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Research Article

Performance optimization of oxy-fuel combustion diesel engine with EGR based on fuel injection parameters using response surface methodology (RSM)

Raghavendra UGRARAM[1,*], R. Meenakshi REDDY[2], B. Chandra Mohana REDDY[1]

[1]*Department of Mechanical Engineering, Jawaharlal Nehru Technological University Anantapur (JNTUA), Ananthapuramu, Andhra Pradesh, 515002, India*
[2]*Department of Mechanical Engineering, G. Pulla Reddy Engineering College, Kurnool, Andhra Pradesh, 518007, India*

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ABSTRACT

The interest in research on diesel engine emission reduction is on the rise. A novelistic combustion technique called Oxy-Fuel Combustion (OFC) with 40% of Exhaust Gas Recirculation (EGR) is studied experimentally on a diesel engine at 25% engine load conditions. Although, in OFC nitrogen oxides (NOx) emissions are eliminated and CO, HC emissions are reduced, there is a considerable reduction in Brake Thermal Efficiency (BTE) and increased Brake Specific Fuel Consumption (BSFC) than the Conventional Air Combustion (CAC). In the present study Response Surface Methodology (RSM) Optimization technique is used to optimize the fuel injection parameters of OFC to improve its performance.
Start Of Injection (SOI), Duration Of Injection (DOI) and Mass Of Fuel Injected (MFI) are the factorial variables considered for the optimization. To examine the impacts of the selected factorial variables on BTE and BSFC, regression models were formulated and verified to be statistically significant. The Multi-Objective Genetic Algorithm results reveal that the optimum conditions are SOI at 358 CAD, DOI at 15.8 degrees, and MFI at 0.0106 g. The validity of the model was confirmed through the experimental results and demonstrated that the prediction error is below 5%. The experimental results of OFC diesel engine with the optimum conditions indicate that BTE is improved from 14.8 to 24.1% and BSFC reduced from 527.7 to 402.3 g/kW-h.
According to the observations of this study, it is concluded that OFC with EGR can be deployed in a diesel engine with no design modifications and the drop in performance in comparison with CAC can be recovered with the RSM optimization.

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***Corresponding author.**
*E-mail address: raghuugraram@gmail.com

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INTRODUCTION

Several emerging technologies aim to enhance the overall efficiency and fuel economy of traditional engines, aligning with the demands for cleaner and more efficient diesel engines. Recognizing the significant role of oxygen (O_2) in the combustion process, some researchers have explored the influence of increased oxygen concentration in the intake charge on diesel combustion [1, 2]. The utilization of oxygen-enriched air is widely recognized for its ability to enhance burn rates and expedite heat release, ultimately leading to increased combustion efficiency and power output. Research on employing oxygen-enriched air in diesel engine applications has shown that even a slight augmentation in oxygen levels can markedly diminish smoke emissions and decrease levels of carbon monoxide, unburned hydrocarbon and particulate matter. Nevertheless, these studies have also reported a notable increase in NOx emissions. Consequently, a range of approaches have been proposed to manage and control NOx emissions, including introduction of water at high-pressure into the combustion chamber, utilizing EGR or diluents additions and optimizing injection parameters [3-5]. In their research, Zhao et al. [5] studied the impact of oxygen-enriched air combustion in a diesel engine, on combustion characteristics, engine performance, and emissions. Their findings revealed that increasing the intake charge with oxygen concentration resulted in the suppression of PM emissions, but there was a notable increase in NOx emissions. Moreover, the study suggested that augmenting intake air humidification could reduce NOx emissions, however, it also exhibited negative impacts on indicated power and PM emissions.

Recently, there has been a growing attention toward oxy-fuel combustion and nitrogen-free combustion, combined with Carbon Capture and Storage (CCS) methods, aiming to achieve emissions without carbon and enhance combustion efficiency. Traditionally, the focus of most oxy-fuel combustion technologies has been on large-scale gas turbines or coal-fired power plants [6-9]. Given that IC engines play a pivotal role as primary power sources in the transportation sector, adopting OFC and CCS technology in this context has noteworthy implications. OFC involves the use of pure oxygen for combustion instead of regular air or oxygen-enriched air. This approach eliminates nitrogen from the intake charge, leading to the complete elimination of nitrogen oxides (NOx) emissions. Consequently, the combustion reaction produces only carbon dioxide and water vapor as byproducts. The utilization of oxy-fuel in Internal Combustion engines was first suggested by Osman in 2009 [9]. In this study, a water injection system was incorporated to regulate the in-cylinder temperature and augment heat absorption during the combustion process. In 2017, Kang et al. [10] carried out an experimental analysis on the impacts of OFC and EGR on a Homogeneous Charge Compression Ignition (HCCI) engine. The EGR is simulated in a surge tank by mixing carbon dioxide (CO2) and water vapor (H2O). Furthermore, a water injection system is employed to explore its potential in mitigating abnormalities in the OFC. The results revealed that injecting water at high-pressure and high temperature with precise timing could effectively manage combustion abnormalities. Additionally, this approach contributed to an enhancement in the engine's thermal efficiency. The adoption of OFC presents the advantage of eliminating the need for increasingly costly and intricate NOx after-treatment systems. Moreover, this approach also yields favorable fuel economy and remarkably low levels of particulate emissions. However, replacing the atmospheric air with pure oxygen, results in an accelerated combustion process, and leading to a shortened ignition delay. Simultaneously, there is a minimization of premixed combustion and a maximization of diffusion combustion. The heightened heat release rate significantly reduces the time required to complete the entire heat release process. The accelerated combustion process, shortened ignition delay and rapid heat release is anticipated to elevate the flame temperature with reduced performance. There are multiple engine operational conditions, injection parameters and combustion variables that have a direct impact on engine performance. Hence, the utilization of a multivariate systematic analysis emerges as crucial for acquiring comprehensive and precise insights into the operational traits of combustion engines, as opposed to relying solely on a univariate analysis. While addressing the multivariate problems, employing Design of Experiments (DOE) stands out as a highly reputable and cost-effective method for examining the impacts of different parameters on the output variable. This approach has been widely acknowledged and applied in studies by Najafi et al. [11], Jiang and Zheng [12], Venugopal et al. [13], Yusri et al. [14].

The Response Surface Method (RSM), integrating mathematical and statistical techniques, stands as a highly valuable tool for modeling and optimization across various engineering problems. This multivariate method concurrently evaluates the impacts of different factors and their interrelationships to pinpoint the system with the optimal performance and define the ideal conditions. RSM presents the advantage of demanding less time compared to other statistical methods and necessitating fewer tests than full factorial design experimentation [15, 16]. In a study conducted by Khoobbakht et al. [17], the Response Surface Method (RSM) was employed to optimize the engine operating parameters of a diesel engine running on blends of diesel, biodiesel, and ethanol. The investigation revealed the best composition to achieve the highest thermal efficiency. Lleri et al. [18] analyzed a diesel engine powered by canola oil methyl ester and investigated the influence of alterations in engine speed and fuel injection timing on engine performance and exhaust emissions. Further, using the experimental results a second-order full quadratic response surface models were derived, enabling the prediction of responses from input factors with a 95% confidence interval. Rezaei et al. [19] employed Taguchi Design of Experiments to analyze the split injection strategy in an engine operating under Premixed Charge Compression

Ignition (PPCI) combustion mode. Their conclusion highlighted that the Taguchi method was not only feasible but also an effective approach for conducting parametric studies in this context. Pandian et al. [20] utilized RSM analysis to examine the influence of injection parameters on a Direct Injection (DI) diesel engine performance and emissions. The conclusion of the research emphasizes the desirability approach within the framework of RSM to be an efficient and straightforward optimization technique. Smith et al. [21] conducted a comprehensive study on optimizing the injection parameters of a common-rail diesel engine using RSM. The study demonstrated that RSM could effectively reduce experimental runs while providing significant insights into the interaction effects between injection pressure, timing, and nozzle geometry on engine performance and emissions. The results highlighted a notable improvement in fuel efficiency and a reduction in NOx emissions, confirming the efficacy of RSM in engine optimization. In another significant study, Chen and Wang [22] applied RSM to optimize the dual-fuel injection strategy in a heavy-duty diesel engine. Their research focused on the simultaneous optimization of fuel consumption and emission levels, considering variables such as injection timing, pilot quantity, and boost pressure. The use of RSM allowed for the development of a quadratic model that accurately predicted engine behavior under various operating conditions. The optimization process led to a 15% reduction in particulate matter and a 10% improvement in thermal efficiency, showcasing the practical benefits of RSM in real-world engine applications.

Gupta et al. [23] explored the application of RSM in optimizing biodiesel blends for use in diesel engines. Their study evaluated the performance and emission characteristics of various biodiesel-diesel blends under different engine loads and speeds. By employing RSM, they were able to identify the optimal blend ratio that maximized engine efficiency and minimized harmful emissions. The findings indicated that a blend of 20% biodiesel with 80% diesel provided the best trade-off between performance and environmental impact, demonstrating RSM's capability to handle complex optimization problems involving multiple response variables. A recent study by Lee et al. [24] further extended the use of RSM in optimizing exhaust gas recirculation (EGR) and turbocharging parameters in a turbocharged diesel engine. Their research aimed to minimize NOx and soot emissions without compromising engine performance. By constructing a response surface model, the researchers were able to predict the optimal settings for EGR rate and turbocharger boost pressure. The optimized parameters achieved a 25% reduction in NOx emissions and a 20% decrease in soot formation, illustrating the potential of RSM to enhance diesel engine performance while meeting stringent emission standards.

These studies collectively underscore the growing reliance on RSM for diesel engine optimization, highlighting its versatility and effectiveness in improving engine performance and reducing emissions. The consistent results across different research efforts validate RSM as a valuable tool in the ongoing quest for more efficient and environmentally friendly diesel engines.

As previously noted, the implementation of OFC technology has predominantly been employed in gas turbines and power plants, with limited exploration of its application in Internal Combustion engines. However, implementation of OFC with EGR has yielded a reduced BTE and increased BSFC. Table 1 represents a brief comparison of diesel engine performance under OFC with EGR against the CAC.

Table 1. Performance comparison of OFC and CAC

Output Variable	Units	CAC	OFC+EGR
BTE	%	20.1	14.8
BSFC	g/Kw-hr	420.2	527.7

The present experimental study with RSM optimization is conducted to investigate the best fuel injection parameters namely Start of Injection (SOI), Duration of Injection (DOI), and Mass of Fuel Injected (MFI), to recover the loss in BTE and BSFC with OFC with EGR implementation in a diesel engine at 1500 rpm and 25% load conditions. As a future scope, one could extend the same study by employing the same approach on OFC diesel engine at all load conditions to stabilize the combustion environment with better performance output. This extension could also involve applying the RSM technique and subsequently comparing the results with other methodologies such as Least Squares Support Vector Machines, Taguchi and Artificial Neural Networks.

MATERIALS AND METHODS

Experimental Setup

In the current experimental studies are performed on a single-cylinder, four-stroke Oxy-Fuel Combustion diesel engine integrated with EGR and an eddy current dynamometer. The details of the engine specifications can be found in Table 2, and a schematic representation of the engine test setup is provided in Figure 1.

Table 2. Engine specifications

Parameter	Units	Value
Engine type	--	4-Stroke, Single Cylinder water-cooled Diesel Engine
Rated Speed	rpm	1500
Bore Diameter	mm	87.5
Stroke	mm	110
Compression ratio	--	15.6:1
Orifice Diameter	mm	29.6
Loading	--	Electric loading

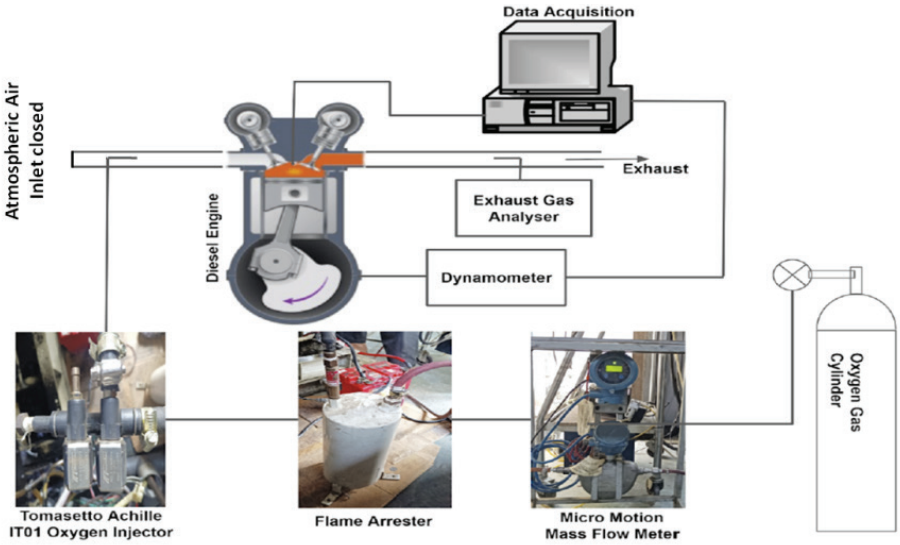


Figure 1. Schematic diagram of the experimental setup.

OFC diesel engine utilizes pure oxygen instead of regular air for reacting with hydrocarbon fuel. This results in combustion products primarily consisting of only carbon dioxide (CO_2), water vapor (H_2O) and excess unburnt oxygen (O_2). The diesel engine is operated under OFC mode by closing the air inlet manifold and by injecting the oxygen into the inlet pipe. Tomasetto Achille IT01 rail gas injector is used to inject the oxygen and the mass flow rate of the injected oxygen is controlled by injection pulses with respect to the crank angle. To regulate the quantity of oxygen injection per cycle and to control the combustion temperature, overheating issues associated with OFC diesel engine, a portion of the exhaust gasses are introduced back into the engine by using EGR technique. To safeguard the setup in the situations of misfiring, a flame arrester is placed in the upstream of the oxygen cylinder and before the engine. Throughout the experimentation, the engine is operated at a constant speed of 1500 rpm and the steady state combustion data were collected at 25% of full load. To ensure the reliability, repeatability and consistency of combustion data, the engine was run for 12 minutes to attain steady state operating condition before data collection. An incremental step of 5% is used to switch the engine load conditions from 0% to 25%. The engine was operated continuously for duration of 5 minutes at every specific test condition followed by the data collection.

Error Analysis

The experimental data acquisition accuracy is subjected to the parameters considered during the test, equipment errors and uncertainty. The calibration of the devices, their use, the observer's ability to interpret the data, and the constancy of the ambient conditions all have a significant impact on the uncertainties. The instruments' related uncertainties are assessed using a partial differentiation method and the independent parameter uncertainties are taken into account by determining the mean values of 16 repeated readings. The experimental absolute uncertainty using the mentioned methods is discovered to be 2.8%.

Response Surface Methodology

RSM encompasses a range of mathematical and statistical methods customized for modeling and resolving various problems, where the goal is to optimize a response influenced by multiple factors. Figure 2 depicts the flowchart of the RSM study, illustrating the sequential steps involved in the process. In the current study, RSM is applied for modeling, prediction, and optimization of the fuel injection parameters of an OFC diesel engine.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{j \geq i}^{k} \beta_{ij} X_i X_j + \varepsilon \quad [1]$$

The Equation 1 is a representation of a response surface model, where Y indicates the response variable, Xi denotes the numeric values of the factors, and terms β0, βi, βii, and βij signify regression coefficients. The indices i and j pertain to linear and quadratic terms, while the experimental error is indicated by ε. In the context of this model, the fitted equations are used to generate the response surface plots to visually depict the relationship between the factorial variables and response variables.

The Central Composite Rotatable Design (CCRD) is chosen for its capability to offer relatively precise predictions. To create a Central Composite Rotatable Design (CCRD) for studying SOI ranging from 330 to 365 [CAD], DOI ranging from 7.5 to 22 [CAD], and MFI ranging from 0.008 to 0.011 [g], the center points were defined as SOI:

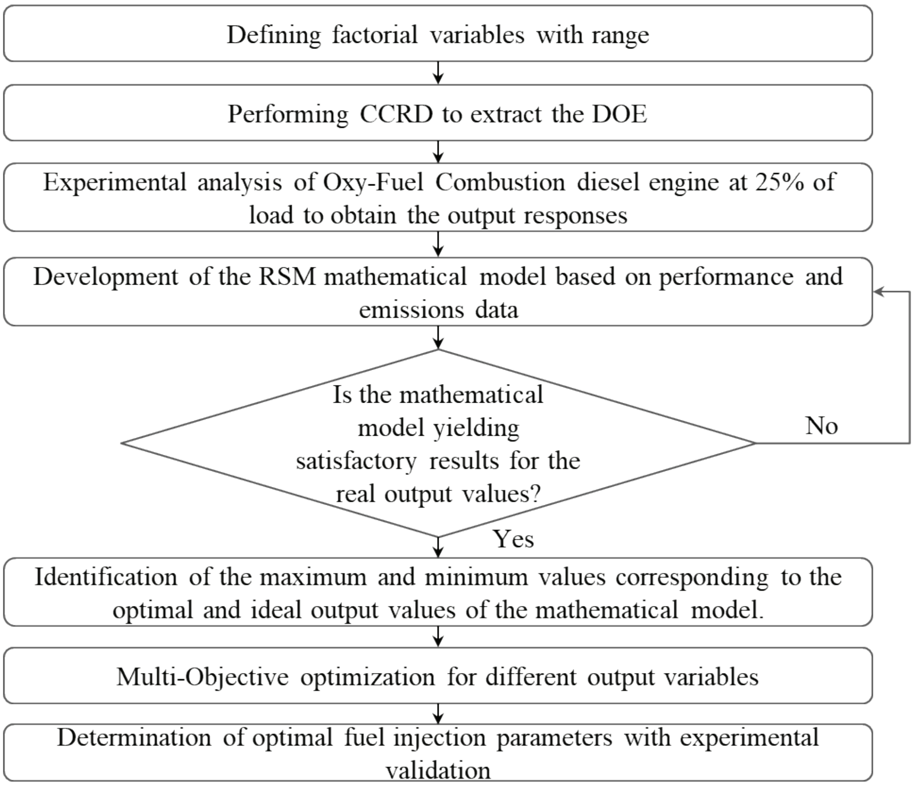


Figure 2. RSM optimization flow chart.

347.5 [CAD], DOI: 14.75[CAD], MFI: 0.0095 [g] and α was calculated as 1.682 for three factors. The design matrix included 8 factorial points, 6 center points and 6 axial points, totaling 20 experiments. Each factor's high (+1), low (-1), center (0), and star points (±α) were transformed back to original units. The star points are strategically positioned at the faces of the cubic portion of the design, thus classifying this design as a face-centered CCRD. The experiments were randomized to minimize bias, and the resulting data were analyzed using regression to fit a quadratic model. Table 3 illustrates the DOE extracted using the CCRD method. The engine experiments were carried out with the derived factorial variables and the corresponding responses on BTE, BSFC were noted. Given the intricate and non-linear nature of combustion in an Internal Combustion engine, a second-order model was deployed to analyze the correlation among the input factorial variables and their corresponding responses. The optimal combination of input factorial variables can be established by utilizing the desirability approach within the framework of RSM.

The various solutions derived using the desirability approach is subsequently validated through confirmatory experimental trials, adhering to the established optimization criterion. The criterion in this study is to maximize the BTE while simultaneously minimizing the BSFC.

RESULTS AND DISCUSSION

This section discusses the influence of factorial variables in diesel engine fuel injection, including start of injection, injection duration, and mass of fuel injection, on the engine's output responses such as brake thermal efficiency and brake specific fuel consumption when operating under oxy-fuel combustion mode. The aim of the optimization is to improve the performance of diesel engine with OFC to be greater or at least equal to CAC performance.

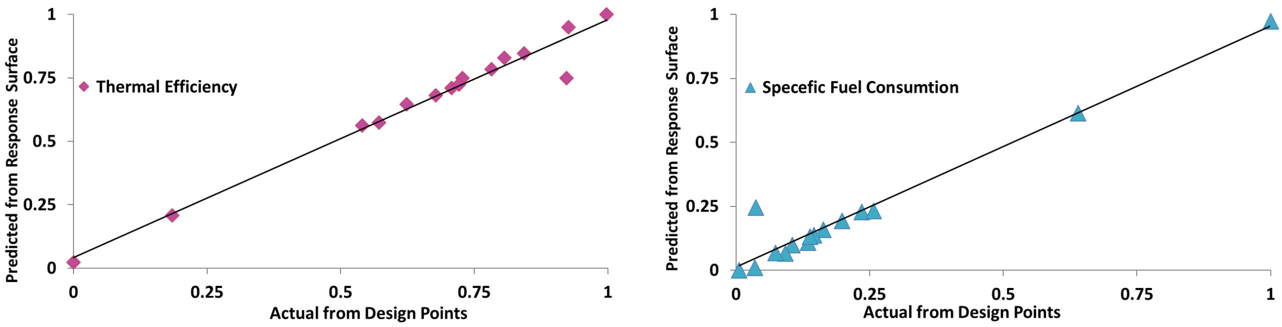
ANOVA Analysis

The correlation between the predicted variables from the response surface and the output of the design points is shown in Figure 3. The comparison illustrates the models commendable accuracy and a strong correlation between their predictions and the actual outcomes.

The analysis of variance (ANOVA) results concerning the response surface quadratic and Two-Factor Interaction models pertaining to BTE and BSFC are represented in Table 4 and 5 respectively. In this study, ANOVA analysis was employed with a significance level set at α=0.05, corresponding to a confidence level of 95%. The p-value is a crucial parameter in ANOVA analysis, in this context, the maximum acceptable p-value for a model is set at 0.05. Models exhibiting p-values exceeding 0.05 are deemed irrelevant in the analysis. A p-value below 0.05 is indicative of the factor having a statistically significant impact on

Table 3. Design of experiments matrix

Design Point	Start of Injection (SOI) [CAD]	Duration of Injection (DOI) [degree]	Mass of Fuel Injected (MFI) [g]	BTE [%]	BSFC [g/kW-h]
1	337.5	7.75	0.00996	14.2	648.7
2	331.2	16.5	0.0115536	21.6	427.7
3	333.5	21.5	0.011288	25.2	365.6
4	335.8	8.5	0.0118192	14.2	647.7
5	336.5	21	0.011	26.2	488.6
6	338.2	15.5	0.0088976	24.2	381.0
7	340.5	20.5	0.008632	27.8	331.7
8	342.8	11.5	0.0094288	20.2	457.1
9	343.2	10.6	0.008942	19.8	434.2
10	345.2	13.5	0.0110224	22.5	410.4
11	347.5	12.5	0.0107568	23.0	401.6
12	348.6	9	0.00988	20.0	446.8
13	349.8	7.5	0.0102256	20.7	445.8
14	352.2	17.5	0.00996	26.6	346.5
15	354.5	10.5	0.0104912	24.6	374.7
16	356.8	18.5	0.0096944	26.5	347.4
17	359.6	21.5	0.0104	14.0	628.5
18	359.2	9.5	0.0081008	23.3	395.9
19	361.5	19.5	0.0091632	11.1	689.1
20	363.8	14.5	0.0083664	23.2	397.6



(a) (b)

Figure 3. Actual and predicted values of (a) BTE and (b) BSFC.

the developed model. In other words, it suggests that the observed results are unlikely to have occurred by chance, strengthening the evidence that the factor plays a meaningful role in influencing the model.

In Table 4 and 5, both linear and second-order coefficients of BSFC and BTE are deemed significant. It is noteworthy that the interaction coefficients associated with BSFC and BTE also exhibit significance. In Table 6, additional diagnostic parameters for assessing the developed model of response variables are presented. For BSFC and BTE, the values of R2, Adj. R2, Pred. R2 and adequate precision fall comfortably within the specified limits for accuracy and adequacy of the model in capturing the desired responses. This demonstrates the robustness of the model. Furthermore, the polynomial regression equations for BSFC and BTE are detailed in Table 7.

Effect of Factorial Variables on BTE

The impact of variation of factorial variable on BTE is represented in surface responses in Figure 4 and the 2-dimentional variations are represented in Figure 5.

BTE in OFC is lower than the CAE because the energy conversion initiates prior to the TDC owing to a shorter combustion duration and early ignition. Additionally, there

Table 4. ANOVA table of BTE

Source	Model	A	B	C	AB	AC	A2
SS	1102.68	818.2	6.8	3.892	2.056	0.32	39.02
F Value	4105.86	18999.64	146.98	95.4	43.76	7.09	846.24
p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.031	<0.0001	<0.0001

Table 5. ANOVA table of BSFC

Source	Model	A	B	C	AB	AC	A2
SS	0.224	0.162	0.0035	0.0083	0.00024	0.0046	0.0192
F Value	1012.62	3442.06	94.67	220.54	6.02	130.65	464.28
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.018	<0.0001

Table 6. Model evaluations

	SD	Mean	C.V. %	PRESS	R2	Adj R2	R2pred
BTE	0.109	22.68	0.92	1.042	0.998	0.998	0.999
SFC	0.008	438	2.01	0.004	0.999	0.999	0.998

Table 7. Equations of polynomial models

Output Function	Equation
BTE	$23.65 + 9.24xA - 0.832xB + 0.539xC + 0.624xAB - 0.025xAC - 2.86xA^2$
SFC	$406.2 - 0.009xA + 0.1xB - 0.032xC - 0.002xAB + 0.01xAC + 0.09xA^2$

is a remarkable change in the chemical and physical properties of the in-cylinder working fluid when the entire nitrogen volume is substituted with oxygen. In OFC, the thermal diffusivity of the combustion gases is increased, leading to enhanced flame propagation and accelerated fuel oxidation. Consequently, the overall combustion duration is reduced, and the combined impact of these factors shifts the start of combustion to an earlier CAD compared to CAC.

Figure 4a, 4b and 5a, 5b represents the variation of BTE with SOI and DOI. The delayed SOI and higher DOI is regulating the early combustion and rate of combustion of OFC by adapting the required equivalence ratio. Also, at the higher SOI, DOI the rate of heat transfer between the in-cylinder fluid and the cylinder walls is reduced, as the presence of relative duration of high thermal diffusivity and thermal conductivity fluid per cycle is reduced. So, the cumulative effect of early, rate of combustion and reduced wall heat transfer loses are yielding an increased BTE by increasing the SOI and DOI.

Figure 5a, 5b represents the 2-dimensional independent variation of SOI, DOI on BTE, it is noted that there is a threshold for the SOI, DOI any SOI beyond 360 CAD, DOI of 22 CAD is having an adverse effect on BTE, which could be attributed to the reduced combustion efficiency, due to inappropriate injection, equivalence ratio and ignition delay. From Figure 4a, 4c, it is observed that the MFI has a contrasting variation with SOI and DOI, the optimal MFI-SOI corresponding to the maximum BTE is close to 0.01 [g], whereas the MFI-DOI is 0.0085 [g]. Nevertheless, Figure 5c indicates that the MFI has a minimal impact on the BTE.

Effect of Factorial Variables on BSFC

With the complete substitution of nitrogen volume by oxygen, the average equivalence ratio is significantly lower in OFC. This leads to lean combustion, consequently reducing the indicated power in OFC and so in OFC, to generate equivalent energy for a specific load a larger quantity of fuel was necessary than the CAC, thus the BSFC is higher in OFC.

The surface responses of BSFC are represented in Figure 6 and the 2-dimentional variations are shown in Figure 7. A similar trend in variation of BSFC is observed as that of the BTE. During higher DOI the rate of fuel injection Vs. CAD will be lower, which has a profound influence on the equivalence ratio. The delayed SOI and higher DOI is reducing the BSFC, indicating the favorable improvement

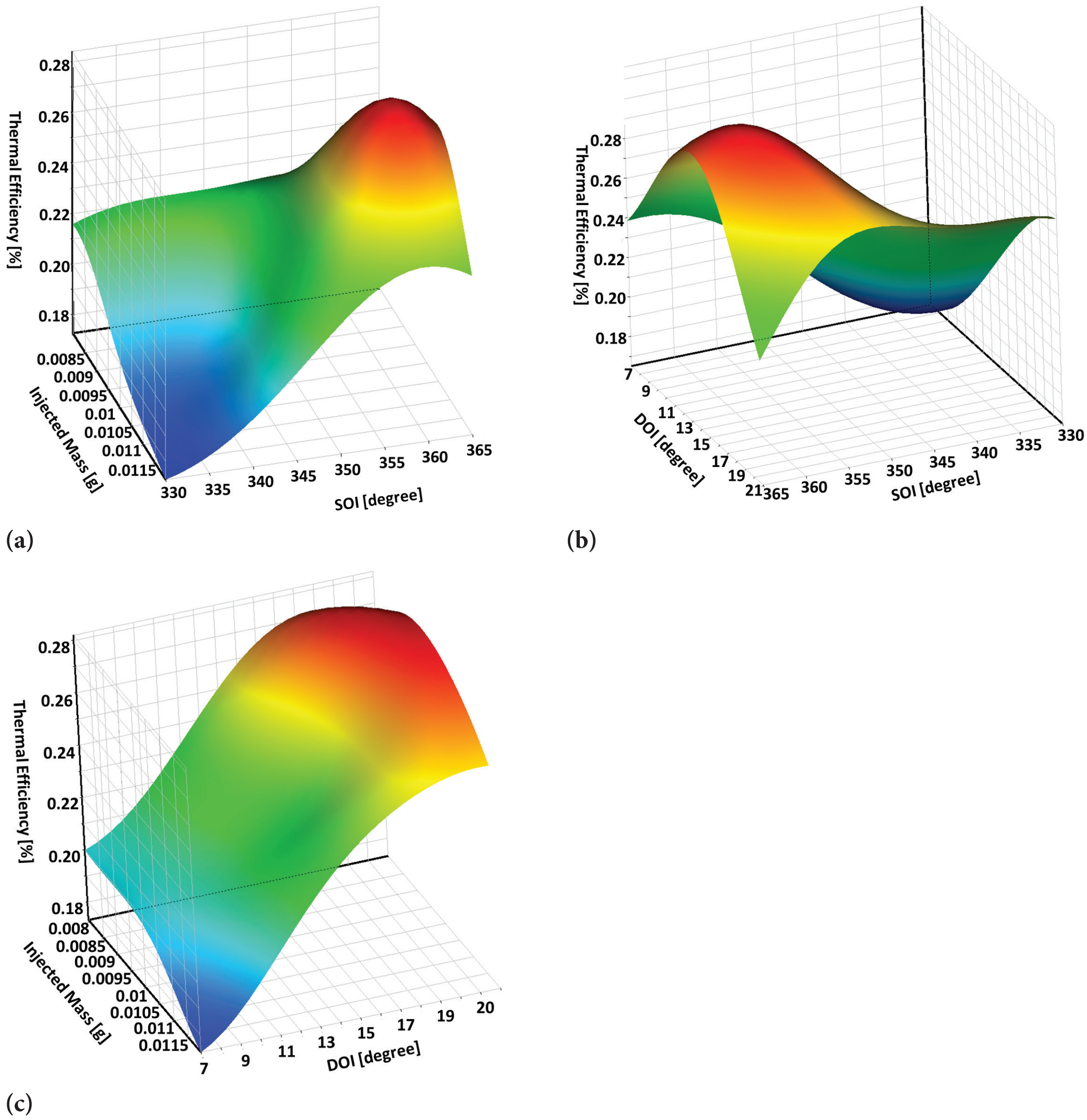


Figure 4. Surface response plots. (a) BTE vs. SOI, MFI. (b) BTE vs. SOI, DOI. (c) BTE vs. DOI, MFI.

in equivalence ratio and improved performance. Figure 6a, 6c demonstrates the impact of MFI to be converging with SOI and DOI for BSFC, the MFI corresponding minimum BSFC is close to 0.01 [g] in correlation with both SOI and DOI. From Figure 7c represents that the range of influence of MFI on BSFC is relatively lower than the SOI and DOI.

Optimization and Validation

The result of optimum DOI, SOI indication in Figure 4a, 4b and 6a, 6b illustrates the range of factorial variables considered for the DOE is perfect fit for the optimization. However, the trend of BTE increase and reduction of BSFC is not progressively linear, the DOI corresponding to the highest BTE, lowest BSFC is noted at 16 in-conjunctions with SOI and the same value is noted as close to 21 in-variations with MFI, this denotes the intricate interdependent influences of factorial variables on output variables.

The objective of the optimization is to aid in the recovery of performance losses in OFC by carefully selecting the appropriate injection parameters. In this study, Multi Objection Genetic Algorithm (MOGA) is opted to execute optimization with constraints to maximize the BTE and to minimize the BSFC with equal weightage. The computed optimum candidate factorial variables by MOGA are shown in Table 8.

Table 8. Optimum factorial variables

Variable	Computed Optimum value	Units
SOI	358	CAD
DOI	15.8	degrees
MFI	0.0106	g

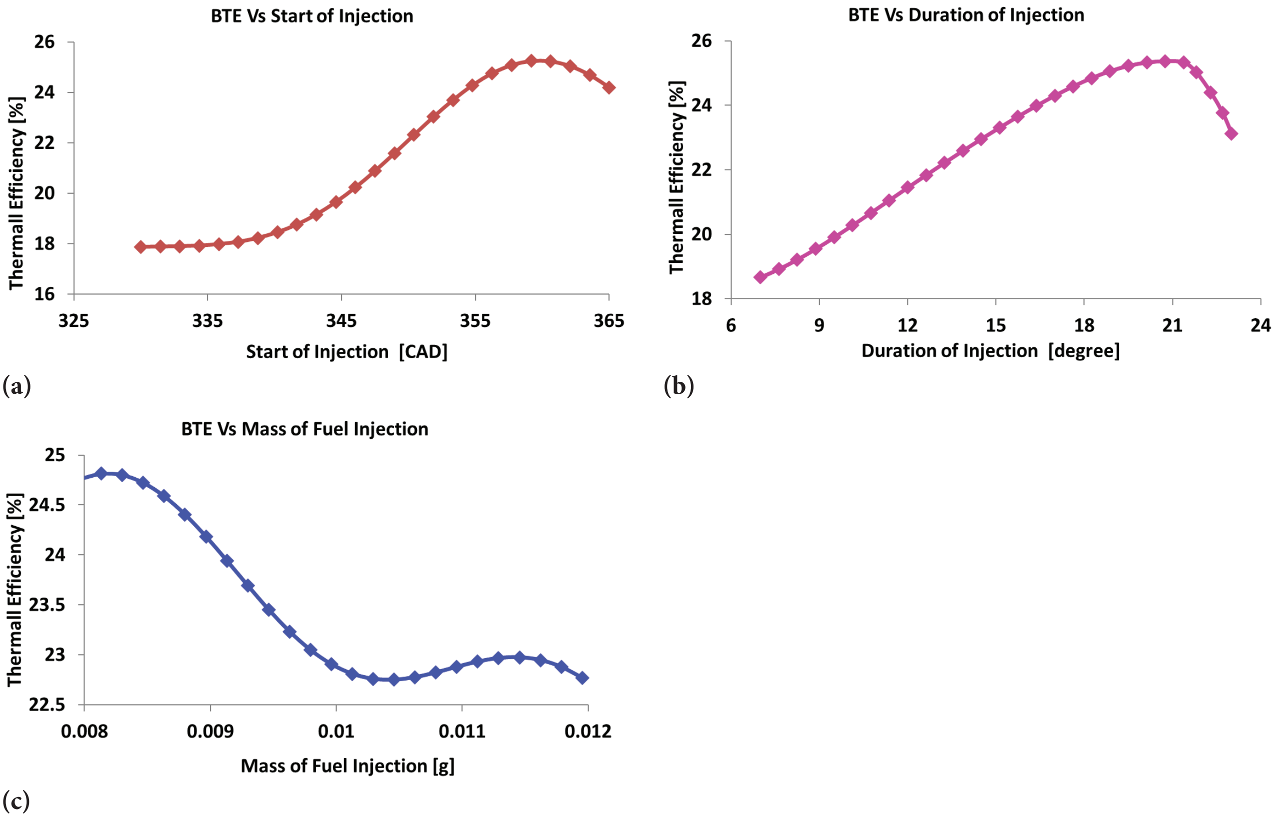


Figure 5. BTE variation with (a) start of injection, (b) duration of injection, (c) mass of fuel injection.

The experimental validation of MOGA optimum injection parameters is performed with 4 trails and the average output values are recorded for documentation. The actual experimental results vs. the predicted results of the BTE, BSFC with the computed optimum injection parameters are consolidated in Table 9. The predicted error falls within the 5% limit and, therefore, can be deemed significant for acceptance.

Table 10 demonstrates the comparison of performance of diesel engine under various combustion environments at 25% engine load condition. By deploying RSM and MOGA, the BTE of OFC is improved from 14.8% to 24.1%, which is surpassing the 20.58% BTE of CAC, similarly the BSFC of OFC is also reduced from 527.7 g/kW-h to 402.3 g/kW-h, which is close to the 420.2 g/kW-h BSFC of CAC.

The experimental results of the optimum factorial variables concludes that objective of the study to recover the

Table 9. Comparison of experimental results vs. predicted results

Output Variable	Units	Experimental results	Predicted results	Error
BTE	%	24.1	25.23	4.7%
BSFC	g/kW-hr	402.3	385.4	4.2%

Table 10. Performance comparison of diesel engine with optimization

Output Variable	Units	CAC	OFC+EGR	RSM optimized OFC+EGR
BTE	%	20.1	14.8	**24.1**
BSFC	g/kW-hr	420.2	527.7	**402.3**

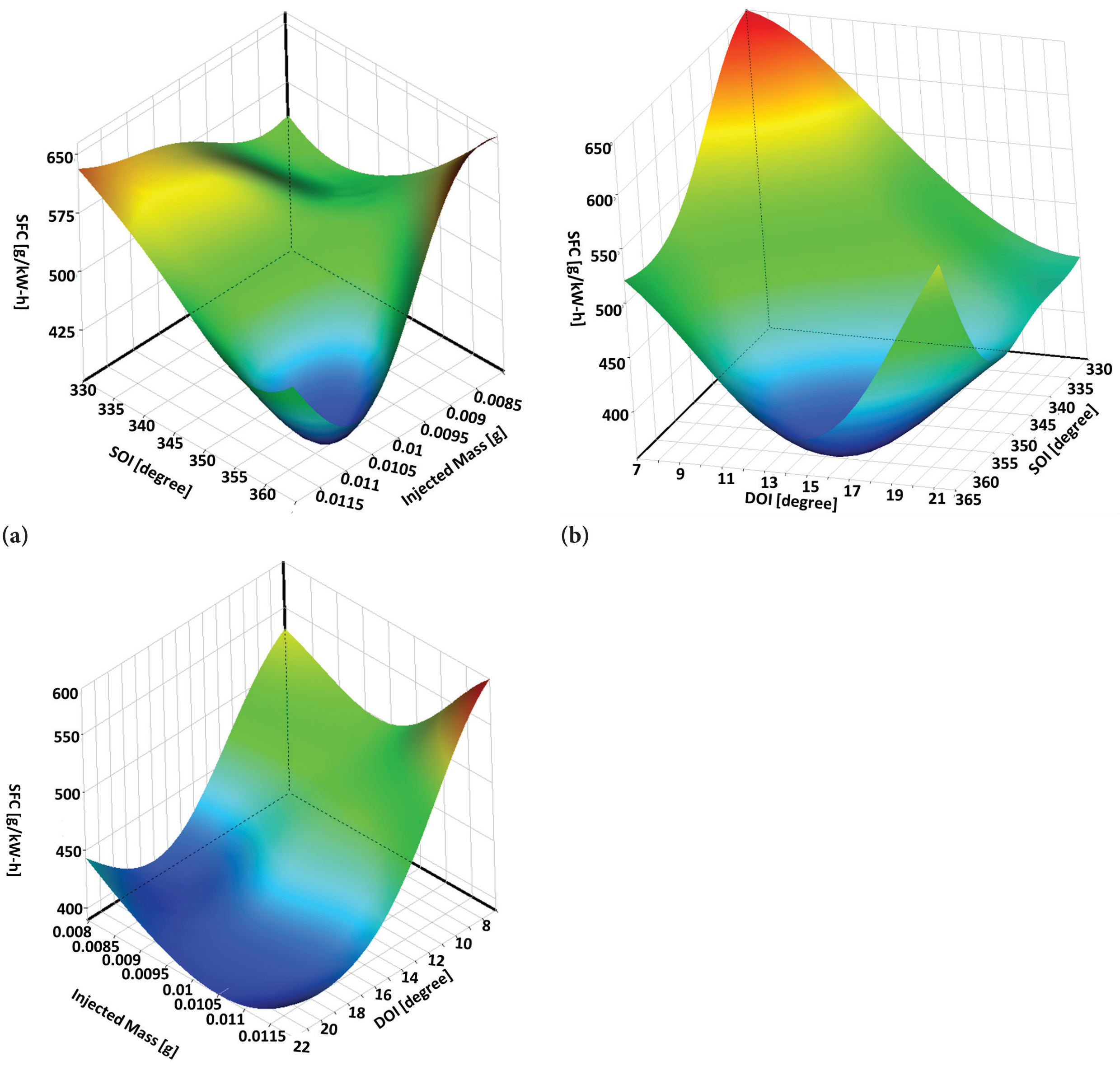


Figure 6. Surface response plots. (a) BSFC vs. SOI, MFI. (b) BSFC vs. SOI, DOI. (c) BSFC vs. DOI, MFI.

loss in BTE and BSFC with OFC implementation in a diesel engine at 1500 rpm and 25% load conditions is met. Also, the proposed models, employing RSM for BTE and BSFC, are sufficiently effective in elucidating the impact of Start of Injection (SOI), Duration of Injection (DOI), and Mass of Fuel Injected (MFI) on the performance of the OFC diesel engine.

CONCLUSION

The present study is carried out to optimize the BTE and BSFC of OFC Diesel Engine by deploying RSM to predict the optimal combination of the three injection parameters namely Start of Injection (SOI), Duration of Injection (DOI), and Mass of Fuel Injected (MFI) at 1500 rpm and 25% load conditions. An ANOVA analysis has been conducted to assess the significance of the experiments and the designed model. Drawing conclusions from the experimental results, the following observations can be made

1. The coefficient determination of R^2 for BTC and BSFC is 0.998 and 0.999 respectively.
2. The optimal combination of the three input factorial variables is determined and reported as Start of Injection at 358 CAD, Duration of Injection at 15.8 degrees and Mass of Fuel Injected at 0.0106 g.
3. The optimal solution computed by MOGA is validated through experimental analysis and the error in experimental results vs.. the predicted results is within 5%.

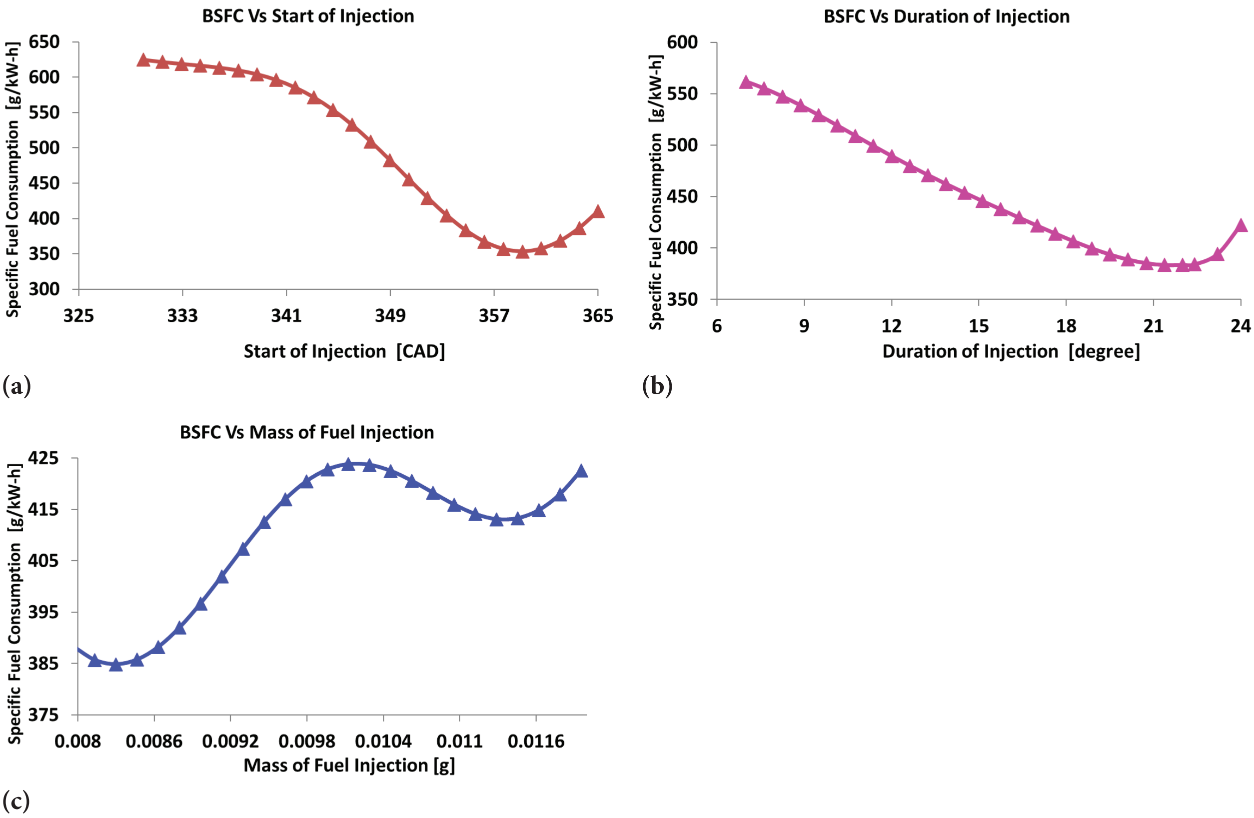


Figure 7. BSFC variation with (a) start of injection, (b) duration of injection, (c) mass of fuel injection.

4. With the optimal solution the BTE of OFC is improved from 14.8% to 24.1%, and the BSFC of OFC is reduced from 527.7 g/kW-h to 402.3 g/kW-h.

In conclusion, with the optimal injection parameters a remarkable improvement in performance of OFC diesel engine is noted and the objective of the study accomplished as the BTE of the optimized OFC with EGR is more than the CAC and is also complemented with lower BSFC with no engine modifications. Further, it is concluded that RSM is an efficient and powerful optimization method that can be applied for OFC diesel engine to optimize the combustion environment to make it more practical and feasible even at higher engine load conditions.

NOMENCLATURE

Abbreviations

ANOVA	Analysis Of Variance
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CAC	Conventional Air Combustion:
CAD	Crank Angle Degree
CSS	Carbon Capture and Storage
DI	Direct Injection
DOE	Design of experiments: DOE
DOI	Duration of Injection
EGR	Exhaust Gas Recirculation
MFI	Mass of Fuel Injected
MOGA	Multi Objection Genetic Algorithm
OFC	Oxy-Fuel Combustion
PM	Particulate matter
PPCI	Premixed Charge Compression Ignition:
RSM	Response Surface Methodology
SOI	Start Of Injection
TDC	Top Dead Centre
UHC	Unburned hydrocarbon

AUTHORSHIP CONTRIBUTIONS

All authors contributed to the study conception and design. Data collection, simulations and analysis were performed by Raghavendra Ugraram. The first draft of the manuscript was written by Raghavendra Ugraram and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared they have no relevant financial or non-financial interests to disclose.

ETHICS

There are no ethical issues with the publication of this manuscript.

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