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A COMPARATIVE STUDY OF MULTI RESPONSE PERFORMANCE INDEX (MRPI) BASED OPTIMISATION TECHNIQUES FOR CI ENGINE PERFORMANCE AND EXHAUST EMISSION WITH WASTE COOKING OIL (WCO) BIODIESEL

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ABSTRACT

Biodiesel has been found to be a novel solution over the conventional fuel because of its non-toxic, ecofriendly and renewable nature. The principal component of vegetable oils or animal fats are triglycerides which on cooking coverts to free fatty acids (FFA). Repeated use of cooking oil increases the FFA content. Waste Cooking Oil (WCO) having high FFA is not suitable for consumption and also for open dumping because of its non-biodegradable and toxic nature. Being very easily available and cheap, WCO can be put in to use for synthesis of biodiesel in a sustainable and cost-efficient way. Here in this work, a comparison of results of two different multi-response optimisation based techniques, viz, Assignment of Weight and DEAR (Data Envelopment Analysis Based Ranking) has been carried out with WCO derived biodiesel in blended form in CI engine for its Performance and Exhaust Emission study. In this work Blend (BXX), Load (in kg), Compression ratio and EGR (in %) were taken as controlling factors each at three different levels i.e., low, medium and high. Similarly BP in kW, BTE in % and BSFC in kg/kWh were considered as responses for performance whereas CO, HC and NOx (all in ppm) were considered as responses for exhaust emission. The results of both the optimisation techniques were compared and then validated. The Multi Response Performance Index (MRPI) calculated in each of the techniques gave similar common excellent operating conditions. The 10% biodiesel diesel blend exhibited common optimal condition for engine performance and exhaust emittance at 12 kg load with compression ratio 17:1 and EGR at 15%.The results were further validated using average performance and average signal-to-noise ratio(S/N) graph for both techniques. Moreover it was also validated through separately developed regression models based on MRPI in both the cases with the help of MINITAB-21 statistical software. From the MRPI based ANOVA done in both the cases using the same software, engine load is the crucial factor followed by biodiesel diesel blend percentage, compression ratio and EGR (%).

Keywords: WCO, Assignment of Weight, DEAR, MRPI, ANOVA.

1. INTRODUCTION

In this era of modernization, the demand for fossil fuel for energy applications is growing exponentially. The majority of energy demand is met by traditional energy sources such as coal, petroleum, and natural gas (NG). However, these fuels have a finite supply that is concentrated in only few places throughout the world. With the growing consumption, these resources are rapidly becoming extinct. Also the gradual increasing pollution created by the fossil fuels has become a burning issue in case of the sustainability of the environment. Thus the large-scale exhaustion of non-renewable energy sources has caused society to face a significant energy crisis and environmental disruptions.

But the global need for energy continues to rise. Due to this limitation, renewable energy sources have become increasingly appealing. Alternative fuels are the most practical option to fulfill this expanding need. They will not only fulfill the increasing demand but also reduce carbon footprint.

Biofuels, specifically biodiesel, is one such fuel with a lot of promise. Biodiesel has been demonstrated to be the most effective fossil fuel alternative. Because being renewable, biodegradable and non-toxic, it outperforms petroleum-based fuels [1]**.** Biodiesel is an inexhaustible and eco-friendly substitute to conventional hydrocarbon-based fuels, obtained from different vegetable oils and animal fats. Waste cooking oil (WCO) is another prominent feedstock for FAME (Fatty acid methyl ester) synthesis because of its easy accessibility, low price and potential to reduce environmental pollution associated with improper disposal [2]. With the over and again use of WCO its free fatty acid (FFA) content increases which is not found to be hygienic so far the sound physical health and longevity of a person is concerned. So instead of spilling and digesting the WCO can be put in to use for production of biodiesel. Generally transesterification process is mainly employed in many cases for synthesis of biodiesel from its feedstock. This biodiesel production method is simple and user friendly. But, in case of large number of productions, it kills both time and cost. So, to obtain the optimal setting by statistical process for producing biodiesel economically at its highest yield is always being a very much need for any commercial or industrial applications. Similarly the statistical process optimisation for getting the optimal setting of running the CI engine with the biodiesel blended oil is also very much needed for attaining its high performance and less exhaust emission [3, 4].

While producing biodiesel from raw vegetable oil or WCO in alkaline or acidic condition on commercial basis, *Y.Zhang et al. [2003]* in their study reviewed four different continuing process flow sheets. Their analysis on technical advantages and constraints showed that alkali-catalysed method using virgin vegetable oil needs comparatively less number of concerned instruments but requires relatively costly raw materials than the other processes. So, the application of WCO for the biodiesel production reduces the cost of raw material. It was also proved that with WCO as feedstock, the acid-catalysed process being more practical with less complication compared to alkali-catalysed process and hence can be recommended as a better challenging alternative [5]. *Zlatica J. Predojevic and Biljana D. Škrbic [2009]* in their work performed transesterification reaction on fried oil. The cleaning of the resulting mixture was carried out using one of three techniques: washing it with silica gel, 5% phosphoric acid, or hot distilled water. In the study, a highest yield of 92% was obtained with the first two techniques whereas the lowest yield of 89% was achieved with the third one. It was because of excessive washing to attain neutral pH, indicating that these treatments are preferable for the refining of crude methyl esters synthesized by the two-step alkali transesterification reaction of unused frying oils [6]. An another investigation of transesterification of WCO to FAME using base-catalytic and supercritical methanol methods done by *Ayhan Demirbas [2010]* explored the influence of controlling factors on biodiesel production and properties, highlighting the challenging prospect of WCO as a feedstock [7]. *Saydut A. et al [2010]* compared the transesterification based synthesis from refined sunflower oil and WCO, carried out at reaction temperature of 60℃ and alcohol to oil molar ratio of 6:1. Both were found to have a greater effect on yield. Sodium hydroxide proved to be more productive and economical compared to potassium hydroxide. While testing on common CI engine, biodiesel made from used cooking oil resulted in higher engine performance and fewer emissions [8]. *A.B.M.S. Hossain and A.M. Al-Saif [2010]* studied the FAME synthesis from waste soybean oil and pure soybean oil as feedstock. In the study it was experienced that there is no significant difference in biodiesel yield using both the feedstock. In regard of the alcohol used in the transesterification method, the maximum production was attained with methanol followed by ethanol and 1-butanol. The optimum reaction condition was found to be 1:6 oil-to-methanol molar ratio, 1% wt. KOH and 40^0 C reaction temperature. The work showed that waste cooking soybean oil can be used as a generous source of biodiesel employed as fuel in blended mode for diesel engines [9]. A review was carried out by *M.C. Math [2010]* on the earlier work done for biodiesel production through different transesterification technologies from WCO. Their fuel properties were studied and matched with petro-diesel. The paper also presented the FAME specifications proposed by different countries. An acid-catalysed transesterification process proved to be highly fruitful when the FFA content of feedstock is greater than 1 wt. %. Although, the high catalyst concentration and molar ratio needed in this method leads to corrosion problems. In order to overcome the problem of low solubility of methanol in oils a new technology (Biox process) was developed. For stabilisation of the methanol the process used a co-solvent [10]. *Ganesh L. Maddikeri et.al.[2012]* reviewed the prospective use of WCO as a cost-effective source for biodiesel and also the benefits and limitations of transesterification reaction. To get rid of the deactivation of the catalyst by the impurities and problem faced in separation of pure products, pretreatment was found to be most essential. Here, in the feedstock preparation, the different concerned physical and chemical pretreatment methods were needed to remove the fatty acids and other contaminants. The application of cosolvent in transesterification process changes its heterogeneous nature to a homogeneous phase with an increase in biodiesel yield. Hydrodynamic cavitation reactors were found to have very high energy efficiency among the different process intensifying approaches. They suggested that fried cooking oil produced biodiesel could be applied in diesel engines without any significant engine modification. With the application of affordable and inexpensive source like WCO and process-intensifying techniques, the processing cost of biodiesel can be decreased significantly [11]. *Zahira Yaakob et.al.[2013]* studied a comprehensive overview of the pre-treatment and the usage of WCO for the synthesis of FAME by using several methods, different type of reactors, alcohol and catalyst. This paper revealed transesterification as an efficient and cost-effective amongst the most widely used processes for biodiesel production. The paper also deals with the purification and the study of the produced biodiesel, process control factors and several economic issues. From the results it was found that to eliminate solid impurities and reduce FFA and water contents, WCO requires several pre-treatment steps. In pre-treatment process washing stage, centrifugation, flash evaporation, and acid esterification are included. Several types of catalyst have been applied extensively for esterification reaction such as homogeneous catalyst (acidic and basic), heterogeneous catalyst (acidic and basic), enzymes. It was known that base homogeneous catalyst face a large challenge in terms of the FFA and water contents in the oil. Methanol is applied in the reaction because of its obtainability, high activity and low price [12]. *M. Rakib Uddin et.al. [2013]* analysed the biodiesel synthesis from WCO by three-step method and also carried out a regression analysis of the process. Diluted sodium hydroxide solution was used for saponification in this method. The optimum molar ratio for saponification by aqueous sodium hydroxide was 1:2 oil to NaOH and reaction time was 2 hrs at 100°C.In acidification and esterification different ratios were being chosen. For finding out the optimum conditions for esterification reaction a factorial design was applied. From the result it was found that at optimum conditions 99.06% conversion of the FFA to FAME was obtained with its viscosity and yield of 3.29 mm^2/s and 79% wt/wt respectively. The produced biodiesel behaved nearly as the petro-diesel. They suggested that WCO produced biodiesel here can be efficiently used with petro-diesel in blended form [13]. While dealing with a diesel plant of a fast food restaurant in Dhaka, *Md Ehsan and Md T. H. Chowdhury [2014]* investigated the technical possibilities and economy of biodiesel synthesis using alkaline-based catalyst from WCO. This reuse of the used oil can fulfil the extra necessity of diesel as well as enhance the net profit of the concern. Generally CH_3OH (methanol) and NaOH (sodium hydroxide) as base catalyst are preferred due to their low cost and high yield. Single stage transesterification (SST) process is found to be most economical and user friendly amongst different processes. The study also showed that WCO available at the fast food restaurants at nearly no cost and used for biodiesel production does not make any sense if otherwise the cost associated with proper dumping of the WCO is taken care of [14]. *N.H Said et. al. (2015)* reviewed the different heterogeneous solid catalysts in biodiesel production through the transesterification of WCO. Solid catalysts with the reaction aggregate are found to be non-corrosive resulting in a green and environmentally friendly process. It was economically beneficial because of its ability of recycling and repeated uses. Hence using heterogeneous catalyst in the transesterification process for the production of FAME using WCO as a raw material is becoming more popular and attractive [15]. The high FFA content of WCO creates a lot of obstacles in deriving biodiesel from it. In this regard *Sahar et al. [2018]* tried esterification of WCO using different acid catalysts (HCl, H_2SO_4 and H_3PO_4) and H_2SO_4 catalysed reaction was proved to be the most efficient since the FFA reduced up to 88.8% at 60^0 C with 1:2.5 methanol to oil molar ratio. Alkali catalyst KOH was applied in the process and 94% yield of FAME was obtained in the presence of 1% catalyst at 50^0C [16]. *Gurunathan Manikandan et al. [2023]* presented a review work to discover WCO as biodiesel feedstock. The paper focuses on the WCO related health issue and potential of WCO as biodiesel for revenue generation. The study also explored emission of less pollutant in the exhaust up to a 20% of biodiesel blending with diesel without major modifications to the engine. Presently in India, only an inadequate 0.13% of total comestible oil ingestion is used as WCO source for FAME generation. A techno-economic analysis was carried out to discover the feasibility of generating 1 litre of FAME. Life cycle assessment (LCA) was proved to be a compulsory and crucial activity in assessing the influence of WCO biodiesel on socio-economic and green environment. In addition exergy analysis will deliver adequate facts about the generation and validation of WCO as a biodiesel [17].

2. METHODOLOGY

The waste cooking oil for this work was collected from a college canteen. It was derived from fried refined oil which was used for papad frying. The oil was filtered for solid impurities by using filter paper. After that, different requisite physico-chemical properties of the oil were found out based on ASTM methods as shown in the Table 1. The experimental reactions were done in a batch stirred reactor through Transesterification. Here Methanol was chosen as the reactant alcohol whereas KOH was applied as the alkali catalyst because of its capability to catalyze at low temperature and also having high yield rate and relatively low price.

Table1 Determination of ASTM based properties of WCO [2, 9]

Properties	Units	ASTM Test method	Obtained values of WCO
Density at 15^{0}C	kg/m^3	D1298	912.78
Kinematic viscosity @ 40^{0}C	cSt	D445	32.45
Saponification number	mgKOH-g^{-1}	D5558	14.025
Iodine Value	g Iodine/g of sample	D5554	31.876
FFA content	%	D974	0.561

After production of the biodiesel, three blends of the biodiesel i.e., B0, B10 and B20 were prepared by blending with petro-diesel. Here the natural diesel being considered as B0, the blends B10 and B20 were prepared mixing respectively 10% and 20% biodiesel with natural diesel. Table 2 displays different properties of the WCO derived biodiesel based on ASTM methods.

Table 2 Determination of ASTM based properties of biodiesel derived from WCO [2, 9]

Properties	Units	Biodiesel		Obtained values of WCO biodiesel
		Test method ASTM D6751	Limits	
Density at 15^{0}C	kg/m^3	D941	860 - 900	895
Kinematic viscosity @ 40^{0}C	cSt	D445	1.9 - 6	4.35
Calorific value	MJ/kg	D240	35-41	39.72
Flash point	^{0}C	D93	>130	168.4
Fire point	^{0}C	D6751	176	178.8
Poor point	^{0}C	D97	-4 to -1	-1
Cloud point	^{0}C	D2500	-3 to 15	3
Cetane number	-	D613	>47	51

2.1 Engine Specification

After the production of FAME and preparing its mixtures with petro-diesel, it was tested in a Compression Ignition Engine. The test rig was equipped with a single cylinder, 4-stroke, CRDI VCR Engine with the facility of EGR and open ECU. The engine specifications are shown in Table 3.

Table 3 C.I Engine Test Rig Specification (Source: ASTU Energy Lab)

Make	Kirloskar
Product code	244
Type	Single cylinder, 4-stroke, Water cooled, Constant speed
Rated power	3.5 kW @ 1500 rpm
Compression ratio	12:1 to 18:1
Cylinder diameter	87.5 mm
Stroke length	110 mm
Common rail	With pressure sensor and pressure regulating valve
EGR	SS, Water cooled
Piezo sensor	Make PCB USA, Combustion: Range 350 Bar with low noise cable
Fuel tank	Capacity = 15 lit. Type: Dual compartment, with fuel metering Pipe of glass
Calorimeter	Pipe in pipe
Software	“Enginesoft” Engine performance analysis software
Pump	Make Kirloskar, Type Monoblock
Overall dimension	W 2000 mm x D 2500 mm x H 1500 mm
Sensor for emission detection	Emission Analyzer, Make- Testo, Germany

In the experiment for monitoring and measuring the exhaust emission CO, HC and NOx (all in ppm), Testo-350 Exhaust Gas Analyser was used. VCR Engine Test Rig with data acquisition system has been shown in Fig.1 whereas Testo-350 exhaust emission gas analyser with its sensor probe inside the exhaust pipe have been shown in Fig.2and Fig.3 respectively.

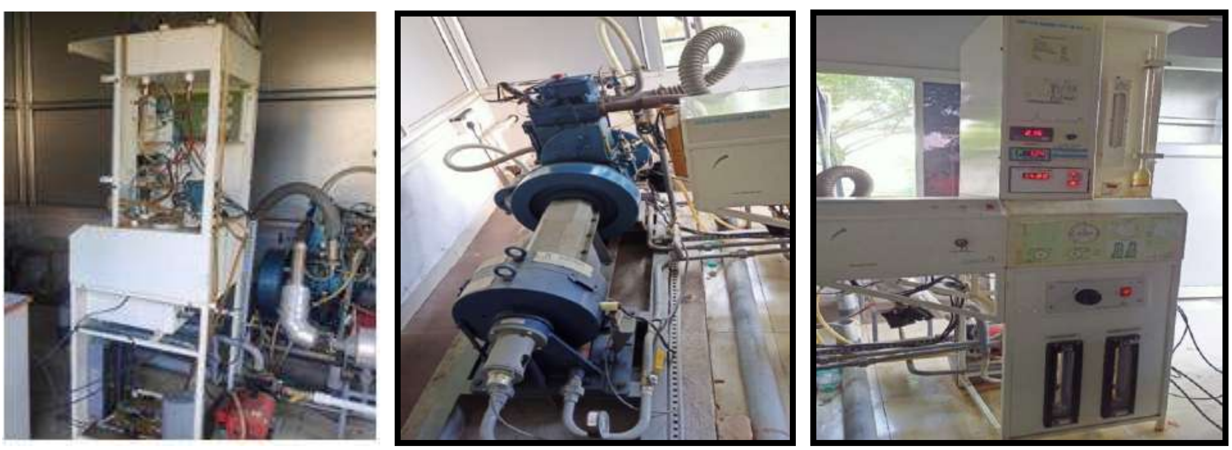

Fig. 1 VCR Engine Test Rig with data acquisition system (Source: ASTU Energy Lab)

Fig. 2 Testo-350 exhaust emission gas analyser (Source: ASTU Energy Lab)

Fig. 3 Sensor probe inside the exhaust pipe (Source: ASTU Energy Lab)

2.2 Strategy for Design of Experiment:

Any engineering process has always some definite outcomes controlled by some parameters or factors. In the design of experiment these factors are categorized in some definite levels such as low, medium and high. Finally the optimal setting of the factors with their concerned levels is determined using different process optimization processes. The controlling factors considered in this work have been shown in Table 4 with their respective levels.

Table 4 Control Factors with respective levels

Control Factors	**Levels**		
	1	2	3
Blend (A)	B0	B10	B20
Load in kg (B)	3	7	12
Compression ratio (C)	16:1	17:1	18:1
EGR (%) (D)	5	10	15

After the selection of the factors with their levels, the tests or experimental runs are arranged with different unbiased setting of the factor levels. In Taguchi's design of experiment, these experimental runs or treatment conditions (TC) are specially designed according to an arrangement called Taguchi's Orthogonal Array (OA). Here, prior to the practical runs a particular OA is selected based on the degrees of freedom for all the process controlling factors. In this work L_9 has been selected as the concerned OA for running the experiments and accordingly the data were collected as shown in the following Table 5 [18].

Table 5 Responses of treatment conditions

TC	Control Factors				Responses					
	Blend (A)	Load (kg) (B)	Comp. ratio (C)	EGR (%) (D)	BP (kW)	BTE (%)	BSFC (kg/kW-hr)	CO (ppm)	HC (ppm)	NOx (ppm)
1	B0	3	16:1	5	0.88	8.73	0.91	205	502	26
2	B0	7	17:1	10	1.99	13.72	0.55	242	423	55
3	B0	12	18:1	15	3.34	13.97	0.49	452	910	75
4	B10	3	17:1	15	0.87	13.69	0.57	180	435	38
5	B10	7	18:1	5	2.00	13.47	0.58	200	420	58
6	B10	12	16:1	10	3.52	15.17	0.51	320	882	78
7	B20	3	18:1	10	0.89	7.79	1.07	152	387	42
8	B20	7	16:1	15	2.05	11.36	0.74	183	392	61
9	B20	12	17:1	5	3.44	15.01	0.56	292	773	85

2.3 DATA ANALYSIS:

2.3.1 (a) Analysis based on Assignment of Weights technique:

In this technique the concerned weights are determined according to the nature of quality characteristics for the responses, such as larger-the- better, smaller-the-better, nominal-the- best etc. Here, the responses like Brake power and BTE follow larger-the better, whereas the responses Brake Specific Fuel Consumption , Carbon Monoxide, unburnt Hydrocarbons and NO_X follow smaller-the better and the weights are determined accordingly. For larger-the-better characteristics the individual response (data) is divided by the total response whereas for smaller-the-better characteristics the reverse normalization procedure is applied. The Multi Response Performance Index values for different treatment conditions are then determined using Eq (i) as follows: [18]

$$(MRPI)_i = W_1Y_{11} + W_2Y_{12} + \ldots\ldots + W_jY_{ij} \quad \text{Eq (i)}$$

Where $(MRPI)_i$= MRPI of the i^{th} treatment condition

W_j=Weight of the j^{th} response/dependent variable

Y_{ij}= Observed data of i^{th} treatment condition under j^{th} response

The MRPI for different treatment conditions have been calculated from the above relations stepwise as shown in Table-6(a), (b), (c) and (d).

Table 6 (a) Treatment condition wise weights for Engine Performance

TC	BP (kW)	W_{BP}	BTE (%)	W_{BTE}	BSFC (kg/kWh)	1/BSFC	W_{BSFC}
1	0.88	0.04636	8.73	0.07732	0.91	1.09890	0.0759
2	1.99	0.10485	13.72	0.12151	0.55	1.81818	0.1257
3	3.34	0.17597	13.97	0.12373	0.49	2.04082	0.1410
4	0.87	0.04584	13.69	0.12125	0.57	1.75439	0.1213
5	2.00	0.10537	13.47	0.11930	0.58	1.72414	0.1192

6	3.52	0.18546	15.17	0.13435	0.51	1.96078	0.1355
7	0.89	0.04689	7.79	0.06899	1.07	0.93458	0.0646
8	2.05	0.10801	11.36	0.10061	0.74	1.35135	0.0934
9	3.44	0.18124	15.01	0.13294	0.56	1.78571	0.1234
	ΣBP_i=18.98		Σ BTE $_{i}$= 112.91			Σ1/BSFC $_{i}$= 14.46885	

Table 6 (b) Treatment condition wise weights for Engine Exhaust Emission

TC	CO (ppm)	1/CO	W_{CO}	HC (ppm)	1/HC	W_{HC}	NOx (ppm)	1/NO_x	W_{NOx}
1	205	0.00488	0.1208	502	0.00199	0.11256	26	0.03846	0.21569
2	242	0.00413	0.1024	423	0.00236	0.13358	55	0.01818	0.10196
3	452	0.00221	0.0548	910	0.00110	0.06209	75	0.01333	0.07477
4	180	0.00556	0.1376	435	0.00230	0.12990	38	0.02632	0.14757
5	200	0.00500	0.1239	420	0.00238	0.13454	58	0.01724	0.09669
6	320	0.00313	0.0774	882	0.00113	0.06407	78	0.01282	0.07190
7	152	0.00658	0.1630	387	0.00258	0.14601	42	0.02381	0.13352
8	183	0.00546	0.1354	392	0.00255	0.14415	61	0.01639	0.09193
9	292	0.00342	0.0848	773	0.00129	0.07310	85	0.01176	0.06597
		$\Sigma 1/CO_i$= 0.04037			$\Sigma 1/HC_i$= 0.01770			$\Sigma 1/NO_{xi}$ = 0.17832	

Table 6(c) Treatment condition wise MRPI in Assignment of Weights technique

BP*W_{BP}	BTE* W_{BTE}	BSFC*W_{BSFC}	CO*W_{CO}	HC*W_{HC}	NO_x*W_{NOx}	MRPI
P	Q	R	S	T	U	=P+Q+R+S+T+U
0.04080	0.67499	0.069069	24.7640	56.5051	5.6079	87.66875
0.20865	1.66715	0.069135	24.7808	56.5043	5.6078	88.82877
0.58776	1.72846	0.069090	24.7696	56.5019	5.6078	89.26919
0.03988	1.65987	0.069141	24.7680	56.5065	5.6077	88.65272
0.21075	1.60695	0.069136	24.7800	56.5068	5.6080	88.77067
0.65281	2.03816	0.069105	24.7680	56.5097	5.6082	89.64394
0.04173	0.53746	0.069122	24.7760	56.5059	5.6078	87.53215
0.22142	1.14294	0.069116	24.7782	56.5068	5.6077	88.31733
0.62348	1.99540	0.069104	24.7620	56.5063	5.6075	89.57184

Table 6 (d) Treatment Condition Wise MRPI for L_9 Orthogonal Array in Assignment of Weights technique

TC	Factors				MRPI
	A	B	C	D	
1	1	1	1	1	87.66875
2	1	2	2	2	88.82877
3	1	3	3	3	89.26919
4	2	1	2	3	88.65272
5	2	2	3	1	88.77067
6	2	3	1	2	89.64394
7	3	1	3	2	87.53215

8	3	2	1	3	88.31733
9	3	3	2	1	89.57184

The level totals of different factors are obtained using the data in the Table 6(d) and shown in Table 7.

Table 7 Level totals of MRPI in Assignment of Weights technique

Control Factors	**Level Totals of MRPI**		
	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Blend (A)	88.589	***89.022***	88.474
Load in kg (B)	87.951	88.639	***89.495***
Compression ratio (C)	88.543	***89.018***	88.524
EGR (%) (D)	88.670	88.668	***88.746***

The optimum setting of the factors has been obtained at levels 2, 3, 2 and 3 as shown in the Table 7 i.e., ***blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%).***

2.3.1 (b) Confirmation Analysis for results of Assignment of Weights technique:

For validation of the above obtained results from Assignment of Weights technique, two graphs namely Average Performance and Average S/N graph have been generated as plotted in the Fig. 4 and Fig. 5 respectively using MINITAB-21 software.

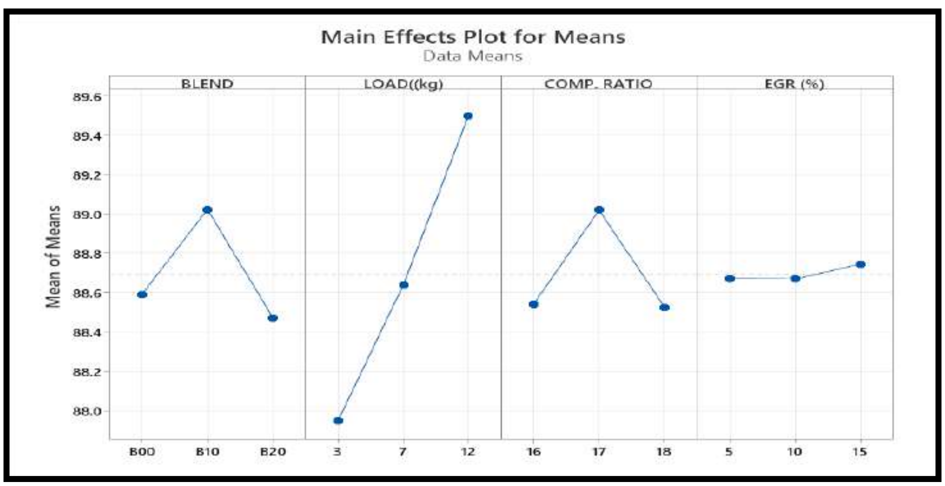

Fig. 4 Average Performance Graph (Assignment of Weights technique)

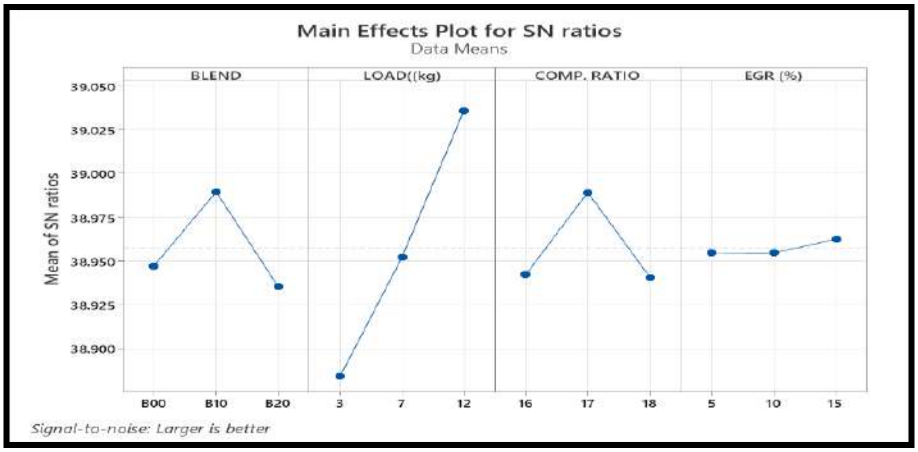

Fig. 5 Average S/N Graph (Assignment of Weights technique)

The obtained optimal setting of the factors i.e., ***blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%)*** has been validated as seen from the above graphs in Fig1 and Fig2. The practical confirmation run also validated the same setting.

Moreover for the above validation, regression analysis was also carried out. Based on the MRPI values in the assignment of weight technique as obtained in Table 6(d), a regression model was generated using Minitab-21 statistical software as shown in the Eq (ii).

MRPI= 88.6930-0.10407 BLEND_B00+ 0.32704 BLEND_B10- 0.22296 BLEND_B20-0.74407 LOAD (kg)_3- 0.05630 LOAD (kg)_7+ 0.80037 LOAD(kg)_12- 0.15407 COMP.RATIO_16+ 0.32370 COMP. RATIO_17- 0.16963 COMP. RATIO_18- 0.02407 EGR (%)_5- 0.02630 EGR (%)_10+ 0.05037 EGR(%)_15 Eq (ii)

The model summary of the developed regression model is shown in the Table 8.

Table 8 Regression model summary in Assignment of weights technique

S	R-sq	R-sq (adj)	R-sq (pred)
0.0157527	99.97%	99.95%	99.93%

A comparison of the MRPI values obtained from both experimental and model equation Eq (ii) has been shown in the Table 9 and based on these a concerned comparative graph has been plotted as shown in the Fig.3.

Table 9 Comparison of experimental and regression model based values of MRPI (Assignment of weights technique)

TC	MRPI values	
	Experimental based	Regression model based
1	87.67	87.66
2	88.83	88.83
3	89.27	89.27
4	88.65	88.65
5	88.77	88.77
6	89.64	89.64
7	87.53	87.53
8	88.32	88.31
9	89.57	89.57

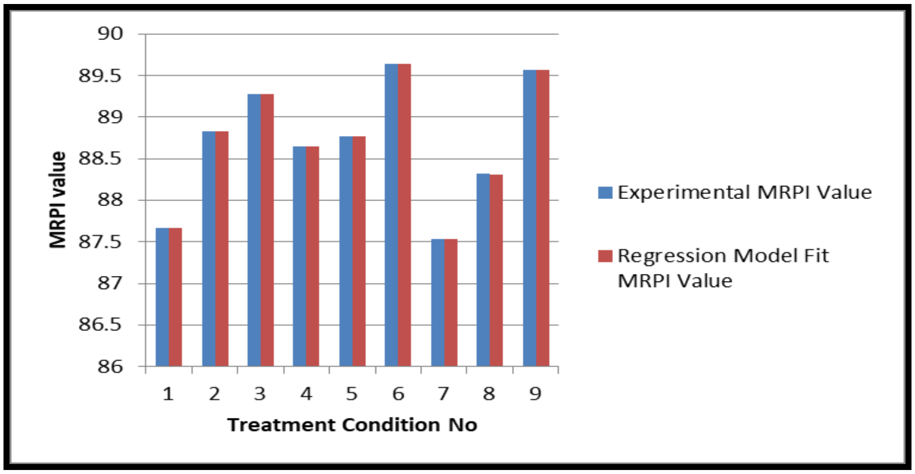

Fig. 6 Comparative graph of experimental and regression model based values of MRPI (Assignment of weights technique)

From the model summary (R^2=99.97%) of Table 8 and the graph, as shown in the Fig.6, it is observed that the obtained model values of MRPIs for all treatment conditions in assignment of weight technique closely matched with their respective experimental values. The MRPI value for the previously obtained optimal setting $A_2B_3C_2D_3$ using model Eq (ii) was found to be 90.19 and this value was the highest out of all obtained values of Table 9. Thus the obtained optimal setting i.e., $A_2B_3C_2D_3$ has been additionally validated by the developed regression model also.

2.3.2 (a) Analysis based on DEAR technique:

In this technique the weights for all the responses and their respective weighted data are calculated using the same previous rule as followed in assignment of weights approach. Then the total sum weighted data of larger-the-better type is divided by total sum weighted data of smaller-the-better type or nominal-the-best type to find the treatment condition wise all the concerned MRPIs and finally the solution is found out [18]. Here the MRPIs in DEAR technique have been derived as observed in the Table 10 and Table 11.

Table 10 Treatment condition wise MRPI in DEAR technique

$BP*W_{BP}$	$BTE*W_{BTE}$	$BSFC*W_{BSFC}$	$CO*W_{CO}$	$HC*W_{HC}$	NO_x*W_{NOx}	MRPI
U	V	W	X	Y	Z	=(U+V)/(W+X+Y+Z)
0.04080	0.67499	0.069069	24.7640	56.5051	5.6079	0.008232
0.20865	1.66715	0.069135	24.7808	56.5043	5.6078	0.021573
0.58776	1.72846	0.069090	24.7696	56.5019	5.6078	0.026638
0.03988	1.65987	0.069141	24.7680	56.5065	5.6077	0.019548
0.21075	1.60695	0.069136	24.7800	56.5068	5.6080	0.020904
0.65281	2.03816	0.069105	24.7680	56.5097	5.6082	0.030947
0.04173	0.53746	0.069122	24.7760	56.5059	5.6078	0.006661
0.22142	1.14294	0.069116	24.7782	56.5068	5.6077	0.015691
0.62348	1.99540	0.069104	24.7620	56.5063	5.6075	0.030118

Table 11 Treatment Condition Wise MRPI for L_9 Orthogonal Array in DEAR technique

TC	Factors				MRPI
	A	B	C	D	
1	1	1	1	1	0.008232
2	1	2	2	2	0.021573
3	1	3	3	3	0.026638

4	2	1	2	3	0.019548
5	2	2	3	1	0.020904
6	2	3	1	2	0.030947
7	3	1	3	2	0.006661
8	3	2	1	3	0.015691
9	3	3	2	1	0.030118

The level totals of different factors are found from the data obtained in above Table 11 and have been summarised as shown in Table 12.

Table 12 Level totals of MRPI in DEAR technique

Control Factors	**Level Totals of Mrpi**		
	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Blend (A)	0.01881	***0.02380***	0.01749
Load in kg (B)	0.01148	0.01939	***0.02923***
Compression ratio (C)	0.01829	***0.02375***	0.01807
EGR (%) (D)	0.01975	0.01973	***0.02063***

The optimal condition of the factors has been obtained at levels 2, 3, 2 and 3 as shown in the Table 12 i.e., ***blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%).***

From above it has been observed that both the techniques have arrived at the same conclusion. A confirmation run was performed for validation of this setting and that well agreed with the setting.

2.3.2 (b) Confirmation analysis for results of DEAR technique:

For validation of the above obtained results from DEAR technique, here also two graphs namely Average Performance and Average S/N graph have been generated using MINITAB-21 software as previously done. These are shown in the Fig. 7 and Fig. 8.

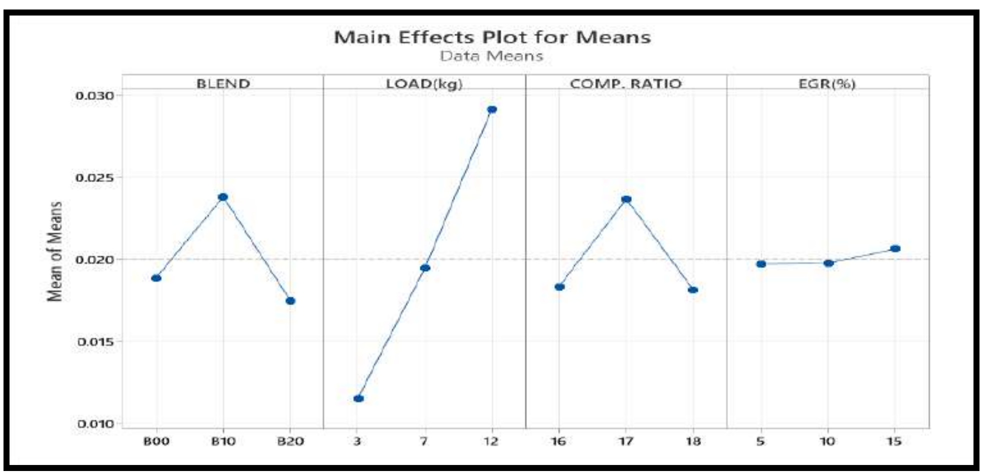

Fig. 7 Average Performance Graph (DEAR technique)

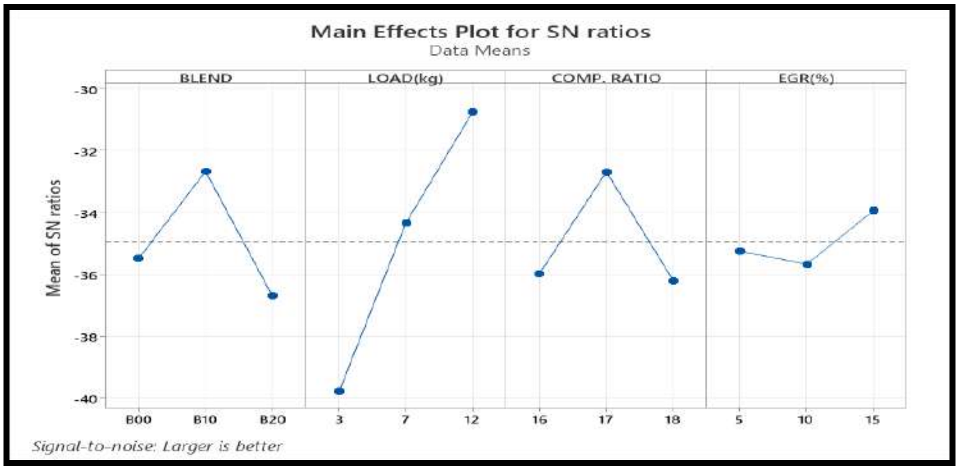

Fig. 8 Average S/N Graph (DEAR technique)

As seen from above, both the graphs in Fig.7 and Fig.8 validated the obtained optimal setting i.e., ***blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%).*** Similarly this optimal setting was also validated in the practical confirmation run.

Here also for the above validation, regression analysis was carried out as previously done. Based on the MRPI values in the DEAR technique as obtained in Table 11, a regression model was generated using Minitab-21 statistical software as shown in the Eq (iii).

MRPI= 0.020007-0.001174 BLEND_B00+ 0.003770 BLEND_B10- 0.002596 BLEND_B20-0.008507 LOAD (kg)_3- 0.000596 LOAD (kg)_7+ 0.009104 LOAD(kg)_12- 0.001707 COMP.RATIO_16+ 0.003637 COMP. RATIO_17-0.001930 COMP. RATIO_18- 0.000319 EGR (%)_5- 0.000274 EGR (%)_10+ 0.000593 EGR(%)_15 Eq (iii)

The model summary of the developed regression model is shown in the Table 13.

Table13 Regression model summary in DEAR technique

S	R-sq	R-sq (adj)	R-sq (pred)
0.0002253	99.95%	99.93%	99.88%

A comparison of the MRPI values obtained from both experimental and model equation Eq (iii) has been shown in the Table 14 and based on these a concerned comparative graph has been plotted as shown in the Fig.6.

Table 14 Comparison of experimental and regression model based values of MRPI (DEAR technique)

TC	MRPI values	
	Experimental based	Regression model based
1	0.0082	0.0083
2	0.0216	0.0216
3	0.0266	0.0266
4	0.0195	0.0195
5	0.0209	0.0209
6	0.0309	0.0309
7	0.0067	0.0067
8	0.0157	0.0157
9	0.0301	0.0298

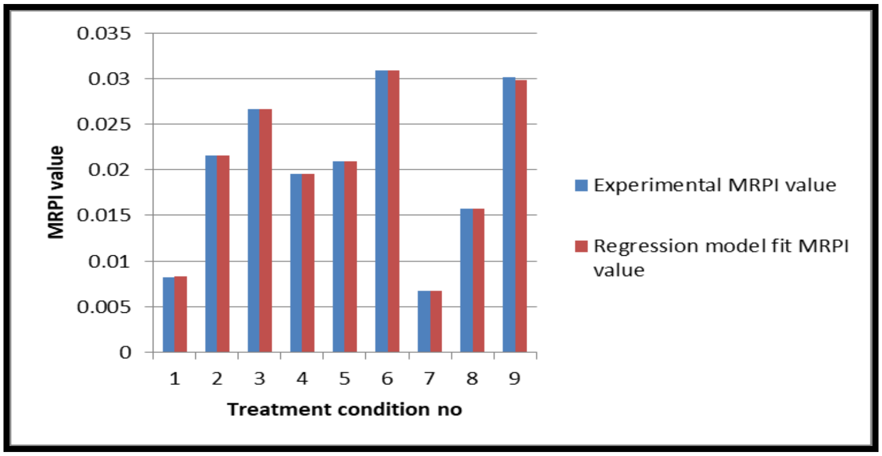

Fig. 9 Comparative graph of experimental and regression model based values of MRPI (DEAR technique)

From the model summary (R^2=99.95%) of Table13 and the graph, as shown in the Fig.9, it is observed that the obtained model values of MRPIs for all treatment conditions in DEAR technique closely matched with their respective experimental values. The MRPI value for the previously obtained optimal setting $A_2B_3C_2D_3$ using model Eq (iii) was found to be 0.0371 and this value was the highest out of all obtained values of Table 14. Thus the obtained optimal setting i.e., $A_2B_3C_2D_3$ has been additionally validated by the developed regression model also.

2.3.3 ANOVA (Analysis of Variance):

With the help of the MRPI values obtained from Table 6(d) and Table11, the ANOVA was calculated using MINITAB-21 software as shown in the Table15 and Table16 respectively.

Table 15 MRPI based ANOVA (Assignment of Weights technique)

Source	DOF	Adj. SS	Adj. MS	F value
Blend (A)	2	1.5075	0.75374	3037.45
Load(kg) (B)	2	10.7767	5.38834	21714.19
Comp. Ratio (C)	2	1.4157	0.70784	2852.48
EGR (%) (D)	2	0.0343	0.01714	69.06
Error	18	0.0045	0.00025	
Total	26	13.7386		

Table 16 MRPI based ANOVA (DEAR technique)

Source	DOF	Adj. SS	Adj. MS	F value
Blend (A)	2	0.000201	0.000101	1980.80
Load(kg) (B)	2	0.001400	0.000700	13800.36
Comp. Ratio (C)	2	0.000179	0.000089	1761.91
EGR (%) (D)	2	0.000005	0.000002	46.80
Error	18	0.000001	0.000000	
Total	26	0.001786		

From the above Table15 and Table16 for ANOVA, it was observed that Load (i.e., factor B) was found to be the most significant followed by Blend (i.e., factor A), Comp. Ratio (i.e., factor C) and EGR (%) [i.e., factor D] over the performance and emissions of the engine. Thus in both the techniques the same order of significance was obtained.

3. CHARACTERISTIC GRAPHS:

3.1 Performance Characteristic Graph:

The different performance characteristic graphs of the present work have been shown in the Fig.10, Fig.11 and Fig.12 respectively.

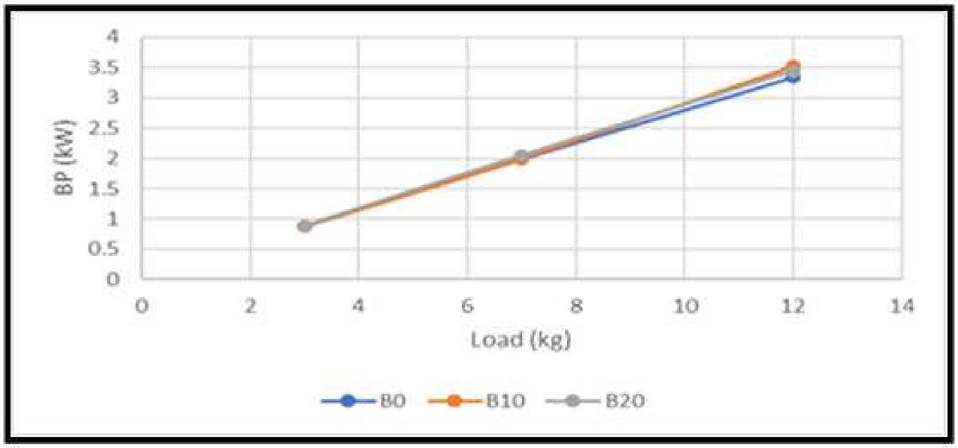

Fig. 10 Effect of Load on BP at various blends

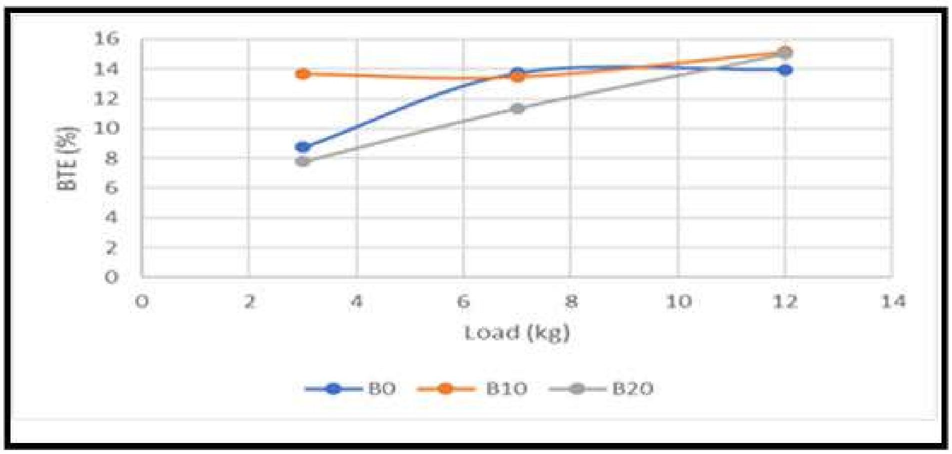

Fig. 11 Effect of Load on BTE at various blends

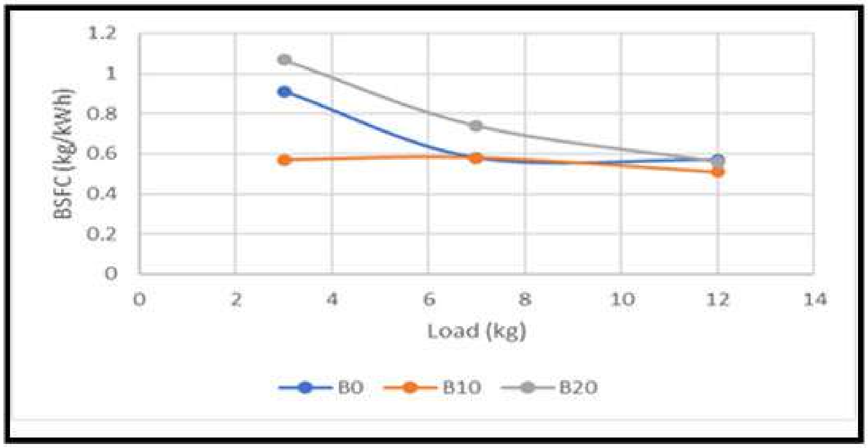

Fig. 12 Effect of Load on BSFC at various blends

3.2 Exhaust Emission Characteristic Graph:

The different exhaust emission characteristic graphs of the present work have been shown in the Fig.13, Fig.14 and Fig.15 respectively.

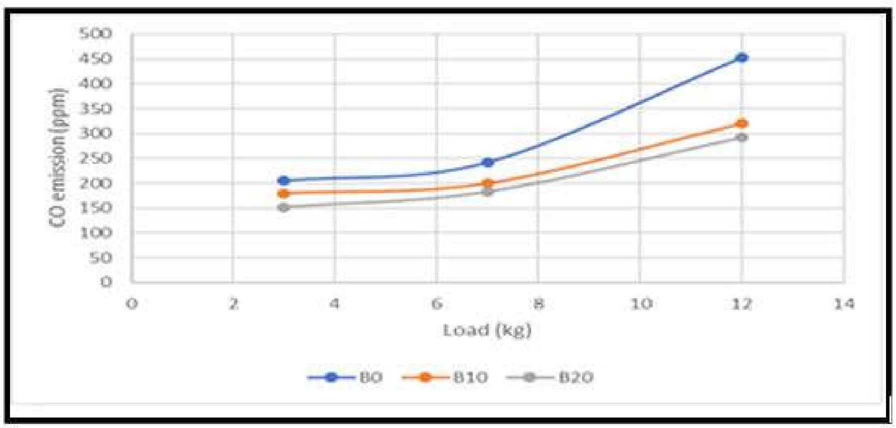

Fig. 13 Effect of Load on CO emission at various blends

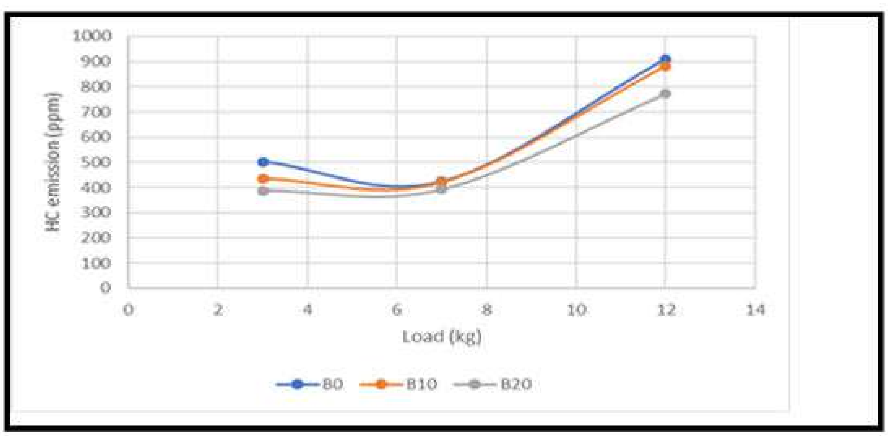

Fig. 14 Effect of Load on HC emission at various blends

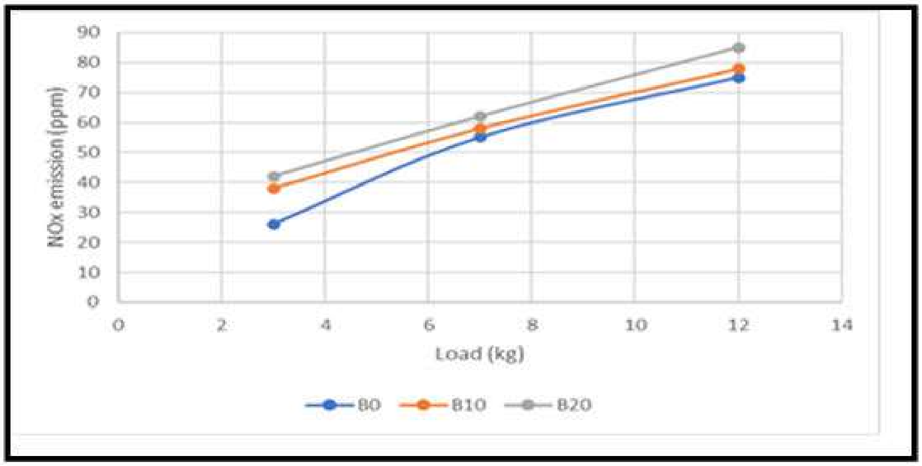

Fig. 15 Effect of Load on NOx emission at various blends

4. RESULTS AND DISCUSSIONS

The study showed that both the weighted MRPI techniques resulted in the same optimal condition for engine multi response process optimization while running with WCO biodiesel blended oil. Their results were validated through average performance and average signal- to- noise (S/N) ratio graphs. Also it was validated through regression analysis. In the study, WCO biodiesel blended oil was observed to exhibit similar combustion trend with conventional diesel. For the response of engine performance and emissions, the following observations were revealed in the study.

4.1 Engine Performance:

From the study it was seen that the engine performance responses i.e., BP and BTE with larger-the-better quality characteristic and BSFC with smaller-the-better quality characteristic were all optimized for blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%). The fuel atomization and evaporation processes were enhanced after successive running of engine at the high load leading to partial improvement in fuel air mixing [19]. So far the thermal efficiency is concerned, due to availability of O_2 contained in the biodiesel, the performance of B10 was found to be comparatively successful. The relatively less dense and viscous fuel oil in blended condition helped in its full and proper combustion [4]. Both the BP and BTE were found to be comparatively superior for B10 blend at the highest load as seen from the Fig.10 and Fig.11 respectively. Rich amount of oxygen present in biodiesel ensures complete burning of engine fuel in the cylinder leading to lower BSFC at higher load [3]. As seen from the Fig 12 the BSFC was found to be comparatively less for B10 blend at the highest load.

4.2 Engine Exhaust Emissions:

In this work, the exhaust emissions i.e., CO, HC and NOx with smaller-the-better quality characteristic were also found to be optimized for blend ratio at medium level (i.e., B10), load at high level (i.e., 12 kg), compression ratio at medium level (i.e., 17:1) and EGR at high level (i.e., 15%). With the rise in load, CO and HC emission increases for all types of fuel as shown in Fig.13 and Fig.14 [19]. However, with the rise of biodiesel content in the blended fuel these are observed to be reduced [4]. The emissions of NOx with blended biodiesel were marginally greater than conventional diesel as shown in Fig.15. Comparatively a better performance for blend B10 was observed out of all, which may be because of lower viscosity and availability of adequate oxygen present in the fuel itself [4].

In the study of significance of factors, the load was diagnosed to be the most significant followed by blend, compression ratio and EGR in both the techniques of optimisations.

5. CONCLUSION

WCO has been experienced as an easily abundant source for biodiesel generation at nearly no cost. The work here paved the way for using the non-biodegradable and toxic WCO that is being generated daily from the canteen for the production of biodiesel. The biodiesel produced from this unwanted WCO which can be used in the blended mode with petro-diesel for running the diesel generator set which is being used for the power backup of the canteen itself. This work here helped in the engine compatibility testing for using the produced biodiesel as the blended fuel so far its performance and emission is concerned. The application of different statistical tools and techniques in the present work helped in ensuring and validating the common optimal setting of the process control factors. Converting the waste to useful energy in this way will not only add to economy but it will also help in sustaining the green environment and enhancing the longevity of both the people and the society in coming days.

6. ACKNOWLEDGEMENT

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