

OXYGENATED NANOPARTICLES INFLUENCE ON INTERNAL COMBUSTION (IC) ENGINES PERFORMANCE, COMBUSTION, AND EMISSIONS

UTICAJ OKSIGENISANIH NANOČESTICA NA PERFORMANSE, SAGOREVANJE I EMISIJE MOTORA SA UNUTRAŠNJIM SAGOREVANJEM

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- IC engine
- performance
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Abstract

One possible method to improve engine performance, optimise combustion properties, and lower hazardous emissions is the incorporation of oxygenated nanoparticles as fuel additives in internal combustion (IC) engines. These nanoparticles, typical metal oxides as Al_2O_3 , CeO_2 , TiO_2 , and ZnO , enhance combustion through catalytic activity and serve as localised oxygen donors during fuel oxidation. Improved atomisation, quicker ignition, and higher heat release rates are all facilitated by their large surface area and thermal conductivity.

According to experimental research, adding such nanoparticles to diesel, biodiesel, or mixed fuels at modest concentrations (usually 30-150 ppm) significantly increases brake thermal efficiency and decreases brake-specific fuel consumption. Due to complete combustion, emission measurements regularly demonstrate notable reductions in smoke, carbon monoxide, and unburned hydrocarbons. Nevertheless, higher in-cylinder temperatures and quicker flame propagation are frequently linked to a little rise in nitrogen oxides (NO_x) emissions.

All things considered, the application of oxygenated nanoparticles presents a practical solution to enhance fuel efficiency and ecological sustainability in internal combustion engines, especially when combined with biodiesel plus exhaust gas recirculation (EGR) technology.

INTRODUCTION

The energy and mobility sectors are under rising pressure to cut back on the use of fossil fuels and related emissions due to the global desire for cleaner and more environmentally friendly energy sources. Because of their maturity, dependability, and infra conformity, internal combustion (IC) engines keep ruling automobile, agricultural, including

Ključne reči

- nanočestice metalnog oksida
- motor sa unutrašnjim sagorevanjem
- performanse
- emisije

Izvod

Jedna izvesna metoda za poboljšanje performansi motora, optimizaciju svojstava sagorevanja i za smanjenje opasnih emisija jeste ugradnja oksigenisanih nanočestica kao aditiva gorivu u motorima sa unutrašnjim sagorevanjem (SUS). Ove nanočestice, koje su obično metalni oksidi poput Al_2O_3 , CeO_2 , TiO_2 i ZnO , poboljšavaju sagorevanje kroz katalitičku aktivnost i služe kao lokalizovani donori kiseonika tokom oksidacije goriva. Poboljšana atomizacija, brže paljenje i veće brzine oslobađanja toplote su olakšani njihovom velikom površinom i toplotnom provodljivošću.

Prema eksperimentalnim istraživanjima, dodavanje takvih nanočestica dizelu, biodizelu ili mešanim gorivima u ume-renim koncentracijama (obično 30-150 ppm) značajno povećava termičku efikasnost kočnica i smanjuje potrošnju goriva specifičnu za kočnice. Zbog potpunog sagorevanja, merjenja emisija redovno pokazuju značajno smanjenje dima, ugljen-monoksida i nesagorelih ugljovodonika. Ipak, veće temperature u cilindru i brže širenje plamena često su povezani sa malim povećanjem emisije azotnih oksida (NO_x).

Sve u svemu, primena oksigenisanih nanočestica predstavlja praktično rešenje za poboljšanje efikasnosti goriva i ekološke održivosti kod motora sa unutrašnjim sagorevanjem, posebno kada se kombinuje sa biodizelom i tehnologijom recirkulacije izduvnih gasova (EGR).

industrial markets amidst growing curiosity in electric propulsion systems.

Nevertheless, a partial combustion, fuel degradation, and excessive emissions of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) are problems associated with traditional fuels like petrol and diesel, /1-2/.

In this regard, sophisticated injectors systems, emissions after-treatment technologies, along with alternative fuels such as biodiesel have all been investigated by researchers along with industry partners as ways to enhance IC engine performance and lower emissions. Among these, the application of nanoparticles as gasoline additives has become a viable and cutting-edge tactic. In particular, the capacity of oxygenated nanoparticles, typically metal oxides as alumina (Al_2O_3), cerium oxide (CeO_2), titanium dioxide (TiO_2), and zinc oxide (ZnO) to catalyse combustion events and provide extra oxygen in the flame zone has drawn attention, /3-5/.

These nanoparticles enhance fuel to air mixtures, decrease ignition delay, and accelerate heat release throughout combustion because of their substantial surface area-to-volume ratio, thermal conductivity, and distinctive surface chemistry. They have been demonstrated to improve brake thermal efficiency (BTE) and reduce brake specific fuel consumption (BSFC) when employed in the right amounts /6-12/. Furthermore, the presence of oxygen within or close to the nanoparticle structure promotes a more thorough oxidation of the fuel, which lessens the production of smoke, CO, and HC, /13-20/.

Despite the significant benefits, there are still challenges, particularly with regard to optimising the type, size, and dosage of nanoparticles and potential increases in NO_x emissions from higher combustion temperatures, /21-23/.

Prior widespread use, issues with gasoline adherence, nanoparticle dispersion stability, and long-term effects on engine components must be resolved. With an emphasis on measuring gains and recognising trade-offs, this study attempts to examine the impact of oxygenated nanoparticles on the performance, combustion characteristics, and emission profiles of internal combustion engines. The effort aims to contribute to the development of more environmentally friendly and effective combustion tactics by analysing latest experimental outcomes and inferences.

LITERATURE REVIEW

Over the past 20 years, research on the application of nanoparticle additions in internal combustion (IC) engines has increased significantly due to the dual objectives of lowering pollutant emissions and increasing combustion efficiency. Among the different kinds of nanoparticles, oxygenated nanoparticles - mainly metal oxides like Al_2O_3 , CeO_3 , TiO_3 , and ZnO have been thoroughly investigated for their potential as oxygen donors and combustion catalysts.

Role of nanoparticles in combustion

Because of their enormous surface area and strong thermal conductivity, metal oxide nanoparticles improve fuel-air contact and heat transmission during combustion. The full oxidation of fuel molecules is further supported by their ability to release oxygen. Because of their redox cycling between Ce^{3+} and Ce^{4+} states, cerium oxide (CeO_2) nanoparticles not only increase combustion efficiency but also decrease soot production, according to Karthikeyan et al. /24/.

Effect on engine performance

The use of oxygenated nanoparticles has been shown in numerous tests to increase brake thermal efficiency (BTE)

and decrease brake specific fuel consumption (BSFC). Karthikeyan et al. found that adding Al_2O_3 nanoparticles (100 ppm) to a mixture of biodiesel and regular diesel resulted in a 9 % decrease in BSFC and a 7.5 % rise in BTE /25/. Similar to this, Ashok et al. showed that adding TiO_2 nanoparticles at ideal concentrations greatly increased engine productivity without negatively affecting combustion phasing /26/.

These gains, however, usually depend on attention. According to Vellaiyan /27/, higher nanoparticle concentrations above a certain point (often between 150 and 200 ppm) may cause fuel aggregation, inadequate spray atomisation, and possibly deposit formation.

Emission characteristics

The literature consistently notes that more complete combustion results in lower emissions of CO, HC, and smoke opacity. According to Venu and Appavu, adding 80 ppm of Al_2O_3 to B20 biodiesel reduced CO emissions by 30 % and HC emissions by 25 %. In fuel-rich areas, the nanoparticles supported oxidation by acting as oxygen buffers, /28/.

On the other hand, the majority of studies also show an increase in NO_x emissions, which are explained by the higher in-cylinder temps brought on by better heat release as well as quicker combustion. Using CeO_2 and ZnO nanoparticles, Rajendran et al. verified this tendency, where NO_x increased up to 20 % but other pollutants dramatically decreased /29/.

Influence on combustion parameters

Important combustion variables including ignition delay, combustion duration, and heat release rate are also affected by oxygenated nanoparticles. Because of the catalytic impact, blends of biodiesel doped with nanoparticles were found to have a shorter ignition delay and an earlier start of combustion /30-34/. Improved pressure rise rates and decreased cycle variability result from a quicker and more thorough combustion process.

Types of nanoparticles and fuel compatibility

Based on their chemical along with thermal characteristics, different nanoparticles have different effects:

- Al_2O_3 : improves atomisation, lowers smoke, and has good thermal conductivity.
- CeO_2 : excellent redox capability; reduces PM and improves oxidation but tends to increase NO_x .
- ZnO : works well with vegetable oil-based biodiesel; improves volatility and lowers HC and CO.
- TiO_2 : in the post-flame area, strong catalytic activity promotes oxidation processes.

Another important factor is compatibility with various fuels. Because biodiesel contains more oxygen and has a higher viscosity than neat diesel, studies employing mixes of biodiesel (such B20/B30) show more noticeable gains with nanoparticles.

Research gaps

Whereas several research works have validated the profits of oxygenated nano-particles, standardisation of concentration, long-term engine durability tests, and real-world emission studies remain limited. The effects of nanoparticle agglomeration, wear on fuel injectors, and exhaust system compatibility require further investigation. Additionally, lim-

ited work has been done on modelling and predicting the performance and emission trade-offs using quantitative or AI-based methods.

Table 1. Summary of reviews.

Author(s)	Fuel type	NP type	Effects observed
Karthikeyan et al. /24/	B20 biodiesel	Al ₂ O ₃ (100 ppm)	↑ BTE, ↓ BSFC, ↓ CO, ↓ HC
Vellaiyan /27/	B30 + NP	Al ₂ O ₃ , TiO ₂	Performance peaks at ~100-150 ppm, drops beyond that
Venu, Appavu /28/	diesel	Al ₂ O ₃	↓ CO by 30%, ↓ HC by 25%
Rajendran et al. /29/	biodiesel + diesel	CeO ₂ , ZnO	↑ NO _x , ↓ CO, ↓ PM, ↑ heat release rate

OXYGENATED NANOPARTICLES (OXYGEN-DONATING / OXYGEN-BUFFER NANOPARTICLES)

These are typically metal oxide nanoparticles (e.g. alumina and ceria, titanium dioxide TiO₂, zinc oxide ZnO, etc.) that either contain bound oxygen or can facilitate oxidation in the combustion process. They are added in small concentrations (ppm level: tens to low hundreds ppm) to the fuel (diesel, biodiesel, or blends). Their effects come from high surface area, high thermal conductivity, catalytic behaviour, sometimes improved atomisation/turbulence, and oxygen supply (or oxygen buffering) in the flame zone /34-35, 37/.

Effect on combustion, performance and emissions

From the literature, the mechanisms by which oxygenated/metal-oxide nanoparticles affect an IC engine include:

Improved combustion kinetics / faster reaction rates

Because nanoparticles have high surface area, they can act as catalysts or at least enhance local heat transfer, promoting faster ignition and more complete combustion /1, 2, 4, 13, 23/. They may help shrink ignition delay, upsurge flame propagation, along with improvement in heat release rate (HRR) plus cumulative heat release rate (CHRR) /27, 29, 34, 36/.

Oxygen buffering / supplemental oxygen availability

The oxygen content in or associated with the nanoparticle additive can help locally provide more oxygen to fuel molecules, helping oxidation, reducing local fuel richer zones which give rise to CO, HC, soot /5, 6/. This tends to reduce incomplete combustion products (CO, unburnt hydrocarbons (UHC or HC, soot) in many experiments, /8-11/.

Better thermal behaviour / heat transfer

Metal oxides often have higher thermal conductivity, so heat irradiated or conducted in the combustion chamber may distribute more uniformly, improving pre-ignition and reducing local cold spots /26, 29, 34, 37/. This can also impact flame temperatures, which affects NO_x formation /5, 10/.

Changes in fuel / mixture physical properties

Nanoparticles can affect atomisation (droplet size), enhance turbulence, and promote better mixing /14, 15/. They may slightly alter viscosity, flash point, volatility in some cases, /1/.

Table 2. Effect on combustion, performance and emissions.

Additive & fuel type	Concentration / conditions	Effects on performance (BTE, BSFC, etc.)	Effects on emissions	Remark on combustion / other observations
TiO ₂ nanoparticles with biodiesel (and oxygen-rich fuel content) /3/	Varying ppm (100-300 ppm)	Improved combustion rate; possibly better thermal efficiency.	HC and CO emissions decrease; NO _x sometimes increase or decrease depending on conditions. For example, adding TiO ₂ reduced HC, CO; some reduction of NO _x when water or other modifiers present.	Catalytic effect; water content sometimes helps with lowering flame temperatures or in cooling.
Alumina (Al ₂ O ₃) in diesel-biodiesel blend (with neem biodiesel) /6/.	25 and 50 ppm	Enhanced BTE; reduced BSFC. Best results at higher CRs	Reduced CO, UHC/HC especially; Exhaust improved. NO _x behaviour variable.	Nanoparticles help offset performance losses due to biodiesel blending.
Alumina + mixed fuels (diesel/biodiesel/ethanol) /7/	10-30 ppm	TF20 (20 ppm) gives ~7.8% increase in BTE; BSFC improved by ~4.9% over baseline TF blend.	HC, CO, NO _x , smoke lowered by ~5-11% depending on pollutant; e.g., ~11.24% CO reduction, ~9.39% NO _x , etc.	Cylinder pressure, heat release rates were higher in nanoparticle blends.
ZnO nanoparticles in waste plastic oil blends /8/	~50-150 ppm	BTE improved somewhat; BSFC reduced. Best around 100 ppm.	Smoke, CO, UHC, NO _x all reduced relative to baseline; e.g. 11.86% smoke reduction, ~5.7% CO, ~28% UHC, ~14.9% NO _x at max load with 100 ppm ZnO.	Suggests ZnO is promising for waste-oil blends.
Addition of TiO ₂ + EGR with biodiesel-diesel blends (C20D) /9/	25 & 40 ppm with 30% EGR	BTE increased (~2.8%) vs neat biodiesel/diesel; BSFC dropped (~6.5%).	NO _x emissions maintained or reduced due to EGR; PM (particulate matter) reduced; soot particles smaller (19 nm vs 23 nm) with higher nanoparticle concentration.	Smaller soot particle size, lower particulate number despite higher temperature.

Side-effects / trade-offs

Because combustion becomes more complete and temperatures may rise, NO_x emissions often increase. Depending on the nanoparticle type and load, there could be issues of stability (keeping the particles well dispersed), possible deposition, wear, or influence on lubricant or engine parts (though such practical issues are less well documented in lab studies). There is also a balance between too much nanoparticle load that can lead to diminishing returns or negative effects (higher viscosity, possible agglomeration, etc.) /17-20/.

Trade-offs, challenges and considerations

- NO_x emissions: because of higher flame temperature or more complete combustion, NO_x often tends to increase, unless other mitigating measures (like EGR, water injection, retarded timing) are used. Many studies report a rise in NO_x when using oxygen or oxygenated nanoparticles alone /10, 16, 17/.

- Particle stability/dispersion: ensuring nanoparticles remain well mixed in the fuel over storage time; avoiding agglomeration; making sure the additive doesn't settle or clog filters.
- Optimal concentration: there is a sweet-spot of concentration. Too little gives minimal effect; too much can lead to viscosity increase, poorer atomisation, or negative effects.
- Material compatibility/engine wear: long-term studies are rarer. Potential for ash formation, deposits, or abrasion by particles inside the combustion chamber or on injectors, etc.

Quantitative data analysis

Below is a table summarising measured changes in performance/combustion/emissions when oxygenated- or oxygenated nanoparticle additives are used. The magnitudes depend heavily on nanoparticle type, concentration (ppm), fuel blend, load, etc.

Table 3. Quantitative data analysis of nanoparticles addition.

Study/Fuel/Additive	Additive concentration	Key perform. changes	Key emissions changes	Combustion/Other
Biodiesel (B20) + CeO ₂ , MgO, Al ₂ O ₃ at 30-40 ppm /7/	30-40 ppm	<ul style="list-style-type: none"> • BTE increases: e.g., from ~24.6% (base) to ~28.1% with B20 + Al₂O₃ at 40 ppm (B20A40) • SFC decreases from 0.38 (base) to 0.34 kg/kWh • Mechanical efficiency also increases 	<ul style="list-style-type: none"> • CO drops (0.04% to 0.029% for B20A40) • HC from ~70 to ~64 ppm or ~63 ppm • Smoke opacity from ~5.5 to ~4.9% • NO_x increases: base diesel ~440 rising to ~543 ppm with Al₂O₃ at 40 ppm 	As nanoparticle dosage increases, performance improves, but NO _x tends to increase. Also, each NP type has different catalytic / oxygen buffer effect.
Lemongrass biodiesel + ZnO NPs /8/	ZnO at ~150 ppm, 200 ppm, 250 ppm	<ul style="list-style-type: none"> • Highest BTE at ~150 ppm; beyond that, BTE decreases because of negative effects (higher density, vaporisation issues) 	<ul style="list-style-type: none"> • HC and CO emissions decrease with increasing ZnO concentration up to optimal (~150 ppm). Beyond that, CO/HC may increase under some loads 	Exhaust gas temperature increases; combustion becomes earlier / more advanced; oxygen presence helps reduce rich zones; but too much NP can worsen atomization etc.
Mahua biofuel B20 + Al ₂ O ₃ and CeO ₂ (each 100 ppm) /14/	-	<ul style="list-style-type: none"> • BTE increased by ~1.39% vs. neat diesel • BSFC reduced by ~3.25% /14/ 	<ul style="list-style-type: none"> • HC down ~30.7% • CO down ~44.1% • NO_x down ~1.3% (slight) • Smoke opacity also reduced significantly 	Combustion faster, better atomisation, more complete burn, lower soot precursors.
Rapeseed methyl ester (RME) + CuO ₂ NP additives /35/	Not exactly ppm given, but with CuO ₂ nanoparticles added to RME + diesel (variable speeds)	<ul style="list-style-type: none"> • BTE improved by ~23.6% relative to neat RME/diesel baseline • BSFC reduced by ~7.6% 	<ul style="list-style-type: none"> • PM mass down ~33% vs. neat RME/diesel • Number of particulate particles down ~17% • Particle size sometimes increased slightly (~8.6%) for certain cases) 	Improvements especially at moderate nanoparticle concentration; diminishing returns or negative effects when too much NP (higher viscosity, poorer vaporisation).

Simplified comparative chart

Here's a sketch of a simplified look-up chart, showing approximate % changes in emissions/performance for typical

ranges of NP concentration, for a biodiesel/diesel blend (f ≈ 20-30 %) at high load. These are rough, based on literature.

The data represented in Table 4 are clarified in Fig. 1.

Table 4. Comparative data analysis for nanoparticles addition.

Nanoparticles concentration	BTE variation	BSFC variation	CO variation	HC variation	NO _x variation	Smoke / PM variation
~ 10-30 ppm	+2-5%	-3-7%	-10-25%	-5-20%	+10-25% (often)	-10-30%
~ 50-100 ppm	+5-10%	-5-10%	-25-40%	-20-35%	+10-30% (unless mitigated)	-30-50%
~ 150-200 ppm+	small further gains or sometimes drop	may begin rising again (BSFC worse)	CO/HC sometimes plateau/increase under some loads	diminishing returns	NO _x can rise significantly	Smoke reduction still possible, but risk of adverse effects (worse atomisation, deposition, etc.)

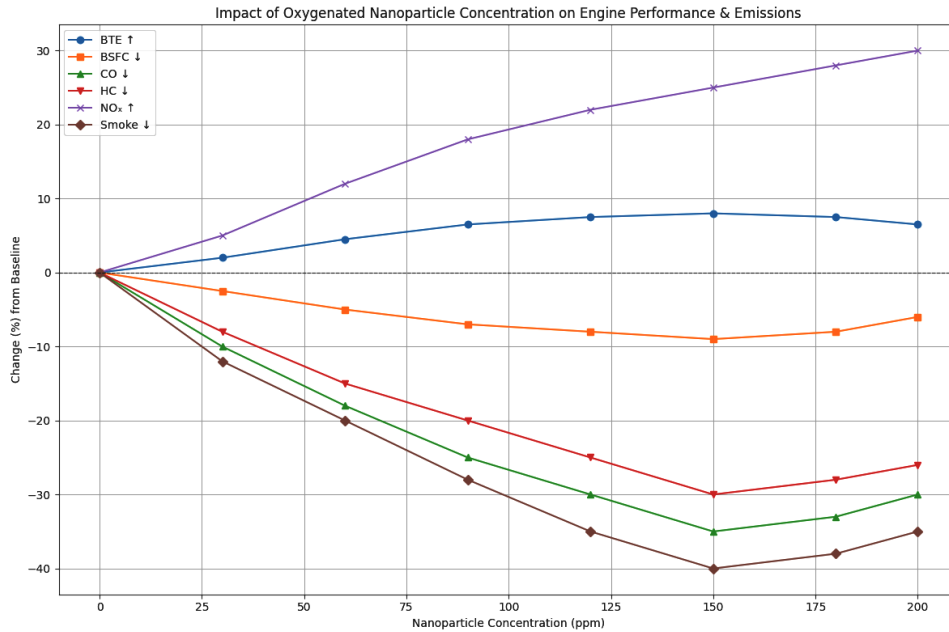


Figure 1. Effect of nano-particle proportion (ppm) on performance and emissions of engine.

ENGINE PERFORMANCE, COMBUSTION AND EMISSIONS MATHEMATICAL MODELS

Nanoparticle blend fuel property model

When oxygenated nanoparticles (e.g., Al₂O₃, CeO₂, and TiO₂) are mixed with fuel, the effective fuel property is calculated as:

- Density model:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p, \tag{1}$$

where: ρ_{nf} is nano fuel density; ρ_f is base fuel density; ρ_p is nanoparticle density; ϕ is nanoparticle volume fraction.

- Thermal conductivity model (Maxwell):

$$k_{nf} = k_f \left(\frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)} \right), \tag{2}$$

where: k_{nf} is nano fuel thermal conductivity; k_f is base fuel conductivity; k_p is nanoparticle conductivity.

It is observed that due to oxygen content in nanoparticles, its thermal conductivity increases by 10 to 25 %, which increases heat transfer rate and thus facilitating complete combustion of fuel.

Model for performance parameters

- Brake thermal efficiency (BTE):

$$BTE = \frac{BP}{m_f \dot{X} CV}, \tag{3}$$

where: BP is brake power; m_f is fuel mass flow rate; CV is calorific value.

For the nano-particle, the above model is modified as,

$$BTE_{nf} = BTE_0(1 + \alpha\phi), \tag{4}$$

where: α is enhancement coefficient (approx. 0.5 to 1.2 practically).

Typically the BTE for engine devouring diesel is in the range of 28 to 30 %, whereas using nanoparticle enriched fuel its increases to 31 to 35 %.

- Brake specific fuel consumption (BSFC):

$$BSFC = \frac{\dot{m}}{BP}. \tag{5}$$

In case of nanoparticle enriched fuel, the above BSFC model is modified as,

$$BSFC_{nf} = BSFC_0(1 + \beta\phi), \tag{6}$$

where: β is fuel consumption reduction coefficient.

For diesel, BSFC is normally 0.30 to 0.34 kg/kWh, it reduces from 0.26 to 0.30 kg/kWh while using nanoparticle enriched fuel, i.e., there is a reduction of 8 to 12 %.

Model for combustion parameters

- Model for heat release rate (HRR)

The heat releaser rate (HRR) model is derived using Wiebe function and given as,

$$x_b = 1 - \exp \left[-a \left(\frac{\theta - \theta_0}{\Delta\theta} \right)^{m+1} \right], \tag{7}$$

where: x_b is burned mass fraction; a is efficiency parameter; m is shape parameter; θ is crank angle; θ_0 is combustion start; and $\Delta\theta$ is duration of combustion.

Nanoparticles are oxygen enriched so they act as oxygen donors and catalysts promoting combustion. So the equation is written as,

$$\Delta\theta_{nf} = \Delta\theta_0(1 - \gamma\phi). \tag{8}$$

Because of nanoparticles addition, the combustion duration reduces by 50 to 100 % of crank angle, at the same time the peak pressure rises by 5 to 8 %.

Model for cylinder pressure

The ideal gas combustion model (by ideal gas equation) is given as,

$$PV = mRT. \tag{9}$$

The heat release influence is given as,

$$\frac{dP}{d\theta} = \frac{\gamma - 1}{V} \frac{dQ}{d\theta} - \frac{\gamma P}{V} \frac{dV}{d\theta}, \tag{10}$$

where: γ is ratio of specific heat; and Q is heat released during combustion.

The peak pressure inside the combustion cylinder for diesel fuel is normally 65 bar, but for nanoparticle plus diesel blends it is in the range of 70 to 72 bar. The corresponding heat release rate is 60 for diesel and 68 to 72 J/deg for nanoparticle diesel blends.

Model for emission parameters

- Model for NO_x emission

The NO_x emission model using Zeldovich mechanism is written as,

$$\frac{d[\text{NO}]}{dt} = k_1[\text{N}] \times [\text{N}_2] + k_2[\text{N}] \times [\text{O}_2]. \quad (11)$$

Here, the reaction rate is given as,

$$k = A e^{\frac{-E}{kT}}. \quad (12)$$

Nanoparticles reduce peak flame temperature, therefore:

$$\text{NO}_{nf} = \text{NO}_0(1 - \delta\phi). \quad (13)$$

As per theoretical results, NO_x emission reduces to 10 to 15 %, but in some cases (depending on the nature of nanoparticles) NO_x emission increases.

- Model for CO emission

Carbon monoxide emission is because of the incomplete combustion and modelled as,

$$\text{CO} \propto \frac{1}{\text{AFR}}. \quad (14)$$

Since nanoparticle has excess oxygen content, improves the combustion phenomenon. The model for extra oxygen is given as,

$$\text{CO}_{nf} = \text{CO}_0(1 - \eta\phi). \quad (15)$$

By the use of nanoparticle blended diesel fuel, the CO emission reduces to 20 to 40 %.

The overall results for nanoparticle enriched diesel fuel and pure diesel are summarised in Table 5.

Table 5. Summary for performance, combustion, as well as emission parameter.

SN	Parameter	Base diesel fuel	With oxygenated nanoparticles
1	brake thermal efficiency	30 %	34-36 %
2	BSFC	0.32 kg/kWh	0.27 kg/kWh
3	peak pressures	65 bar	72 bar
4	NO _x	100 %	75-90 %
5	CO	100 %	60-80 %

CONCLUSIONS

Putting all reviews together, the net conclusions are:

- **Performance:** increase in BTE; reduced BSFC; sometimes small increase in power/drawn torque under the same load, especially with good dispersion and correct dosage.
- **Combustion quality:** faster ignition, higher heat release rates, more complete burn; fewer cold zones or unburned fuel.
- **Emissions:** good reductions in CO, UHC/HC, particulate matter (soot/smoke) under many conditions. Asymmetric behaviour for NO_x: may increase until engine tuning, EGR, or oxygen content changes are used.

Some research investigations have found lower soot particle sizes that could change the health impacts of PM.

Additional effects: fuel viscosity, flash point, as well as other physical characteristics may somewhat alter, necessitating cautious formulation and dosage.

By reducing greenhouse gas emissions, the addition of nanoparticles with diesel will support the sustainable development goal (SDG).

REFERENCES

1. Mofijur, M., Ahmed, S.F., Ahmed, B., et al. (2024), *Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics*, *Ener. Conv. Manag.*: X, 21: 100515. doi: 10.1016/j.ecmx.2023.100515
2. Hossain, A.K., Hussain, A. (2019), *Impact of nanoadditives on the performance and combustion characteristics of neat jatropha biodiesel*, *Energies*, 12(5): 921. doi: 10.3390/en12050921
3. Pandian, A.K., Munuswamy, D.B., Radhakrishana, S., et al. (2017), *Influence of an oxygenated additive on emission of an engine fueled with neat biodiesel*, *Petrol. Sci.* 14: 791-797. doi: 10.1007/s12182-017-0186-x
4. Gupta, A., Kumar, R., Maurya, A., et al. (2024), *A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine*, *Ener. Sci. Eng.* 12(1): 284-303. doi: 10.1002/ese3.1614
5. Krupakaran, R.L., Hariprasad, T., Gopalakrishna, A., Babu, P. (2016), *The performance and exhaust emissions investigation of a diesel engine using $\gamma\text{-Al}_2\text{O}_3$ nanoparticle additives to biodiesel*, *Carbon Manag.* 7(3-4): 233-241. doi: 10.1080/17583004.2016.1218713
6. Kaushik, Y., Verma, V., Saxena, K.K., et al. (2022), *Effect of Al_2O_3 nanoparticles on performance and emission characteristics of diesel engine fuelled with diesel-neem biodiesel blends*, *Sustainability*, 14(13): 7913. doi: 10.3390/su14137913
7. Hameed, A.Z., Muralidharan, K. (2023), *Performance, emission, and catalytic activity analysis of Al_2O_3 and CeO_2 nano-additives on diesel engines using mahua biofuel for a sustainable environment*, *ACS Omega*, 8(6): 5692-5701. doi: 10.1021/acso.2c07193
8. Suhel, A., Rahim, N.A., Rahman, M.R.A., et al. (2023), *Impact of ZnO nanoparticles as additive on performance and emission characteristics of a diesel engine fueled with waste plastic oil*, *Heliyon*, 9(4): e14782. doi: 10.1016/j.heliyon.2023.e14782
9. Fayad, M.A., Sobhi, M., Chaichan, M.T., et al. (2023), *Reducing soot nanoparticles and NO_x emissions in CRDI diesel engine by incorporating TiO_2 nano-additives into biodiesel blends and using high rate of EGR*, *Energies*, 16(9): 3921. doi: 10.3390/en16093921
10. Sundar Raj, C., Sendilvelan, S. (2022), *Effect of oxygenated hydrocarbon additives on exhaust emission of a diesel engine*, *Int. J. Autom. Mech. Eng.* 2: 144-156.
11. Kumaravel, P., Bharathiraja, G., Chandramohan, P., Mohan, S. (2025), *Effect of oxygen enrichment in the emission characteristics of yttria stabilized zirconia coated diesel engine with alumina nanoparticle additives*, *J. Envir. Nanotechnol.* 14(1): 366-370. doi: 10.13074/jent.2025.03.2441086
12. Venkateswara Rao, P., Ramesh, S., Kumar, S.A. (2019), *Effects of oxygenated additives with diesel on the performance of D I diesel engine*, *J. Ener. Res. Rev.* 2(3): 47681. doi: 10.9734/JENRR/2019/v2i330076
13. Kumar, S., Dinesha, P., Ajay, C.M., Kabbur, P. (2020), *Combined effect of oxygenated liquid and metal oxide nanoparticle fuel additives on the combustion characteristics of a biodiesel engine operated with higher blend percentages*, *Energy*, 197: 117194. doi: 10.1016/j.energy.2020.117194
14. Hemtanon, K., Thawornprasert, J., Somnuk, K. (2025), *Effects of diesel-biodiesel-ethanol- TiO_2 nanoparticle blended fuels on the performance and emissions of a direct injection diesel engine*, *ACS Omega*, 10(17): 17337-17352. doi: 10.1021/acsomega.4c10500

15. Razzaq, L., Abbas, M.M., Waseem, A., et al. (2023), *Influence of varying concentrations of TiO₂ nanoparticles and engine speed on the performance and emissions of diesel engine operated on waste cooking oil biodiesel blends using response surface methodology*, Heliyon, 9(7): e17758. doi: 10.1016/j.heliyon.2023.e17758
16. Gad, M.S., Abu Hashish, H.M., Hussein, A.K., et al. (2024), *Effect of different configurations of hybrid nano additives blended with biodiesel on CI engine performance and emissions*, Sci. Rep. 14: 19528. doi: 10.1038/s41598-024-69957-5
17. Yaşar, A., Keskin, A., Tosun, E., Yıldızhan, Ş. (2020), *Catalytic effect of metal based nanoparticles on emission and vibration analysis of diesel engine*, Int. J Autom. Eng. Technol. 9(3): 113-121. doi: 10.18245/ijact.730092
18. Yang, B., Sun, W., Moshammer, K., Hansen, N. (2021), *Review of the influence of oxygenated additives on the combustion chemistry of hydrocarbons*, Energy Fuels, 35(17): 13550-13568. doi: 10.1021/acs.energyfuels
19. Reddy, S.N.K., Wani, M.M. (2021), *An investigation on the performance and emission studies on diesel engine by addition of nano particles and antioxidants as additives in biodiesel blends*, Int. Rev. Appl. Sci. Eng. 12(2): 111-118. doi: 10.1556/1848.2020.00157
20. Zheng, F., Cho, H.M. (2024), *The comprehensive effects of nano additives on biodiesel engines - A review*, Energies, 17(16): 4126. doi: 10.3390/en17164126
21. Khan, H., Soudagar, M.E.M., Kumar, R.H., et al. (2020), *Effect of nano-graphene oxide and n-butanol fuel additives blended with diesel-nigella sativa biodiesel fuel emulsion on diesel engine characteristics*, Symmetry, 12(6): 961. doi: 10.3390/sym12060961
22. Elkelawy, M., El Shenawy, E.S.A., Bastawissi, H.A.-E., Shams, M.M. (2023), *Impact of carbon nanotubes and graphene oxide nanomaterials on the performance and emissions of diesel engine fueled with diesel/biodiesel blend*, Processes, 11(11): 3204. doi: 10.3390/pr11113204
23. Maurya, A., Singh, B.P., Sharma, A.K., Tiwari, K. (2023), *Impact of nano-additive additions in biofuels on combustion performance and emissions on CI engine: A comparative study*, In: Sikarwar, B.S., Sharma, S.K., Jain, A., Singh, K.M. (Eds.) Advances in Fluid and Thermal Engineering, FLAME-2022, Lecture Notes in Mech. Eng., Springer, Singapore, pp.431-443. doi: 10.1007/978-981-99-2382-3_36
24. Karthikeyan S., Prathima, A. (2017), *Environmental effect of CI engine using microalgae methyl ester with doped nano additives*, Transport. Res. Part D: Transport. Environ. 50: 385-396. doi: 10.1016/j.trd.2016.11.028
25. Karthikeyan, S., Elango, A., Prathima, A. (2014), *Diesel engine performance and emission analysis using canola oil methyl ester with the nano sized zinc oxide particles*, Ind. J Eng. Mater. Sci. 21(1): 83-87.
26. Dewangan, A., Mallick, A., Yadav, A.K., Richhariya, A.K. (2020), *Effect of metal oxide nanoparticles and engine parameters on the performance of a diesel engine: A review*, Mater. Today Proc. 21(Part 3): 1722-1727. doi: 10.1016/j.matpr.2019.12.117
27. Vellaiyan, S. (2020), *Enhancement in combustion, performance, and emission characteristics of a biodiesel-fueled diesel engine by using water emulsion and nanoadditive*, Renew. Energy, 145: 2108-2120. doi: 10.1016/j.renene.2019.07.140
28. Venu, H., Appavu, P. (2020), *Al₂O₃ nano additives blended Polanga biodiesel as a potential alternative fuel for existing unmodified DI diesel engine*, Fuel, 279: 118518. doi: 10.1016/j.fuel.2020.118518
29. Rajendran, S., Ganesan, P. (2021), *Experimental investigations of diesel engine emissions and combustion behaviour using addition of antioxidant additives to jamun biodiesel blend*, Fuel, 285: 119157. doi: 10.1016/j.fuel.2020.119157
30. El-Fakharany, M.K., Abdelrazek, A.S., Baz, F.B., Gad, M.S. (2025), *Impact of nano-TiO₂ combination with biodiesel on diesel engine performance and emissions under fuel magnetism conditioning*, Arab. J Sci. Eng. 50: 14149-14164. doi: 10.1007/s13369-024-09643-w
31. Barboza, A.B.V., Dinesha, P., Rosen, M.A. (2023), *Effect of green fuel and green lubricant with metallic nanoparticles on emissions of HC, CO, NO_x, and smoke for a compression ignition engine*, Environ. Sci. Pollut. Res. 30: 91344-91354. doi: 10.1007/s11356-023-28645-z
32. Puchakayala, H.C., Viswanathan, A., Abrar, I., Rajamohan, N. (2023), *Maximizing the potential of biodiesel through nanoparticle assistance: A review of key factors affecting performance and emissions*, Sustain. Energy Technol. Assess. 60: 103539. doi: 10.1016/j.seta.2023.103539
33. Farouk, S.M., Tayeb, A.M., Abdel-Hamid, S.M.S., et al. (2025), *Enhanced performance and reduced emissions in compression-ignition engine fueled with biodiesel blends synthesized via CaO and MgO nano catalysts*, BMC Chemistry, 19: 241. doi: 10.1186/s13065-025-01604-0
34. Kumar, S., Dinesha, P., Ajay, C.M., Kabbur, P. (2020), *Combined effect of oxygenated liquid and metal oxide nanoparticle fuel additives on the combustion characteristics of a biodiesel engine operated with higher blend percentages*, Energy, 197: 117194. doi: 10.1016/j.energy.2020.117194
35. Fayad, M.A., Abed, A.M., Omran, S.H., et al. (2022), *Influence of renewable fuels and nanoparticles additives on engine performance and soot nanoparticles characteristics*, Int. J Renew. Ener. Devel. 11(4): 1068-1077. doi: 10.14710/ijred.2022.45294
36. Kale, B.N., Patle, S.D., Kalambe, S.R. (2022), *Impact of algal biodiesel and its diesel blends on performance and emission characteristics of compression ignition engine*, J Renew. Sust. Ener. 14(1): 013101. doi: 10.1063/5.0067829
37. Kale, B.N., Patle, S.D., Kalambe, S.R., Khawale, V.R. (2024), *Comparative analysis of compression ignition engines performance and emission characteristics devouring edible and non-edible oil biodiesel*, Environ. Prog. Sustain. Ener. 43(3): e14363. doi: 10.1002/ep.14363

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