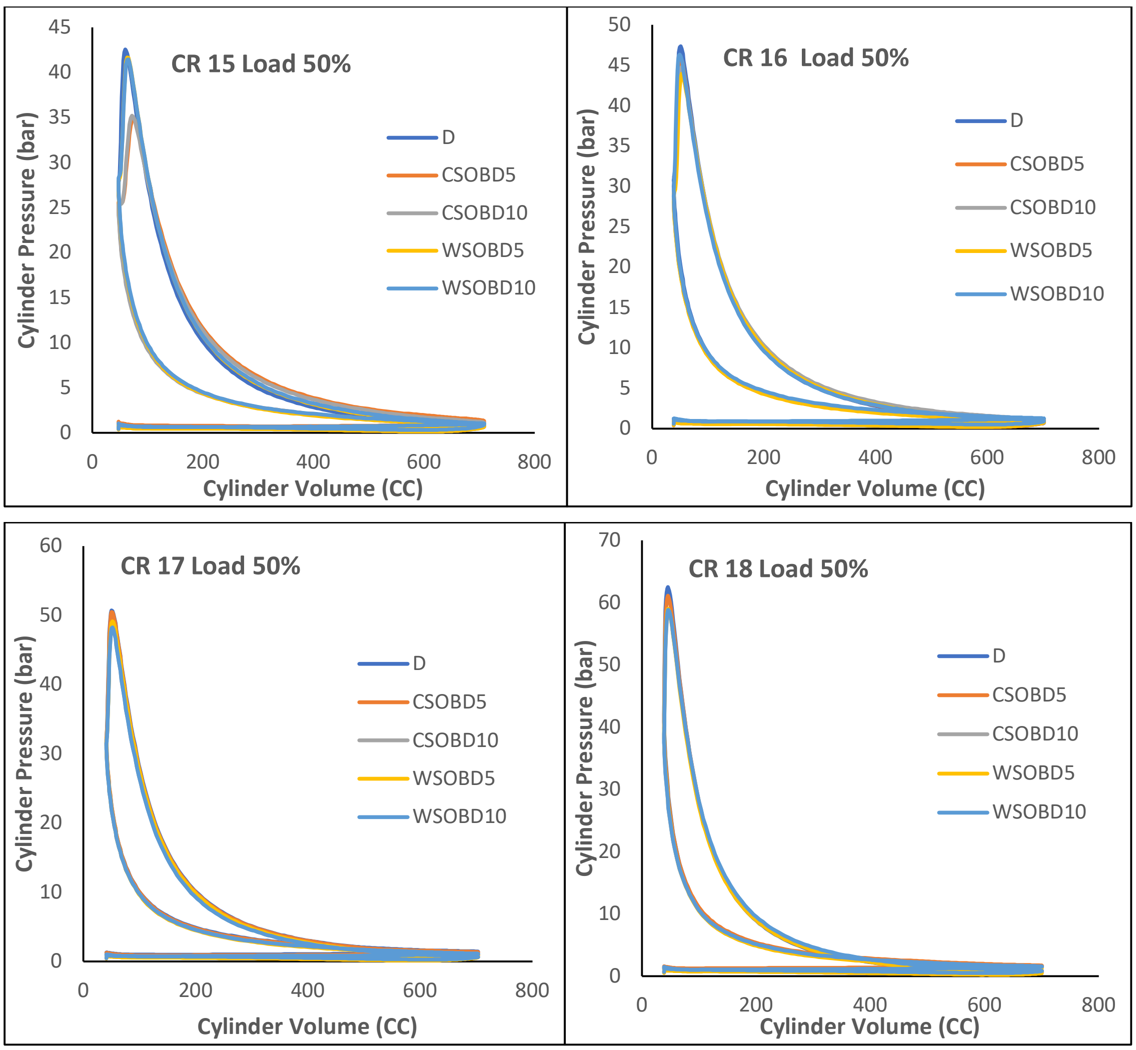

Fig 4.25: Variation of cylinder pressure with cylinder volume of Diesel(D), CSOBD andWSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 50 % load

These fuel blends possess distinct characteristics, including ignition properties and energy content. However, it's worth noting that modern diesel engines are engineered to adapt to a variety of fuels. They achieve this by making real-time adjustments to parameters such as injection timing and the fuel-air mixture to ensure consistent combustion behavior. While promising results are observed at all CR values, CR 17 and CR 18 stand out as the compression ratios where the maximum cylinder pressure of CSOBD and WSOBD closely approaches that of Diesel.

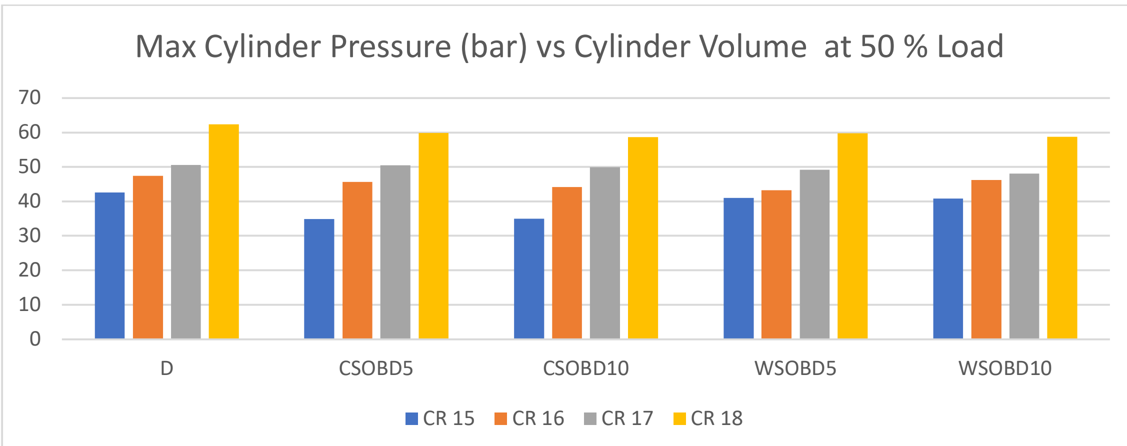

Fig 4.26: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at 50 % load

4.1.3.4 Variation of Cylinder pressure with Cylinder volume at 75 % load from CR 15 to CR 18

The diagram depicted below sheds light on the variations evident in the Pressure-Volume (PV) curve involving traditional diesel fuel and an array of biodiesel blends when subjected to a 75% load as shown in **Fig. 4.27 and Fig. 4.28**. When we compare the PV curves of the biodiesel blends with those of pure diesel, it becomes clear that these differences are minimal and of little consequence. Notably, while the PV curve of diesel exhibits a slightly more pronounced peak pressure at a compression ratio (CR) of 15 in contrast to the blend, the overall pattern remains consistent for both diesel and the blend across various compression ratios. This consistency can be attributed to engine control systems, particularly the engine control unit (ECU), which are responsible for optimizing combustion regardless of the fuel used. These systems make real-time adjustments to parameters like fuel injection timing and the quantity of fuel injected to achieve efficient combustion, ensuring that cylinder pressure stays relatively stable. While this trend is consistent across all CR values, it's particularly noteworthy that at CR 17 and CR 18, the maximum cylinder pressure for CSOBD and WSOBD closely resembles that of Diesel.

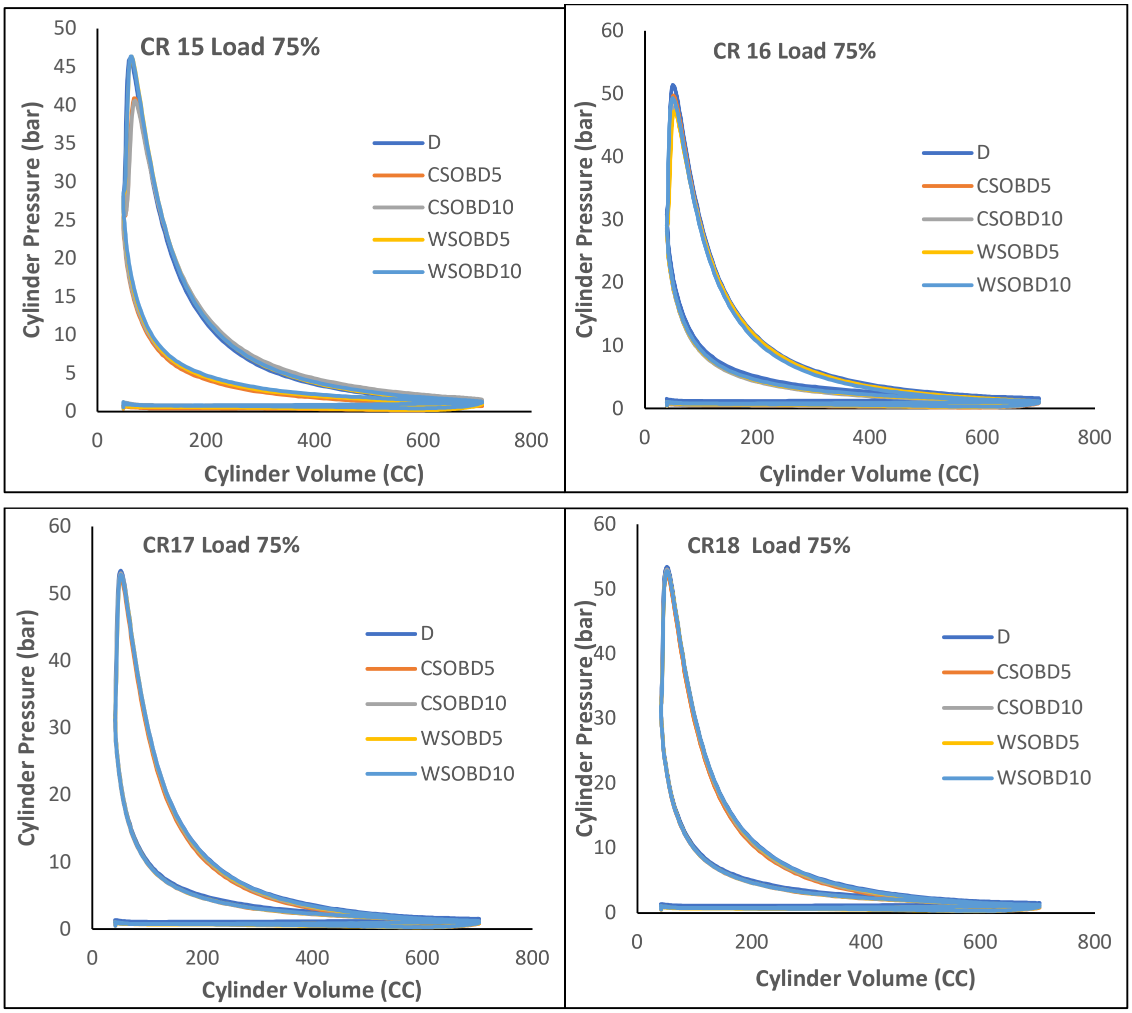

Fig 4.27: Variation of cylinder pressure with cylinder volume of Diesel(D), CSOBD andWSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 75 % load

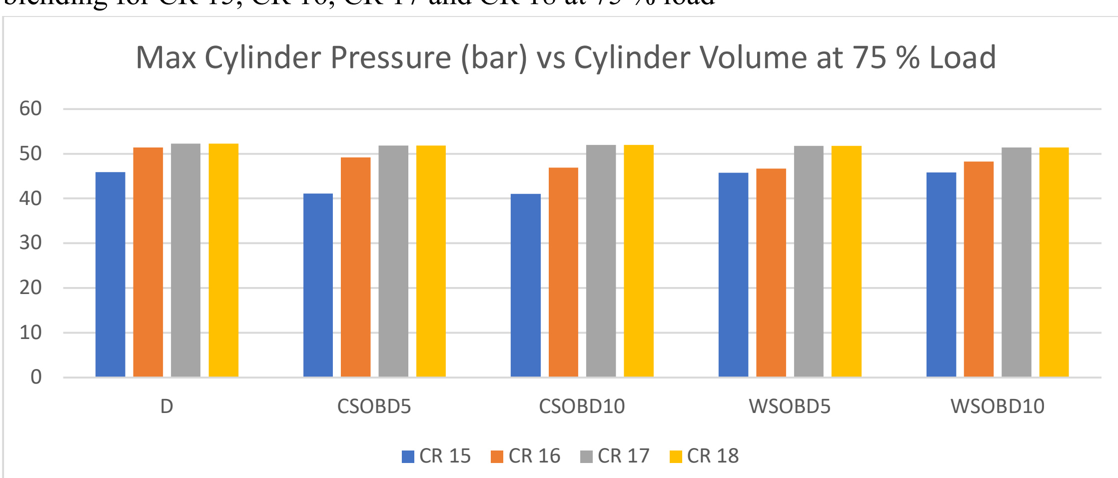

Fig 4.28: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at 75 % load

4.1.3.5 Variation of Cylinder pressure with Cylinder volume at full load (100 %) from CR 15 to CR 18

The diagram below serves to highlight the distinctions found within the Pressure-Volume (PV) curve involving standard diesel fuel and a diverse range of biodiesel blends, all of which were subjected to a full load as shown in **Fig. 4.29 and Fig. 4.30**. When we compare the PV curves of the biodiesel blends with those of pure diesel, it becomes evident that these differences are minor and of little consequence. Notably, while the PV curve of diesel exhibits a slightly more pronounced peak pressure at a compression ratio (CR) of 15 compared to the blend, the overall trend remains consistently unchanged for both diesel and the blend across a spectrum of compression ratios.

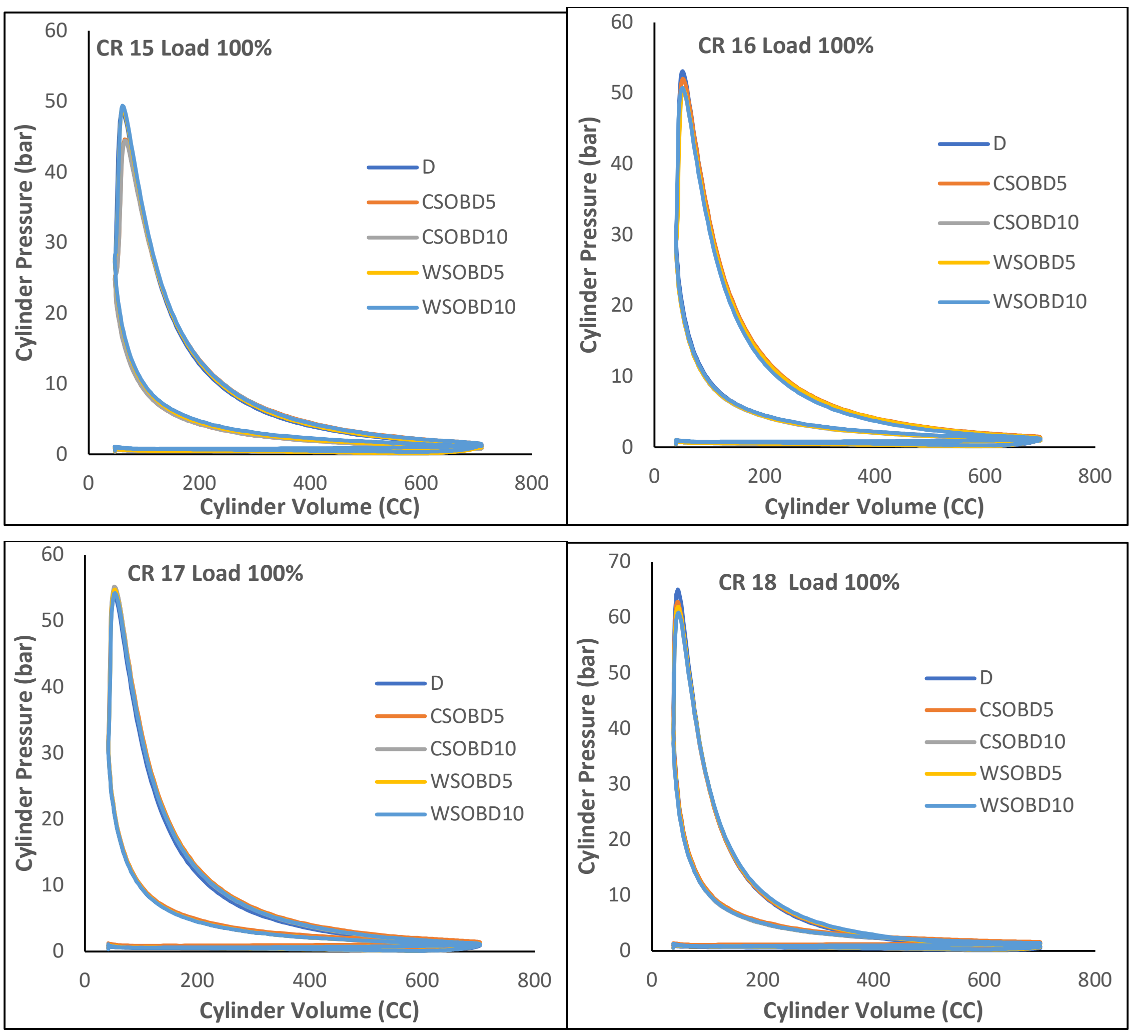

Fig 4.29: Variation of cylinder pressure with cylinder volume of Diesel(D), CSOBD andWSOBD blending for CR 15, CR 16, CR 17 and CR 18 at 100 % load

This unchanging pattern in cylinder pressure concerning cylinder volume for Diesel, CSOBD, and WSOBD is primarily attributed to the engine's design, compression ratio, and the presence of sophisticated control systems that allow it to adapt seamlessly to varying fuel properties. It's particularly interesting to observe that at CR 16 and CR 17, the maximum cylinder pressure of CSOBD and WSOBD matches that of Diesel, indicating a harmonious performance.

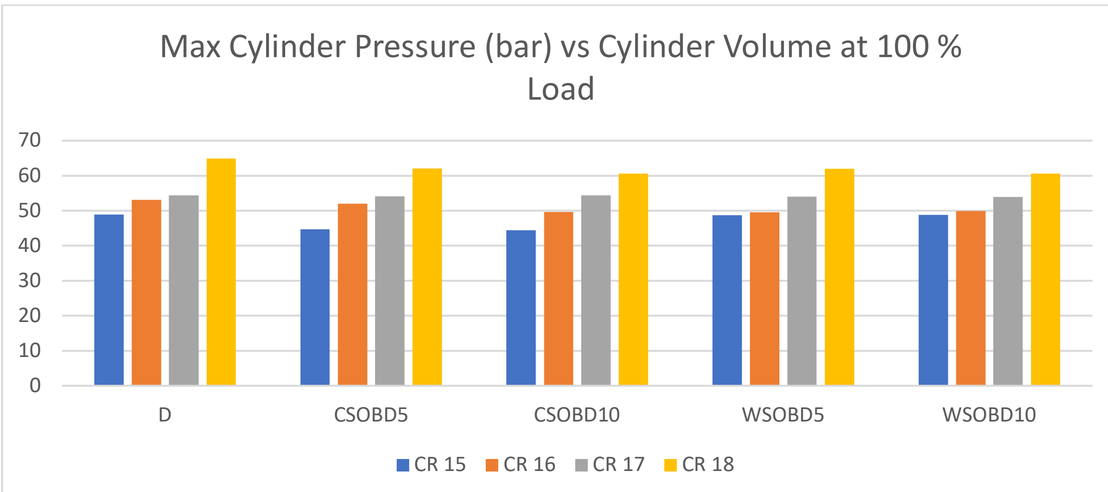

Fig 4.30: Maximum Cylinder Pressure obtained using Diesel (D), CSOBD and WSOBD for CR 15, CR 16, CR 17 and CR 18 at 100 % load

4.2.1 Performance Characteristics from CR 15 to CR 18

4.2.1.1 Variation of Specific fuel consumption (SFC) with load from CR 15 to CR 18

The graphical representation highlights how Specific Fuel Consumption (SFC) changes with varying loads for compression ratios (CR) ranging from 15 to 18, with a specific focus on diesel-fuel blends as shown in **Fig. 4.31**. Remarkably, the graphs consistently demonstrate a similar trend for different blends across all load conditions, signifying minimal variations.

When considering why SFC tends to be lower for blended diesel with biodiesel compared to pure diesel, several factors come into play. Biodiesel, which is derived from renewable sources like vegetable oils, generally has a higher oxygen content. This higher oxygen content promotes more complete combustion in the engine, leading to increased thermal efficiency and reduced SFC. Additionally, biodiesel has superior lubricating properties, which can reduce friction within the engine, further enhancing its overall efficiency. These combined factors contribute to the observed lower SFC in blended diesel-biodiesel fuels, making them an environmentally friendly and efficient choice for internal combustion engines. At a compression ratio of 15, CSOBD5 achieves its maximum specific fuel consumption (SFC) of 0.77 kg/kWhr, while WSOBD5 reaches a maximum SFC of 0.67 kg/kWhr. With a compression ratio of 16, CSOBD5 attains its peak SFC of 0.65 kg/kWhr, and WSOBD5 achieves a maximum SFC of 0.62 kg/kWhr. At a compression ratio of 17, CSOBD5 reaches its highest SFC of 0.69 kg/kWhr, while WSOBD5's maximum SFC is 0.67 kg/kWhr. Finally, at a compression ratio of 18, CSOBD5 reaches its peak SFC of 0.61 kg/kWhr, and WSOBD5 attains a maximum SFC of 0.59 kg/kWhr. The CSOBD10 blend achieves its lowest fuel consumption rate of 0.17 kg/kWhr at 75% load, while the WSOBD10 blend hits a minimum of 0.05 kg/kWhr at full load.

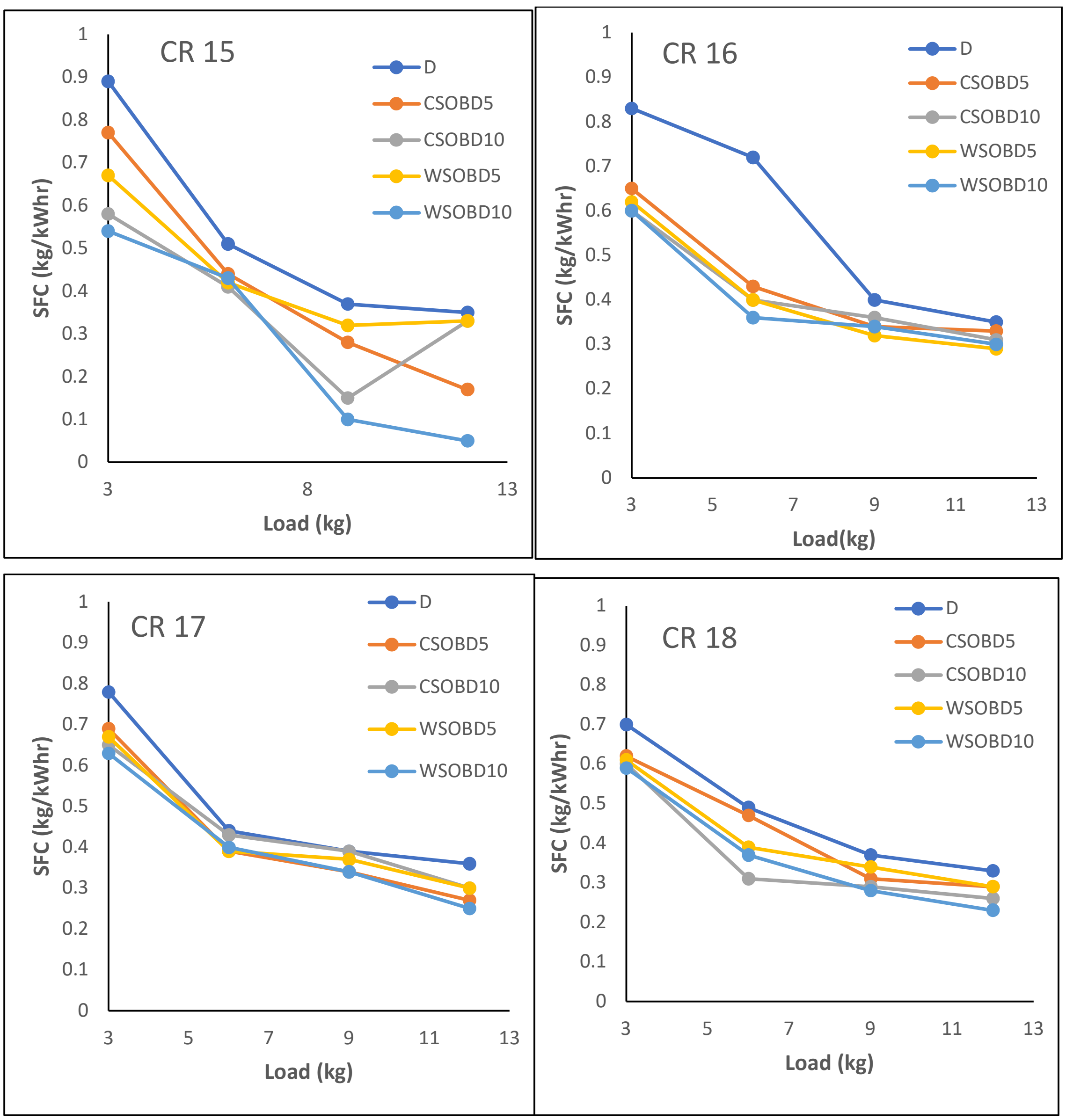

Fig 4.31: Variation of Specific fuel consumption with Load at CR 15, CR 16, CR 17 and CR 18

4.2.1.2 Variation of Break Thermal Efficiency (BTE) with load from CR 15 to CR 18

The graphical representation depicts as shown in **Fig. 4.32,** how Break Thermal Efficiency (BTE) varies with changing loads across a spectrum of compression ratios (CR), specifically within the range of 15 to 18. These analyses focus on diesel-fuel blends. Interestingly, regardless of the load conditions, the graphs consistently exhibit a similar trend for various blends, suggesting minimal deviations. Blended diesel with biodiesel tends to exhibit slightly lower Break Thermal Efficiency (BTE) compared to pure diesel due to several factors. Biodiesel, a key component in these blends, has distinct combustion characteristics, including a longer ignition delay, potentially leading to less efficient combustion. Additionally, biodiesel typically has a lower energy density, meaning it contains less energy for the same volume of fuel, resulting in slightly reduced engine power and thermal efficiency. While biodiesel offers superior lubricity, excessive use in blends can lead to lubrication-related challenges that impact engine efficiency. Despite these effects on efficiency, biodiesel blends often achieve reduced emissions, contributing to their positive environmental impact. The trade-off between efficiency and sustainability plays a crucial role in selecting fuel blends for specific applications. At a compression ratio (CR) of 15, the CSOBD5 fuel blend achieves its maximum Break Thermal Efficiency (BTE) of 27.43, while WSOBD5 attains a maximum BTE of 25.54. As the compression ratio increases to 16, CSOBD5 reaches its peak BTE of 26.38, closely followed by WSOBD5 with a maximum BTE of 26.21. At a higher compression ratio of 17, CSOBD5 exhibits an impressive maximum BTE of 29.73, while WSOBD5 achieves a commendable maximum BTE of 29.36. Finally, at a compression ratio of 18, CSOBD5 records a peak BTE of 28.28, and WSOBD5 maintains a strong performance with a maximum BTE of 28.30.

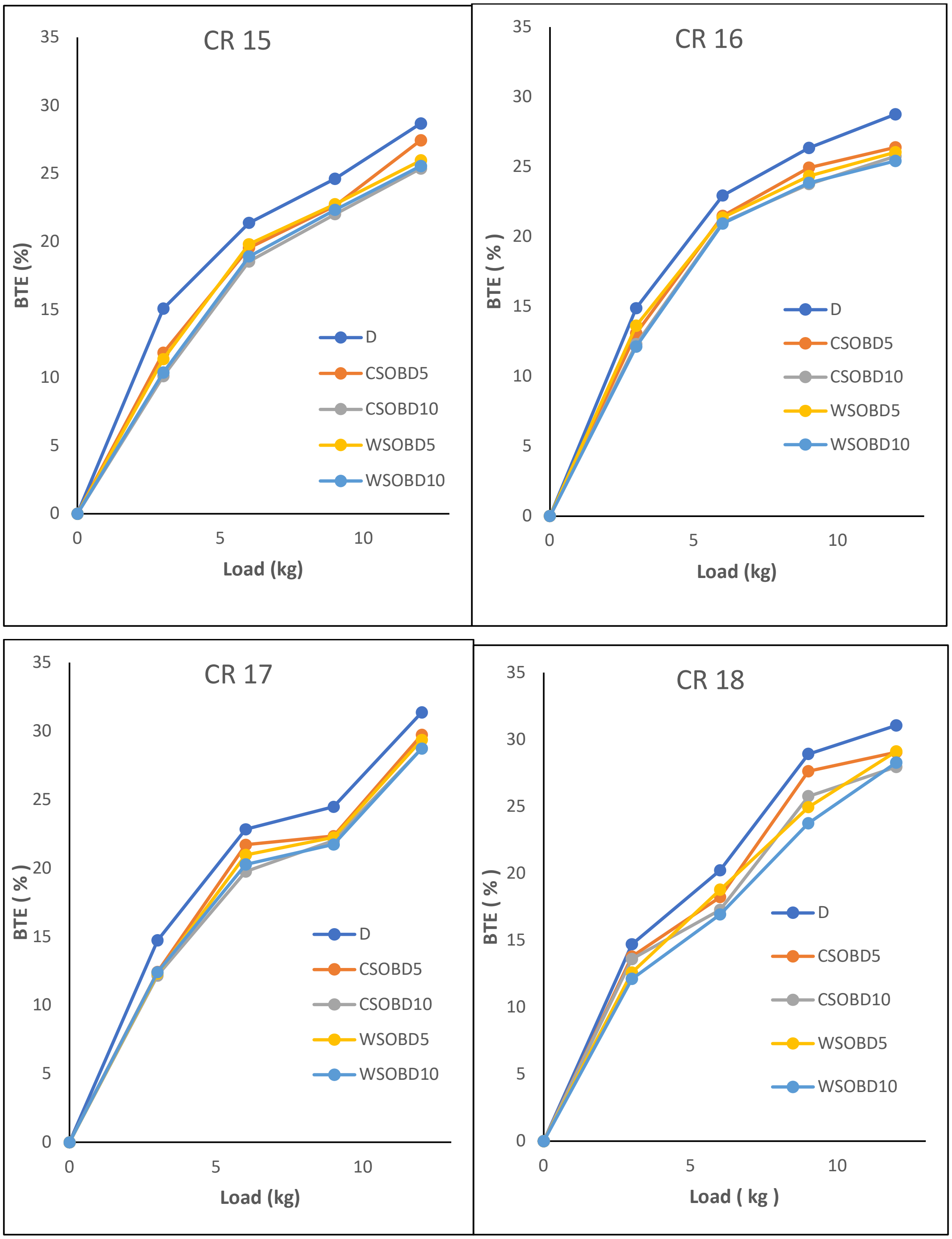

Fig 4.32: Variation of Break Thermal Efficiency with Load at CR 15, CR 16, CR 17 and CR 18

Chapter 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

Waste cooking oil emerges as a valuable and eco-friendly resource for biodiesel production, owing to its organic constituents that pose minimal environmental harm. Moreover, its ready availability in hotels and restaurants further enhances its appeal as a biodiesel feedstock. In contrast, crude cooking oil stands apart due to distinct cost and viscosity attributes, thereby raising notable concerns. This research endeavor facilitates a direct comparison of the combustion traits exhibited by biodiesel blends derived from crude and waste soybean oil within a diesel engine context. The study entails the formulation of CSOBD (Crude Soybean Oil Biodiesel) and WSOBD (Waste Soybean Oil Biodiesel) blends, each incorporating biodiesel at 5% and 10% concentrations with conventional diesel fuel. The ensuing investigation delves into the combustion characteristics exhibited by these blends when subjected to testing within a Variable Compression Ratio (VCR) Diesel engine. Through meticulous experimentation, this study aims to uncover nuances in combustion behavior, seeking to discern potential differences and similarities between biodiesel derived from crude versus waste soybean oil. The conducted analysis could potentially shed light on the implications of feedstock choice in terms of combustion efficiency and emissions profiles. Such insights are instrumental in forging a comprehensive understanding of biodiesel's performance in engine applications, facilitating informed decisions regarding fuel selection and contributing to the broader discourse on sustainable energy sources.

Based on the experimentation involving biodiesel assessment within a diesel engine using varying blend ratios, several noteworthy findings can be drawn:

- It is evident from the through literature study that waste cooking oil will be a prospective feedstock for biodiesel production specifically for developing nations like India.
- The recorded cylinder pressure for biodiesel blends in relation to crank angle is consistently lower than that of diesel fuel under all load conditions. Particularly noteworthy is the observation that at a compression ratio (CR) of 17, both CSOBD and WSOBD exhibit maximum pressures that closely approach those of diesel. Moreover, at a load condition of 75%, the biodiesel blends demonstrate their most favorable results in

this regard.

- Minor variations in Net Heat Release (NHR) become apparent when comparing the two biodiesel types, crude (CSOBD) and waste (WSOBD). There's an observable pattern of fluctuations as the compression ratio (CR) increases, with some decreases followed by increases in NHR. Notably, at a compression ratio of 17 and under a 25% load, the maximum NHR_{max} for both CSOBD and WSOBD approaches that of diesel, highlighting their competitive performance in these conditions.
- The measured peak pressure of biodiesel blend is lower than diesel fuel at all load conditions and increases with at higher CRs.
- Throughout various compression ratios (CRs), except for CR 15, it is observed nearly identical values for cylinder pressure relative to cylinder volume. However, at CR 17 and CR 18, under a 75% load, the maximum cylinder pressure for both CSOBD and WSOBD closely matches that of diesel, signifying their comparable performance in these specific conditions.
- When considering Specific Fuel Consumption (SFC), the CSOBD5 blend achieves its highest value at 0.77 kg/kWhr, while at a load of 3, WSOBD5 reaches 0.67 kg/kWhr. The CSOBD10 blend achieves its lowest fuel consumption rate of 0.17 kg/kWhr at 75% load, while the WSOBD10 blend hits a minimum of 0.05 kg/kWhr at full load.
- In terms of Break Thermal Efficiency (BTE), the CSOBD5 blend attains its peak efficiency at 29.73, while WSOBD5 reaches 29.36 under full load and at compression ratio 17.

5.2 Scope of Future Work

The present study engages in a comparative exploration of how varying ratios of biodiesel to diesel impact the combustion characteristics of a diesel engine. This avenue of research opens up possibilities for further investigations in this field.

Potential avenues for extended research include:

- Conducting investigations employing diverse catalysts and fuel additives for biodiesel production, and assessing their influence on diesel engine performance across different blending proportions.
- Undertaking a comprehensive comparative assessment of performance and emission traits within a Diesel engine, encompassing an array of both edible and non-edible oils, in both crude and waste forms.
- Expanding the study to examine the effects of employing different blending ratios of

biodiesel and diesel, specifically investigating their impacts on performance, combustion behaviour, and emissions under distinct compression ratios and load conditions.

- Conducting an in-depth performance and emission analysis, employing biodiesel derived from diverse cooking oils including fish oil, vegetable oil, and non-edible oils.
- Evaluating the performance, combustion dynamics, and emissions of a diesel engine when integrating a mixture of both crude and waste oil-based biodiesel.

These prospective research directions extend the scope of understanding regarding the utilization of biodiesel in diesel engines. They hold the potential to yield valuable insights into the intricate interplay between fuel sources, blending ratios, catalysts, additives, and combustion behavior, ultimately contributing to the advancement of sustainable and efficient energy solutions.

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