Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
e-ISSN: 2395-3454

Vol. 17 | No. 4 | pp. 1411-1418 | 2018

Original Research Paper | Open Access

Optimized Bio-Fuel Formulation by Taguchi's Approach and its Effect in DI CI Engine on the Performance and Emission Characteristics

Hariram V.*†, Godwin John J., Seralathan S.* and Micha Premkumar T.***

*Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Hindustan University, Chennai, Tamil Nadu, India

**Department of Automobile Engineering, Hindustan Institute of Technology and Science, Hindustan University, Chennai, Tamil Nadu, India

Corresponding author: Hariram V.

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 10-05-2018
Accepted: 11-06-2018

Key Words:
Biodiesel
Fuel stability
Taguchi's approach
Emission Characteristics

ABSTRACT

Use of biodiesel in compression ignition engine is widely recognized due to its reduced exhaust emissions, enhanced carbon dioxide cycle, less toxicity and improved safety. Biodiesel derived from vegetable and biological sources encompasses a substantial quantity of saturated FFA, which leads to increased kinematic viscosity. The present work aims at comparing the feasibility of using the methyl esters of cottonseed and alga (*Stoechospermum marginatum*) oil separately in a compression ignition engine. The bio-oils were transesterified through base catalysed transesterification using methanol and potassium hydroxide as catalyst. Addition of *n*-butanol up to 10% improves the physico-chemical properties of fuel, thereby promoting enhanced combustion. The test fuels were formulated on analysing their stability through Taguchi's approach in design of the experiments. The L_9 orthogonal array show cast a stable blend as mineral diesel 80%, biodiesel 20% and *n*-butanol oxygenate 10% for 21 days without precipitation. The performance and emission analysis of the test fuel blends showed higher brake thermal efficiency with lower brake specific energy consumption for algal biodiesel blends. The oxygenated blends of algal biodiesel emitted lesser carbon monoxide, hydrocarbons and smoke in comparison with cottonseed biodiesel.

INTRODUCTION

One of the important resources in the engine world is energy. The major sources that have been used for decades are fossil fuels like coal, petroleum, natural gas, etc. Usage of these sources has depleted the fossil fuels, whereas the global demand for the fuel has been increasing on a daily basis. A survey from the energy department has stated that the fuel energy available would last approximately fifty years. Usage of the non-renewable sources has also released enormous greenhouse gases, which affect the climatic conditions. Tremendous damage to the atmosphere due to the usage of non-renewable energy sources has given the pathway to the usage of renewable sources in the recent decades. Sustainable renewable energy resource is the major trend in research these days. Based on these terms, energy research has been started like on solar energy, wind energy, energy from biomass, etc. All this energy being proposed over the recent years, is not able to be on par with petroleum fuel. This gave a better reason for the development of liquid biofuels. Biodiesel is produced from the non-edible oil sources to meet the demand.

Sumprasit et al. (2016) investigated the energy recovery in the form of biodiesel from *Spirulina platensis* microalgae. Based on the study, proper cell disruption technique, organic solvent for lipid recovery and suitable catalyst for transesterification were used which gave better conversion of fatty acid methyl ester up to 79.5 %. Faried et al. (2017) studied the biodiesel production from microalgae. In order to have a better yield, initial cultivation conditions were considered most important since that has the highest possibility on lipid yield. Hence, the light, temperature for the growth and pH value of the water for the algal mass growth were kept strict. These conditions gave better oil yield, which on transesterification gave the biodiesel yield up to 84%. Shankar et al. (2017) have done research on biodiesel synthesis from cotton seed oil using homogeneous alkali catalyst and heterogeneous multi walled carbon nanotubes. Studying the characterization factors like temperature, alcohol to oil ratio, amount of alkali to be used and reaction time the process of conversion was done which yielded 95% biodiesel. Srinivasarao et al. (2015) studied the *Pongamia pinnata* oil conversion to biodiesel and its working characteristics. Considering the free fatty acid value >2% acid esterification and base transesterification were performed. Base catalyst used was KOH 1% by weight and molar ratio of 6:1, these conditions gave better biodiesel yield of 84%. Also, it is noticeable that KOH reacts better than NaOH. Chen et al. (2018) have performed research on the algal biodiesel production. The potential of algal biodiesel was verified based on the fuel properties which have detailed closer values mentioning that algae can be a better source for biodiesel production. Simikic et al. (2018) studied the influence of biodiesel on the performance in stationary and non-stationary conditions of farm tractors. This study revealed the fact that use of biodiesel reduced the engine power and increased the fuel consumption. Thermal efficiency of the engine slightly got increased on using biodiesel blends. Islam et al. (2017) reviewed many studies to understand the future needs for engine performance by using algal biodiesel. It is revealed in the study that usage of algal biodiesel slightly increases the fuel consumption but a better thermal efficiency is possible. It is mentioned that selecting algal biodiesel will have greater impact in fuel quality and engine performance.

Alloune et al. (2017) have investigated the performance, combustion and emission characteristics using *Citrullus colocynthis* L. methyl ester. It was clearly stated that usage of cent per cent biodiesel increased the brake specific fuel consumption and increased the brake thermal efficiency. Madiwale et al. (2018) studied the performance analysis of diesel engine fuelled with four different biodiesel such as jatropha, soybean, palm and cottonseed using ethanol as an additive. The investigations revealed the effect of adding ethanol which improved the brake power, and increased BSFC and the brake thermal efficiency. Sakthivel et al. (2017) reviewed the properties, performance and emission aspects of third generation biodiesel. Their study revealed the fact that usage of third generation biodiesel reduced the pollutants like CO, UBHC and PM. Increasing trend was noticed in BSFC and NO_x emission. Suresh et al. (2016) studied the biodiesel production from waste cooking oil and its performance and emission characteristics. The BTE of WCCO 10 was reported to be 26.64% for maximum load. The usage of blend has reported reduction in CO and HC emissions. Al-Samaraae et al. (2017) investigated the safflower biodiesel's engine performance and emission characteristics. The research investigation reported that there was reduction in engine brake power, torque, CO and HC emission. Slight increase was seen in BSFE and NO_x emission. Vijay Kumar et al. (2017) have reviewed many research studies and reported that adding additives to the biodiesel improves the combustion, performance and emission reduction.

In this research work, the oil is recovered from vegetable oil and non-vegetable oil which was selected based on its fuel properties being closer to the diesel fuel. Based on the free fatty acid content being less than 2%, base catalysed transesterification was considered for biodiesel conversion. The main objective of the research was to improve the performance and emission reduction of the biodiesel.

Fig. 1(A): Cottonseed and recovered oil (B). Algal biomass and recovered oil.

SOURCE AND BIO-OIL RECOVERY

Fig. 1(A) shows the cottonseed oil extracted from the cottonseed. The oil extraction from the cottonseed was carried out by mechanical pressing/mortar and pestle method and then the solvent extraction is performed to remove the complete oil from the seeds. Since the oil recovered from the extraction had FFA content less than 2%, acid esterification is not required. Base transesterification was carried out using potassium hydroxide and methanol. The solution prepared was kept in agitation at 450 rpm and at the temperature of 65°C. Later the prepared solution is kept in a separating funnel for two days to check the visible ring formation. This method yielded the methyl ester of cottonseed oil up to 94%. Fig. 1(B) shows the oil recovered and extracted from the *Stoechospermum marginatum* biomass collected from the intertidal zone in Mandapam, Tamil Nadu. The collected biomass was dried first in an oven for an hour and then in atmospheric air for a day. Then the dried content was pulverized to powder having the size less than 1.5 mm. Using *n*-hexane as the extraction solvent in the Soxhlet apparatus, bio-oil was extracted. To remove all the *n*-hexane, it was heated until it got evaporated. Same transesterification method was followed as that of cottonseed oil. The oil extracted from the algal biomass on transesterification yielded 94% of algal oil methyl ester.

FUEL FORMULATION

Mineral diesel, cotton seed biodiesel and algal biodiesel are the test fuels that were used in this research. To utilize the renewable energy on volume basis, biodiesel of 20% is blended with mineral diesel. There is no need for the modification in engine if the blend of biodiesel is up to 20%. Further, to improve the combustion, performance and emission characteristics, oxygenated additive was added to the diesel-biodiesel blend. The test fuels prepared for this study are shown in Fig. 2. Cottonseed oil and algal biodiesel source was selected because the physico-chemical properties were very close to the diesel fuel property. Using calibrated equipment's fuel blends were tested for its fuel properties having ASTM D6751 as the standard. Table 1 represents the Taguchi table. Fuel formulation was done using the diesel fuel, biodiesel and oxygenated additive. Taguchi method using orthogonal arrays was used to formulate the stability of fuel blends. Orthogonal array table was used to carry out the various fuel concentrations to lessen the number of experiments to be conducted. Diesel, biodiesel and oxygenate concentration were optimized in Table 2. DOE method using orthogonal array of four parameters and three levels was implemented. Table 2 depicts the L^9 orthogonal array for oxygenated fuel formulation. The stability of the blends was tested in terms of fortnight weeks for the above mentioned sets of experiments. Experiment number 5 was stable for three weeks without precipitation. All the other experiments were stable only for a week, whereas experiment number 3 and 9 got precipitated within a week. Based on

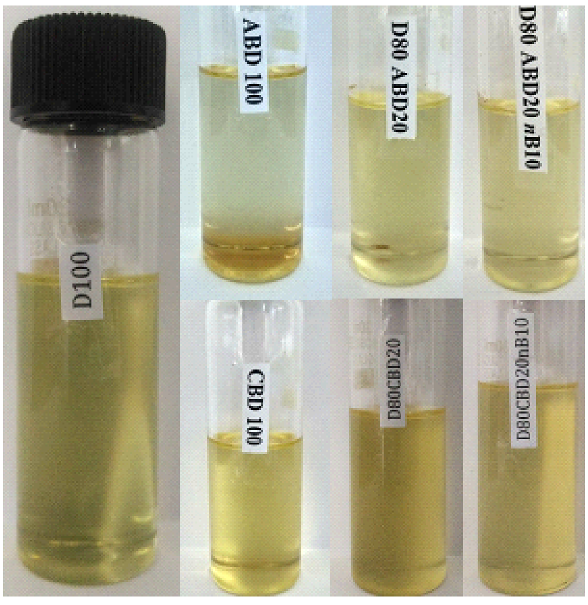

Fig. 2: Test fuels used in engines.

Table 1: Taguchi Table for $L_9 3^4$.

Parameters	Concentration Level 1 [L1]	Concentration Level 2 [L2]	Concentration Level 3 [L3]
Diesel	70	80	90
Biodiesel	10	20	30
Oxygenate additive	2	6	10

the stability, 80% diesel fuel, 20% biodiesel and 10% *n*-butanol blend were taken for the engine testing.

The density of CBD and ABD were 885 kg/m^3 and 865 kg/m^3 respectively which are 3.95% and 1.73% higher than mineral diesel. By adding 20 parts of biodiesel methyl ester to the mineral diesel, the density and kinematic viscosity were higher than diesel.

Adding the oxygenate, *n*-butanol to these blends has decreased the viscous nature. This viscous behaviour of the blend with oxygenates, helps in improving the performance and emission characteristics. A decrease in calorific value is noticed for both the biodiesel at 6.8% and 16.2% in comparison to mineral diesel. Adding *n*-butanol to these blends increased the calorific value by improving the energy release. Cetane number represents the combustion behaviour as it fastens the reaction. Higher the cetane number, lesser the ignition delay which ensures better combustion. Flash points of the biodiesel have ensured better storage of the fuel (ABD 100-114°C, CBD 100-150°C), which was higher than mineral diesel as shown in Table 3.

Kirloskar 240PE engine is used to perform the experiments and its schematic layout is shown in Fig. 3. Water cooled engine and its bore and stroke length is 87.5 and 110 mm respectively. For all operating conditions compression ratio is kept constant as 17.5:1 and 23° bTDC injection timing. Eddy current water cooled dynamometer was coupled with engine to load the engine. Strain gauge type load cell sensor was used to measure the load applied using the digital load indicator having a range of 0 to 50 kg. 3.5kW rated power engine having constant speed of 1500 rpm was installed on the automated facility which signals the controls to NI USB-6210 data acquisition device. Cylinder pressure was measured by SM111A22 piezo sensor which has a range of 5000 psi. To locate the top dead centre position and crank angle degree of the engine rotation, high precision Kubler make 8.3700.1321.0360 crank angle encoder was utilized. Orifice meter attached to the manometer measured the mass flow rate of air. Fuel flow transmitter measures the fuel flow. The engine speed was found by the crank angle sensor. Engine soft analysis software documents all the performance and emission details in a computer system. Table 4 represents the engine specifications.

Table 2: L_9 orthogonal array fuel formulation.

Experiment No.	Diesel	Biodiesel	Oxygenated Additive	Variable Not specified	Stability (in days)
1	70	10	2	0	5
2	70	20	6	0	7
3	70	30	10	0	3
4	80	10	6	0	5
5	80	20	10	0	21
6	80	30	2	0	6
7	90	10	10	0	9
8	90	20	2	0	5
9	90	30	6	0	3

Table 3: Test fuel properties.

S. No.	Properties	D100	ABD 100	CBD 100	D80 ABD20	D80 CBD20	D80 ABD20*n* B10	D80 CBD20*n* B10	ASTM D6751
1.	Density @15°C (kg/m³)	850	865	885	853	857	849	852	860-900
2.	Kinematic Viscosity @40°C (mm²/s)	2.6	4	4.3	2.9	3.1	2.3	2.4	3.5-5.0
3.	Calorific Value (kJ/kg)	44800	41750	37500	44190	43340	43178	42405	-
4.	Cetane Number	46	53	52	47	46	49	48	47-51
5.	Flash point (°C)	64	114	150	74	81	71	77	101-130
6.	Oxygen content	-	10	8	-	-	-	-	2.5-12

Table 4: Test engine specification.

Model	Kirloskar 240 PE Engine
Bore and stroke	87.5 × 110 mm
Compression ratio	17.5 : 1
Crank angle sensor	Model 8.3700.1321.0360-Kubler Germany with dia: 37mm, Resolution: 1degree
Data acquisition device	NI USB-6210, 16-bit, 250kS/s.
Dynamometer Arm Length	185 mm
Dynamometer type	Eddy current water cooled
Fuel Type	Diesel
Load indicator	Digital, Range 0-50kg, Supply 230VAC
Load sensor	Load cell, type strain gauge, range 0-50kg
Make/No of cylinders	Kirloskar/1
Piezo sensor	SM111A22 - PCB Piezotronics make, Range 5000 psi, Diaphragm stainless steel type and hermetic sealed with built-in PCB charge amplifier 422E55
Rated power	3.5KW @ 1500 rpm
Rated speed	1500 rpm
Software	"Engine Soft" Engine performance analysis software
Start of Injection Timing	23° bTDC
Swept volume	661.45 cc

RESULTS AND DISCUSSION

The performance and emission characteristics of the algal biodiesel, cottonseed biodiesel and their blend with oxygenated additives are discussed here. The performance characteristics brake thermal efficiency, brake specific energy consumption, CO, HC, smoke and NO_x emission are discussed clearly based on the results obtained on operating the compression ignition engine with the constant speed of 1500 rpm, 17.5:1 compression ratio and injection timing of 23°bTDC.

Fig. 4(A) represents the brake thermal efficiency of D80CBD20, D80CBD20*n*B10, CBD 100 and diesel fuel with respect to BMEP. It is noticeable from the graph that during lower load and medium load, diesel fuel has the high-

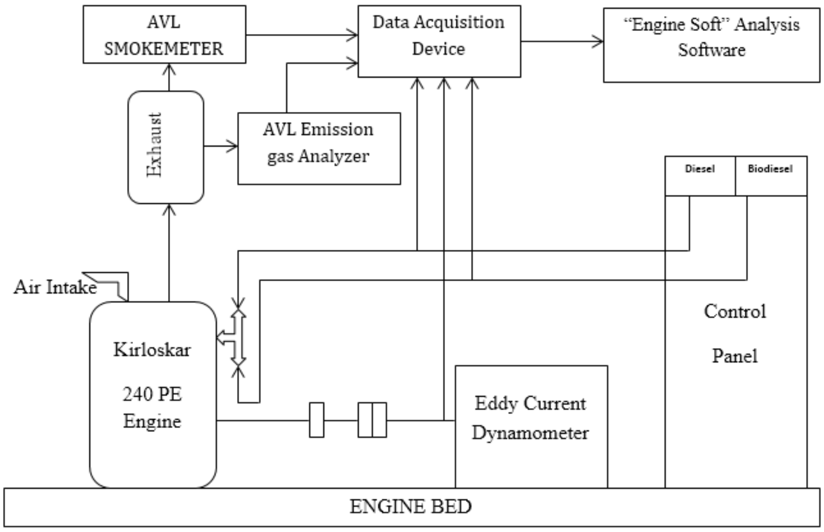

Fig. 3: Test engine schematic diagram.

est brake thermal efficiency. This might be due to less viscosity of diesel fuel which allows better atomization. This leads to better combustion and higher thermal efficiency. During higher loads generally it is noted that thermal efficiency is higher due to the high essence of reach of temperature. But, it is notable that D80CBD20*n*B10 showed the highest BTE at higher load which may be due to the addition of oxygenated additive which leads to better combustion due to the presence of excess oxygen than usual content. From the Fig. 4(B) it can be noted that BTE of algal biodiesel and its blend along with oxygenated additive has higher thermal efficiency than cottonseed biodiesel. This may be due to the higher oxygen content than cottonseed biodiesel which leads to complete combustion. Also the viscosity of algal biodiesel was noted to be lesser than cottonseed biodiesel which might have led to proper atomization leading to good combustion. The highest BTE was noted to be 34.26% by D80ABD20*n*B10.

Fig. 4(C) depicts the brake specific energy consumption of cottonseed biodiesel, its blend along with its oxygenated additive, and diesel fuel with respective to BMEP. From the plot it is clear that diesel has the lowest BSEC during low and medium loads. This may be due to the higher calorific value of the diesel fuel. Since CBD 100 has the lowest calorific value the energy consumption is very high. During higher load, D80CBD20*n*B10 detailed the lowest BSEC, this may be due to closer value of calorific value to diesel fuel and also at higher loads the temperature will be high which leads to better combustion. Fig. 4(D) depicts the BSEC versus BMEP of D100, D80ABD20, D80ABD20*n*B10, and ABD 100. The lowest BSEC was reported by D80ABD20*n*B10 as 13.86 MJ/kWh. This may be due to the higher cetane number which leads to shortest ignition delay displaying better combustion with appropriate amount of fuel.

Performance analysis

Emission analysis: Fig. 5(A) represents the CO emission of cottonseed biodiesel, its blend along with oxygenated additive, and diesel fuel. From the graph it is clear that diesel fuel has the highest CO emission factor, this may be due to the unavailability of oxygen content in the diesel fuel. It is in decreasing trend from lower to higher loads which may be due to the lower ignition delay at higher engine loads. It is noted that CBD100 has the lowest CO emission because of the higher oxygen content which helps in the conversion of CO to CO_2. At the highest BMEP it was found that CO emission of CBD100 tends to increase which may be due to less time for the complete combustion. Fig. 5(B) represents the algal biodiesel, its blend, its oxygenated additive and diesel fuel with respect to BMEP. Similar trend was noticed in algal biodiesel blends and oxygenated additive, but with comparably lesser emission. The lowest CO emission was noted as 0.08% by D80ABD20*n*B10.

Fig. 5(C) represents the unburnt hydrocarbon emissions of cottonseed biodiesel and its blend. The same for algal biodiesel is represented by Fig. 5(D). Diesel fuel detailed the highest UBHC emission, this may be due to improper combustion and lesser oxygen content in the diesel fuel. As the biodiesel and its blend are used, the fuel burns completely inside the combustion chamber which reduces the UBHC emission drastically. As the oxygenated additive are added to the blend, the oxygen content increases more, improving the complete combustion, which reduces the

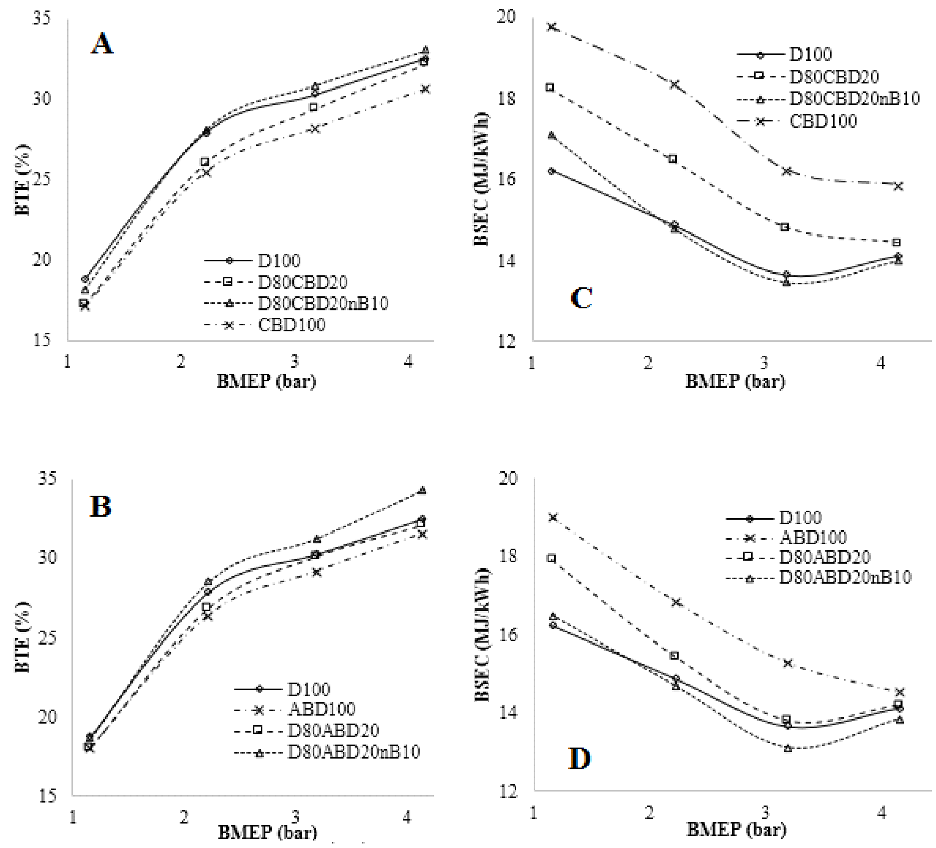

Fig. 4: Variation in BTE for CBD (A, B) and ABD (C, D).

unburnt emissions. The lowest emission was detailed by ABD100 during lower and medium loads which may be due to the higher cetane number, whereas at highest load, oxygenated blend reported the lowest UBHC as 35.8 ppm.

Fig. 5(E) represents the smoke emission of cottonseed biodiesel, its blend along with its oxygenated additive and diesel fuel. The effect of adding biodiesel to the diesel fuel, details the reduction of smoke opacity. Increased oxygen content in additive, improves the complete combustion in the diesel-biodiesel-oxygenated additive blend which diminishes the smoke percentage more than diesel-biodiesel blend. Algal biodiesel and its blends along with oxygenated additives smoke emission is represented in Fig. 5(F). It can be noted that adding *n*-butanol to the diesel-biodiesel blend, higher evaporation rate, shorter ignition delay and improved ignition characteristics reducing the smoke emission. The lowest emission at highest BMEP was detailed by ABD 100 as 2% (Godwin et al. 2017).

NO_x emission occurs due to various conditions like higher temperature, response time, fuel properties, engine design and operating conditions. Fig. 6(A) depicts the variation in oxides of nitrogen of cottonseed biodiesel, its blend and oxygenated additive with respect to BMEP at various load conditions, whereas the same for algal biodiesel is depicted in the Fig. 6(B). Adding biodiesel to the diesel fuel increased the oxides of nitrogen because of the oxygen content present in it. Adding *n*-butanol to the blend gives better combustion and higher heat release rates. Algal biodiesel has higher oxygen content than cottonseed biodiesel, which on adding more oxygenated additive to the blend shows the highest oxides of nitrogen emission. Highest NO_x emission was detailed by oxygenated additive blends D80CBD20*n*B10 as 1231 ppm and D80ABD20*n*B10 as 1258 ppm.

CONCLUSIONS

The conclusions for this research were made based on the oil recovery, transesterification, various performance and emission characteristics.

- Oil recovered from the cottonseed and algal biomass was transesterified by means of base catalysed transesterification as the FFA content was < 2%. Con-

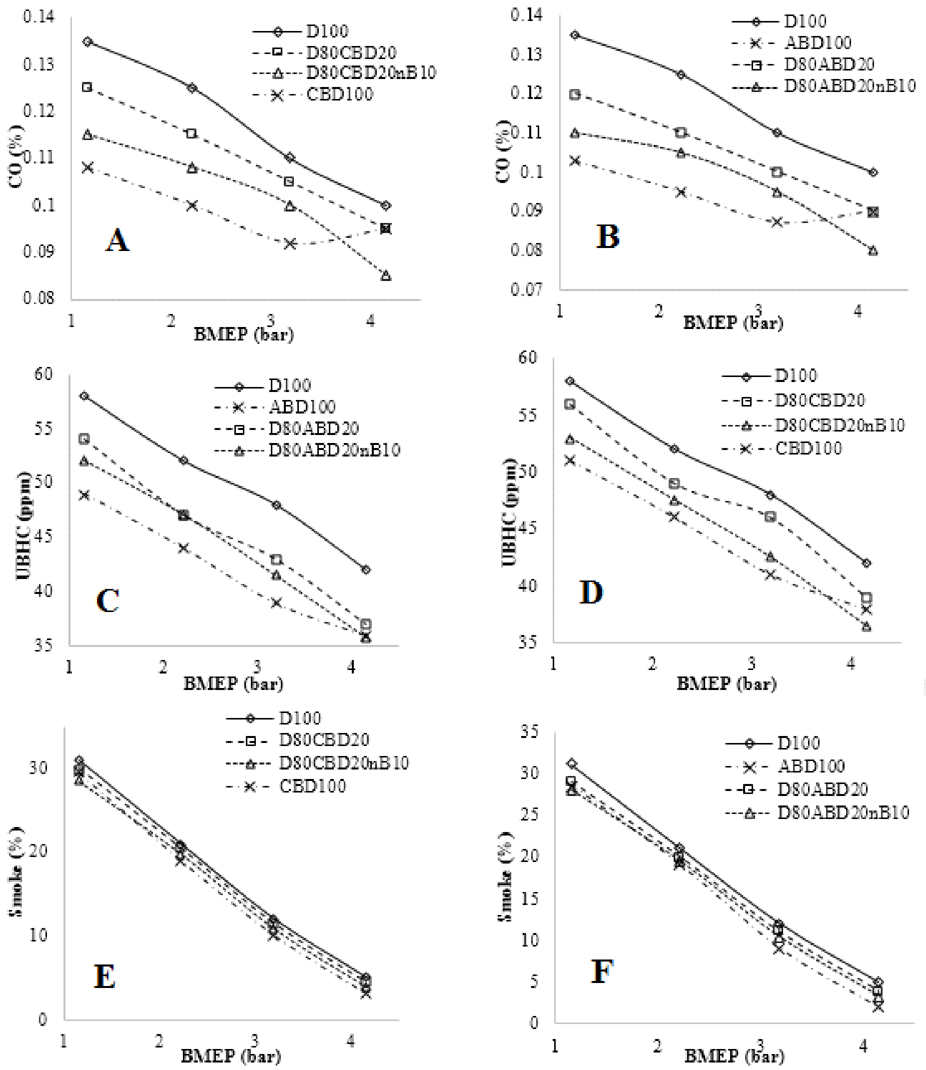

Fig. 5: Variation in CO, UBHC and smoke for CBD and ABD.

version of oil to methyl ester yielded 94% biodiesel.

- Test fuels formulation was performed by means of Taguchi method which detailed the better blend concentration as 80% diesel, 20% biodiesel and 10% oxygenated additive, which had the stability for three weeks without any precipitation.
- Brake thermal efficiency depicted that diesel had higher BTE than biodiesel and diesel-biodiesel blend which may be due to the lower viscosity of diesel fuel. The highest BTE % was detailed by oxygenated blend, whereas comparing cottonseed and algal oxygenated blend D80ABD20*n*B10 depicted 34.26%.
- As the biodiesel was added to the mineral diesel, the brake specific energy consumption increased, this may be due to the lower calorific value of biodiesel. Highest BSEC was reported by cent percentage biodiesel fuel which may be due to lowest calorific value, whereas lowest BSEC was depicted by oxygenated blend which may be due to the higher cetane number improving the combustion. The lowest BSEC was reported by D80 ABD 20*n*B10 as 13.86 MJ/kWh.
- Diesel fuel showed the higher CO emission which may be due to the absence of oxygen content in diesel fuel. Adding biodiesel to the diesel fuel reduced the CO emission. The lowest CO emission was noted as 0.08% reported by D80ABD20*n*B10 which may be due to the presence of more oxygen.

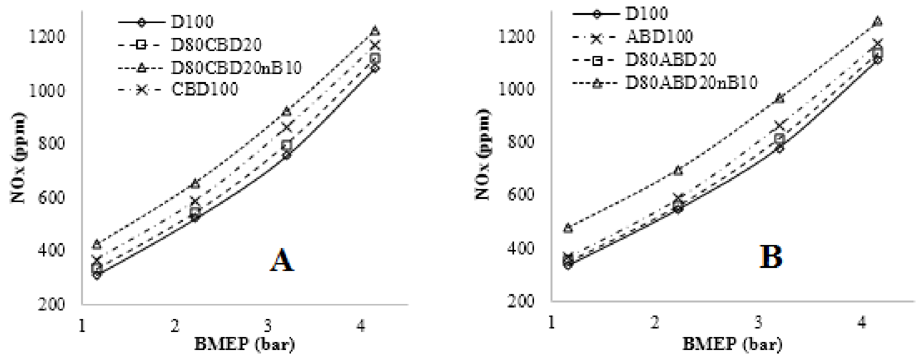

Fig. 6: Variation in NO_x for CBD and ABD.

- Diesel fuel detailed the highest UBHC emission, this may be due to improper combustion and lesser oxygen content in the diesel fuel. The lowest emission was detailed by ABD100 during lower and medium loads, which may be due to the higher cetane number, whereas at highest load, oxygenated blend reported the lowest UBHC as 35.8 ppm.
- Adding oxygenated additive *n*-butanol to the diesel-biodiesel blend, higher evaporation rate, shorter ignition delay and improved ignition characteristics reducing the smoke emission were observed. The lowest emission at highest BMEP was detailed by ABD 100 as 2%.
- General trend of NO_x emission was detailed in this research that adding biodiesel increased the oxides of nitrogen emission which may be due to the presence of oxygen, enhancing the better combustion which increases NO_x. Highest NO_x emission was detailed by oxygenated additive blends D80CBD20*n*B10 as 1231 ppm and D80ABD20*n*B10 as 1258 ppm.

REFERENCES

Alloune, R., Balistrou, M., Awad, S., Loubar, K., and Tazerout, M. 2017. Performance, combustion and exhaust emissions characteristics investigation using Citrullus colocynthis L. biodiesel in DI diesel engine. Journal of the Energy Institute, 1-11.

Al-Samaraae, R.R., Atabani, A.E., Uguz, G., Kumar, G., Arpa, O., Ayanoglu, A., Mohammed, M.N. and Farouk, H. 2017. Perspective of safflower (*Carthamus tinctorius*) as a potential biodiesel feedstock in Turkey: characterization, engine performance and emissions analyses of butanol-biodiesel-diesel blends. Biofuels, pp. 1-17.

Chen, J., Li, J., Dong, W., Zhang, X., Tyagi, R.D., Drogui, P. and Surampalli, R.Y. 2018. The potential of microalgae in biodiesel production. Renewable and Sustainable Energy Reviews, 90: 336-346.

Faried, M., Samer, M., Abdelsalam, E., Yousef, R.S., Attia, Y.A. and Ali, A.S. 2017. Biodiesel production from microalgae: Processes, technologies and recent advancements. Renewable and Sustainable Energy Reviews, 79: 893-913.

Godwin, John, Hariram Venkatesan and Seralathan Sivamani 2017. Emission reduction using improved fuel properties of algal biodiesel and its blends. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 40(1): 45-53.

Islam, M.A., Heimann, K. and Brown, R.J. 2017. Microalgae biodiesel: Current status and future needs for engine performance and emissions. Renewable and Sustainable Energy Reviews, 79: 1160-1170.

Madiwale, S., Karthikeyan, A. and Bhojwani, V. 2018. Properties investigation and performance analysis of a diesel engine fuelled with jatropha, soybean, palm and cottonseed biodiesel using ethanol as an additive. Materials Today: Proceedings, 5: 657-664.

Sumprasit, N., Wagle, N., Glanpracha, N. and Annachhatre, A.P. 2017. Biodiesel and biogas recovery from *Spirulina platensis*. International Biodeterioration & Biodegradation, 119: 196-204.

Sakthivel, R., Ramesh, K., Purnachandran, R. and Mohamed Shameer, P. 2017. A review on the properties, performance and emission aspects of the third generation biodiesels. Renewable and Sustainable Energy Reviews, 82(3): 2970-2992.

Simikic, M., Tomic, M., Savin, L., Micic, R., Ivanisevic, I. and Ivanisevic, M. 2018. Influence of biodiesel on the performances of farm tractors: Experimental testing in stationary and non-stationary conditions. Renewable Energy, 121: 677-687.

Shankar, A.A., Pentapati, P.R. and Prasad, R.K. 2017. Biodiesel synthesis from cottonseed oil using homogeneous alkali catalyst and using heterogeneous multi walled carbon nanotubes: Characterization and blending studies. Egyptian Journal of Petroleum, 26(1): 125-133.

Srinivasarao, M. and Anand, R.B. 2015. Production characterization and working characteristics in DICI engine of *Pongamia* biodiesel. Ecotoxicology and Environmental Safety, 121: 16-21.

Suresh, S., Sinha, D. and Murugavelh, S. 2016. Biodiesel production from waste cotton seed oil: Engine performance and emission characteristics. Biofuels, 7(6): 689-698.

Vijay Kumar, M., VeereshBabu, A. and Ravi Kumar 2018. The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine. Alexandria Engineering Journal, 57: 509-516.