Journal of Ship and Marine Structures

Journal homepage:
https://karyailham.com.my/index.php/jsms/index
ISSN: 3036-0137

# Optimization Study of Blended Nanoparticles – Palm Biodiesel Fuel on The Performance of Marine Diesel Engine

Che Wan Mohd Noor[1,2,*], Anas Safuan Zainu[1]

[1] Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21300 Kuala Nerus, Terengganu, Malaysia
[2] Fuel and Engines Research Interest Group, Universiti Malaysia Terengganu, 21300 Kuala Nerus, Terengganu, Malaysia

**ARTICLE INFO**

***Article history:***
Received 10 March 2024
Received in revised form 16 April 2024
Accepted 19 May 2024
Available online 30 June 2024

***Keywords:***
Nanoparticle-enhanced biodiesel; Response Surface Methodology (RSM); marine diesel engine optimization

**ABSTRACT**

The marine shipping industry's significant contribution to global emissions has intensified the search for cleaner fuel alternatives. This study investigated the optimization of nanoparticle-blended palm biodiesel fuel for marine diesel engine applications, focusing on both performance enhancement and emissions reduction. Three types of metal oxide nanoparticles ($SiO_2$, $Al_2O_3$, and $TiO_2$) were evaluated at concentrations of 50, 100, and 150 ppm in a B20 palm biodiesel blend. Initial stability tests over a 15-day period revealed that only $SiO_2$-blended samples maintained the required stability for engine testing. Experimental investigations were conducted on a Cummins NT-855 marine diesel engine coupled with a 250-kW dynamometer, operating at a constant speed of 1400 rpm under varying load conditions. Response Surface Methodology (RSM) with Central Composite Design (CCD) was employed to optimize the relationship between input variables (engine load and nanoparticle concentration) and response parameters (brake torque, brake power, and emissions). The study revealed that $SiO_2$ nanoparticles at 67.26 ppm concentration under 200 Nm engine load provided optimal performance, achieving 95.3% desirability with significant reductions in CO, $CO_2$, and NOx emissions. Statistical analysis through ANOVA validated the model's accuracy with an $R^2$ value exceeding 0.95. This research demonstrates the potential of nanoparticle-enhanced biodiesel as a viable solution for reducing marine engine emissions while maintaining performance standards.

## 1. Introduction

International shipping transportation plays a pivotal role in the global economy, with the sector responsible for transporting approximately 90% of global trade [1-3]. This extensive maritime activity, however, comes with significant environmental implications. In 2015, the global shipping fleet consumed approximately 298 million tonnes of fuel, resulting in substantial emissions of $CO_2$, greenhouse gases (GHG), sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter [4]. The International Maritime Organization's (IMO) implementation of a global 0.5% sulphur content limit on marine fuels in January 2020 has compelled the shipping industry to explore alternative marine

* *Corresponding author.*
*E-mail address: che.wan@umt.edu.my*

https://doi.org/10.37934/jsms.5.1.112b

bunker fuels with improved environmental performance. The environmental impact of combustion-related emissions, including nitrogen oxides (NOx), carbon monoxide (CO), total unburned hydrocarbons (HC), soot, and greenhouse gases, has become increasingly concerning. Additionally, the reliance on petroleum-based fuels, being non-renewable resources, poses potential energy security risks for future generations [5,6]. These challenges have intensified the search for sustainable alternative fuel solutions in the maritime sector. Among various alternatives, biodiesel has emerged as a promising candidate due to its comparable fuel characteristics to conventional diesel and its potential for reduced environmental impact [7,8].

Palm biodiesel, in particular, has gained significant attention due to its favourable properties and widespread availability. Recent studies have demonstrated that palm oil-based biodiesel offers several advantages, including high cetane number, good oxidation stability, and reduced emissions compared to conventional diesel [9]. However, certain limitations such as higher viscosity and lower energy content have prompted researchers to investigate enhancement strategies. One particularly promising approach involves the integration of nanoparticles as fuel additives [10,11]. The addition of nanoparticles to biodiesel has shown remarkable potential in improving fuel performance while simultaneously reducing exhaust emissions. Recent research has demonstrated that various types of nanoparticles, including metal oxides ($Al_2O_3$, $TiO_2$) and carbon-based materials (CNTs, graphene oxide), can significantly enhance combustion characteristics and engine performance [12-14]. These improvements include increased brake thermal efficiency, reduced specific fuel consumption, and lower emissions of NOx and particulate matter.

Response Surface Methodology (RSM) has emerged as a powerful statistical tool for optimizing complex processes in engine research. Several studies have demonstrated its effectiveness in biodiesel optimization. Uslu *et al.,* employed RSM to optimize nanoparticle concentrations in biodiesel blends, achieving an overall high desirability value of 0.7665 [15]. Similarly, Khan *et al.,* utilized RSM to optimize the engine performance parameters and found RSM is an efficient and effective optimization technique for gasoline engines operating within multi-objective optimization configurations [16]. The Box-Behnken design, a specific RSM approach, has proven particularly effective for fuel optimization studies. The advantage of RSM lies in its ability to generate mathematical models that accurately predict system behaviour while minimizing the number of required experiments. Recent studies have demonstrated its effectiveness in handling multiple response variables simultaneously. Singh *et al.,* used RSM to optimize ZnO nanoparticle concentrations in ternary biodiesel blends, resulting in improved engine performance and reduced emissions [17].

Despite these advancements, significant research gaps remain in understanding the complex interactions between nanoparticle-enhanced palm biodiesel and marine diesel engine performance, particularly in the context of optimization using RSM. Therefore, this study aims to investigate the effects of different nanoparticle concentrations on palm biodiesel fuel properties, optimize the blending parameters using Response Surface Methodology, evaluate emission characteristics under various engine operating conditions, and develop predictive models for engine performance and emissions using RSM to facilitate future optimization efforts.

## 2. Methodology
### *2.1 Fuel Preparation*

Commercial-grade diesel fuel (B0) and palm-derived biodiesel (B100) meeting EN 14214 standards were obtained from a certified local supplier. The B20 blend was prepared by mixing 80% diesel and 20% biodiesel by volume using a calibrated mechanical stirrer operating at 1000 rpm for

30 minutes at room temperature (25 ± 2°C). The base fuel properties were verified through laboratory testing according to ASTM standards to ensure consistency throughout the experiments. Three types of metal oxide nanoparticles were selected: silicon dioxide ($SiO_2$, 50 nm), aluminium oxide ($Al_2O_3$, 40 nm), and titanium dioxide ($TiO_2$, 30 nm), each with purity exceeding 99.5%.

Nine distinct fuel samples were prepared by blending B20 with each type of nanoparticle at concentrations of 50, 100, and 150 ppm. The blending process parameters were established based on previous successful studies in nanoparticle-fuel preparation. The ultrasonication frequency of 30 kHz for 30 minutes was adopted following the optimal parameters identified by Gavhane *et al.*, who demonstrated that this frequency provided effective nanoparticle dispersion while preventing particle agglomeration [18]. The magnetic stirring speed of 2400 rpm for 30 minutes was based on the work of Mostafa *et al.,* who found this combination optimal for achieving uniform nanoparticle distribution in diesel blends [19]. The stability evaluation period of 15 days was maintained under a controlled temperature of 25 ± 2°C and relative humidity of 60 ± 5%, following the protocols established by previous researchers for nanoparticle-enhanced fuel stability studies [12,20,21]. Visual inspections revealed that only $SiO_2$-blended samples maintained stability without sedimentation, while $TiO_2$ and $Al_2O_3$ blends showed significant sedimentation, making them unsuitable for engine testing due to potential injection system damage. Consequently, only the $SiO_2$ nanoparticle-blended samples were selected for subsequent engine performance testing.

### *2.2 Engine Testing*

The experimental investigations were conducted on a Cummins NT855 marine diesel engine, a 4-stroke inline 6-cylinder configuration specifically designed for marine applications. The engine was coupled to a SAJ SE-250 eddy-current dynamometer with a maximum power absorption capacity of 250 kW. Engine control and data acquisition were managed through an integrated digital control system. The complete engine specifications are presented in Table 1.

The test setup incorporated comprehensive instrumentation for performance and emissions analysis (Figure 1). Torque measurements were conducted using a high-precision load cell integrated with the dynamometer, while engine speed was monitored via a digital tachometer with ±1 rpm accuracy. The engine loading was precisely controlled through the SE-250 dynamometer controller by modulating the electromagnetic field strength. Tests were performed at five discrete load points (0, 50, 100, 150, and 200 Nm) while maintaining a constant engine speed of 1400 ± 5 rpm. Exhaust gas emissions were continuously monitored using a calibrated TAYLOR gas analyser capable of measuring CO, $CO_2$, HC, NOx, and $O_2$ concentrations. All measurements were recorded after achieving steady-state conditions, defined as parameter variations within ±2% over a 3-minute period.

**Table 1**
Engine specifications

| Specification | Description |
|---|---|
| Engine type | 4-cycle, Inline, 6-cylinder |
| Bore and Stroke | 139 mm x 152 mm |
| Displacement volume | 14 litters |
| Compression ratio | 14.5 |
| Maximum torque | 1068 Nm |
| Maximum power | 201 kW |
| Cooling system | Water cooling |

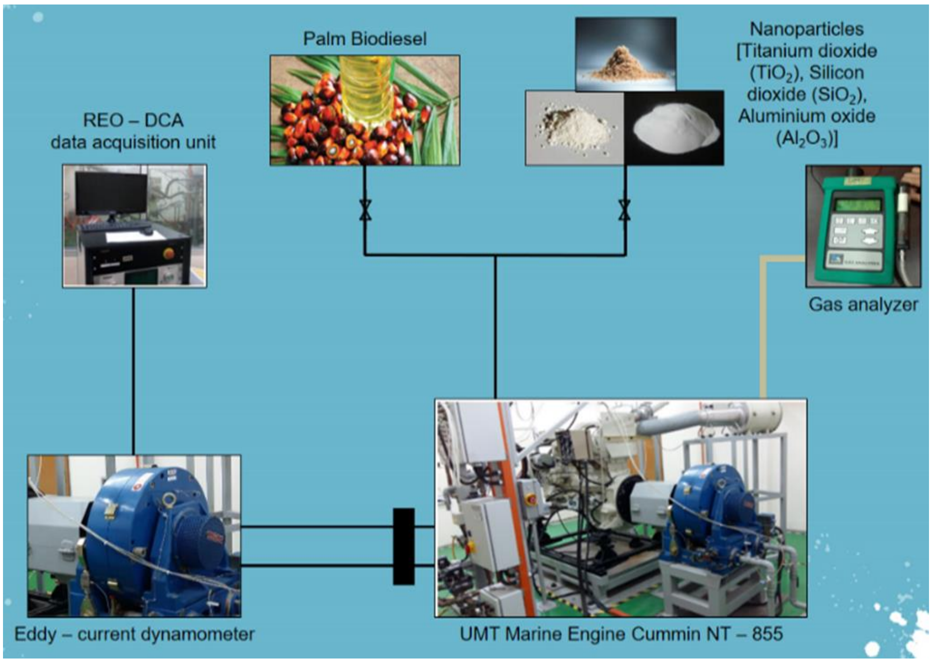


**Fig. 1.** Schematic diagram of the experimental setup

### *2.3 Design of Experiment*

The experimental investigation utilized Response Surface Methodology (RSM) through Design Expert Software to optimize engine performance and emission parameters. A Central Composite Design (CCD) was implemented to establish the relationship between input variables and response parameters. Two independent variables were considered: engine load ($X_1$: 100-200 Nm) and $SiO_2$ nanoparticle concentration ($X_2$: 50-150 ppm). The response variables encompassed both performance parameters (brake torque and brake power) and emission characteristics (CO, $CO_2$, and NOx emissions) as listed in Table 2. The experimental design comprised 13 runs, including centre points to ensure statistical validity. The mathematical relationship between the response variables (Y) and independent variables was modelled using a second-order polynomial equation:

$$y = b_0 + b_1x_1 + b_2x_2 + b_{11}{x_{11}}^2 + b_{22}{x_{22}}^2 + b_{12}x_1x_2 \quad (1)$$

Where $X_1$ represents the engine load and $X_2$ represents the nanoparticle concentration. The statistical significance of the developed models was evaluated through analysis of variance (ANOVA), and the adequacy of the models was verified using various statistical criteria including $R^2$, adjusted $R^2$, predicted $R^2$, and lack of fit tests. Three-dimensional response surface plots and contour plots were generated to visualize the interactive effects of the independent variables on the response parameters and to identify optimal operating conditions.

**Table 2**
Experimental design matrix

| Std. run | A: Engine load (Nm) | B: $SiO_2$ concentration (ppm) | Brake torque (Nm) | Brake power (kW) | CO (vol%) | $CO_2$ (vol%) | NOx (ppm) |
|---|---|---|---|---|---|---|---|
| 11 | 150 | 100 | 15.6 | 22.4 | 0.26 | 45.1 | 1515 |
| 2 | 200 | 50 | 20 | 28.7 | 0.35 | 142.9 | 793 |
| 9 | 150 | 100 | 15.4 | 22.1 | 0.26 | 45.5 | 1515 |
| 7 | 150 | 50 | 15.5 | 22.2 | 0.35 | 129.9 | 1654 |
| 13 | 150 | 100 | 20.4 | 29.3 | 0.29 | 52.1 | 1668 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 150 | 100 | 15.4 | 22.1 | 0.26 | 46.1 | 1537 |
| 1 | 100 | 50 | 10.3 | 14.7 | 0.31 | 90.8 | 1648 |
| 8 | 150 | 150 | 15.6 | 22.4 | 0.32 | 58.6 | 1514 |
| 4 | 200 | 150 | 20.4 | 29.3 | 0.32 | 86.8 | 1648 |
| 5 | 100 | 100 | 15.4 | 22.1 | 0.26 | 45.6 | 1537 |
| 10 | 150 | 100 | 15.4 | 22.2 | 0.26 | 45.2 | 1537 |
| 3 | 100 | 150 | 10.2 | 14.6 | 0.28 | 31.2 | 1141 |
| 6 | 200 | 100 | 20.4 | 29.3 | 0.29 | 52.1 | 1668 |

## 3. Results and Discussion

### *3.1 Fuel Properties*

The primary fuel properties of B0 (pure diesel), B20 (biodiesel blend), B100 (pure biodiesel), and the fuel blends with nanoparticles were evaluated, as summarized in Tables 3 and 4.

**Table 3**
Properties of B0, B20, and B100 fuels

| Property | Method | Units | B0 | B20 | B100 |
|---|---|---|---|---|---|
| Kinematic viscosity (40°C) | ASTM D7042 | $mm^2/s$ | 3.4725 | 3.4737 | 3.9160 |
| Density (15°C) | ASTM D7042 | $kg/m^3$ | 811.89 | 815.62 | 834.91 |
| Heating value | ASTM D240 | J/g | 45886 | 44747 | 42130 |

**Table 4**
Comparison of thermo-physical properties of fuel blends

| Fuel Blend | ppm | Kinematic viscosity ($mm^2/s$) | Density ($kg/m^3$) | Heating value (J/g) |
|---|---|---|---|---|
| B20 + $SiO_2$ | 50 | 3.5916 | 817.74 | 45090 |
| B20 + $SiO_2$ | 150 | 3.7792 | 820.36 | 45122 |
| B20 + $Al_2O_3$ | 50 | 3.6224 | 818.28 | 44958 |
| B20 + $TiO_2$ | 150 | 3.6019 | 817.96 | 45110 |

The evaluation of fuel properties revealed significant improvements in the blends with nanoparticle additives. The B20 blend with $SiO_2$ nanoparticles exhibited enhanced density and heating values compared to the base biodiesel. Specifically, the B20 + $SiO_2$ (150 ppm) blend showed a notable increase in kinematic viscosity and density, leading to better fuel performance. However, it was observed that the blends with $TiO_2$ and $Al_2O_3$ nanoparticles experienced sedimentation issues, which could affect the stability and performance of the fuel. Consequently, these blends were deemed unsuitable for further engine testing due to potential operational concerns.

### *3.2 Analysis of Variance (ANOVA)*

The ANOVA results provide insights into the statistical significance of the regression models developed for engine performance and emissions. Table 5 summarizes the results of the Analysis of Variance (ANOVA) conducted for the experiments, along with the numerical data concerning the p-values. The probability value (p-value) serves as a criterion for determining the minimum significance level at which the null hypothesis can be rejected. According to the ANOVA results, all models have a p-value of less than 0.05, indicating statistical significance. Additionally, Table 5 displays the regression model coefficients, $R^2$ values, and p-values for each dependent variable. The findings reveal that the proposed models are suitable, with minimal deviations and acceptable $R^2$ values for all independent variables (responses). By comparing the predicted data from the models with the experimental data, the validation process confirms that the models fit well and the variables are highly correlated.

**Table 5**
Analysis of variance (ANOVA)

| Source | Brake Power | p-value | Brake Torque | p-value | CO emission | p-value | $CO_2$ emission | p-value | $NO_x$ emission | p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| A- Engine Load | 26.81 | 0.0004 | 26.81 | 0.0004 | 10.59 | 0.0140 | 17.06 | 0.0044 | 0.2546 | 0.6260 |
| B- Concentration of $SiO_2$ | 0.0102 | 0.9216 | 0.0069 | 0.9354 | 7.09 | 0.0324 | 45.75 | 0.0003 | 0.2339 | 0.6402 |
| AB | - | - | - | - | 9.107E-15 | 1.0000 | 0.0240 | 0.8812 | 15.04 | 0.0037 |
| $A^2$ | - | - | - | - | 0.3625 | 0.5661 | 0.0861 | 0.7777 | - | - |
| $B^2$ | - | - | - | - | 43.86 | 0.0003 | 40.85 | 0.0004 | - | - |
| $R^2$ | 0.7284 | | 0.7283 | | 0.9039 | | 0.9397 | | 0.6331 | |

*3.3 Engine Performance Model*
*3.3.1 Brake torque*

The interaction effect of nanoparticle concentration in B20 blended with $SiO_2$ and engine speed on brake torque is illustrated in Figures 2 and 3. The contour surface plot in these figures shows that the addition of $SiO_2$ in B20 fuel increases brake torque across all engine speeds. As both the concentration of nanoparticles in the fuel and engine speed increase, the brake torque also increases. The graph demonstrates a clear trend where higher concentrations of $SiO_2$ nanoparticles combined with increased engine speeds result in enhanced brake torque. This indicates that $SiO_2$ acts as an effective additive in improving engine performance.

This relationship is represented by the regression model obtained using Design Expert Software, as shown in Eq. (2).

$$\text{Brake Torque} = 16.15 + 4.15\text{A} + 0.0667\text{B} \tag{2}$$

*3.3.2 Brake power*

Figures 4 and 5 present the predicted values of brake power for B20 blended with $SiO_2$ at various engine speeds. The contour surface plot reveals that increasing the nanoparticle content in the B20 fuel leads to a slight increase in engine brake power across all engine speeds, suggesting optimized combustion. The data clearly show that both engine speed and nanoparticle concentration in B20 fuel significantly affect brake power, as described by the regression model in Eq. (3).

$$\text{Brake Power} = 23.18 + 5.98\text{A} + 0.1167\text{B} \tag{3}$$

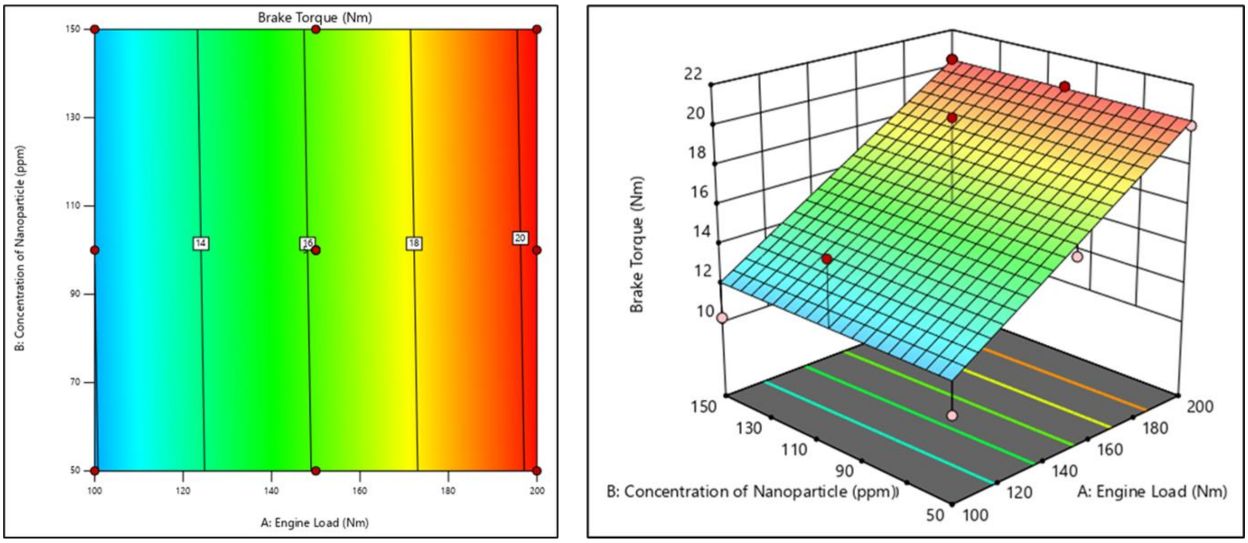


**Fig. 2.** Interaction effect of nanoparticle concentration and engine speed on brake torque

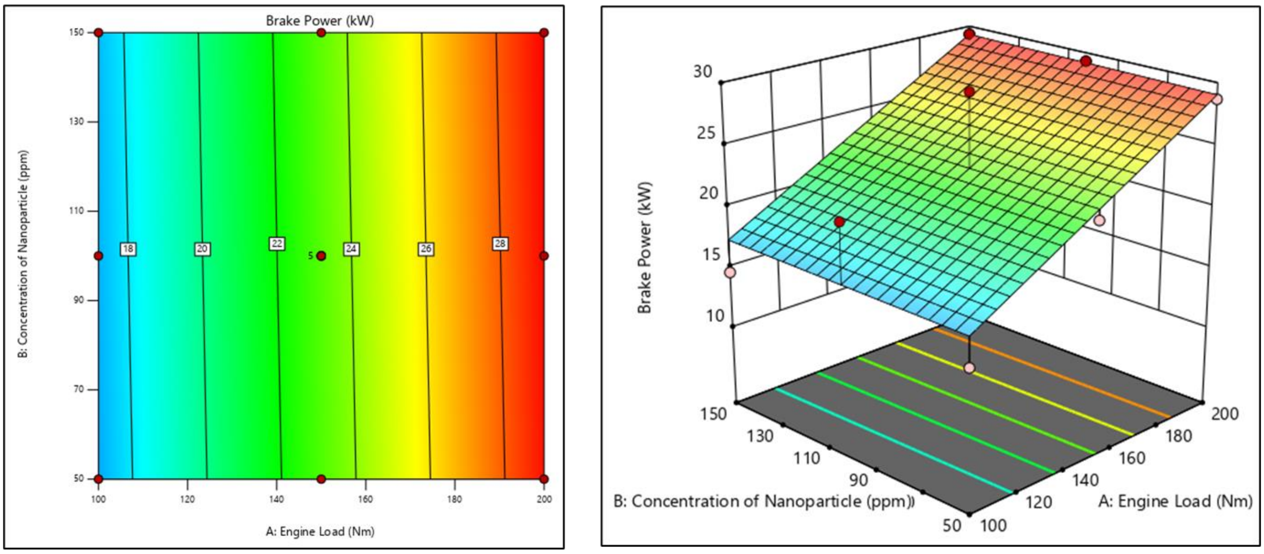


**Fig. 3.** Interaction effect of nanoparticle concentration and engine speed on brake power

### *3.3.3 Carbon monoxide (CO) emission*

The variation of CO emission with engine speed and nanoparticle concentration in B20 fuel is illustrated in Figure 4. The graph clearly shows that increasing the concentration of nanoparticles in the fuel results in a decrease in CO emissions. This trend suggests that higher nanoparticle concentrations enhance combustion efficiency, leading to more complete fuel combustion. The regression model for estimating CO emissions is presented in Eq. (4).

$$\text{CO Emission} = -0.27 - 0.0183\text{A} + 0.015\text{B} + 0.005\text{A}^2 - 0.055\text{B}^2 \quad (4)$$

The combined figure highlights the effectiveness of nanoparticle additives in reducing CO emissions across various engine speeds. Specifically, the presence of $SiO_2$ nanoparticles in the biodiesel blend significantly lowers the amount of carbon monoxide produced during combustion. This reduction is likely due to the improved catalytic activity of the nanoparticles, which facilitates a more complete oxidation of carbon-based compounds in the fuel. As a result, the emission of partially oxidized products, such as carbon monoxide, is minimized.

### *3.3.4 Carbon dioxide ($CO_2$) emission*

The interaction effect of engine speed and nanoparticle concentration in biodiesel fuel on $CO_2$ emission is illustrated in Figure 5. The experimental results indicate that $CO_2$ content increases with the rise in nanoparticle concentration. This phenomenon can be attributed to the improved combustion efficiency brought about by the addition of nanoparticles. Enhanced combustion results in a more complete oxidation of the fuel, thereby increasing the production of $CO_2$ as a byproduct.

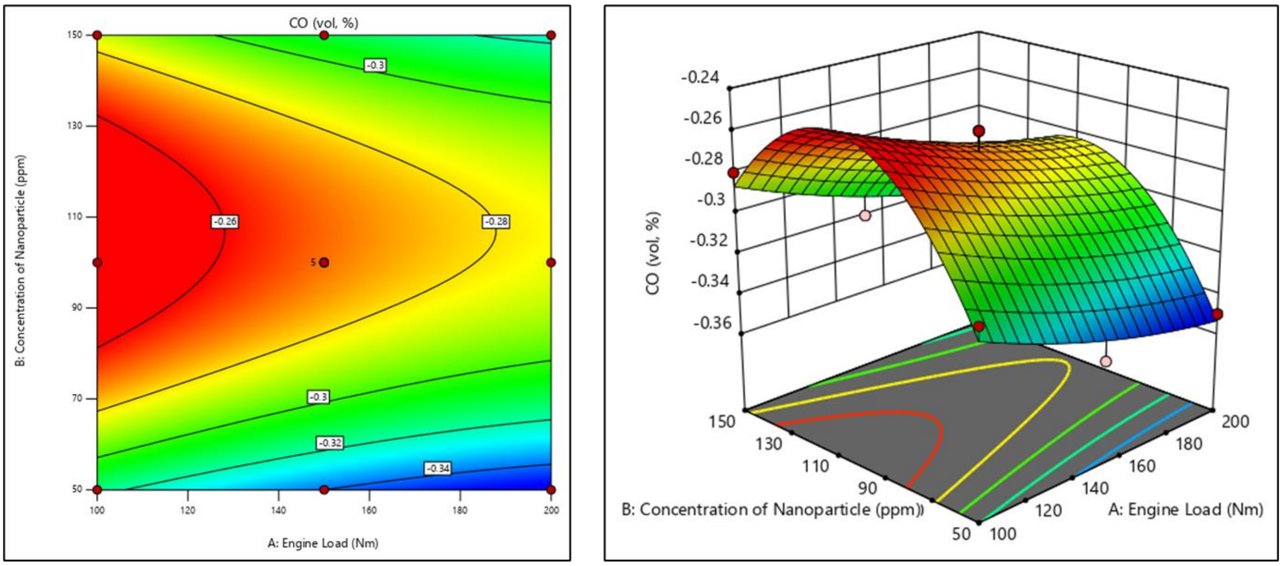


**Fig. 4.** Interaction effect of nanoparticle concentration and engine speed on CO emission

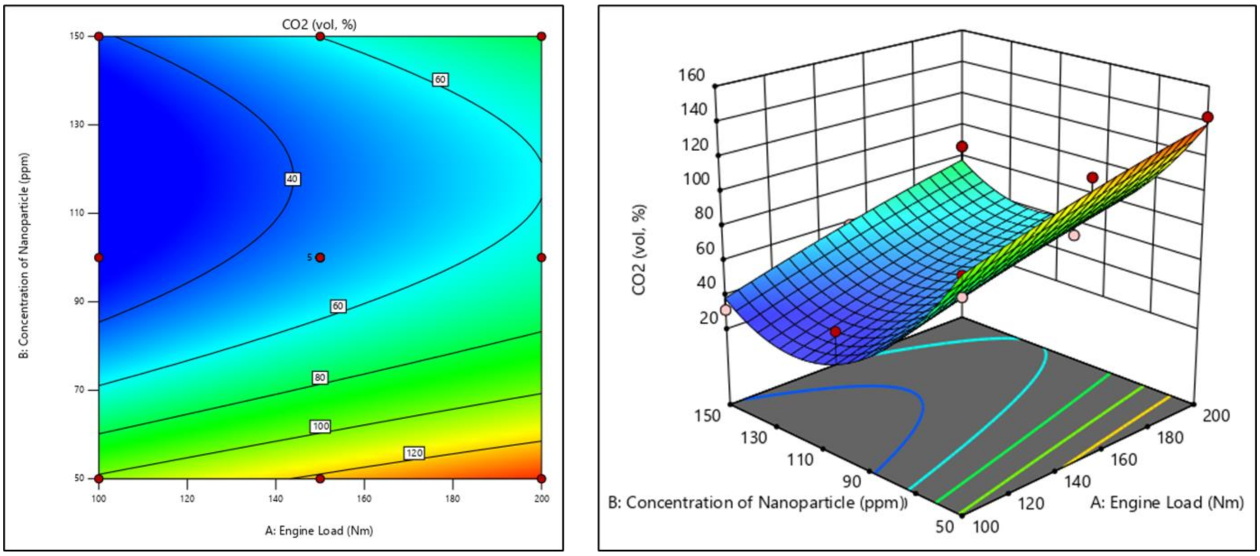


**Fig. 5.** Interaction effect of nanoparticle concentration and engine speed on $CO_2$ emission

The amount of $CO_2$ emission depends on the air-fuel ratio and the concentration of CO emission. As the CO emissions decrease due to more efficient combustion, the conversion of CO-to-$CO_2$ increases, reflecting the completion of the combustion process. The regression model for estimating $CO_2$ emissions is presented in Eq. (5).

$$\mathrm{CO_2\ Emission} = 47.96 + 19.03\mathrm{A} - 31.17\mathrm{B} + 0.875\mathrm{AB} - 1.99\mathrm{A}^2 + 43.41\mathrm{B}^2 \quad (5)$$

### *3.3.5 Nitrogen oxides (NOx) emission*

The trend of NOx emissions with respect to engine speed and nanoparticle concentration in B20 fuel is illustrated in Figure 6. The surface plot indicates that NOx concentration increases with higher nanoparticle concentrations. This increase can be attributed to the elevated combustion temperatures resulting from the improved combustion efficiency facilitated by the nanoparticles. The regression model for estimating NOx emissions is presented in Eq. (6).

$$\mathrm{NO_X\ Emission} = 1490.38 - 36.17\mathrm{A} + 34.67\mathrm{B} + 340.50\mathrm{AB} \tag{6}$$

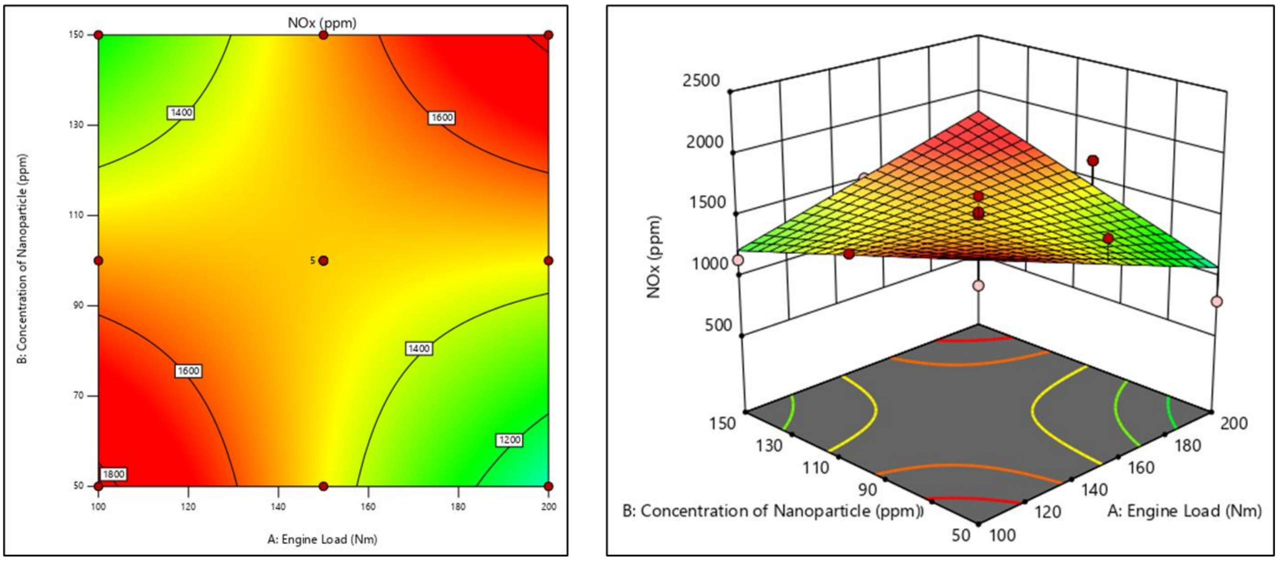


**Fig. 6.** Interaction effect of nanoparticle concentration and engine speed on NOx emission

The graph reveals that as the concentration of nanoparticles in the biodiesel blend rises, the NOx emissions also increase. This trend is primarily due to the higher temperatures achieved during combustion, which promote the formation of nitrogen oxides. While improved combustion efficiency is beneficial for reducing CO and $CO_2$ emissions, it also necessitates careful management of NOx emissions to meet environmental regulations. Further research could explore methods to mitigate NOx formation while maintaining the benefits of enhanced combustion provided by nanoparticle additives.

### *3.4 RSM-Based Optimization*

Optimization using response surface methodology (RSM) revealed significant interactions between engine load, oxide nanoparticle concentration, and emission parameters. The optimization criteria for the response, including their lower and upper limits, importance, and weight, are shown in Table 6. The weights range from 0.1 to 10, with higher weights (>1) indicating greater importance to the objective, while weights less than 1 indicate lesser importance. The relative significance of the parameters varies among them. In this optimization process, more importance is given to CO, $CO_2$, and $NO_x$ emissions.

**Table 6**
Optimization criteria of emission and performance parameters

| Parameter | Limits | | Weight | | Importance | Criterion |
|---|---|---|---|---|---|---|
| | lower | upper | lower | upper | | |
| A: Engine load | 100 | 200 | 1 | 1 | 5 | In range |
| B: Concentration of $SiO_2$ | 50 | 150 | 1 | 1 | 5 | In range |
| Brake torque | 10.2 | 20.4 | 1 | 1 | 5 | Maximize |
| Brake power | 14.6 | 29.3 | 1 | 1 | 5 | Maximize |
| CO | -0.35 | -0.26 | 1 | 0.1 | 5 | Minimize |
| $CO_2$ | 31.2 | 142.9 | 1 | 0.1 | 5 | Minimize |
| $NO_x$ | 793 | 1668 | 1 | 0.1 | 5 | Minimize |

The optimization process, utilizing a desirability approach, presented five solutions for B20 blended with $SiO_2$ nanoparticles at different concentrations, as shown in Table 7. Higher desirability solutions, which are closer to the set criteria, are preferred. Among these solutions, Solution 1 optimizes the running condition with a desirability of 0.953, achieved at 200 Nm of engine load and 67.26 ppm of $SiO_2$ concentration.

**Table 7**
Solutions of five highest desirability based on optimization criteria

| No. | Engine load (Nm) | Concentration of $SiO_2$ (ppm) | Brake torque (Nm) | Brake power (kW) | CO (%) | $CO_2$ (%) | $NO_x$ (ppm) | Desirability |
|---|---|---|---|---|---|---|---|---|
| 1 | 200 | 67.26 | 20.26 | 29.09 | 0.32 | 103.44 | 1208.59 | 0.953 |
| 2 | 200 | 51.86 | 20.24 | 29.06 | 0.35 | 134.41 | 1092.97 | 0.905 |
| 3 | 200 | 51.68 | 20.24 | 29.06 | 0.35 | 134.82 | 1091.64 | 0.933 |
| 4 | 200 | 72.81 | 20.27 | 29.10 | 0.31 | 94.31 | 1250.17 | 0.929 |
| 5 | 200 | 79.83 | 20.28 | 29.12 | 0.30 | 84.28 | 1302.84 | 0.908 |

The optimization study highlights the significant interplay between engine load, $SiO_2$ nanoparticle concentration, and exhaust emissions. By fine-tuning these parameters, it is possible to achieve optimal engine performance while minimizing harmful emissions. The desirability approach aids in identifying the most favourable operating conditions that balance performance and environmental considerations. Higher engine loads and moderate $SiO_2$ concentrations (as seen in Solution 1) lead to a desirable balance of high brake torque and power, with reduced CO and $NO_x$ emissions. The increase in $CO_2$ emissions, although indicative of improved combustion efficiency, requires careful management to ensure compliance with environmental standards.

These findings underscore the potential benefits of integrating $SiO_2$ nanoparticles into biodiesel blends, promoting cleaner and more efficient marine diesel engine operations. Further studies could explore the long-term effects of nanoparticle additives and investigate alternative nanoparticle materials to further enhance fuel performance and emission control.

## 4. Conclusions

In conclusion, this study was designed to investigate the combined impacts of blended nanoparticles – palm biodiesel fuel on the engine performance and emission characteristics of a marine diesel engine and to determine the optimization evaluation of various types of nanoparticles blended with palm biodiesel fuels on the performance and emission of a marine diesel engine. The results of the experiments are summarized as follows:

i. The combined impacts of blended nanoparticles – palm biodiesel fuel have improved biodiesel performance while lowering pollutants from the exhaust.
ii. The response model produced is found to be significant with p-values of less than 0.05.
iii. Regression statistics such as goodness of fit ($R^2$) and goodness of predictions (adjusted $R^2$) are in good agreement with each other, with the difference between them being less than 0.2, with the exception of $NO_x$ emission, where the difference is greater than 0.2.
iv. Optimization, with the objective to determine the best desirability, resulted in blended nanoparticles with palm biodiesel fuel at a concentration of 67.26 ppm and an engine load of 200 Nm, achieving a maximum desirability of 95.3%.

These findings demonstrate the potential of nanoparticles to enhance the performance and emission characteristics of biodiesel fuels in marine diesel engines, highlighting their viability as a cleaner and more efficient alternative to conventional fuels. Further research and optimization could continue to improve these outcomes, paving the way for more sustainable marine transportation solutions.

**Acknowledgement**
The authors would like to acknowledge the financial support from the Ministry of Higher Education of Malaysia under the Fundamental Research Grant Scheme (Ref No.: FRGS/1/2020/WAB05/UMT/02/2 and Vote No. 59626).

## References
[1] Tran, Tien Anh. "Effect of ship loading on marine diesel engine fuel consumption for bulk carriers based on the fuzzy clustering method." *Ocean Engineering* 207 (2020): 107383. https://doi.org/10.1016/j.oceaneng.2020.107383
[2] Gerlitz, Laima, Eike Mildenstrey, and Gunnar Prause. "Ammonia as clean shipping fuel for the Baltic Sea region." *Transport and Telecommunication Journal* 23, no. 1 (2022): 102-112.https://doi.org/10.2478/ttj-2022-0010
[3] Balcombe, Paul, James Brierley, Chester Lewis, Line Skatvedt, Jamie Speirs, Adam Hawkes, and Iain Staffell. "How to decarbonise international shipping: Options for fuels, technologies and policies." *Energy conversion and management* 182 (2019): 72-88. https://doi.org/10.1016/j.enconman.2018.12.080
[4] Svanberg, Martin, Joanne Ellis, Joakim Lundgren, and Ingvar Landälv. "Renewable methanol as a fuel for the shipping industry." *Renewable and Sustainable Energy Reviews* 94 (2018): 1217-1228. https://doi.org/10.1016/j.rser.2018.06.058
[5] Yan, Junhao, Suya Gao, Weihua Zhao, and Timothy H. Lee. "Study of combustion and emission characteristics of a diesel engine fueled with diesel, butanol-diesel and hexanol-diesel mixtures under low intake pressure conditions." *Energy Conversion and Management* 243 (2021): 114273. https://doi.org/10.1016/j.enconman.2021.114273
[6] Ulukardesler, Ayse Hilal. "Biodiesel production from waste cooking oil using different types of catalysts." *Processes* 11, no. 7 (2023): 2035. https://doi.org/10.3390/pr11072035
[7] Nayab, Rida, Muhammad Imran, Muhammad Ramzan, Muhammad Tariq, Muhammad Babar Taj, Muhammad Nadeem Akhtar, and Hafiz MN Iqbal. "Sustainable biodiesel production via catalytic and non-catalytic transesterification of feedstock materials–A review." *Fuel* 328 (2022): 125254. https://doi.org/10.1016/j.fuel.2022.125254
[8] Kosuru, Sai Mani Yogesh, Yashraj Delhiwala, Prasad Babu Koorla, and Mallaiah Mekala. "A review on the biodiesel production: Selection of catalyst, pre-treatment, post treatment methods." *Green Technologies and Sustainability* 2, no. 1 (2024): 100061. https://doi.org/10.1016/j.grets.2023.100061
[9] Dey, S., N. M. Reang, P. K. Das, and M. Deb. "A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel." *Journal of cleaner production* 286 (2021): 124981. https://doi.org/10.1016/j.jclepro.2020.124981
[10] Uslu, Samet. "Optimization of diesel engine operating parameters fueled with palm oil-diesel blend: Comparative evaluation between response surface methodology (RSM) and artificial neural network (ANN)." *Fuel* 276 (2020): 117990. https://doi.org/10.1016/j.fuel.2020.117990

[11] Saxena, Vishal, Niraj Kumar, and Vinod Kumar Saxena. "A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine." *Renewable and Sustainable Energy Reviews* 70 (2017): 563-588. https://doi.org/10.1016/j.rser.2016.11.067

[12] Chen, Yanhui, Jian Zhang, Zhiqing Zhang, Bin Zhang, Jingyi Hu, Weihuang Zhong, and Yanshuai Ye. "A comprehensive review of stability enhancement strategies for metal nanoparticle additions to diesel/biodiesel and their methods of reducing pollutant." *Process Safety and Environmental Protection* (2024). https://doi.org/10.1016/j.psep.2024.01.052

[13] Gupta, Aveek, Ravinder Kumar, Ashish Maurya, Mohammad H. Ahmadi, Bulbul Ongar, Anara Yegzekova, Jeet Prakash Sharma, Sumit Kanchan, and Sagar Shelare. "A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine." *Energy Science & Engineering* 12, no. 1 (2024): 284-303. https://doi.org/10.1002/ese3.1614

[14] Nagappan, M., A. Devaraj, J. M. Babu, Nishant Vibhav Saxena, Om Prakash, Prashant Kumar, and Abhishek Sharma. "Impact of additives on Combustion, performance and exhaust emission of biodiesel fueled direct injection diesel engine." *Materials Today: Proceedings* 62 (2022): 2326-2331. https://doi.org/10.1016/j.matpr.2022.04.114

[15] Uslu, Samet, Suleyman Simsek, and Hatice Simsek. "RSM modeling of different amounts of nano-TiO2 supplementation to a diesel engine running with hemp seed oil biodiesel/diesel fuel blends." *Energy* 266 (2023): 126439. https://doi.org/10.1016/j.energy.2022.126439

[16] Khan, Osama, Mohd Zaheen Khan, Bhupendra Kumar Bhatt, Md Toufique Alam, and Manoj Tripathi. "Multi-objective optimization of diesel engine performance, vibration and emission parameters employing blends of biodiesel, hydrogen and cerium oxide nanoparticles with the aid of response surface methodology approach." *International Journal of Hydrogen Energy* 48, no. 56 (2023): 21513-21529. https://doi.org/10.1016/j.ijhydene.2022.04.044

[17] Singh, Ashish Kumar, Harveer Singh Pali, and Mohammad Mohsin Khan. "Response surface optimization approach to enhance the performance of diesel engine using ternary blends of biobutanol and biodiesel doped with ZnO nanoparticles." *Energy Conversion and Management* 300 (2024): 117899. https://doi.org/10.1016/j.enconman.2023.117899

[18] Gavhane, R. S., A. M. Kate, Manzoore Elahi M. Soudagar, V. D. Wakchaure, Sagar Balgude, I. M. Rizwanul Fattah, Nik-Nazri Nik-Ghazali et al. "Influence of silica nano-additives on performance and emission characteristics of Soybean biodiesel fuelled diesel engine." *Energies* 14, no. 5 (2021): 1489. https://doi.org/10.3390/en14051489

[19] Mostafa, A., M. Mourad, Ahmad Mustafa, and I. Youssef. "Influence of aluminum oxide nanoparticles addition with diesel fuel on emissions and performance of engine generator set using response surface methodology." *Energy Conversion and Management: X* 19 (2023): 100389. https://doi.org/10.1016/j.ecmx.2023.100389

[20] Antony, Godwin. "Ecological effect of corn oil biofuel with SiO2 nano-additives." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 41, no. 23 (2019): 2845-2852. https://doi.org/10.1080/15567036.2019.1576079

[21] Jin, Chuanhao, Jiangjun Wei, Buze Chen, Xingyao Li, Dongxuan Ying, Li Gong, and Weihao Fang. "Effect of nanoparticles on diesel engines driven by biodiesel and its blends: A review of 10 years of research." *Energy Conversion and Management* 291 (2023): 117276. https://doi.org/10.1016/j.enconman.2023.117276