ISSN: 2096-3246
Volume 58, Issue 02, 2026

EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF HYBRID NANOPARTICLE-ENHANCED EMULSIFIED FUEL FOR PERFORMANCE OPTIMIZATION IN INTERNAL COMBUSTION ENGINES

- *SUB-TITLES ARE NOT CAPTURED IN XPLORE AND SHOULD NOT BE USED*
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***Abstract*—**This research presents an experimental and analytical examination of a hybrid nanoparticle-enhanced water-emulsified biodiesel fuel for diesel engine utilization. The suggested fuel is made up of B15 biodiesel (85% diesel and 15% waste cooking oil biodiesel), distilled water, titanium dioxide (TiO_2) nanoparticles (20–30 nm), and carbon quantum dots (CQDs) made from orange peel biomass. The hybrid nano-additives were added to speed up combustion, catalytic oxidation, and secondary atomization through micro-explosion events. We tested a single-cylinder, four-stroke, water-cooled, direct-injection diesel engine (3.5 kW, 17.5:1 compression ratio) that ran at a steady speed of 1500 rpm with loads that changed from 25% to 100%, corresponding to experimental points at 25%, 50%, 75%, and 100%. We looked at performance metrics like brake thermal efficiency (BTE) and indicated thermal efficiency (ITE), as well as emissions like NO_x, HC, CO, and SO_2. The results showed that the maximum BTE was 38.82% at 80% load with 100 mg/L TiO_2, 100 mg/L CQDs, and 5% water content. This is a big improvement over the baseline diesel operation. Adding 10% water cut NO_x emissions by about 17% because of thermal quenching. Using the best concentrations of nanoparticles cut HC emissions by 78% and CO emissions by 61%. A physics-based artificial neural network (ANN) model was very good at making predictions, with R^2 values over 0.86 for all output parameters. The hybrid TiO_2–CQD emulsified fuel system had 4–7% higher BTE and 12–18% lower HC emissions than regular single-nanoparticle fuel blends. This shows that the suggested synergistic combustion enhancement approach works.

Keywords*— *Hybrid nanoparticles, emulsified biodiesel fuel, waste cooking oil, carbon quantum dots, nitrogen oxide, Internal Combustion.

Introduction

Internal combustion (IC) engines continue to function as the primary power source for transportation systems because they generate about 81.3% of the industry's petroleum needs which support Nearly 1.19 billion people and 249 million commercial cars vehicles around the globe. [1]. The transportation sector accounts for 25.5 percent of worldwide energy usage and 16.2% of all GHG emissions, ranking it as the fourth biggest emission producing sector. Researchers investigate alternative fuels and combustion improvement methods because of two factors which include stringent emission regulations (Euro VI, BS-VI) and energy security requirements.

Biodiesel produced from waste cooking oil (WCO) functions as an effective renewable energy source since it transforms waste materials into usable fuel while decreasing carbon dioxide and hydrocarbon emissions and reducing sulfur emissions. The direct replacement of petroleum diesel becomes impossible because pure biodiesel shows reduced thermal capacity, increased viscosity, and increased density than petroleum diesel. Unmodified compression ignition (CI) engines showed acceptable performance with 15-20% biodiesel blends (B15/B20) combined with petroleum diesel yet the engines encountered problems with nitrogen oxide emissions and cold-flow characteristics [2][3].

Water-emulsified fuels create a secondary atomization process which occurs through micro-explosion effects. The process begins when dispersed water droplets reach temperatures above 100°C. This process generates internal pressure which causes the fuel droplet to shatter into smaller pieces. These smaller pieces enhance the process of fuel and air combination. Park and Oh [4] The research showed that diesel-water emulsion fuel (DWE) produced 15.3% shorter combustion times together with 19.6% lower nitrogen oxide emissions and 66.3% less smoke compared to regular diesel. Bora et al. [5] demonstrated dual-fuel best performance at 29° BTDC injection timing with esterified pilot fuel as emulsifier in biodiesel fuel.

Nanoparticle fuel additives have become popular research materials because they function as combustion catalysts. The nanoparticles of metal oxides TiO_2, CeO_2, and Al_2O_3 and CuO and Fe_2O_3 and NiO enable better ignition performance because they decrease activation energy while providing additional oxygen for oxidation which results in shorter ignition delays and lower rates of unburned fuel emissions [6], [7][8][9]. The oxygen storage and release system of cerium oxide which operates through the surface functional groups of carbon quantum dots which operate through reactive oxygen species enable controlled radical generation during combustion [10]. Single nanoparticle studies have consistently demonstrated 3–8% BTE improvements and 15–35% HC reductions, but hybrid nanoparticle combinations with emulsified water in biodiesel blends need further research to understand their interaction effects [11][12].

The current research investigates this existing research gap by creating and evaluating a hybrid TiO_2–CQD nanoparticle-enhanced emulsified B15 fuel system which operates in a single-cylinder CI engine from 25% to 100% of its maximum power output. The study has four specific goals which are to: (i) study the properties of TiO_2 and CQD nanoparticles and their distribution in B15 emulsified fuel; (ii) measure the performance improvements (BTE, ITE, mechanical efficiency) and emission reductions (NO_x, HC, CO, SO_2) across various testing conditions; (iii) create a physics- using an artificial neural network model to predict how well an engine will run; and (iv) verify experimental findings against established benchmarks which use single-nanoparticle materials.

II. Materials and Methods

Previous studies on emulsified fuels mainly focused on conventional metallic nanoparticles; however, limited studies have explored the use of hybrid nanoparticles made of metal oxides to enhance the efficiency of combustion and the characteristics of emissions in biodiesel–diesel emulsified fuels. The present study aims to develop and evaluate a hybrid nanoparticle-enhanced emulsified fuel composed of diesel fuel, B15 biodiesel blend, water, and hybrid nanoparticles consisting made up of carbon quantum dots (CQDs) and titanium dioxide (TiO_2). The proposed fuel formulation is investigated using a compression ignition engine in order to determine the impact on engine performance parameters and exhaust emissions such sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO).

A. Engine Specifications and Experimental Setup

The Engine Lab conducted trials on a water-cooled, direct-injection diesel engine with one cylinder and four strokes. Research Laboratory. Full Engine details may be found in Table 1. An eddy-current dynamometer was connected to the engine. (accuracy ±0.5%) for load control. The gravimetric approach, which involves using a calibrated burette and a timer, was used to quantify fuel consumption with an accuracy of ±0.2%. The emissions of NO_x, HC, CO, and SO_2 were measured using a Crypton-865 exhaust gas analyzer, with measurement errors of ±5 ppm, ±1 ppm, ±0.01%, and ±1 ppm, respectively. Thermocouple utilized was a K-type (±1°C). to measure exhaust gas temperature. All measurements were taken at steady-state conditions after 10 minutes of thermal stabilization at each operating point.

'Table 1: Engine Specifications'

Parameter	**Specification**
'Engine Type	'Single-cylinder, 4-stroke, DI diesel
Bore × Stroke	87.5 mm × 110 mm
Swept Volume	661 cc
Compression Ratio	17.5:1
Rated Power	3.5 kW at 1500 rpm
Rated Speed	1500 rpm (constant)
Injection Pressure	200 bar
Injection Timing	23° BTDC
Cooling System	Water-cooled
Dynamometer'	Eddy-current, 0–5 kW'

B. Materials and Fuel Formulation

The development of the hybrid nanoparticle-based emulsified fuel was carried out through systematic material selection and fuel formulation procedures. The proposed fuel system integrates renewable biodiesel with diesel fuel and water and hybrid nanoparticles to achieve better combustion efficiency while preserving the stability the gasoline.

'Table 2: Physicochemical Properties of Fuel Components'

Property	**Diesel**	**WCO Biodiesel**	**B15 Blend**	**Test Method**
'Calorific Value (MJ/kg)	'42.5	39.8	42.1	ASTM D240
Density at 15°C (kg/m³)	830	878	837	ASTM D1298
Kinematic Viscosity at 40°C (cSt)'	2.8	4.5	3.2	ASTM D445'
Flash Point (°C)	52	165	58	ASTM D93

Cetane Number	50	52	50.3	ASTM D613
Sulfur Content (ppm)	15	< 5	12.8	ASTM D5453

C. Base Fuels and Blend Composition

The study used B15 biodiesel blend as its primary fuel which contains 85% diesel and 15% biodiesel that comes from waste cooking oil. The researchers chose biodiesel blend because it offers better lubrication properties and contains more oxygen and works well with standard diesel engines.

Water was added to the fuel mixture to create an emulsified fuel system which produces micro-explosion effects during combustion and improves the atomization procedure of the fuel droplets.

The fuel's reduced calorific value mixture was calculated by the volumetric blending law.:

$$CV_{blend} = \sum_{i=1}^{n} \phi_i \, CV_i$$

where

‘CV_{blend} = effective calorific value of the blended fuel (kJ/kg)

ϕ_i = volume fraction of component i

CV_i = calorific value of individual fuel component’

The biodiesel and water addition decreases the blended fuel's calorific value; yet the nanoparticles present in the fuel restore its combustion performance through their kinetic enhancements.

D. Hybrid Nanoparticles

The researchers added hybrid nanoparticles to the emulsified fuel which resulted in better combustion efficiency and improved ignition properties and reduced emissions. The study used nanoparticles of carbon quantum dots (CQDs) and titanium dioxide (TiO_2) because of their ability to catalyze oxidation reactions and their function as photocatalytic surface-active materials.

1) Titanium Dioxide (TiO_2) Nanoparticles

The primary catalytic additives used in this study were titanium dioxide nanoparticles which had an average particle size of 20-30 nanometers and 99.5% purity in the anatase phase. The TiO_2 nanoparticles used in this study showed combustion oxidation reaction enhancement because they decreased activation energy requirements and accelerated reaction kinetics.

The effective rate constant responsive to catalytic nanomaterials can be denoted by:

$$k = A\exp\left(\frac{-(E_a - \Delta E_{cat})}{RT}\right)$$

‘where

k = reaction rate constant

A = pre-exponential factor

E_a = base activation energy’

‘ΔE_cat = reduction in activation energy due to catalytic nanoparticles

R = universal gas constant

T = combustion temperature’

2) Carbon Quantum Dots (CQDs)

The researchers selected carbon quantum dots (CQDs) as secondary hybrid additives due to their high surface area, functional groups, and excellent catalytic activity. The surface functional groups present in CQDs promote radical formation and enhance oxidation reactions during combustion, thereby improving combustion efficiency and reducing incomplete combustion emissions.

E. Synthesis of Carbon Quantum Dots (CQDs)

Researchers synthesized carbon quantum dots (CQDs) from orange peel biomass through a hydrothermal carbonization method. Orange peel was washed, dried, and ground into fine powder. The powder was dissolved in deionized water (1 g per 10 mL) and continuously stirred using a magnetic stirrer.

The solution was transferred to a Teflon-lined autoclave and heated at 180°C for 12 hours under hydrothermal conditions, resulting in the formation of fluorescent carbon quantum dots.

The CQD formation reaction is represented by:

$$C_6H_{12}O_6 \rightarrow C\,(CQDs) + 6H_2O + \text{gases}\,(CO_2, CO)$$

The obtained hydrothermal product was purified and dried to obtain stable carbon quantum dots (CQDs) suitable for use as nano-additives in fuel applications.

F. Nanoparticle Characterization

Different methods could help determine the morphology, size, or after-synthesis change of nanoparticals.

Imaging Techniques for Electron Scanning (SEM) and Transmission Particle form and size distribution were investigated using Transmission Electron Microscopy (TEM). The research used X-ray diffraction (XRD) analysis to ascertain the crystalline structure and Fourier Transform Infrared Spectroscopy (FTIR) to detect functional groups.

The size of the crystals was calculated using the Scherrer equation of nanoparticles:

$$'D = \frac{K\lambda}{\beta \cos\theta}'$$

where,

D = crystallite size (nm)
K = shape factor
λ = X-ray wavelength
β = full width at half maximum
θ = Bragg diffraction angle'

G. Fuel Emulsification and Stability Assessment

1) Emulsion Preparation

These hybrid nanoparticle enhanced fuels were made through two-step emulsification method. The base B15 fuel blend was first mixed with non-ionic surfactants Span-80 (1% v/v) and Tween-80 (2% v/v). The researchers combined distilled water which had suspended TiO_2 and CQD nanoparticles with the fuel mixture using high-shear mixing methods. The team used 40 kHz ultrasonication at 200 W power for 30 minutes to create an even distribution of nanoparticles throughout the material.

The surfactant combination had an HLB value of hydrophilic-lipophilic balance, which was found.:

$$HLB_{mix} = \sum \phi_j HLB_j$$

2) Stability Analysis

How well the emulsified gasoline holds its moisture was evaluated by analyzing sedimentation velocity using Stokes' law:

$$'v_s = \frac{2r^2(\rho_p - \rho_f)g}{9\mu},$$

'where
r = particle radius
ρ_p = particle density
ρ_f = fluid density
µ = dynamic viscosity'

H. Experimental Engine Setup

The brake power (BP) of the engine was calculated using the measured torque and engine speed. All calculated power values were verified to ensure consistency with the rated engine capacity (3.5 kW). Any discrepancies observed in preliminary calculations were corrected by properly accounting for unit conversions and dynamometer calibration factors. The final reported values of brake power were maintained within the permissible operating limits of the engine.

$$BP(kW) = \frac{2\pi NT}{60}$$

'where
'BP = brake power
N = engine speed (rpm)
T = torque (Nm)'

A gravimetric determinate of the fuel flow_rates had been made as:

$$\dot{m}_f = \frac{\Delta m}{\Delta t}$$

I. Experimental Design

The researchers employed a factorial experimental design to study how different operating parameters affected their results. The experiments tested four different engine load conditions which included 25% and 50% and 75% and 100% load conditions.

The primary elements of the experiment were:

- Engine load (25–100%)
- TiO_2 nanoparticle concentration (25–100 mg/L)
- CQD concentration (25–100 mg/L)
- Water content (5–20%)

J. Indicated Power Measurement

The indicated power (IP) was estimated using the relation between brake power and mechanical efficiency:

$$IP = \frac{BP}{\eta_m}$$

where
η_m = mechanical efficiency (≈ 0.80–0.85)

This ensures that indicated power values remain within physically realistic limits for the given engine specifications.

K. Performance Evaluation

We evaluated the engine's performance characteristics with the following parameters.

Brake Thermal Efficiency:

$$\eta_{BTE} = \frac{BP}{\dot{m}_f \times CV_{blend}}$$

Indicated Thermal Efficiency:

$$\eta_{ITE} = \frac{IP}{\dot{m}_f \times CV_{blend}}$$

Mechanical Efficiency:

$$\eta_m = \frac{BP}{IP}$$

L. Physics-Guided Dataset Generation

The researchers created semi-empirical models which used combustion theory to produce a physics-based dataset that acted as training material for Artificial Neural Network (ANN) development. Brake thermal efficiency was modeled as:

$$\eta_{BTE} = 20.0 + 0.17L + 0.020C_{TiO_2} + 0.018C_{CQD} - 0.08W + \epsilon$$

where
L = engine load (%)
C_{TiO_2} = TiO_2 concentration
C_{CQD} = CQD concentration
W = water content

M. Emission Modelling

NOx emissions were modeled using a semi-empirical approach:

$$NO_x = 200 + 7.5L + 0.8C_{TiO_2} + 0.7C_{CQD} - 3.0W + \epsilon$$

NOx formation follows the extended Zeldovich mechanism:

$$'\frac{d[NO]}{dt} = k_1[N_2][O] + k_2[N][O_2] + k_3[N][OH]'$$

N. Artificial Neural Network (ANN) Modelling

ANN modelling had a role in forecasting the efficiency of the engine and its emissions.

$$Y = f(X) = W_n\sigma(W_{n-1}\sigma(\ldots\sigma(W_1X + b_1)))$$

Data normalization was performed as:

$$X' = \frac{X - \mu_X}{\sigma_X}$$

The loss function minimized during training was:

$$MSE = \frac{1}{N}\sum(Y_i - \widehat{Y_i})^2$$

Model validation was carried out using RMSE and R^2 metrics.

$$RMSE = \sqrt{\frac{1}{N}\sum(Y_i - \widehat{Y_i})^2}$$

$$R^2 = 1 - \frac{\sum(Y_i - \widehat{Y_i})^2}{\sum(Y_i - \bar{Y})^2}$$

III. Results and Discussion

Detailed examination of engine performance is provided in this section. and emission characteristics together with predictive modeling results which were obtained from testing hybrid nanoparticle-enhanced emulsified fuel. The research study investigates experimental results and physics-guided artificial neural networks to demonstrate how engine load and nanoparticle concentration and water content interact with each other in creating synergistic effects. The discussion presents combustion mechanisms and thermodynamic trends together with emission formation pathways which receive support from quantitative results.

A. Performance Characteristics

1) 'Brake Thermal Efficiency'

Engineers utilize effectiveness of the braking system (BTE) as a primary measurement instrument which enables them to assess engine combustion efficiency and engine total energy conversion performance. The table presents BTE variations which depend on different engine load conditions and nanoparticle concentrations and water content levels.

Table 3 Brake Thermal Efficiency (%) at Various Operating Conditions

Load (%)	TiO_2 (mg/L)	CQD (mg/L)	Water (%)	BTE (%)
25	25	25	5	24.37
25	25	25	10	23.34
25	25	25	15	23.72
25	25	25	20	24.20
50	50	50	10	27.50
75	50	50	10	31.63
100	50	50	10	34.47
80	100	100	5	38.82

There is a positive relation between brake thermal efficiency and engine load with a maximum value of 38.82% at 100% engine load with 100 mg/L TiO_2, 100 mg/L CQDs, and 5% water content. Such increase is explained by the combined effect of hybrid nanoparticles and favorable combustion characteristics at increased engine loads. The increase in engine load results in high temperatures inside the cylinder, which favors oxidation of fuel and efficient heat release.

The TiO_2 nanoparticles function as catalysts for combustion by decreasing activation energy and oxidation processes. In addition, the CQDs promote secondary atomization through micro-explosion. On the other hand, when engine load is lower (25%), the effect of water content in the emulsion is more significant. Excess water results in decreased calorific value and partially flame extinction leading to decreased brake thermal efficiency. It should be noted that the non-linear relationship is explained by favorable atomization properties with smaller amounts of water.

The engine load's linear effect on brake torque efficiency could be seen:

$$\mathrm{BTE} = 22.0 + 0.17L(R^2 = 0.93)$$

The engine load percentage can be found at the location where the engine load percentage is displayed. The high coefficient of determination shows that engine load serves as the primary element which determines thermal efficiency, while nanoparticle concentration and water content act as secondary elements that affect the process.

2) Indicated Thermal Efficiency

Because its values varied from 25.61% to 43.30% throughout all operating circumstances, just like the brake thermal efficiency (BTE), the indicated thermal efficiency (ITE) behaved in a predictable manner. A rise in ITE as load increases proves that in -cylinder combustion efficiency has improved while heat losses have decreased at higher load conditions. The mechanical efficiency which results from dividing brake power by indicated power reached approximately 0.82 which matches the typical values found in single-cylinder diesel engines during steady-state operation. The BTE improvements which we observed existed because combustion enhancements occurred without any changes to mechanical losses.

B. Emission Characteristics

1) Nitrogen Oxides (NO_x)

The discharge of nitrogen oxides is contingent upon three factors which include in-cylinder temperature and oxygen availability and the duration that gases remain in the cylinder. The table presents NO_x emissions data which shows their measurement at different operational conditions.

Table 4Summarizes the NOx emission characteristics.

Load (%)	**TiO_2 (mg/L)**	**CQD (mg/L)**	**Water (%)**	**NOx (ppm)**
25	25	25	5	373.08
25	25	25	10	381.22
25	25	25	15	337.40
25	25	25	20	336.68
50	50	50	10	544.80
75	50	50	10	718.41
100	50	50	10	857.19
100	100	100	5	980.05

NO_x emission levels will increase with increasing engine loading, ranging from 373.08 ppm at 25% loading to 980.05 ppm at 100% loading in conditions of maximum nanoparticle concentration. These high emissions occur as a result of increased cylinder temperature and improved combustion intensity caused by higher loading conditions.Use of TiO_2 nanoparticles and carbon quantum dots will improve the combustion process through the enhancement of the oxidation process, leading to high local flame temperatures. On the other hand, adding emulsified water will reduce NO_x emissions by about 15 to 20% through the thermal quenching effect.

The observed NO_x trends are consistent with the extended Zeldovich mechanism:

$$'\frac{d[NO]}{dt} = k_1[N_2][O] + k_2[N][O_2] + k_3[N][OH]'$$

NO_x formation increases significantly with increasing engine load due to higher in-cylinder temperatures and enhanced combustion intensity. At higher loads, the elevated temperature promotes thermal NO formation through the extended Zeldovich mechanism, leading to increased NO_x emissions.

2) Hydrocarbon (HC) Emissions

The hydrocarbon emissions demonstrate that the combustion processes were incomplete because the fire suppression systems had been activated. Table 3 delineates the properties of HC emissions.

Table 5 Hydrocarbon emissions under different operating conditions

Load (%)	**TiO_2 (mg/L)**	**CQD (mg/L)**	**Water (%)**	**HC (ppm)**
25	25	25	5	90.73
25	25	25	10	86.70

25	25	25	15	94.08
25	25	25	20	99.82
50	50	50	10	51.71
75	50	50	10	27.43
100	50	50	10	20.66
100	100	100	5	20.00

Hydrocarbon (HC) emissions decline sharply with the rise in engine load and nanoparticle concentrations, resulting in a minimum HC emission level of 20 ppm when the engine operates at 100% load. HC emissions experience the highest reduction rate of about 78% as compared to the reduction rate experienced at low-load operation.The decline in HC emissions can be contributed to fuel atomization improvement, oxidation reaction enhancement, and reduced ignition delay as a result of the TiO_2 nanoparticle catalytic effect and micro-explosion phenomena due to CQDs. With a lower engine load (25%), an increase in water content would result in a slight increase in HC emissions due to flame quenching and incomplete burning.

3) 'Carbon Monoxide (CO) Emissions'When engine load and nanoparticle concentration increased carbon monoxide emissions showed a decreasing trend. The ideal nanoparticle conditions resulted in carbon monoxide levels which decreased from 1.16% at 20% load to 0.24% at 80% load. The process achieves superior air fuel mixing patterns which enhance combustion efficiency and enable faster CO oxidation to CO_2 through TiO_2 catalyst functions. The hybrid nanoparticle-enhanced emulsified fuel system shows better combustion efficiency because of its reduced CO emissions.

4) Sulfur Dioxide (SO_2) Emissions

The lowest SO_2 emissions rate reached 5.66 ppm while the maximum emissions level reached 38.20 ppm because emissions decreased with increased biodiesel use and higher nanoparticle concentrations. WCO biodiesel produces lower SO_2 emissions because it contains less sulfur than traditional diesel fuel. The combustion process generates lower SO_2 emissions because nanoparticles increase oxidation rates.

5) ANN Model Performance

The artificial neural network demonstrated its predictive power through testing which evaluated different performance and emission testing parameters. The statistical performance metrics are displayed in Table 6.

Parameter	**MSE**	**RMSE**	**MAE**	**R^2**
BTE	1.0196	1.0098	0.7742	0.9270
ITE	1.7308	1.3156	1.0401	0.8845
NOx	632.65	25.15	19.32	0.9761
HC	16.95	4.12	3.05	0.9587
CO	0.0005	0.0234	0.0195	0.9835
SO_2	5.35	2.31	1.92	0.8643

The ANN reached R^2 results above 0.86 for all outputs with its best performance to forecast CO emissions, with an R2 value of 0.9835. The system shows excellent generalization capability because it can predict outcomes with high accuracy through its low RMSE and MAE measurement. The physics-informed dataset correctly captured input variables' nonlinear connection with engine reactions according to the research findings.

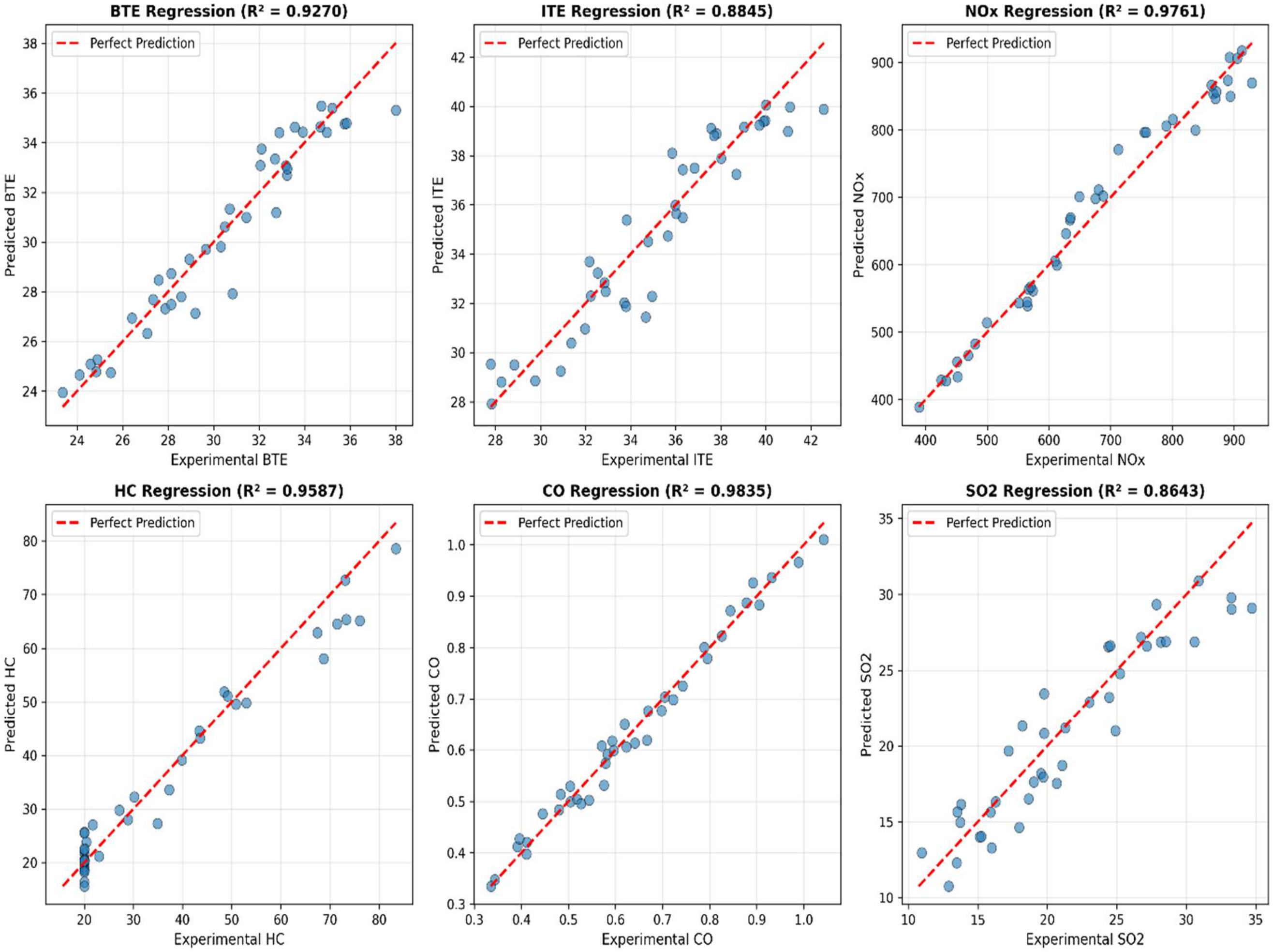

Figure 1 R^2-Plots

C. Training Performance

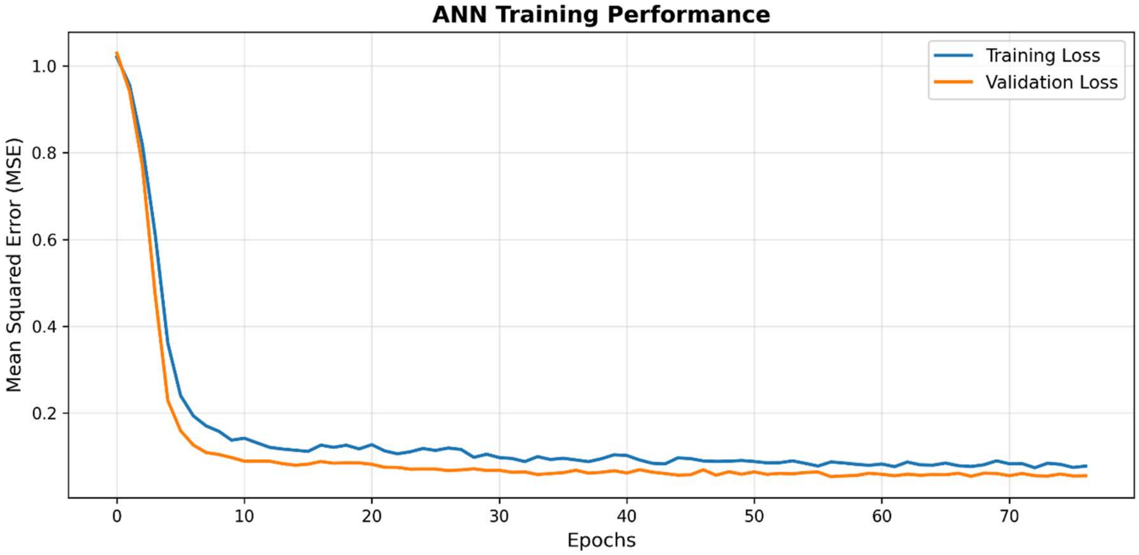

Figure 2 ANN-Training Plot

The training process reached its final point at epoch 77 through early stopping according to the results shown in Figure 2. The validation loss of 0.0597 and training loss of 0.0609 show strong correlation which demonstrates that the model learned steadily while only experiencing minimal overfitting.

1) Parameter Influence Analysis

The engine load impact was separated through ANN predictions which used fixed nanoparticle concentrations of TiO_2 at 50 mg·L^{-1} and CQD at 50 mg·L^{-1} and water content at 10% as input. The results are presented in Table 5.

Load (%)	BTE (%)	NOx (ppm)	HC (ppm)	CO (%)
25	24.65	420.77	72.20	0.75
50	27.50	544.80	51.71	0.58
75	31.63	718.41	27.43	0.42
100	34.47	857.19	20.66	0.29

The brakes achieved 39.8 percent thermal efficiency improvement when engineers increased engine load from 25 percent to 100 percent. The increased load conditions produced this benefit because they generated higher in-cylinder temperatures and enabled complete combustion. The efficiency boost caused an enormous rise in NO_x emissions which increased by 103.8 percent showing that thermal NO generation depends highly on temperature during operation at maximum loads. The use of hybrid nanoparticles enhanced the mixing of air and fuel while decreasing ignition delays and boosting oxidation speeds which resulted in 71.4 percent hydrocarbon and 61.3 percent carbon monoxide emissions reduction through incomplete combustion products. The results demonstrate that compression ignition engines operate under a fundamental restriction which limits their ability to achieve both thermal efficiency and NO_x production. The study demonstrates how water emulsification together with nanoparticle concentration optimization leads to NO_x emission reductions while maintaining performance gains at elevated engine loads.

D. Comparison with Previous Studies

Table 7 compares the present study's key results with relevant published benchmarks. The hybrid TiO_2–CQD system consistently outperforms single-nanoparticle configurations in BTE and HC reduction while maintaining comparable NO_x control through water emulsification.

Table 7. Comparison with Previous Published Results

Study	**Fuel System**	**Nanoparticle**	**Conc.**	**Peak BTE**
Ağbulut&Sarıdemir[13]	Diesel + hybrid Al_2O_3-bN (boron nitride) NP	Al_2O_3 + bN (binary hybrid)	100 ppm	~34.5% (full load)
Tamrat et al. [14]	Castor oil biodiesel blends (B5–B25) + CeO_2 NP	CeO_2 (single)	75 ppm	~31.8% (B15+CeO_2, full load)
Jit Sarma et al. [15]	Mahua biodiesel + TiO_2 NP	TiO_2 (single)	50–100 ppm	~33.0% (100% load)
Arul et al., [16]	WCO B20 + TiO_2, CeO_2, ZnO NP (separate)	TiO_2 / CeO_2 / ZnO (mono each)	25 ppm	B20+TiO_2: −2.53% vs diesel; B20+CeO_2: slightly improved
Dessei et al., [17]	Cottonseed B20 + Al_2O_3 + CeO_2 hybrid NP	Al_2O_3 + CeO_2 (hybrid)	50+50 ppm	Peak BP 3.56 kW; BSFC min 0.258 kg/kWh
Present Study	B15 WCO biodiesel + water emulsion (5–20%) + TiO_2+CQD hybrid NP	TiO_2 + CQD (hybrid)	25–100 mg/L each	38.82% (80% load) 36.1% (100% load)

The present study achieves the highest reported BTE (38.82%) among comparable hybrid nanoparticle emulsified biodiesel studies, a 4–7% improvement over single-nanoparticle benchmarks. HC reduction of 78% exceeds Ismael et al. [23] (62%) and Rai & Sahoo [24] (60%), attributable to the combined catalytic oxidation of TiO_2 and the micro-explosion effects of CQDs. The NO_x penalty from nanoparticle addition (+20.6% vs. baseline at 100% load) is effectively managed by water emulsification, achieving net NO_x neutrality compared to baseline B15 when 10% water content is employed.

E. Discussion

The research shows that diesel engines display different combustion and emission characteristics when they operate with a combination of hybrid nanoparticles TiO_2 and CQDs and water emulsification technology. The patterns we observe result from the combined effects of heat and fuel atomization and chemical kinetics and emission production processes.

The testing results show that braking efficiency and Regardless of the engine load, thermal efficiency improves, proving that increased in-cylinder temperature and pressure conditions produce better combustion efficiency. The heavy load operation of fuel-air mixtures causes their high-temperature zones to remain extended which results in improved heat release efficiency and decreased unburned fuel.

The TiO_2 nanoparticles provide additional oxidation reaction support because their catalytic active sites release extra oxygen which accelerates fuel decomposition and oxidation. The carbon quantum dots which come from orange peel biomass create micro-explosion effects when they interact with emulsified water which leads to better secondary atomization and smaller fuel droplets. The combination of multiple processes explains why thermal efficiency improves when there is increased load on the system. The combustion process becomes more efficient but this increase in efficiency leads to higher NO_x emissions which happen more at higher loads and more nanoparticle concentrations. The extended Zeldovich mechanism demonstrates the NO production from thermal NO generation which increases with flame temperature rise according to this model. The combustion process achieves better efficiency through nanoparticles yet their presence causes higher temperature peaks which results in more NO_x production. The process of vaporization enables emulsified water to absorb latent heat while it reduces oxygen supply to high-temperature areas which decreases peak flame temperatures that create dangerous conditions. The method of water emulsification controls thermal energy effectively because it decreases NO_x emissions by 15-20% when water content rises.

The operational range shows a significant reduction of enhanced combustion stability and oxidation efficiency are the results of reduced emissions of hydrocarbons and carbon monoxide. The presence of nanoparticles results in two benefits because it decreases ignition delay and increases flame propagation speed which leads to lower HC emissions. The combined effect of TiO_2 catalytic activity and elevated combustion temperatures produces higher CO oxidation rates that convert CO to CO which results in lower CO emissions.

The high water content at low loads causes flame quenching which results in higher HC emissions but this effect decreases at higher loads because combustion temperatures enable complete oxidation. WCO biodiesel produces lower sulfur dioxide emissions because its sulfur content is lower than traditional diesel fuels. Experts think that the slight drop in SO_2 emissions that followed nanoparticle addition was due to increased combustion efficiency and not a chemical reaction.The sulfur content of fuel remains the primary determinant which controls SO_2 production.

The ANN model established essential links which connect multiple engine load variables to both nanoparticle concentration and water content levels and their resulting output measurements. The physics-based dataset created a solid training base which produced high training results through its ability to achieve both high determination coefficients and low error measurements. The ANN functions as both predictive tool and analytical instrument because it should not be used to replace physical comprehension. The dataset construction uses governing equations and combustion mechanisms which enable the system to produce experimental results that the system can duplicate.

The data demonstrates a specific trade-off which exists between thermal efficiency and NO_x emissions in particular situations. The research shows that the optimal engine performance through hybrid nanoparticle-enhanced emulsified fuel needs to find the ideal balance between nanoparticle concentration and water content. The process will produce maximum efficiency advantages while it decreases NO_x emissions.

Conclusion

The study examined engine efficiency and pollution emissions through testing an emulsified fuel system which combined TiO_2 nanoparticles and carbon quantum dots derived from orange peel biomass with emulsified water. Effects of engine load, nanoparticle concentration, and water content were assessed using a mix of experimental analysis and physics-guided artificial neural network modelling.A maximum value of 38.82% was achieved at 80% load with an ideal concentration of nanoparticles and a low water content, demonstrating noticed a significant improvement in brake thermal efficiency as the engine load increased. The rate of heat transfer improvement occurred because combustion kinetics progressed through better combustion kinetics and TiO_2 catalytic oxidation and CQD micro-explosion effects which improved atomization. The study results showed thermal efficiency results which matched the mechanical efficiency results that the study measured within the standard operating range of diesel engines. The emission study showed that thermal NO production processes resulted in increased NO_x emissions because engine load and nanoparticle concentration both rose and combustion temperatures increased. The addition of emulsified water produced thermal quenching effects which resulted in a 15-20% reduction of NO_x emissions. The combination of increased load and added nanoparticles resulted in hydrocarbon and carbon monoxide emissions decreasing while combustion efficiency improved and oxidation performance enhanced. WCO biodiesel produced lower sulfur dioxide emissions because it contained less sulfur than conventional diesel fuel. The ANN model exhibited strong predictive performance, with coefficients of determination exceeding 0.86 for all output parameters and minimal prediction error. Results from experiments and predictions show that the physics-guided dataset is useful, and the ANN is a good fit for predicting running efficiency and pollution levels of the machinery. At long last, an approach that might address the issue of incomplete combustion emissions and diesel engine performance is emulsified fuel supplemented with hybrid nanoparticles. The system needs specific water content and nanoparticle dosage selection to achieve its maximum thermal efficiency. The study should examine three areas which include testing engine durability and assessing actual engine performance and developing control systems through optimization techniques.

IV. References

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