iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** II **Month of publication:** February 2018

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue II, February 2018- Available at www.ijraset.com

Comparative Performance and Exhaust Emissions Study of a Single Cylinder Diesel Engine Using Biodiesel-Diesel Blends of Various Origins

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Abstract: Biodiesel is one of the alternative fuels which is renewable and environmentally friendly and can be used in diesel engines with little or no modifications. The objective of this study is to investigate potential of biodiesel fuels and biodiesel fraction from various feedstocks such as jatropha, palm, cotton, rice bran, rapeseed, linseed as well as from waste cooking oil in terms of the corresponding CI engine performance and exhaust emissions comparing to a reference diesel. The experimental work was carried out on a single-cylinder, four-stroke, direct injection (DI) diesel engine by using Diesel- biodiesel blends prepared in volume percentages 5, 10, 15 and 20% and neat diesel. The engine was operated over a range of engine loads. Results showed that higher brake-specific fuel consumptions (BSFC), Higher exhaust concentrations of nitrogen oxides (NOx) and carbon dioxide (CO_2) while lower carbon dioxide (CO), smoke opacity and hydrocarbon emissions (HC) were observed when using biodiesel fuels compared to diesel fuel. Thus, with the increasing demand for biodiesel, alternative feedstock sources such as those used in this study may be utilized to take advantage of their exciting potential opportunities to increase energy security and environmental benefits.
Keywords: Biodiesel, diesel engine, Performance, Emission characteristics.

I. INTRODUCTION

Replacement of fossil fuels with renewable biofuels has been set as a target worldwide to reduce greenhouse effect and energy dependence as well as to improve agricultural. Biodiesel is gradually gaining acceptance in the market as an environmentally friendly fuel and the demand is expected to increase sharply as an alternative renewable energy source in the near future. Biodiesel fuel is mono alkyl ester derived from vegetable or animal and it can be blended with diesel fuel which has characteristics similar to diesel fuel and has lower exhaust emissions [1–3]. On the other hand, the main drawbacks of vegetable oil have to overcome due to the high viscosity and low volatility which will cause a poor combustion in diesel engines. Transesterification is the process successfully employed to reduce the viscosity of biodiesel and improve the other characteristics [4]. Biodiesel production from different plants jatropha, sun flower, palm oil, pongamia pinnata, rapeseed etc. had been well evaluated for their characteristics [5, 6]. Some literatures reported less emission produced from the biodiesel as compared to the diesel [7, 8]. However, there are also some literatures reported higher emissions produced from biodiesel [9, 10]. This is due to the properties of biodiesel, therefore it is important to understand the chemical properties of biodiesel in order to obtain optimum engine performance and produce less harmful gases compared to diesel fuel. Song et al. [11] studied the effects of biodiesel fuels properties on NO_X and smoke emitted from diesel engine. On average, the biodiesel fuels tend to emit higher NO_X than diesel fuel. Smoke concentrations are generally lower with the biodiesel fuels than with diesel. When exhaust gas recirculation used, smoke concentrations increased and the increase in smoke concentration is relatively smaller than the decrease in NO_X emissions. In addition, biodiesel combustion results in a decrease in hydrocarbon (HC), carbon monoxide (CO), and particulate emissions compared to conventional petrodiesel. Whereas an increase in nitrogen oxides (NO_x) from biodiesel combustion compared to diesel has been reported in several papers [12–14]. Duraisamy et al. [15] investigated the use of mixed biodiesel produced from the mixture of methyl ester jatropha, pongamia, mahua and neem seed oils in a conventional diesel engine. The results indicated that NOX and smoke emissions were slightly higher than diesel fuel. The existing designing of diesel engines does not need any substantial modification. Hamasaki et al. [16] studied the combustion characteristics of a turbocharged direct injection automotive diesel engine fuelled by waste vegetable oil biodiesel and conventional diesel fuel, reporting slight differences in the shape of the heat release rate curve and in the main combustion parameters. Similar results have been obtained by other researchers testing biodiesel from several vegetable oils and animal fats [17-19]. The development of similar stages in the combustion process using biodiesel and diesel fuel resulted in small differences on thermal efficiency, and so the lower energy content of biodiesel led to an increase in specific fuel consumption [20, 21]. This study is targeted to experimentally explore technical operation of biodiesel blends derived from different feedstock in a diesel engine without any hardware modifications. The transesterification process was used to obtain biodiesel from crude vegetable oils. Physical and chemical properties of biodiesel blends were analyzed. The environmental emissions and performance of a stationary type single cylinder diesel engine fuelled with biodiesel blends up to 20% comparing to neat diesel fuel were evaluated at rated engine speed and entire engine load range.

II. MATERIALS AND METHODS

A. Biodiesel Production Process

Transesterification process is used for biodiesel production when free fatty acid content becomes less than 2%. Base catalyzed transesterification is selected as the process to make biodiesel from vegetable oil. If free fatty acid content becomes more than 2%, a two stage process is used for biodiesel production from the oil. The first stage of the process is called esterification, and this is used to reduce the free fatty acid content in the oil by using methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in three hours reaction at 80 ºC. In the second stage, transesterification is a base catalyzed reaction involving mono alkyl esters and glycerin. A mixture of 1% NaOH by weight and 9:1 molar ratio of ethanol are added to esterified oil. First, the oil was heated to 65 ºC and the mixture of catalyst and ethanol was poured in it. The mixture was stirred at 700 rpm for 1.5 hr and poured into a separating funnel and the mixture is allowed to settle for 8 hr in order to have two separate layers. The bottom layer containing glycerol and impurities was removed and upper layer contains biodiesel with water and alcohol. Biodiesel is purified by washing from 3 to 4 times with hot distilled water to get rid of glycerin until PH of water becomes neutral and stirred gently to remove remaining impurities and glycerol. Biodiesel was then taken in a rotary evaporator to remove the moisture. Finally, moisture was removed by using sodium sulfate. Biodiesel blends were prepared at various volumetric proportions such as B5, B10, B15 and B20 (5, 10, 15, and 20% biodiesel in petroleum diesel), respectively.

B. Biodiesel Characterization

Physical and chemical properties of diesel fuel and biodiesels from different origins such as palm, jatropha, cotton, linseed, rapeseed and waste cooking oil were analyzed. The fuel properties were determined following the methods specified in ASTM standards as given in Table 1. Flash points of biodiesel blends were higher compared to diesel fuel. Hence, biodiesel is extremely safe to handle. Kinematic viscosity and density of biodiesel blends were considerably higher than diesel fuel this may result in improper spray characteristics. Calorific values of biodiesel blends were lower than diesel fuel due to oxygen content. Viscosity, flash point, density and calorific value of biodiesel blends were within specifications of ASTM standards.

Table 1: Physical and Chemical Properties of Different Biodiesel Blends

Properties	Diesel oil D100	Palm B100	Ricebran B100	Cotton B100	Linseed B100	Rapeseed B100	Jatropha B100	Waste cooking oil B100
Density at 15 ºC	825.9	872.3	879.8	881	902.7	876.8	875	883
Kinematic viscosity, C st at 40 ºC	2.72	5.02	4.93	4.64	6.61	6.14	5.6	4.77
Flash point, ºC	70	132	120	87	99	114	164	113
Calorific value, kJ/kg	43700	35634	41174	38390	35937	36724	39520	39278

III. EXPERIMENTAL SET UP AND METHODOLOGY

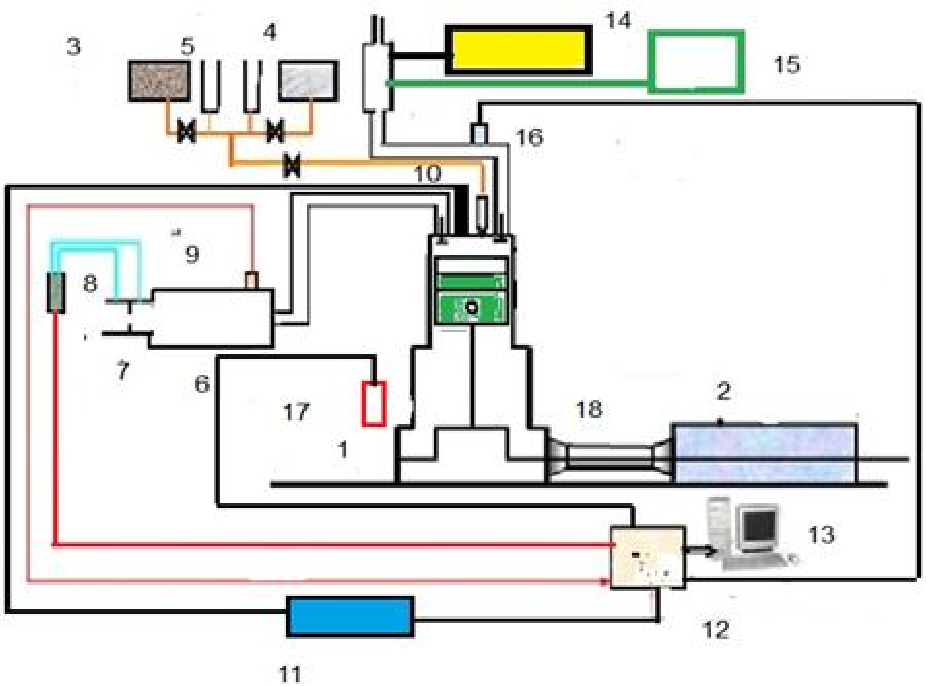
A. Engine Setup

Engine performance and exhaust emissions testing were conducted at the Lab engine testing facility of National Research Centre, Engine, Egypt using a single cylinder, four stroke, air cooled, direct injection, naturally aspirated diesel engine with a maximum power of 5.775 kW at 1500 rpm. The technical specifications of the engine are given in Table 2, and the schematic layout of the experimental test rig is shown in Fig. 1. AC generator of maximum electric power output of 10.5 kW equipped with a load controller has been coupled directly to the engine to determine the engine output brake power. The intake airflow was measured by a sharp edged orifice mounted in the side of an air box, coupled to the engine intake manifold to dampen the pulsations of airflow into the engine. A U tube manometer was used to measure the pressure drop across the orifice. Calibrated thermocouple probes of type (K) were used for temperature measurements at intake air manifold and exhaust gas. Temperature thermocouples signals are readout by a digital thermometer. The engine rotational speed was measured using speed tachometer. Two fuel tanks of crude biodiesel and diesel fuels were mounted to feed the engine. One burette with stopcock and two way valves were mounted for fuel flow rate measurements and selecting between both diesel and biodiesel fuels. A Kistler piezoelectric pressure transducer (model 601A) measures from 0 to 250 bar as pressure range with sensitivity of 16.5 pc/bar and accuracy of 1.118% connected with Nexus charge amplifier (2692-A-0S4) were used for cylinder pressure measurement. The position of the piston top dead center (TDC) was determined using a proximity switch (Type LM12-3004NA) fixed on the output shaft of the engine. A high speed data acquisition card (NI-USB-6210) was used to acquire Data using LABVIEW software. OPA 100 smoke meter and MRU DELTA 1600-V gas analyzer were used for the measurements of smoke opacity and exhaust gas emissions concentrations.

The performance and emissions were studied at 25%, 50%, 75%, and 100% (full load) of the load corresponding to the load at the maximum power at the average speed of 1500 rpm throughout the experiment. Engine power tests are conducted in accordance with SAE Standard Engine Power Test Code for diesel engines (SAE J1349 Revised MAR2008). Baseline engine performance and emissions tests are performed using ULSD reference diesel fuel. Engine performance data for ULSD reference diesel were corrected to the standard atmospheric conditions using the compression ignition engine correction formula according to SAE J 1349-MARCH 2008. Variables such as air and relative humidity are carefully monitored. All the equipments were calibrated in accordance to the respective manufacturer's specifications, prior to conducting the tests. The uncertainties for NO, unburned HC, CO, smoke opacity and thermal efficiency are ±1 ppm, ±1 ppm, ±0.01 % Vol, ± 1 % and ± 1.5 %, respectively. The maximum uncertainty in measurement of brake power, brake specific fuel consumption, and engine speed are found to be 0.85 %, 2.2 % and 0.15 % (± 2 rpm), respectively.

Table 2: Engine specifications.

Engine parameters	Specifications
Type	DEUTZ F1L511
Number of cylinders	1
Number of Cycles	Four stroke
Cooling type	Air cooled
Bore (mm)	100
Stroke (mm)	105
Compression ratio	17.5:1
Fuel injection advance angle	24º BTDC
Rated brake power (kW)	5.775 at 1500 rpm
Number of nozzle holes	1
Injector opening pressure (bar)	175



1- Diesel engine	10- Piezo pressure trnsducer
2- AC generator	11- Charge amplifier
3- Diesel tank	12- Data acquisition card
4- Biodiesel tank	13- Personal computer
5- Burette	14- Exhaust gas analyzer
6- Air surge tank	15- Smoke meter
7- Orifice	16- Exhaust gas temperature thermocouple
8- Pressure differential meter	17- Proximity switch
9-Intake air temperature thermocouple	18- Cardan shaft

Fig.1. Schematic layout of the experimental setup.

IV. RESULTS AND DISCUSSIONS

A. *Variation of Brake Specific Fuel Consumption*

Figure 2 shows the brake specific fuel consumption expressed in kg/kWh (kilograms per kilowatt hour), for the neat diesel fuel, the bio-diesel blends of various origins. The fuel blend mass flow rate is calculated from the respective measured volume flow rate value and the blend density, which is computed by considering the blending ratio and the densities of the fuels involved. Since the comparison is made at the same load (brake mean effective pressure) and speed, which is translated into the same engine power, then these values effectively are directly proportional to the fuel mass flow rate; it is to be noted, however, that the air mass flow rate remains constant under the same operating conditions. It is observed from the figure that the specific fuel consumption for all the bio-diesel blends of various origins is a little higher than that for the corresponding diesel fuel case, with the increase being higher the higher the percentage of the bio-diesel in the blend. The observed increase in fuel consumption when using biodiesel blends can be attributed to the combined effects of the biodiesel properties such as lower heating value and higher density and viscosity as compared to a regular diesel. The higher density of biodiesel indicates that higher mass is injected for the same volume at the same injection pressure while the lower calorific or heating value indicates that a larger quantity of fuel must be injected into the combustion chamber to produce the same power, thus leading to an increase in the specific fuel consumption [22]. Biodiesel blends showed an increase in fuel consumption approximately proportional to the amount of biodiesel blended to the diesel fuel.

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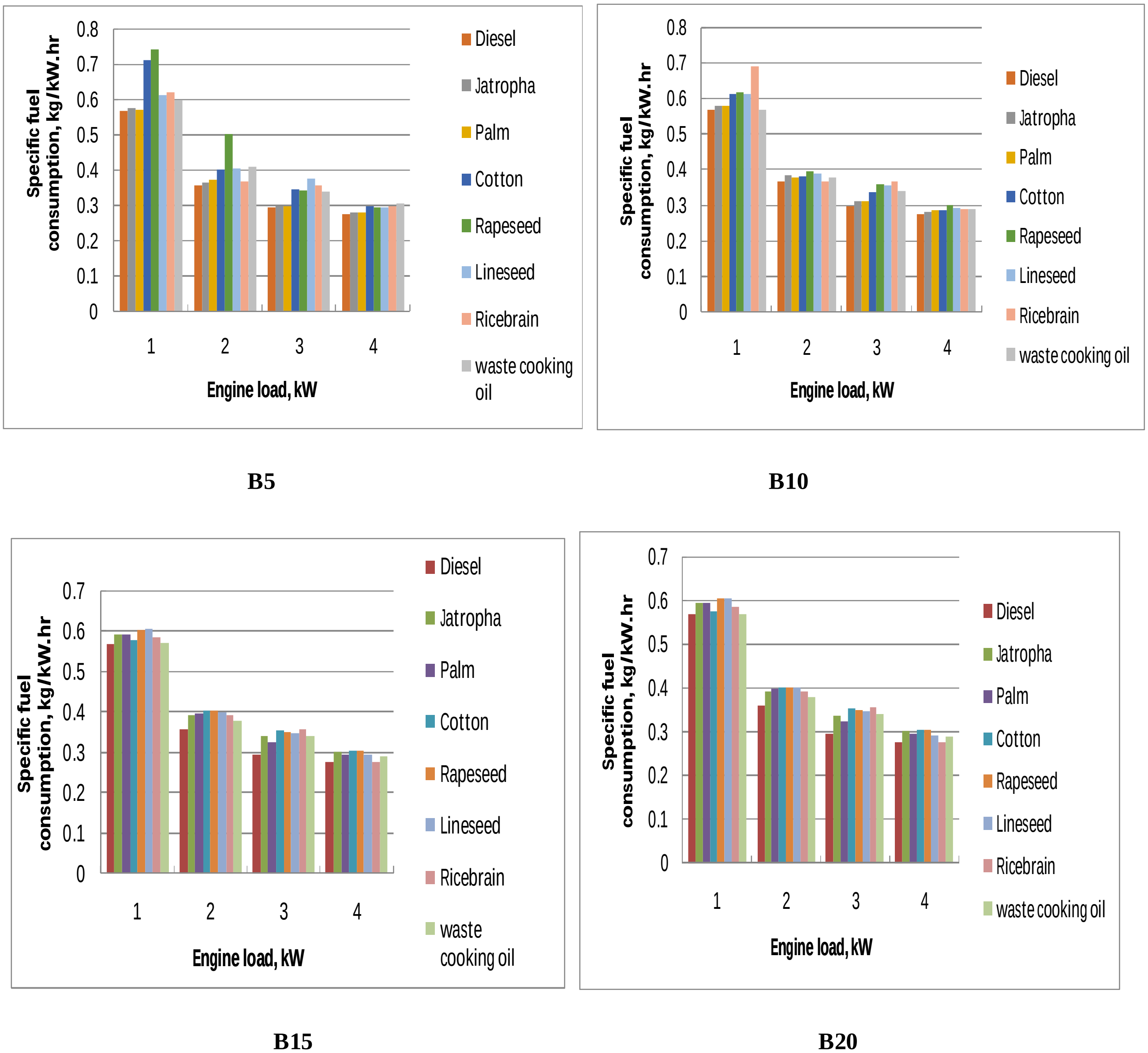

Fig.2. Variation of specific fuel consumption versus engine load for different fuels.

B. Variation of Thermal Efficiency

Figure 3 shows the percentage change of the brake thermal efficiency for biodiesel blends of various origins as compared to neat diesel fuel with load. Thermal efficiency for all biodiesel blends increase with the increase in engine load due to the increase of fuel consumption. From the figure, it can be observed that the trend of brake thermal efficiency is exactly the reverse of BSEC at all loads for all the test fuels. This is because of the brake thermal efficiency being the reciprocal of BSEC. Brake thermal efficiency is slightly lower for biodiesel blends compared to diesel fuel at all engine loads. This drop in thermal efficiency for biodiesel blends may be attributed to the poor combustion characteristics of biodiesel due to lower calorific value, higher density, higher viscosity and poor volatility of biodiesel and its blends as compared to diesel fuel.

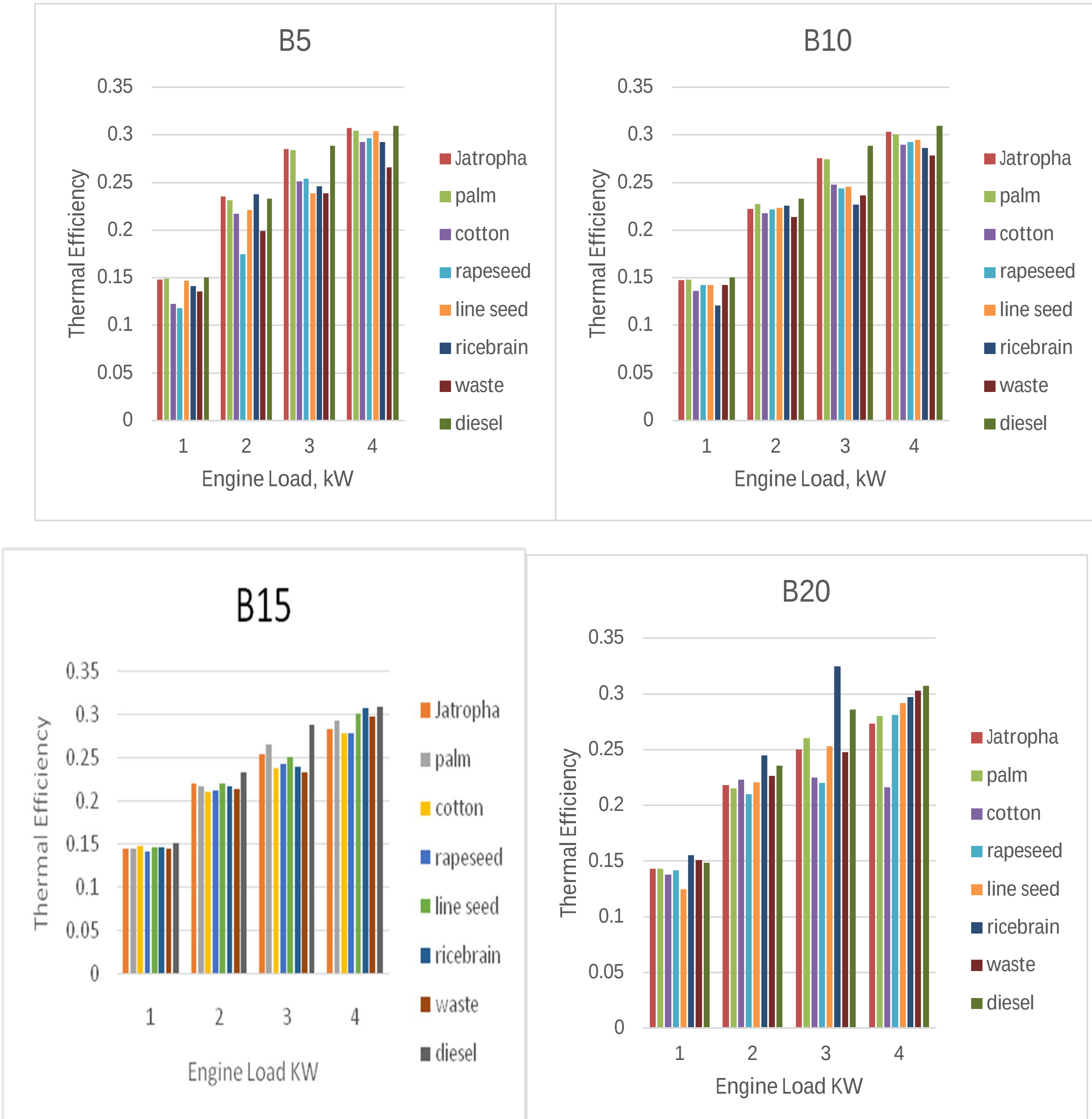

Fig.3. Variation of thermal efficiency with engine load for different fuels.

C. Variation of Exhaust Gas Temperature

The idea of measuring and comparing exhaust gas temperature is to understand the effective utilization of heat energy by the engine. Higher exhaust temperature indicates poor energy utilization by the engine, which in turn represents lower brake thermal efficiency [23]. The dependence of exhaust gas temperature for all tested fuels on load is shown in Fig. 4. Generally, this temperature increases upon increasing engine load. As can be noted from the Figure a higher exhaust gas temperature is recorded for biodiesel blends compared to fossil diesel for the entire engine load. This may be attributed to poor combustion characteristics and increased heat losses of biodiesel blends compared to diesel. This can be perceived by the brake thermal efficiency of the respective fuels.

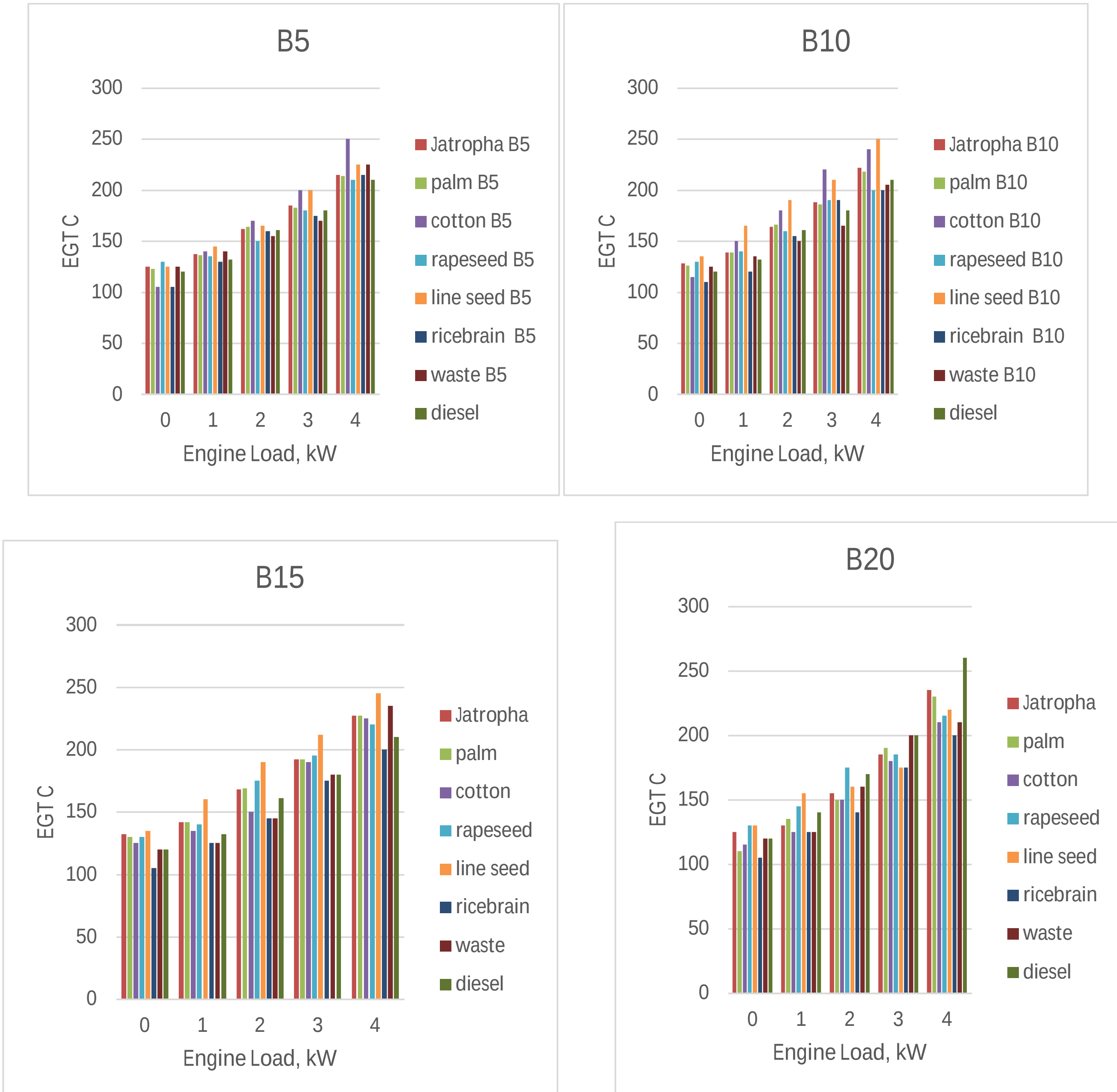

Fig.4. Variation of exhaust gas temperature versus engine load for different fuels.

D. Variation of Air-Fuel Ratio

The rate of decreasing Air/Fuel ratio for different fuels dependences on mass of fuel injected per cycle. Fig.5 shows variation of air-fuel ratio versus engine load for all tested fuels. Air-fuel ratio decreased for all tested fuels with the increase in engine load due to the increase in fuel consumption. Air- fuel ratios for diesel-biodiesel blends B5, B10, B15 and B20 were lower than that for diesel fuel for all engine loads this may be attributed to biodiesel fuels give fuel mass flow rate higher than diesel due to the high viscosity which reduces normal injection pump leakage enough to make a significant change in the volume discharged per stroke and also due to low heating value. This result were in consequence with that obtained by Kinoshitae et al. [24, 25].

Fig.5. Variation of Air-Fuel ratio with engine load for different fuels.

E. Variation of CO_2 Emission

CO_2 emissions corresponding to neat diesel and various biodiesel blends have been compared as shown in Fig. 6. CO_2 emissions were found to be higher for the biodiesel fuels as compared with the reference diesel. The engine fuelled with biodiesel emitted higher CO_2 emissions than diesel due to the lower carbon to hydrogen ratio and higher oxygen content in biodiesel blends [26].

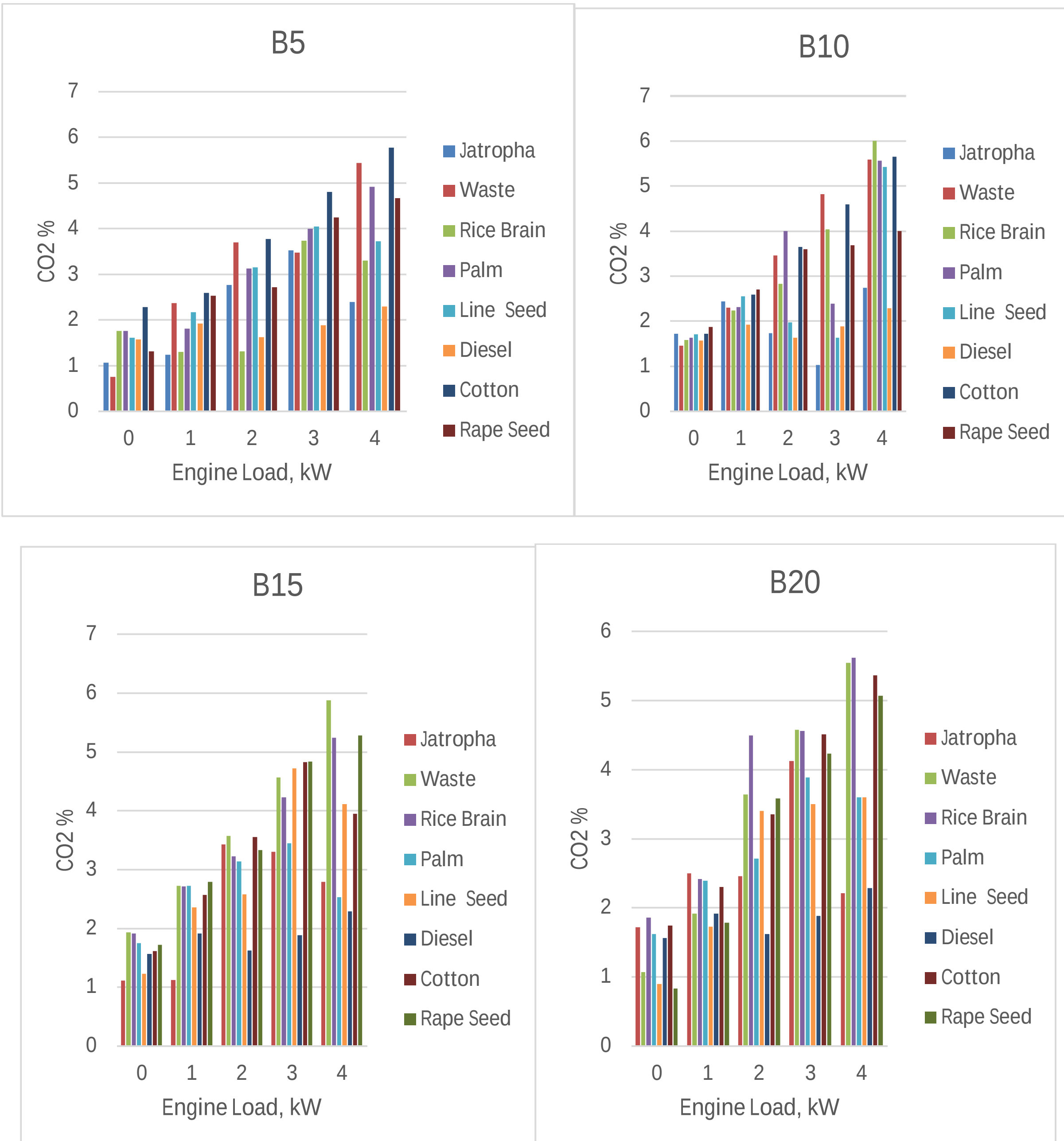

Fig.6. Variation of CO_2 emissions with engine loads for biodiesel blends.

F. Variation of CO Emission

Figure 7 shows the influence of brake power on carbon monoxide (CO) exhaust emissions expressed in percentage by volume for neat Diesel fuel, the bio-diesel blends of various origins. One can observe that the CO emitted by all bio-diesel blends of various origins is lower than that by the corresponding neat Diesel fuel case, with the reduction being higher the higher the percentage of the bio-diesel in the blend. The main reason for reduction of CO emissions can be attributed to the higher oxygen content and lower carbon content in the molecular structure of biodiesel blends as compared to petroleum diesel. The extra oxygen in the biodiesel promotes complete combustion of fuel and thus results in the reduction of CO emissions [27, 28]. It can be also seen when the biodiesel content increases, the CO emission is decreasing by an average of up to 25%. In any case, it should be reminded that the CO emitted levels in Diesel engines exhaust are small in absolute terms, so that they are of no real concern.

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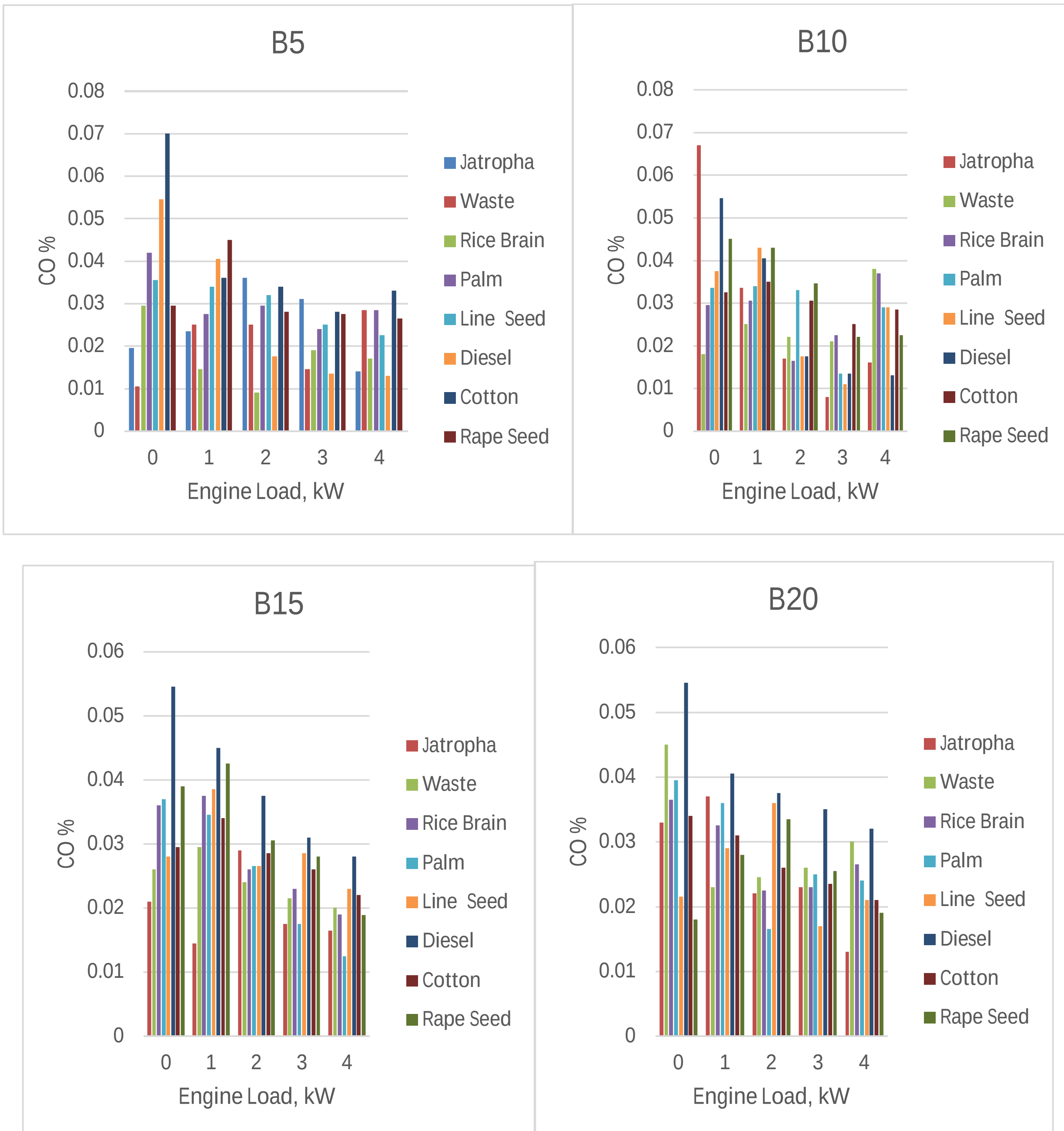

Fig.7. Variation of CO emissions with engine loads for different fuels.

G. Variation of NOx emissions

The effect of brake power on nitrogen oxides' emissions is shown in Fig. 8. In general, NOx (oxides of nitrogen) formation depends on temperature and presence of oxygen. It was observed that all biodiesel fuels have higher NOx concentrations than the reference fuel operation at all loads. The same was observed by other researchers [29, 30]. Presence of oxygen in the biodiesel was enhancing the combustion resulted in higher combustion temperature [38]. This was resulted in increased temperature in the combustion chamber motivated the NOx formation was more. Some researchers [31- 34] argue that the main cause of NOx increase with biodiesel use is the increased cetane number which leads to an advanced combustion by shortening the ignition delay and the higher availability of oxygen which in turn promotes NOx formation.

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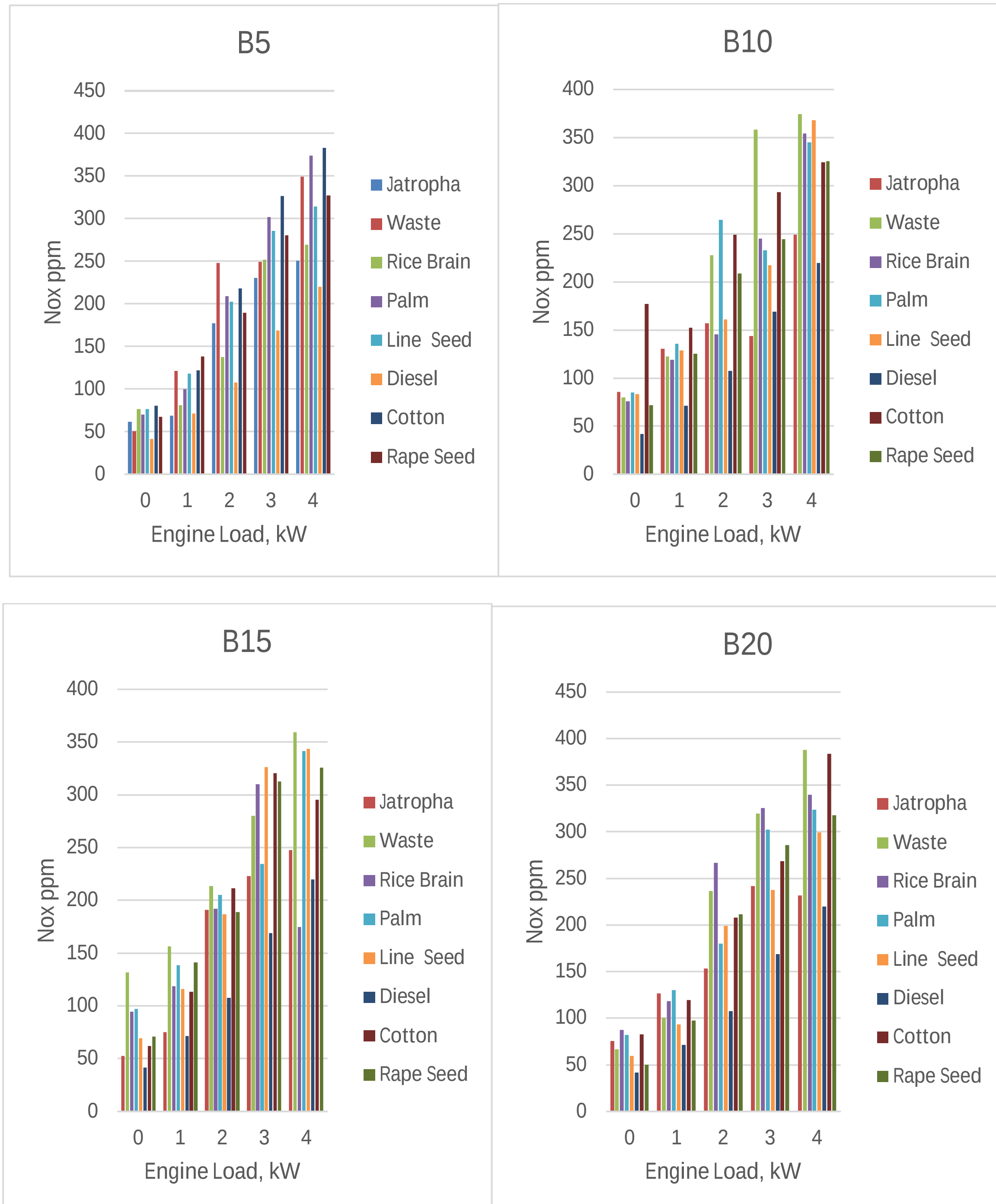

Fig.8. Variation of NOx emissions versus engine load for different fuels.

H. Variation of HC emission

Figure 9 shows the effect of brake power on HC (hydrocarbon) emissions for various biodiesel blends and diesel. The HC emissions were less compared to diesel fuel at all loads. The emissions increase as load increases for all fuels. The decreased trend of HC emissions compared to diesel might be by the help of the lower content of carbon to hydrogen ratio than the normal diesel and presence of up to 11% oxygen in its molecular structure. Many researchers [35, 36] have also reported that the engine fuelled with biodiesel could reduce the HC up to 67%.

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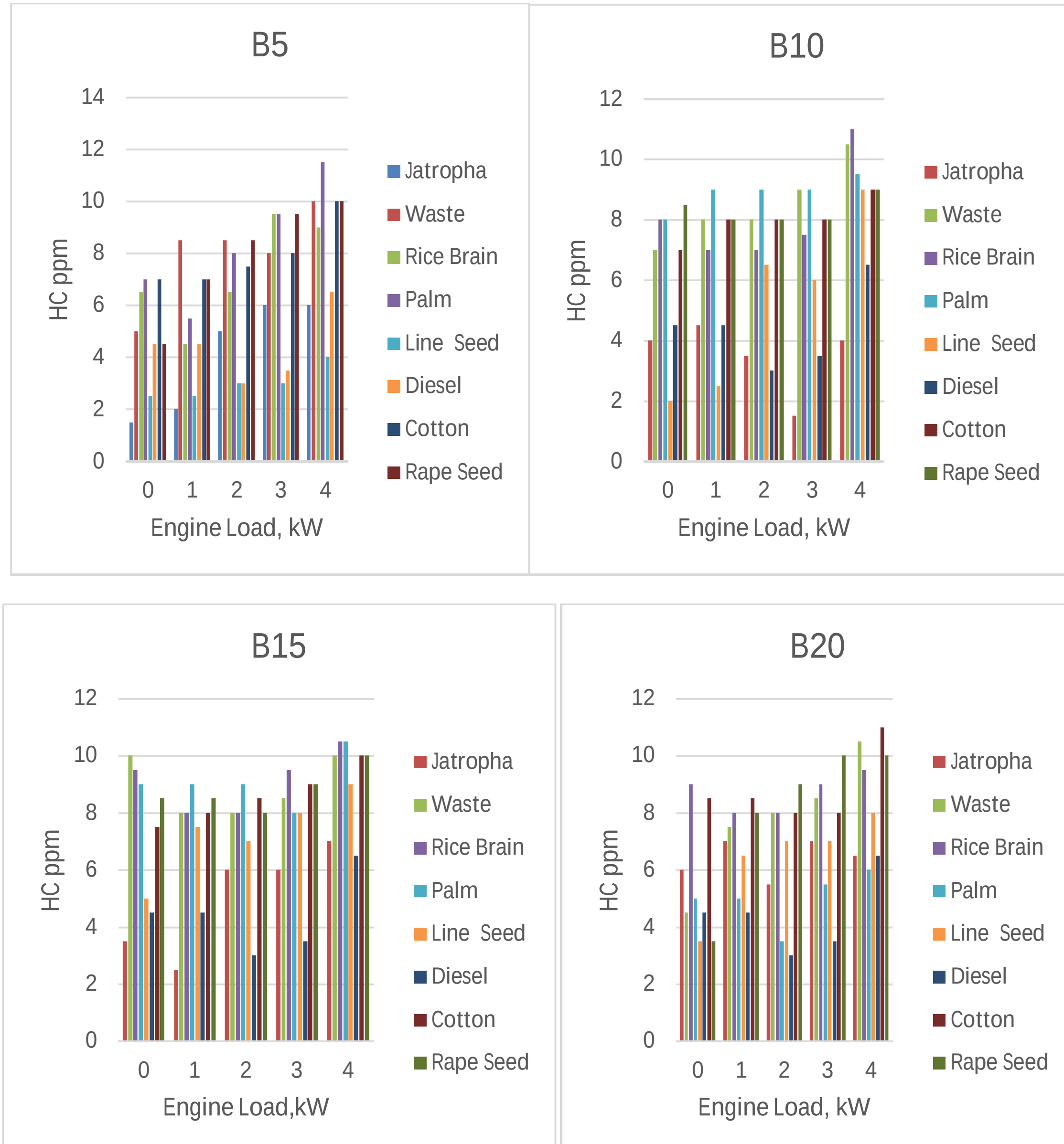

Fig.9. Variation of HC emissions with engine loads for different fuels.

I. Variation of smoke opacity emission

Smoke is the result of incomplete combustion and is formed in the rich mixture zone in the combustion chamber. Fig. 10 indicated, the smoke density measured in the exhaust emissions expressed in milligrams per cubic meter of exhaust gas for the neat Diesel fuel, the bio-diesel blends of various origins, with the organization of the bar diagram as referred to above at different engine loads. Smoke emission increased with the increase in engine output power due to the increase of fuel consumption. One can observe the smoke density was significantly increased with the use of bio-diesel blends of various origins with respect to that of the neat diesel fuel, this being higher the higher the percentage of bio-diesel in the blend. A higher smoke emission is probably due to higher viscosity of biodiesel blends. Presence of branched and ring structures in biodiesel fuel blends.

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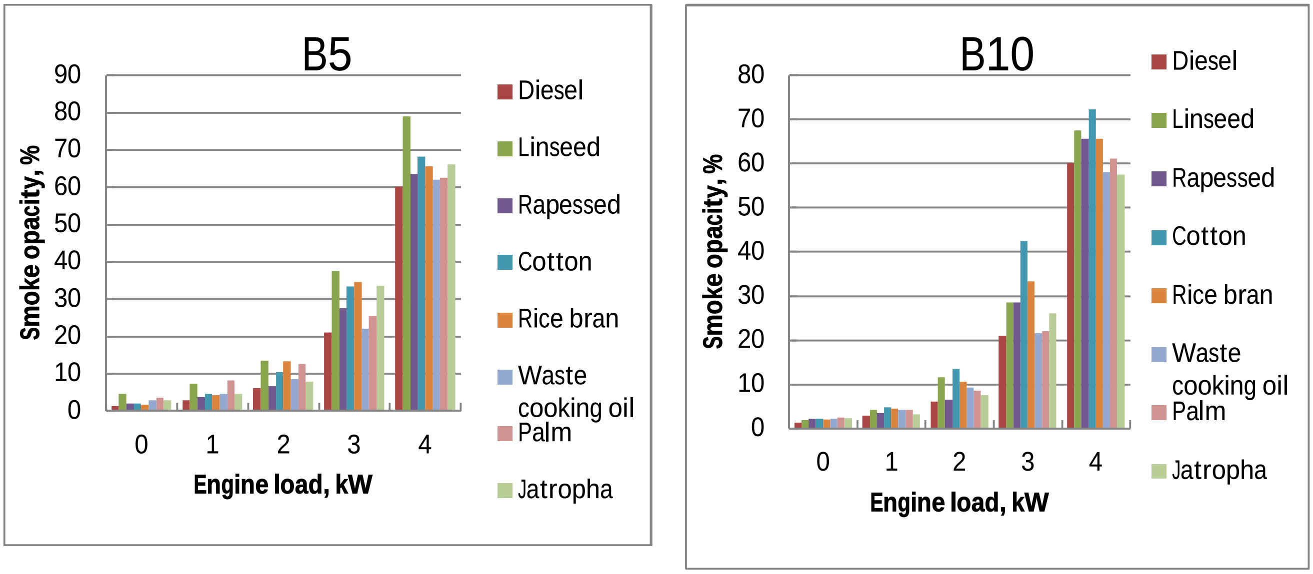
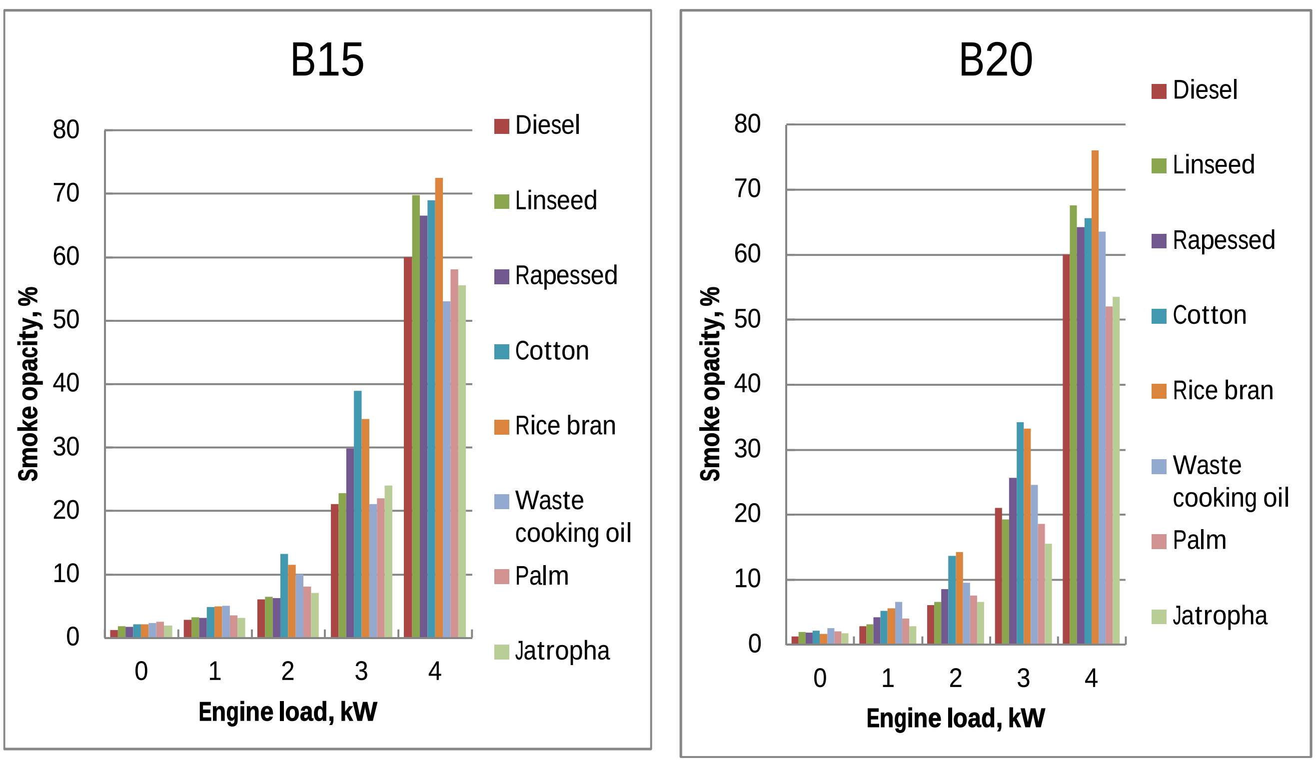


Fig.10. Variation of smoke opacity versus engine load for different fuels.



J. Variation of peak cylinder pressure

Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. Higher peak cylinder pressure and maximum rate of pressure rise correspond to large amount of fuel burnt in premixed combustion stage. Fig.11 shows the variation of peak cylinder pressure for different biodiesel blends compared to diesel at all engine loads. It can be seen that biodiesel blends recorded lower peak cylinder pressures and decreased as the percentages of biodiesel in the blends increases owing to the lower calorific values of biodiesel blends and higher viscosity and lower volatility of biodiesel blended fuels that lead to poor atomization and mixing with air.

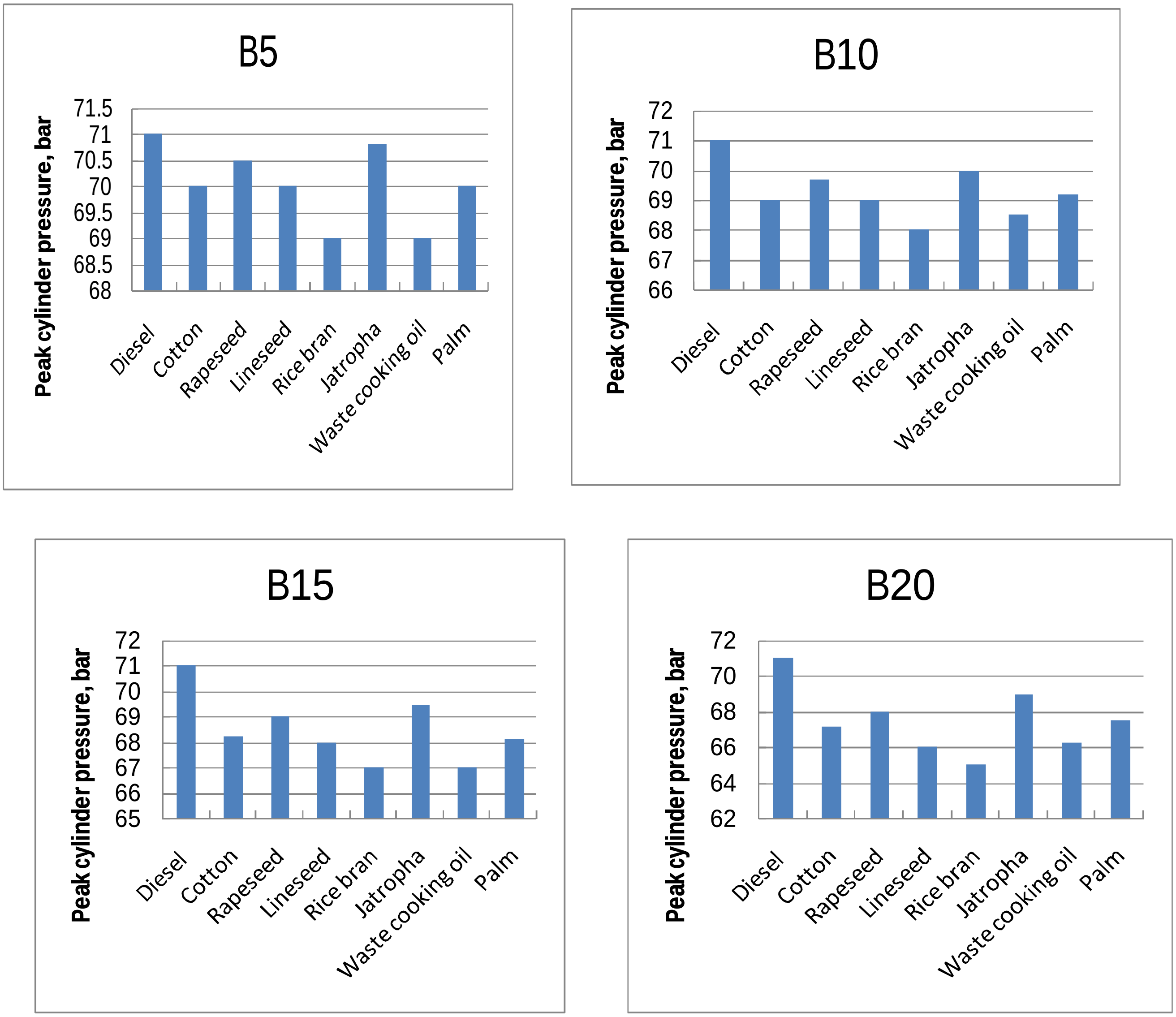


Fig.11.Variation of peak cylinder pressure for different biodiesel blends.

V. CONCLUSIONS

An extended experimental study is conducted to evaluate and compare the use of a high variety of vegetable oils or bio-diesels of various origins as supplements to conventional Diesel fuel at blend ratios of 5/95, 10/90, 15/5 and 20/80 in a direct injection (DI). The series of tests are conducted using each of the above fuel blends with the engine working at a speed of 1500 rpm and at different load. In each test, exhaust smokiness and exhaust regulated gas emissions, such as nitrogen oxides (NOx), carbon monoxide (CO) and unburned hydrocarbons (HC), are measured. Brake specific fuel consumption (BSFC) and brake thermal efficiency are computed from the measured fuel volumetric flow rate and calorific values. The differences in the measured performance and exhaust emission parameters from the baseline operation of the engine, i.e. when working with neat Diesel fuel, are determined and compared.

A. Increase of biodiesel concentration in biodiesel blends led to increase of density, kinematic viscosity, higher heating value and flash point.
B. BSFC values were higher when using the biodiesel fuels rather than the reference diesel.

C. The emission analyses of the CI engine running with biodiesel highlights a reduction in CO, smoke opacity and HC emission under working engine operation conditions. It is also found that when the biodiesel content increases a further reduction in emissions is observed owing to better combustion characteristics imparted by the higher oxygen content of the biodiesel fuels as compared to the reference diesel and the low carbon hydrogen ratio.

D. For all biodiesel contents the NOx and CO_2 emissions increases for all operating conditions of the CI engine. This increase may be explained by the higher oxygen content present in biodiesel and the advanced injection characteristics.

E. Biodiesel blends recorded lower peak cylinder pressures compared to diesel fuel at all engine loads. Peak cylinder pressures decreased as the percentages of biodiesel in the blends increased due to the lower calorific value of biodiesel blends and poor atomization.

F. Biodiesel from the different feedstock used in this study proved their potential as petroleum diesel substitute in terms of delivering similar engine performance and yielding lower exhaust emissions.

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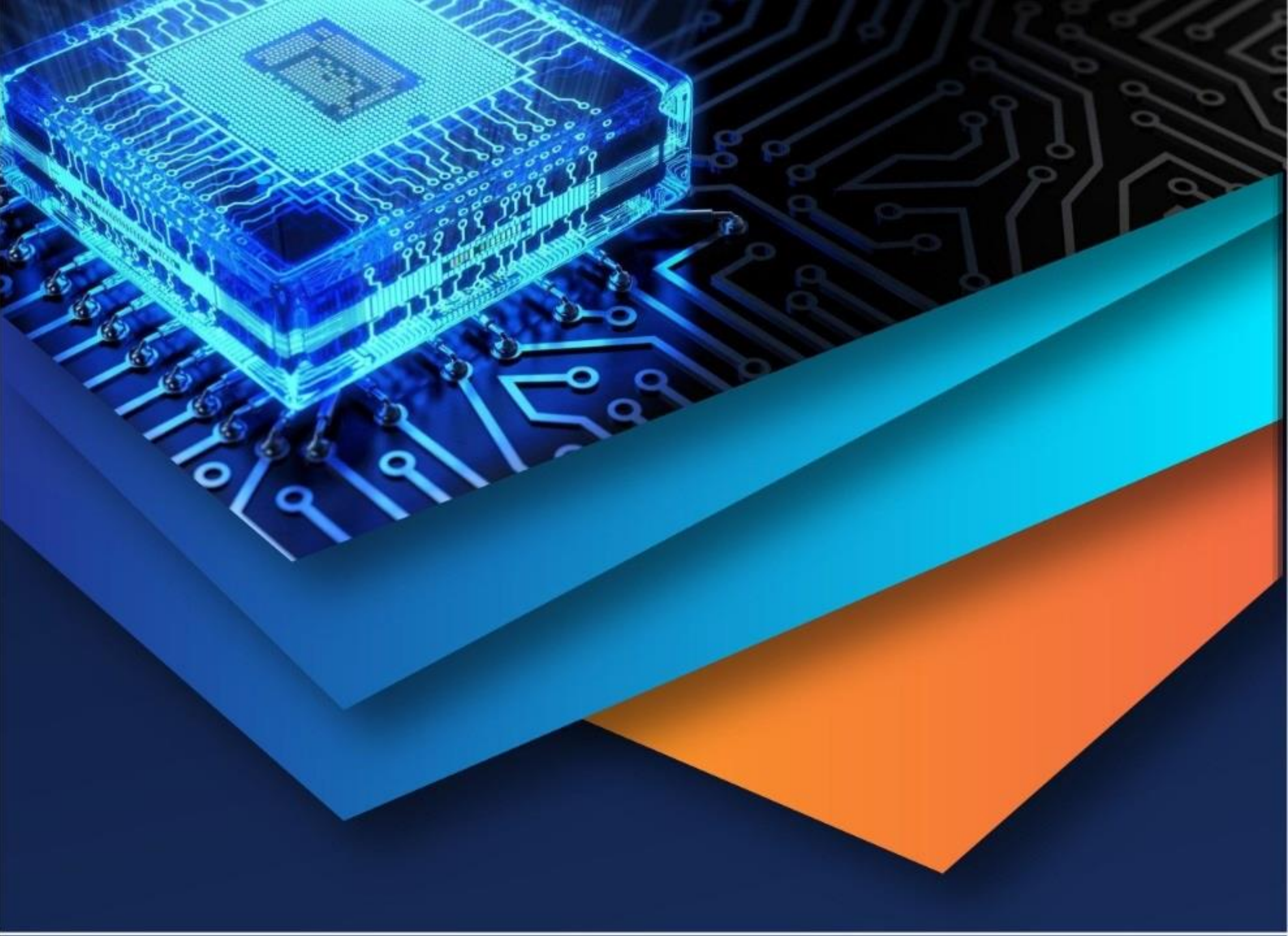

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