

**TOWARD SUSTAINABLE COMBUSTION: A COMPREHENSIVE REVIEW OF NANOPARTICLE-INFUSED BIODIESEL**

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Abstract

Using biodiesel as alternative fuel is a promising option due to its renewable source and favorable combustion qualities, but challenges such as lower calorific value, higher viscosity, poor cold-flow performance, and increased emissions limit its widespread adoption. Recent advances offer potential solutions: nanoparticles can act as catalysts during production and performance enhancers. Metal oxides and carbon-based nanomaterials improve transesterification efficiency, fuel atomization, ignition delay, and thermal conductivity resulting in higher brake thermal efficiency, lower brake-specific fuel consumption and reduced Emissions. The performance depends on optimal dosages (25–100 ppm), and excessive loading risks agglomeration, poor dispersion, or increased viscosity. Despite these results, many application remains limited by challenges related to nanoparticle stability, cost, toxicity, and regulatory approval. This review examines the mechanisms, performance influences, and limitations of nanoparticle-infused biodiesel. By addressing these issues, nanomaterial-enhanced biodiesel could become a viable next-generation fuel that balances performance and environmental concerns.

Keywords: Nanoparticle-infused biodiesel, Metal oxide nanoparticles, Carbon nanomaterials. Brake thermal efficiency, Emission reduction.

Introduction

High-speed development of industrialization, enlargement and population increase followed by the progress of industry has made an unprecedented demand for universal energy systems. Worldwide demand for energy is projected to rise more than 50% by 2050, with electricity consumption alone predicted to constitute almost half of the total energy use [74]. However, despite this trend of electrification remaining fossil fuels mainly coal, oil and natural gas still dominate the entire energy mix outputting the more than 75% of the global GHG (greenhouse

gases) harmful emissions [21]. The burning of these fuels generates large quantities of CO₂, nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM) and other pollutants which are highly associated with climate change, worsening air quality and negative human health influences [50, 41,73]. Beyond environmental values, the fossil fuels are finite resources, which are unevenly distributed among states and thus prone to supply interruptions and political risks [70].

The transportation part is a main contributor (about 24% of global CO₂ emissions) with street transportation responsible for further than 70% of this share [133]. Diesel engines govern heavyweight transportation and industrial requests as results of their high thermal efficiency, torque, durability, and moderately low operational costs [29, 61, 89]. However, diesel engines are also important causes of NO_x and PM emissions [78]. PM emissions are related with breathing and cardiovascular health hazards, while NO_x funds to acid rain, photochemical smoke and ground-level ozone [90].

Biodiesel as a renewable and sustainable fuel

In the middle of the several alternative fuels, biodiesel has appeared as a hopeful substitute for diesel because of its renewable source, environmental benefits, and advantageous combustion features [69, 113]. Biodiesel is usually made through transesterification of vegetable oils, animal fats, waste cooking oils and microalgal lipids, yielding fatty acid methyl esters (FAMES) that can be recycled in compression ignition (CI) engines with slight or no adjustment [27, 91]. Its noteworthy gains contain high biodegradability, non-toxicity, advanced flash point, essential lubricity and a developed cetane number compared with normal diesel [137, 46]. The oxygen ratio in biodiesel also funds more enhancement in combustion, thereby decreasing emissions of CO, unburned hydrocarbons (HC), and PM [40, 78, 72].

Biodiesel production contributes to rural development and enhances energy security by utilizing locally available feedstocks [38]. Waste-based biodiesel also matches with circular economy principles by reducing waste disposal problems and increasing resource efficiency [86]. From carbon cycle aspect, bio-diesel is considered almost environmentally clean or carbon-neutral as the released CO₂ during combustion is roughly equivalent to absorbed through feedstock growth [104].

Limitations of conventional biodiesel

Despite these benefits, biodiesel faces technical and economical constraints that curb its general interest. One significant limitation is its relatively high energy cost with the feedstock expense accounting for as much as 75% of total costs [10]. Relying on edible oil feedstocks escalates the “food versus fuel” argument leading to increased food prices and competing for land and resources [52]. While the non-food oils, waste oils and algal biomass do bring more sustainable changes, but may also require additional pre-treatment step to remove impurities [142, 141].

In terms of performance, biodiesel has lower energy density and calorific value than diesel fuel leading to high brake-specific fuel consumption (BSFC) with slightly reduced power output [59], [106]. Its increased kinematic viscosity impairs atomization, which may cause incomplete combustion, injector coking and deposit formation [93]. Additionally, the combustion of biodiesel generally leads to higher NO_x emissions compared with conventional diesel, attributed to its higher oxygen content and elevated in-cylinder combustion

temperatures [42, 85, 95]. Other properties include inadequate cold-flow; that is, the fuel forms crystals and plugs filters in cold temperatures [87].

1.3 Advancements through nanotechnology

Nanotechnology has developed as a transformative resolution to overcome biodiesel's technical and performance restrictions of application. Nanoparticles (NPs), because of their high surface area to volume ratio, tunable physicochemical Characteristics, and catalytic action, have been shown to improve biodiesel manufacture effectiveness, increase combustion and decrease harmful emissions [45, 100]. In biodiesel blend, nano-catalysts such as TiO_2 , ZnO , CeO_2 , and CaO hurry transesterification, rise yields, and establish greater reusability compared with traditional catalysts [88, 13, 19]. For example, CeO_2 nanoparticles have been described to reach biodiesel yields exceeding 96% while also improving oxidative stability [20].

Nanoparticles in gasoline additives improve combustion, oxidation, ignition delay, and thermal conductivity [120, 62]. These influences may increase BTE, diminish BSFC, and reduce CO, HC, and smoke opacity [1,53, 115]. Catalysis and oxygen-buffering have been studied for metal oxide nanoparticles like TiO_2 , CuO , Al_2O_3 , Fe_3O_4 , and ZnO [130], while non-metallic nanomaterials like graphene oxide (GO) and carbon nanotubes (CNTs) increase thermal conductivity for spray atomization [138, 4].

Mechanisms of nanoparticle influence in biodiesel blends

Biodiesel blends with nanoparticles performed better for numerous reasons. Due to their strong heat conductivity, their combustion flame operating temperature will be greater than the absorption layer, increasing ignition delay and fuel-air mixing [144]. Cerium oxide nanoparticles contribute to the conversion of HC and CO into H_2O and CO_2 by functioning as oxygen donors [128]. Local heating in fuel droplets may cause micro-explosions and subsequent droplet atomization. This improves combustion by increasing the fuel-air interaction [77].

2.1. Oxygen buffering and redox catalysis (Metal oxides)

It is well known that metal-oxide nanoparticles, such as CeO_2 [6], TiO_2 [7] and Fe_3O_4 -NPs [8] have oxygen contents and/or release capabilities. By burning they also function as oxygen sinks supplying fresh, reactive oxygen which is beneficial for the oxidation of hydrocarbons. Reduced CO and HC emissions as well as advanced brake thermal efficiency (BTE) are achieved with this mechanism [16, 135].

2.2. Surface-catalyzed oxidation and radical control (Metal oxides & hybrids)

Nanoparticles like high surface area and intense catalytic activity, along with CeO_2 , ZnO and CuO supported heterogeneous oxidation reactions. They might stabilize, or quench, reactive radicals, leading to pristine combustion and cleaner exhaust. In composite shapes such as TiO_2 - CuO composites, catalytic influences are further enhanced to accelerate oxidation reactions and promoting combustion of the entire [135, 24].

2.3. Thermal transport and spray-evaporation coupling (Metal oxides & carbon-based)

Nanoparticles, such as CuO , Al_2O_3 , carbon quantum dots, graphene oxide (GO) and multi-walled carbon nanotubes (MWCNTs), enhance the thermal conductive behaviour of fuel mixer. The enhanced heat transfer increases the heating rates of droplets and results in micro-explosion phenomenon that contributes well to atomization, evaporation and air mixing with

fuel. These properties together play negative role in ignition delay; and positive role for increase in combustion efficiency [84, 57].

2.4. Soot inhibition and ash interactions (Metal oxides & hybrids)

Oxidants, for example, oxide-forming metal oxides such as CeO_2 and TiO_2 can promote the oxidation of soot precursors over the later stages of combustion to lower particulate matter formation. Hybrid devices, including ferric chloride–graphene composites, can similarly influence ash chemistry preferable towards soot oxidation and lower reduction smoke opacity [16, 145].

2.5 Tribological enhancement and lubricity influences (Metal oxides & carbon-based)

Many nanoparticles enhance the tribological performance of biodiesel blends by forming protective tribofilms on metal surfaces. Materials such as CuO , Al_2O_3 , TiO_2 and ZnO reduces friction factors to a maximum of 80% and wear rates up to 75 %. The layered structure of carbon-based nanomaterial such as GO and CNTs 28, in addition to graphene layers which are the basis for these two materials, also provide an extra lubrication influence. These tribological enhancements increase the life of engine components, such as injectors and piston edges, while promoting more stable fuel injection characteristics [24, 112].

Droplet Heating Regimes: Evaporation, Puffing, and Micro-Explosion

The thermal reaction by heating affects powerfully on the combustion action properties of two liquids emulsion droplets. Depending on air temperature, the composition of droplets and internal nucleation dynamics, droplets undergo evaporation, puffing or micro-explosion. The schematic illustration of these configurations is given in Fig. 1 with corresponding temperature ranges given in Fig. 2 [37].

Evaporation happen at approximately low air temperatures of 373–423 K. In this stage, droplets heat gradually, and surface vaporization happens steadily without structural disruption. The droplet maintains its spherical shape, reducing in size as volatile components diffuse into the surrounding medium. The process is steady, repeatable, and produces no secondary fragments (Fig. 1a). At approximately higher temperatures (423–473 K), weak boiling may related with evaporation, where limited bubble generation occurs but does not destabilize the droplet.

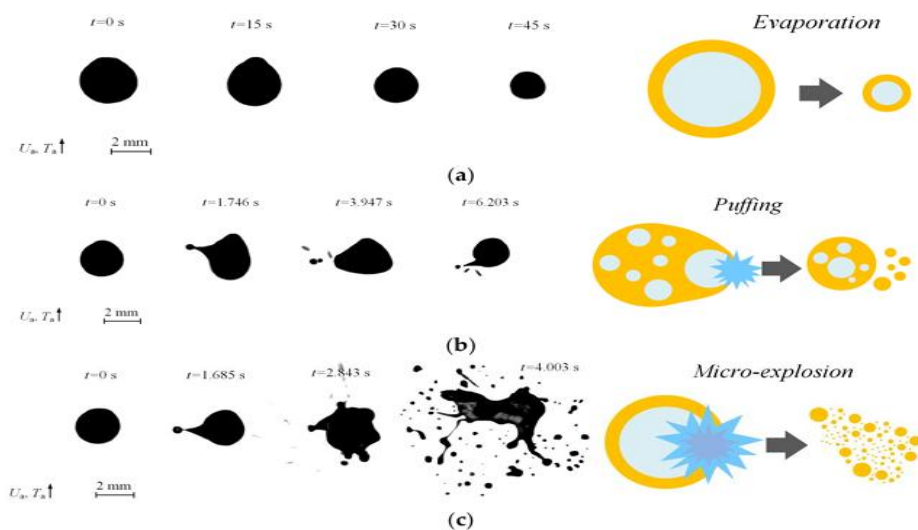


Fig. 1. Schemes of fuel emulsion droplet heating, expansion, evaporation, puffing, and micro-explosion regimes [37]

Puffing and boiling take over at transitional temperatures of 473–573 K. In boiling, contained bubble nucleation remains mild, with bubbles failing without major breakup. In contrast, puffing is categorised by localized nucleation that triggers the implosion of vapor holes, creating audible popping sounds and fractional fragmentation. Secondary droplets are cast out from the parent droplet, and this process becomes more marked at 573–623 K, where bubble dynamics dictate droplet breakup (Fig.1b).

Micro-explosion happens at higher temperatures beyond 673 K and signifies the most disruptive regime. In this case, widespread nucleation grows almost at the same time during the droplet volume (Fig. 1c). Firstly, the droplet surface seems intact, but quick expansion of vapor bubbles leads to catastrophic break. The droplet fragments explosively into a fine spray cloud, often go with vapor jets and loud acoustic signatures. Accelerated imaging confirms that micro-explosions significantly improve atomization and fuel with air mixing.

Transitional behavior between puffing and micro-explosion at 623–673 K is strongly influenced by droplet form, heat, and emulsion stability. Evaporation (373–423 K), evaporation with weak boiling (423–473 K), boiling (473–523 K), stable puffing during boiling (523–573 K), dominant puffing from 573 to 623 K, transition puffing/micro-explosion (623–673 K), and microexplosion above 673 [9].

The shaded intermediate portions in Fig. 2 demonstrate stochastic droplet collapse. The same temperature conditions can have different influences depending on nucleation locations, heating rate, and emulsion stability. This unpredictability makes predicting atomization dynamics difficult and emphasizes the need for comprehensive experimental characterisation to understand and mimic emulsion fuel behavior.

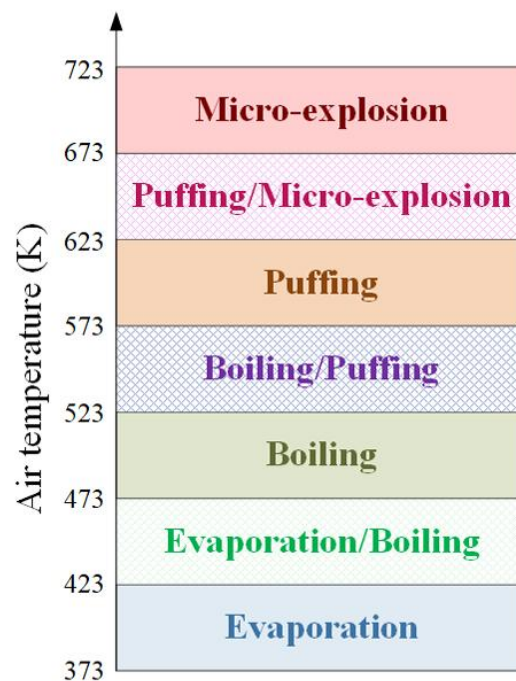


Fig. 2. Temperature ranges of micro-explosion regimes [9].

Environmental, Operational and Stability Considerations of Nanoparticle-Infused Biodiesel. Biodiesel with NPs has higher thermal conductivity, cetane number, oxidative stability, and atomization. These benefits can only be used after overcoming stability, environmental, and financial difficulties and regulatory approval.

Dispersion stability is crucial technically. Nanoparticles agglomerate due to their high surface energy and van der Waals forces, causing sedimentation, aggregation, and hard deposits that resist re-dispersion and obstruct fuel systems [5, 12, 40]. This instability lowers flame surface area, catalytic efficiency, and fuel burning stability. Due to its high viscosity and polar functional groups, biodiesel disrupts colloidal bonding and agglomeration rates. Small, homogenous particles disperse effectively but become more sensitive and less stable if their surface chemistry is not well tuned [5, 147].

Many stabilizing strategies have been studied to overcome instability. Ultrasonication and mechanical stirring are still the best ways to break up clusters and preserve homogeneity, although Span-80 provides steric or electrostatic barriers to keep the dispersion for weeks [40], [147]. Surface functionalization such silanization and polymer coating improves nanoparticle biodiesel compatibility. Hybrid nanoparticles ($\text{TiO}_2\text{-CuO}$, $\text{CeO}_2\text{-graphene oxide}$) use complementary chemistries for stability and combustion, although improper formulation might cause multiphase separation [14, 5].

Environmental and health concerns are major issues. Unsafe industrial use and disposal of metal-based nanoparticles can cause toxicity and environmental damage [126]. Nanomaterial application in fuels lacks regulatory infrastructure, requiring safety criteria before widespread commercialization [90].

Economic viability limits acceptability. Laboratory experiments show significant gains, but costly manufacture, standardization of preparation, and supply chain mixing issues prevent widespread use [75, 55]. Stable sprays reduce injector wear and system fouling, improving combustion efficiency and economics [12, 14, 40]. The performance benefit disappears when stability is insufficient. Both performance improvement and cost effectiveness disappear.

Industrially, successful applications must balance combustion/emission benefits, storage stability, environmental friendliness, cost-effectiveness, and infrastructural compatibility. For future research, standard stability testing procedures should address nanoparticle amount and surface chemistry to combine analytical modeling to estimate lasting durability across diverse storage/operating circumstances [40, 14, 147].

Influence of Nanoparticles on the Physicochemical Properties of Diesel and Biodiesel Fuels

Estimating the effects of nanoparticles on the thermophysical and rheological properties of base fuels is very important, since these characteristics directly effect on combustion performance. The most commonly listed nanofuel properties in the literature are kinematic viscosity, calorific value, density (specific gravity), flash point and cetane number. Standardized testing methods are used to get these properties, involving ASTM D445 for viscosity, ASTM D4809 for calorific value, ASTM D1298/D4052 for density, ASTM D93 for flash point, and ASTM D4737/D613 for cetane number. Table 1. summarizes studies that have investigated some or all of these properties.



Table 1. Properties of Diesel/biodiesel provided with nano materials

Authors , Year	Fuel type	Nanoparticles, Amount (ppm)	Kinematic Viscosity (cST)	Calorific Value (MJ/kg)	Specific Gravity	Flash point (°C)	Cetane No.
[139]	Grape-Seed Oil Biodiesel	Base fuel	4.06	39.07	0.845		55
		CeO ₂ , 100	4.47	38.76	0.853		57
		ZnO, 100	4.42	38.90	0.850		59
[108]	Grape-Seed Oil Biodiesel	Base fuel	4.06	39.07	0.845		55
		CeO ₂ , 50	4.45	38.55	0.852	-	56
		CeO ₂ , 100	4.47	38.76	0.853		57
		ZnO, 50	4.40	38.78	0.849		58
		ZnO, 100	4.42	38.90	0.850		59
[68]	80% Diesel + 20% Grape Seed Oil Methyl Ester	Base fuel	5.55	37.02	0.841	38	-
		CeO ₂ , 50	5.56	38.38	0.843	39	
		CeO ₂ , 100	5.56	38.96	0.846	39	
[18]	Diesel	Base fuel	4.56	48.58	0.841	-	56
		Al ₂ O ₃ , 25	3.70	48.20	0.853		55.4
		Al ₂ O ₃ , 50	3.81	49.32	0.856		55.3
		Al ₂ O ₃ , 100	4.12	49.77	0.873		55.4
		CNT, 25	3.99	49.09	0.841		54.7
		CNT, 50	3.86	50.18	0.846		54.8
		CNT, 100	3.83	51.27	0.850		54.9
		SiO ₂ , 25	4.26	47.31	0.845		55
		SiO ₂ , 50	3.98	47.78	0.835		55.2
		SiO ₂ , 100	4.26	48.60	0.836		55.7
[44]	Diesel	Base fuel	3.60	-	0.834	60	53.8
		Al ₂ O ₃ , 50	3.50		0.834	68	54.4
		CuO, 50	3.50		0.834	66	54.5
[117]	Diesel	Base fuel	3.60	42.00	0.833	60	
		CuO, 0.5% mass fraction	3.50	42.43	0.834	66	
[26]	Diesel	Base fuel	2.98	41.79	0.697	51	
		TiO ₂ , 80 mg/L	3.17	42.04	0.700	72	
[23]	Neat palm stearin biodiesel (PSBD)	Base fuel	4.28	37.51	0.844	140	
		AgO (10 nm), 5	4.12	37.85	0.834	138	
		AgO (20 nm), 5	3.86	38.35	0.804	134	-
		AgO (10 nm), 10	3.98	38.01	0.819	136	
		AgO (20 nm), 10	3.71	38.54	0.797	132	
[105]	80% volume of diesel and 20% of Pongamia oil	Base fuel	3.02	43.68	0.824	69	
		CuO, 50	4.79	43.78	0.835	67	
		CuO, 100	4.85	43.82	0.846	66	
[118]	Mango seed biodiesel	Base fuel	3.80	38.13	0.880	165	58
		ZnO (20 nm)	3.70	38.25	0.820	168	58
		ZnO (40 nm)	3.60	38.75	0.790	171	59
[76]	Diesel	Base fuel	2.70			48	
		MnO, 200 mg/L	2.53	-		44	
		CuO, 200 mg/L	2.24			40	
[136]	Honge Oil Methyl Ester (HOME)	Base fuel	5.60	36.02	-	170	-
		CNT, 25	5.70	34.56		166	
		CNT, 50	5.80	35.10		164	
[98]	Sardine Oil Methyl Ester (SOME)	Base fuel	4.50	37.41	0.890	58	45
		CeO ₂ , 25	5.60	45.37	0.894	191	56
[122]	80% of diesel and 20% of biodiesel from neem oil	Base fuel	3.74	41.90	0.828	65	43.5
[39]	93% diesel + 7% biodiesel from waste cooking oil (WCO)	CeO ₂ , 50	3.71	41.94	0.830	66	43.7
		Base fuel	3.92	42.49	-	74	-
[8]	5% water + 93% Lemongrass Oil (LGO) + 2% span80	CeO ₂ , 90	3.88	42.38		77	
		Base fuel	4.67	35.80	0.906	74	46.3
[97]	Calophyllum Inophyllum Methyl Ester (CIME)	Base fuel	4.99	36.20	0.916	67	48.8
		ZnO, 30	4.72	38.00	0.869	122	52
		ZnO, 50	4.76	37.02	0.871	123	54
		ZnO, 100	4.78	37.32	0.872	126	56
		TiO ₂ , 50	4.73	37.12	0.869	123	53
[6]	20% Calophyllum inophyllum biodiesel + 80% diesel	TiO ₂ , 100	4.75	37.54	0.870	124	55
		Base fuel	3.56	40.92	843.3	69	53.9
		Al ₂ O ₃ , 40	3.64	41.44	858	64	54.6
[99]	Canola biodiesel	Base fuel	4.80		0.915	42	
		TiO ₂ , 300	3.40	-	0.840	56	
[96]	Vegetable methyl ester from WCO blended with diesel	Base fuel	4.24	45.72	0.835		46
		Ag, 40	4.36	46.44	0.855		47
		Ag, 80	4.40	46.68	0.855	-	48
		Ag, 120	4.49	46.92	0.859		50
		CNT, 40	4.74	47.12	0.880		57
		CNT, 80	4.82	48.02	0.884		59

[25]	Tamarind Seed Methyl Ester 20% + 80% diesel (TSME20)	CNT, 120	4.91	48.68	0.892		61
		TSME20	3.86	41.70	0.843	74	48
		Al2O3, 30	3.88	41.75	0.845	75	51
		Al2O3, 60	3.89	41.76	0.846	77	53
		CNT, 30	3.87	41.73	0.845	76	50
[132]	HOME (B20): 20% Honge oil methyl ester + 80% diesel	CNT, 60	3.90	41.74	0.846	78	52
		HOME20	3.50	40.50	0.833	153	57
		Al2O3, 20	3.39	40.53	0.837	149.	53.8
						6	
		Al2O3, 40	3.31	40.88	0.835	142.	54.4
[79]	B20: 20% rubber seed oil + 80% diesel					3	
		Al2O3, 60	3.34	40.65	0.835	144.	54.0
						5	
		B20	4.20	38.00	0.820		
		Al2O3, 10	4.10	42.00	0.830		
[125]	B20 system variants	Al2O3, 15	4.20	41.00	0.850		
		Al2O3, 20	4.20	41.00	0.850		
		Soybean biodiesel	4.78	41.20	0.865	-	49
		Diesel + biodiesel (B20)	3.70	43.00	0.847		42
		D80SBD15E4S1 + Al2O3, 100 mg/L	3.37	42.59	0.840		52
[110]	20% Poultry Litter Oil Methyl Ester + 80% Diesel (B20PLOM)	Base Fuel	-	-	-	-	-
[131]	75% diesel + 25% pongamia methyl ester (B25)	Al2O3, 30 mg/L					
		Base fuel	4.40	41.46	0.843	68	50
		Al2O3, 50	4.35	41.48	0.845	63	51
[51]	85% diesel + 15% 2-methylfuran (MF15)	Al2O3, 100	4.31	41.51	0.848	58	52
		MF15	3.47		0.861		
		MWCNT, 25	3.76		0.860		
		MWCNT, 50	4.00		0.860		
		MWCNT, 100	4.22		0.858		
[103]	Diesel / Palm Oil Methyl Ester (Biodiesel)	Diesel	4.74	-	0.849	-	-
		Palm Oil Methyl Ester (Biodiesel)	5.20		0.867		
		0.1% Graphite Oxide + Diesel	4.33		0.849		
		0.1% Graphite Oxide + Biodiesel	5.41		0.868		
		Diesel	5.80	45.11	0.849	62	47
[101]	Diesel	CeO2, 25 (CDD)	5.20	45.27	0.850	74	44
		Single Wall CNT, 25 (SDD)	5.31	45.54	0.849	168	43
		Graphite Oxide, 25 (GDD)	5.27	45.60	0.849	150	51
		Diesel					
		CeO2, 50	-	-	-	-	-
[123]	LGO25: 75% diesel + 25% lemongrass oil	CeO2, 100					
		LGO25	3.48	41.69	0.870	53	
		CeO2, 50	4.16	41.06	0.910	58	
[31]	JB20D: Jojoba methyl ester-diesel blend	Base fuel	4.06	45.43	0.847		52
		MWCNT, 10	4.10	45.44	0.847		52.7
		MWCNT, 20	4.19	45.45	0.847		53.5
		MWCNT, 30	4.25	45.45	0.847		54.2
		MWCNT, 40	4.31	45.46	0.847		55.4
		MWCNT, 50	4.35	45.46	0.847		56
[34]	5% n-hexane + 30% jojoba methyl ester + 65% diesel	Base fuel	4.05	44.97	0.844		54
		TiO2, 25	4.09	45.00	0.845		55.5
		TiO2, 50	4.11	45.05	0.846		57.6
[34]	Jatropha Methyl Ester (JME)	Base fuel	5.26	40.63	0.883		52
		GO, 25	5.20	40.63	0.884		53.5
		GO, 50	5.13	40.64	0.884		54.5
		GO, 75	5.12	40.65	0.884		56.2
		GO, 100	5.06	40.66	0.846		57.3
[34]	JB20: 20% jatropha methyl ester + 80% diesel	Base fuel	3.33	41.14	0.849		51.6
		Graphene nanoplatelets (GNP), 25	4.05	41.16	0.850		52.3
		GNP, 50	4.18	41.19	0.850		53.5
		GNP, 75	4.21	41.21	0.850		55.2
		GNP, 100	4.22	41.23	0.850		57.4
[30]	JME40B: 60% jatropha methyl ester + 40% n-butanol	Base fuel	3.73	37.53	0.850		43.5
		GO, 50	3.65	37.56	0.851		48.1
		GNP, 50	3.68	37.56	0.851		48.0
		MWCNT, 50	3.69	37.57	0.851		48.0
[124]	Waste pyrolysis oil (WPO)	WPO	2.67	44.35		41	50.5
		25% WPO + 75% Diesel + Al2O3, 25	2.30	44.70	-	40	55
[64]	Terminalia bellirica biodiesel — B20 (20% biodiesel + 100% diesel)	Base fuel	4.22	40.32	0.873	142	62
		50 ppm BZnFMO	4.28	40.86	0.875	140	62
		75 ppm BZnFMO	4.32	41.07	0.878	138	62
[76]	Palm oil biodiesel — B100	Base fuel	4.30	39.60	0.883	140	52
		45 ppm CeO2	4.41	40.95	0.891	122	57



[136]	Mahua oil biodiesel — B20	Base fuel	2.62	41.11	0.850	43	
		25 ppm TiO ₂	2.70	41.17	0.852	40	/
		100 ppm TiO ₂	2.74	41.28	0.858	41	
[68]	Mesua ferrea biodiesel — B20	Base fuel	3.50	39.66	0.872	152	58
		60 ppm Cr ₂ O ₃	3.61	40.34	0.876	147	60
		100 ppm Cr ₂ O ₃	3.73	40.93	0.882	138	61
[107]	Guizotia abyssinica (L.) biodiesel — B10	Base fuel	3.21	43.00	0.820	75	46
		100 ppm Al ₂ O ₃	2.91	45.00	0.834	79	53
		100 ppm TiO ₂	2.98	44.30	0.844	81	52
[119]	Raw linseed oil biodiesel — B20	Base fuel	3.36	40.03	0.834	107	49
		50 ppm Co ₃ O ₄	3.46	43.16	0.836	109	49.7
		100 ppm Co ₃ O ₄	3.56	43.27	0.838	110	50.4
[67]	Waste frying oil biodiesel — B30	Base fuel	4.90	45.29	0.852	76	/
		300 ppm ferrocene	4.85	/	0.853	76	
[47]	Waste frying oil biodiesel — B10	Base fuel	3.17	41.89	0.845	>100	51.14
		100 ppm TiO ₂	3.19	42.73	0.845	>100	52.13
		100 ppm Al ₂ O ₃	3.19	43.05	0.845	>100	51.98
		100 ppm SiO ₂	3.19	42.89	0.845	>100	51.67
							6
[60]	Canola oil biodiesel — B20	Base fuel	3.21		0.839	80	
		50 ppm quantum dots	3.24	/	0.840	77	
		100 ppm quantum dots	3.23		0.840	77	/
[11]	Jojoba biodiesel — B20	Base fuel	3.59	41.93	0.845	71	
		25 ppm CuO	3.68	41.22	0.858	66	
		75 ppm CuO	3.87	41.66	0.871	63	
[64]	Pithecellobium Dulce seed-derived biodiesel — B20	Base fuel	3.22	41.90	0.838	65	55
		100 ppm Groundnut shell nanoparticle	3.20	42.10	0.840	64	54
[65]	Parsley biodiesel — B20	Base fuel	4.01	40.24	0.901	108	54.2
		50 ppm SiO ₂	4.08	41.38	0.907	120	57.2
		100 ppm SiO ₂	4.14	42.53	0.918	127	62.8
[28]	Diesel +Waste Cooking Oil	B0ZnO	2.88	46.73	-	-	49.7
		B20ZnO	3.52	45.17			60
		B40ZnO	4.16	43.63			70.3
[92]	B30(70%Dieseland30%Biodiesel)	B30	3.35	43.20	0.83		
		B30+(100ppm)CarbonNanoTubes	3.37	42.80	0.83		
		B30+(100ppm)TiO ₂	3.36	42.90	0.83		
[35]	Butanol-Diesel blend (B20: 20% Butanol + 80% Diesel	Diesel	2.77	44.80	0.84	55	51.8
		B20	3.22	43.40	0.86	81	53.4
		B20 +30- Al ₂ O ₃	3.12	45.30	0.87	82	54.6
		B20 +50- Al ₂ O ₃	3.06	46.40	0.88	83	55.7
		B20 + 100-Al ₂ O ₃	2.84	47.50	0.89	85	58.3
[129]	Diesel75 %+25 biodiesel B25	25B25ZnO		41.20	0.85		
		25B50ZnO		42.00	0.85		
		25B100ZnO		42.22	0.86		
		25B200ZnO		43.11	0.86		
[114]	Diesel75 %+25 soybean biodiesel	Diesel	2.12	45.00	0.81	55	51
		SBME25	3.56	41.82	0.85	65.7	48.7
		SBME25ZnO25	3.52	43.43	0.85	62.9	52.6
		SBME25ZnO50	3.52	44.84	0.85	60.5	53.7
		SBME25ZnO75	3.53	43.90	0.85	61.9	53.2
[43]	Diesel	Diesel	3.68	42.9	0.82	46	52
	Lemongrass biodiesel	LGB + ZnO 50 ppm	4.18	41.58	0.91	55	58
		LGB + ZnO 100 ppm	4.20	41.62	0.91	55	58
		LGB + ZnO 150 ppm	4.32	41.80	0.91	56	60
		LGB + ZnO 200 ppm	4.52	41.90	0.92	60	61
		LGB + ZnO 250 ppm	4.83	42.10	0.92	62	61
[49]	25% soybean biodiesel in diesel	Diesel	2.12	45.00	0.81	55	51
		SBME25	3.56	41.60	0.85	66	48.7
		SBME25Ce-ZnO25	3.40	43.12	0.84	60	51.6
		SBME25Ce-ZnO50	3.50	44.41	0.84	58	52.8
		SBME25Ce-ZnO75	3.60	44.20	0.85	59	52.9
[36]	B30(70%Dieseland30%Biodiesel)	Diesel	3.14	43.90	0.83		
		B30	3.35	43.00	0.83		
		B30 + CNT	3.37	42.91	0.83		
		B30 + TiO ₂	3.36	42.94	0.83		
		B30 + Al ₂ O ₃	3.35	42.92	0.83		
[134]	Biodiesel-diesel- propanol blend	Diesel	2.56	42.50	0.83	45	
		20% of Biodiesel + 80% of Diesel	2.90	40.50	0.84	61	
		CB20					
		20% of Biodiesel + 75% of Diesel+5% of Propanol	2.88	41.40	0.83	50	
		CB20P5					



		CB20P5 ZnO40	2.67	41.50	0.83	67	
		CB20P5ZnO80	2.66	41.50	0.84	69	
		CB20P5ZnO120	2.72	41.60	0.86	70	
[140]	Diesel + 20 % biodiesel	Diesel		42.20	0.83		
		20B		41.90	0.84		
		20B50ZnO		42.10	0.84		
		20B100ZnO		42.32	0.83		
		20B150ZnO		43.05	0.83		
		20B200ZnO		44.21	0.83		
[3]	Diesel + 20 % biodiesel	Diesel	2.30	45.80	0.83	53	47
		B20	4.50	44.51	0.86	125	50.1
		B20+GO 90 ppm	4.70	44.21	0.86	130	50.5
		B20+MgO 90 ppm	4.60	44.35	0.86	128	50.3
		B20+MWCNT 90 ppm	4.60	44.44	0.85	127	50.4
[82]	Diesel and Waste Cooking Oil Biodiesel	Diesel	4.20	44.52	0.83		45
		WCOB	5.10	37.23	0.88		44
		WCOB CZ50 (CuO Oxide with ZnO)	5.90	38.22	0.88		45
		WCOB CZ100	6.50	38.04	0.88		46.5

Generally, the evaluation of nanoparticles requires balancing calorific value (CV), cetane number (CN), and kinematic viscosity (KV). Additive should enhance CV and CN while keeping KV within the diesel standard range (1.9–4.1 cSt, ASTM D975) to ensure impact atomization and combustion. The impacts of several nanomaterials are summarized below (see Table 2).

Table 2. Optimum Materials and Dosages.

Nanomaterial	Optimum (ppm)	Dosage	Effect on Calorific Value	Effect on Cetane Number	Effect on Viscosity	Best Use Case
CeO ₂	25–100		Maintains baseline (38–42 MJ/kg)	+2 to +5 units	Slightly high (>4.4 cSt)	Ignition promoter
ZnO	40–100		Stable CV (38–41 MJ/kg)	+4 to +11 units	Stable (3.5–4.1 cSt)	CN improvement
CNT/MWCNT	50–100		Strong ↑ (45–51 MJ/kg)	+5 to +15 units	Within safe range (3.7–4.0)	Energy density + CN
Al ₂ O ₃	100		Moderate ↑ (42–47 MJ/kg)	+4 to +6 units	Strong ↓ (2.8–3.3 cSt)	Viscosity stabilizer
Ag	40–120		Moderate ↑ (46–47 MJ/kg)	Small ↑ (≤+4 units)	Stable	Secondary enhancer
TiO ₂	50–100		Low-moderate ↑ (37–45 MJ/kg)	+3 to +5 units	Acceptable	CN improvement

5.1. Cerium Oxide (CeO₂)

CeO₂ is commonly studied due to its oxygen content and catalytic properties. [139] and [108] stated that 100 ppm CeO₂ improved CN from 55 to 57, preserved CV near 38.8 MJ/kg, but elevated KV to 4.4–5.5 cSt, above ASTM limits. [98] established CN enhancements up to 56 at just 25 ppm. These results proposed that CeO₂ at 25–100 ppm can improve ignition value, though viscosity rises may confine higher loadings.

5.2. Zinc Oxide (ZnO)

ZnO validates steady enhancements in both CN and CV while keeping viscosity within adequate limits. [118] presented that 40 nm ZnO at 40 ppm elevated CN to 59, conserved CV at 38.75 MJ/kg and kept KV at 3.6 cSt. [97] stated parallel CN rises (56) at 100 ppm with steady CV. [28] established CN values as high as 70.3 at 40 ppm, although quantities above 120 ppm produced viscosity to exceed bounds. Thus, 40–100 ppm ZnO is optimum for consistent CN improvement while keeping steady viscosity.

5.3. Carbon Nanotubes (CNTs and MWCNTs)

Carbon nanotubes reliably show the major gains in CV, often exceeding 50 MJ/kg. [18] found that 100 ppm CNTs improved CV to 51.27 MJ/kg, CN to 54.9, and sustained KV at 3.8 cSt. [96] stated similar enhancements at 120 ppm, with CV at 48.68 MJ/kg and CN at 61. [31] confirmed that MWCNTs at 50 ppm improved CV (45.46 MJ/kg) and CN (56), with KV quiet within limits. Collectively, CNTs at 50–100 ppm seem optimal for exploiting both energy density and ignition quality.

5.4. Aluminum Oxide (Al_2O_3)

Al_2O_3 offers strong viscosity decrease together with moderate CV and CN enhancements. [35] informed that rising Al_2O_3 dosage from 30 to 100 ppm improved CV from 45.3 to 47.5 MJ/kg, CN from 54.6 to 58.3, and decreased KV to 2.84 cSt, well within standards. [132] also stated CN improvement to 54 at 60 ppm. Generally, 100 ppm Al_2O_3 performs optimal for applications needing viscosity stabilization with reasonable performance gains.

5.5. Silver Nanoparticles (Ag, AgO)

Ag nanoparticles offer modest enhancements comparative to other nanomaterials. [23] and [96] informed that 10–120 ppm Ag nanoparticles improved CV to ~46.9 MJ/kg and CN to ~50, though the gains were smaller than those accomplished with CNTs or ZnO.

5.6. Titanium Dioxide (TiO_2):

TiO_2 gives to sensible CN developments with limited influence on CV. [97] noticed CN rises to 55 at 100 ppm with CV of ~37.5 MJ/kg. [34] further stated CN values of 57.6 at 50 ppm. Thus, TiO_2 is best suitable for ignition quality improvement, though it is less active in refining energy density.

5.7. Synthesis:

Within these studies, CNTs at 50–100 ppm are the most effective for increasing calorific value and cetane number, making them good for power intensive applications. ZnO at 40–100 ppm consistently enhances ignition quality while keeping viscosity within standards. Al_2O_3 at 100 ppm is useful for viscosity control while giving moderate enhancements in CN and CV. CeO_2 improves ignition quality but may increase viscosity beyond allowable limits at higher dosages. Ag and TiO_2 offer additional enhancements, with TiO_2 mainly useful for cetane improvements.

Impact of Nanoparticles on BTE and BSFC

Nanoparticles are also increasingly being recognized to enhance engine performance through increase of combustion efficiency and fuel usage. BTE and BSFC are two significant indicators of engine performance. In the literature, it is well established from extensive studies that nanoparticle additives generally increase BTE but decrease BSFC compared to the base diesel or biodiesel fuels. These improvements are primarily due to the catalyst effect of the nanoparticles that accelerates combustion reactions, enhances atomization and raises heat release rates. Nanoparticles could also act as oxygen donors and combustion promoters, reducing the ignition delay and promoting a more complete oxidation of hydrocarbons. An overview of descriptive studies can be found in Table 3.



Table 3. Impact of adding nanoparticles on BTE and BSFC

Authors, Year	Base Fuel	Nanoparticles & Amount (ppm)	BTE at Full Load (%)	BSFC at Full Load (kg/kWh)
[139]	Grapeseed oil biodiesel	Base fuel	28.8	0.31
		CeO ₂ , 100	30.2	0.30
		ZnO, 100	30.51	0.29
[108]	Grapeseed oil biodiesel	Base fuel	29.2	0.32
		CeO ₂ , 50	29.2	0.315
		CeO ₂ , 100	29.2	0.31
		ZnO, 50	29.3	0.32
		ZnO, 100	29.3	0.315
[68]	80 % Diesel and 20 % Grape Seed Oil Methyl Ester (Base fuel	30.5	0.32
		CeO ₂ , 50	32.5	0.30
		CeO ₂ , 100	35.0	0.29
[18]	Diesel	Base fuel	28.0	0.24
		Al ₂ O ₃ , 25	28.2	
		Al ₂ O ₃ , 50	26.9	
		Al ₂ O ₃ , 100	27.4	
		CNT, 25	27.1	
		CNT, 50	28.3	-
		CNT, 100	28.1	
		SiO ₂ , 25	29.1	
		SiO ₂ , 50	28.6	
		SiO ₂ , 100	28.6	
		[44]	Diesel	Base fuel
Al ₂ O ₃ , 50	27.5			0.32
[26]	Diesel	Base fuel	33.0	0.243
		TiO ₂ , 80 mg/L	33.3	0.20
[23]	Neat palm stearin biodiesel	Base fuel	26.6	0.101
		AgO (10 nm), 5 ppm	27.2	0.098
		AgO (20 nm), 5 ppm	28.2	0.093
		AgO (10 nm), 10 ppm	27.5	0.096
		AgO (20 nm), 10 ppm	28.6	0.091
[105]	80% Diesel + 20% Pongamia Oil	Base fuel	34.3	0.32
		CuO, 50	34.9	0.29
		CuO, 100	35.4	0.27
[118]	Mango Seed Biodiesel	Base fuel	23.9	0.0149
		ZnO (20 nm)	24.7	0.0147
		ZnO (40 nm)	24.9	0.0142
[76]	Diesel	Base fuel	27.5	
		MnO, 100 mg/L	28.5	
		CuO, 100 mg/L	26.5	
[136]	Honge Oil Methyl Ester	Base fuel	23.0	-
		CNT, 25	24.0	
		CNT, 50	25.0	
[98]	Sardine Oil Methyl Ester	Base fuel	31.0	
		CeO ₂ , 25	29.0	
[122]	Diesel 80% + Neem Oil Biodiesel 20%	Base fuel	29.0	0.325
		CeO ₂ , 50	31.8	0.375
[39]	5 % of water, 93 % of Lemongrass Oil and 2 % of span80	Base fuel	31.8	0.305
		CeO ₂ , 90	36.1	0.240
[8]	5% Water + 93% LGO + 2% Span80	Base fuel	27.5	-
		CeO ₂ , 30	29.0	
[97]	Calophyllum Inophyllum Methyl Ester	Base fuel	26.0	0.266
		ZnO, 50	27.5	0.262
		ZnO, 100	28.9	0.258
		TiO ₂ , 50	30.1	0.253
		TiO ₂ , 100	30.5	0.249



[6]	20 % of Calophyllum inophyllum biodiesel +80 % of diesel	Base fuel	33.5	
		Al ₂ O ₃ , 40	35.2	-
[99]	Canola Biodiesel	Base fuel		
		TiO ₂ , 300		
[96]	Vegetable methyl ester from the waste cooking oil blended with diesel	Base fuel		0.223
		Ag, 40		0.221
		Ag, 80	-	0.217
		Ag, 120		0.215
		CNT, 40		0.218
		CNT, 80		0.212
		CNT, 120		0.210
[25]	Tamarind Seed Methyl Ester 20 % blended with 80 % diese	TSME20	34.0	0.252
		Al ₂ O ₃ , 30	35.3	0.243
		Al ₂ O ₃ , 60	35.7	0.241
		CNT, 30	34.7	0.250
		CNT, 60	35.2	0.247
[132]	20 % Honge oil methyl ester and 80 % diesel fuel blend	HOME20	25.65	0.34
		Al ₂ O ₃ , 20	26.35	0.325
		Al ₂ O ₃ , 40	31.31	0.270
		Al ₂ O ₃ , 60	28.85	0.30
[79]	B20 (Rubber Seed Oil + Diesel)	B20	20.0	0.40
		Al ₂ O ₃ , 10	22.0	0.37
		Al ₂ O ₃ , 15	21.0	0.38
		Al ₂ O ₃ , 20	19.0	0.42
[125]	B20 (Soybean Biodiesel)	Base fuel	27.0	0.31
		80 % diesel, 15 % soybean biodiesel, 4 % ethanol, and 1 % isopropanol as a surfactant, Al ₂ O ₃ , 100 mg/L	27.1	0.30
[110]	20 % Poultry Litter Oil Methyl Ester +80 % Diesel	Base fuel	31.0	-
		Al ₂ O ₃ , 30 mg/L	31.9	
[131]	B25 (Pongamia Methyl Ester)	Base fuel	27.6	0.355
		Al ₂ O ₃ , 50	28.91	0.34
		Al ₂ O ₃ , 100	29.7	0.30
[101]	Diesel	Base fuel	24.3	0.323
		CeO ₂ , 25 (CDD)	25.3	0.310
		Graphite Oxide, 25 (GDD)	26.2	0.296
		Single Wall CNT, 25 (SDD)	26.9	0.289
[83]	Diesel	Base fuel	31.7	0.270
		CeO ₂ , 50	32.2	0.260
		CeO ₂ , 100	32.9	0.257
[123]	75 % by volume of diesel and 25 % of lemongrass oil	Base fuel	30.0	0.33
		CeO ₂ , 50	31.1	0.36
[31]	JB20D	Base fuel	35.0	0.2403
		MWCNT, 10	35.5	0.2402
		MWCNT, 20	36.1	0.2220
		MWCNT, 30	36.2	0.2302
		MWCNT, 40	40.2	0.1988
		MWCNT, 50	38.0	0.2007
		MWCNT, 10	35.5 %	0.2422
		MWCNT, 20	36.2 %	0.2400
		MWCNT, 30	40.2 %	0.2398
		MWCNT, 50	38.0 %	0.2395
[34]	5 % n-hexane + 30 % jojoba methyl ester + 65 % diesel fuel	Base fuel	34.1 %	0.43
		TiO ₂ , 25	35.2 %	0.41
		TiO ₂ , 50	36.0 %	0.40
[34]	Jatropha Methyl Ester (JME)	Base fuel	35.7 %	0.2853
		GO, 25	35.9 %	0.2853
		GO, 50	39.5 %	0.2653



		GO, 75	36.1 %	0.2653
		GO, 100	35.2 %	0.2792
[34]	20 % Jatropha methyl ester + 80 % diesel (JB20)	Base fuel	36.9 %	0.2471
		GNP, 25	36.3 %	
		GNP, 50	36.2 %	-
		GNP, 75	32.6 %	
		GNP, 100	32.9 %	
[30]	60 % Jatropha methyl ester and 40 % n-butanol fuel (JME40B)	Base fuel	37.0 %	0.26309
		GO, 50	40.0 %	0.22328
		GNP, 50	38.5 %	0.25023
		MWCNT, 50	37.3 %	0.26095
[124]	Waste pyrolysis oil (WPO)	Base fuel	35.5 %	0.213
[116]	Diesel +Waste Cooking Oil biodiesel B30	25 % WPO + 75 % diesel + Al ₂ O ₃ , 25	44.0 %	0.203
		100 ppm DPA	↑ 2.42%	↓ 2.54% than B30
		50 ppm CeO ₂	↑ 5.74%	↓ 6.35% than B30
[28]	Diesel +Waste Cooking Oil	B0 + 50 ppm ZnO	↑ 4.34%	↓ 5.6% than B0
		B20 + 50 ppm ZnO	↑ 3.28%	↓ 6.44% than B20
		B40 + 50 ppm ZnO	/	↓ 2.5% than B40
[81]	Diesel +20% biodiesel B30	50 ppm RuO ₂	↑ 12.5%	↓ 5.55% than B20
		100 ppm RuO ₂	↑ 18.75%	↓ 6.7% than B20
[17]	(20% Dairy scum oil methyl ester + 80% diesel)	B20	30.55%	0.3 kg/kWh
		B20 + 25 ppm CuO	30.75%	0.3 kg/kWh
		B20 + 50 ppm CuO	30.86%	0.297 kg/kWh
		B20 + 75 ppm CuO	31.26%	0.295 kg/kWh
[54]	Palm Biodiesel	B100	24.11%	
		B100 + 50 ppm TiO ₂	24.99%	/
		B100 + 100 ppm TiO ₂	25.77%	
		B100 + 150 ppm TiO ₂	26.98%	
[121]	The Sheep fat biofuel of 20 % volumetrically blended with diesel of 80 % (B20).	B20	29%	0.29 g/kWh
		B20 + 50 ppm ZnO	31%	0.25 g/kWh
		B20 + 100 ppm ZnO	33.1%	0.22 g/kWh
[15]	spirulina microalgae biodiesel blends	B20 + 50 ppm Ce ₂ O ₃	↑ 2.6% than B20	↓ 5.9% than B20
		B40 + 50 ppm Ce ₂ O ₃	↑ 1.1% than B40	↓ 3.7% than B40
[56]	Algae oil-based biodiesel 25 vol% and 75 vol% of diesel	B25	↑ 13.9% than diesel	↓ 14.75% than diesel
		B25 + 150 ppm CeO ₂	↑ 68.23% than diesel	↓ 41.23% than diesel
		B25 + 150 ppm SiO ₂	↑ 49.73% than diesel	↓ 33.41% than diesel
		B25 + 150 ppm TiO ₂	↑ 32.4% than diesel	↓ 25.62% than diesel
[35]	Butanol-Diesel blend (B20: 20% Butanol + 80% Diesel)	Diesel	-	44.8
		B20	-	43.4
		B20 +30- Al ₂ O ₃	↑ 2.6% than diesel	↓ 8.56% than diesel
		B20 +50- Al ₂ O ₃	↑ 4.7% than diesel	↓ 15.5% than diesel
		B20 + 100-Al ₂ O ₃	↑ 7.8% than diesel	↓ 22.8% than diesel



[129]	Diesel75 %+25 biodiesel B25	25B25ZnO	25.3	0.52
		25B50ZnO	26.8	0.35
		25B100ZnO	27.3	0.23
		25B200ZnO	31.6	0.5
[114]	Diesel75 %+25 soybean biodiesel	Diesel		
		SBME25	23.23	0.27
		SBME25ZnO25	25.923	0.245
		SBME25ZnO50	28.62	0.198
		SBME25ZnO75	27.65	0.234
[43]	Diesel Lemongrass biodiesel	Diesel	34.2	0.35
		LGB + ZnO 50 ppm	31	0.41
		LGB + ZnO 100 ppm	32	0.39
		LGB + ZnO 150 ppm	33	0.38
		LGB + ZnO 200 ppm	29	0.41
		LGB + ZnO 250 ppm	27	0.43
[49]	25% soybean biodiesel in diesel	Diesel	32	0.24
		SBME25	24	0.33
		SBME25Ce-ZnO25	27	0.28
		SBME25Ce-ZnO50	26	0.27
		SBME25Ce-ZnO75	27	0.26
[36]	B30(70%Dieseland30%Biodiesel)	Diesel	21	0.39
		B30	20.5	0.4
		B30 + CNT	22.5	0.37
		B30 + TiO2	22.9	0.38
		B30 + Al2O3	23.7	0.36
[134]	Biodiesel-diesel- propanol blend	Diesel	32	0.26
		20% of Biodiesel + 80% of Diesel CB20	30	0.3
		20% of Biodiesel + 75% of Diesel+5% of Propanol CB20P5	30.2	0.28
		CB20P5 ZnO40	30.5	0.28
		CB20P5ZnO80	30.8	0.26
		CB20P5ZnO120	31.2	0.27
[94]	blend of Cotton Seed, Neem Oil, and Orange Peel Oil Biodiesel	Diesel	24.4	0.35
		B10ZnO30	24.7	0.35
		B10ZnO50	25.3	0.34
		B20ZnO30	23.1	0.37
		B20ZnO50	23.2	0.37
[58]	diesel + methyl ester biodiesel	DF	42	
		DCNT50	41	
		DCNT100	41.5	
		DCNT150	41.5	
		DZnO50	41	
		DZnO100	42	
		DZnO150	43	
[140]	Diesel + 20 % biodiesel	Diesel	30	0.8
		20B	24	0.67
		20B50ZnO	27	0.55
		20B100ZnO	28	0.42
		20B150ZnO	29	0.31
		20B200ZnO	32	0.24
[3]	Diesel + 20 % biodiesel	Diesel	26	0.36
		B20	25	0.37
		B20+GO 90 ppm	28	0.3
		B20+MgO 90 ppm	27	0.32
		B20+MWCNT 90 ppm	30	0.32
[82]	Diesel and Waste Cooking Oil Biodiesel	Diesel	27	0.63
		WCOB	24	0.85
		WCOB CZ50 (CuO Oxide with ZnO)	25	0.83
		WCOB CZ100	26	0.81

Across varied feed stocks and nanoparticle types, a steady trend is noticed: reasonable nanoparticle dosages (typically 50–100 ppm) yield the most consistent enhancements, while extreme amounts may cause agglomeration, poor dispersion, or viscosity rises that obstruct spray quality, as shown in Table 4.

Table 4. Comparison of Nanoparticles on BTE and BSFC

Nanoparticle	Optimum Amount (ppm/mg/L)	BTE Improvement (%)	BSFC Reduction (kg/kWh)
Cerium Oxide (CeO ₂)	100 ppm	↑ from 30.5 → 35.0 [68]; ↑ from 31.8 → 36.1 [39]	↓ from 0.32 → 0.29; ↓ from 0.305 → 0.240
Zinc Oxide (ZnO)	75–100 ppm	↑ from 26.0 → 28.9 [97]; ↑ from 29.0 → 33.1 [121]	↓ from 0.266 → 0.258; ↓ from 0.29 → 0.22
Titanium Dioxide (TiO ₂)	100–150 ppm	↑ from 33.0 → 33.3 [26]; ↑ from 24.1 → 26.98 [54]	↓ from 0.243 → 0.20; ↓ steadily with higher ppm
Aluminum Oxide (Al ₂ O ₃)	40–60 ppm (best), up to 100 ppm	↑ from 22.5 → 27.5 [44]; ↑ from 27.6 → 29.7 [131]	↓ from 0.38 → 0.32; ↓ from 0.355 → 0.30
Carbon Nanotubes (CNTs)	30–50 ppm	↑ from 35.0 → 40.2 [31]; ↑ from 23.0 → 25.0 [136]	↓ from 0.2403 → 0.1988; general decrease with CNTs
Copper Oxide (CuO)	50–100 ppm	↑ from 34.3 → 35.4 [105]; ↑ from 30.6 → 31.3 [17]	↓ from 0.32 → 0.27; ↓ from 0.30 → 0.295
Silver Oxide (AgO)	5–10 ppm	↑ from 26.6 → 28.6 [23]	↓ from 0.101 → 0.091

Cerium Oxide (CeO₂):

CeO₂ is among the most broadly considered nanoparticles due to its oxygen-buffering content. [68] stated that addition 100 ppm CeO₂ to a mixture of 20% grape seed oil methyl ester with diesel improved BTE from 30.5% to 35.0% and reduced BSFC from 0.32 to 0.29 kg/kWh. Also, [39] noticed BTE developments from 31.8% to 36.1% and BSFC decreases from 0.305 to 0.240 kg/kWh in lemongrass biodiesel mixtures. These results showed the catalytic role of CeO₂, which issues lattice oxygen to advance oxidation, with optimal performance at 100 ppm.

Zinc Oxide (ZnO):

ZnO has also exposed extremely steady results crosswise feedstocks. In Calophyllum inophyllum biodiesel blends, [97] observed BTE increasing from 26.0% to 28.9% with 100 ppm ZnO, while BSFC decreased from 0.266 to 0.258 kg/kWh. [118] stated similar results in mango seed biodiesel, where BTE improved from 23.9% to 24.9% and BSFC dropped slightly from 0.0149 to 0.0142 kg/kWh. More newly, [121] presented that in sheep fat biodiesel mixtures, ZnO at 100 ppm enhanced BTE from 29.0% to 33.1% and dropped BSFC from 0.29 to 0.22 g/kWh. These results propose an optimal ZnO range of 75–100 ppm.

Titanium Dioxide (TiO₂):

TiO₂ advances combustion mainly by improving atomization and providing catalytic surfaces. [26] stated that diesel blended with 80 mg/L TiO₂ reached a developed BTE (33.3% vs. 33.0% for normal diesel) and lesser BSFC (0.20 vs. 0.243 kg/kWh). [97] noticed enhanced BTE (30.5%) and decreased BSFC (0.249 kg/kWh) at 100 ppm. [54] established these trends, display that palm biodiesel with up to 150 ppm TiO₂ showed a BTE rise from 24.1% to

26.98%. Generally, TiO_2 displays efficiency over a wider variety (100–150 ppm), with highest benefits about 100 ppm.

Aluminum Oxide (Al_2O_3):

Al_2O_3 improves thermal conductivity and performances as a combustion catalyst. [44] standard a rise in BTE from 22.5% to 27.5% and a BSFC decrease from 0.38 to 0.32 kg/kWh at 50 ppm in diesel. [131] stated parallel results for B25 Pongamia biodiesel, with BTE increasing from 27.6% to 29.7% and BSFC reducing from 0.355 to 0.30 kg/kWh at 100 ppm. However, [79] presented that in B20 rubber seed biodiesel, extreme nanoparticle levels reduced performance, signifying an optimal range of 40–60 ppm.

6.5. Carbon Nanotubes (CNTs):

Because of their high thermal conductivity and unique construction, CNTs are highly active even at little dosages. [31] established that multiwalled CNTs in *Jatropha* biodiesel mixtures elevated BTE from 35.0% to 40.2% and decreased BSFC from 0.2403 to 0.1988 kg/kWh at 40 ppm. [136] established that BTE increases from 23% to 25% with CNTs in Honge oil biodiesel. CNTs therefore realize peak performance at 30–50 ppm, with diminishing revenues at higher amounts.

6.6. Copper Oxide (CuO) and Silver Oxide (AgO):

Both CuO and AgO show strong catalytic action, though at different dosages ranges. [105] stated that CuO at 100 ppm improved BTE from 34.3% to 35.4% and dropped BSFC from 0.32 to 0.27 kg/kWh. [17] also showed that BTE advances from 30.55% to 31.26% with 25–75 ppm CuO . AgO performs active even at very low dosages: [23] established that 10 ppm AgO in palm stearin biodiesel enhanced BTE from 26.6% to 28.6% and decreased BSFC from 0.101 to 0.091 kg/kWh.

6.7. Comparative Insights:

When comparing nanoparticle types, CeO_2 , ZnO , TiO_2 , and CNTs consistently provide the most significant improvements in both BTE and BSFC. CeO_2 is optimal at ~100 ppm, ZnO at 75–100 ppm, TiO_2 at 100–150 ppm, and CNTs at lower ranges of 30–50 ppm. Al_2O_3 and CuO are most effective at moderate amounts (40–100 ppm), while AgO achieves notable benefits at trace levels (5–10 ppm). Variations in optimal amount are influenced by particle size, dispersion stability, and interactions with base fuels.

6.8. Synthesis

Totally, nanoparticles increase BTE and less BSFC by improving combustion through catalytic activity, enhanced atomization, and enhanced oxidation. CeO_2 , ZnO , TiO_2 , and CNTs offer the steadiest and noteworthy benefits, while Al_2O_3 , CuO , and AgO fund successfully at moderate or trace levels. Significantly, the selection of nanoparticle and content must be adjusted to steadiness and dispersion in order to reach sustainable enhancements in engine performance and fuel economy.

Combustion Emissions

nanoparticles have been confirmed to really impact the emissions of biodiesel and its mixtures in CI engines by improving minor atomization and mounting the reaction surface area.

Table 5. Effects of adding nanoparticles on pollutants emission.

Author (s), Year	Base fuel	Nanoparticle, Amount (ppm)	NOx Emission	Specific Smoke Emission	Specific HC Emission
[139]	Groped oil biodiesel	CeO ₂ , 100	-4.19 %	-8.24 %	-2.5 %
		ZnO, 100	-13.13 %	-17.8 %	-7.5 %
[108]	Groped oil biodiesel	CeO ₂ , 50 CeO ₂ , 100 ZnO, 50	-6.5 % for CeO ₂ - 10.8 % for ZnO	- 8.6 % for CeO ₂ -4.6 % for ZnO	- 5 % for CeO ₂ , 100 13 % for ZnO, 100
[18]	Diesel	Al ₂ O ₃ , 25	+38 %	-	(on average)
		Al ₂ O ₃ , 50	+42 %		17.8 ppm for
		Al ₂ O ₃ , 100	+80 %		Al ₂ O ₃ , 50
		CNT, 25	+15 %		6.4 ppm for
		CNT, 50	+40 %		CNT, 25 19.8
		CNT, 100	+81 %		ppm for
		SiO ₂ , 25	+95 %		SiO ₂ , 50
		SiO ₂ , 50	+102 %		
		SiO ₂ , 100	+110 %		
[44]	Diesel	Al ₂ O ₃ , 50	- 6 %	-2	-13 % -8%
		CuO, 50	%		
[117]	Diesel	CeO ₂ , 0.5 mass fraction	-19 %	-	-200 ppm at full load
[26]	Diesel	TiO ₂ , 80 mg/L	+32.2 %		- 18 %
[23]	Neat palm stearin biodiesel	AgO (10 nm), 5 AgO (20 nm), 5 AgO (10 nm), 10 AgO (20 nm), 20	- 3.0 % - 9.0 % -21.0 %	-14.5 % - 32.8 % - 27.5 % - 45.0 %	-8.3 % -25 % - 19.4 % -33.3 %
[105]	80 % waste oil biodiesel and 20 % pongamia oil	CuO, 50	-7.0 % -9.8 %	- 7.5 % - 12.8 %	-6.9 % -7.9 %
[118]	Mango seed biodiesel	ZnO (20 nm)	-3.8 % - 4.1 %	-4.0 % - 3.58 %	-4.4 % - 2.89 %
[136]	Honge oil methyl ester	CNT, 25	-2.5 %	-19.2 %	-11 %
		CNT, 50	-11.5 %	-24.3 %	-18.3 %
[98]	Sardine oil methyl ester	CeO ₂ , 25	+0.5 %	-	-16%
[122]	Blend 90 % diesel and 10 % biodiesel	CeO ₂ , 50	-8.4 %	-4.4 %	-2.7 %
[39]	Rubber seed methyl ester	CeO ₂ , 90	-14.0 %	-	-51%
[8]	Gingelly oil methyl ester (GOME) and 2 % diethyl ether	CeO ₂ , 30	-24.8 %	-6.4%	-35.5%
[97]	Calophyllum inophyllum methyl ester	ZnO, 50	-14.3 %	-7.7 %	-11.7 %
		ZnO, 100	-21.4 %	-23.1 %	-23.5 %
		TiO ₂ , 50	-11.4 %	-24.6 %	-29.4 %
		TiO ₂ , 100	-7.1 %	-30.8 %	-35.3 %
[6]	20 % of Calophyllum inophyllum biodiesel + 80 % of diesel	Al ₂ O ₃ , 40	-7.76 %	-6.2 %	-12.24 %
[99]	20 % Canola Biodiesel + 80 % diesel	TiO ₂ , 300	-5 %	-5.2 %	-3.0 %
[96]	Vegetable methyl ester from the waste cooking oil biodiesel with diesel fuel	Ag, 40	+35.0 %	-	-5.9 %
		Ag, 80	+36.1 %		-11.7 %
		Ag, 120	+42.0 %		-18.2 %
		CNT, 40	+35.1 %		+11.7 %
		CNT, 80	+36.3 %		+17.6 %
		CNT, 120	+41.5 %		+23.5 %
[109]	Tamarind Seed Methyl Ester 20 % blended with 80 % diesel (TSME20)	Al ₂ O ₃ , 30	-7.7 %	-41.4 %	-51.8 %
		Al ₂ O ₃ , 60	-8.7 %	-46.0 %	-60.0 %
		CNT, 30	-9.4 %	-40.8 %	-10.0 %
		CNT, 60	-7.1 %	-40.6 %	-20.0 %
[132]	20 % Honge oil methyl ester and 80 % diesel fuel blend, HOME B20	Al ₂ O ₃ , 20	+1.18 %	-10.9 %	-11.7 %
		Al ₂ O ₃ , 40	-2.96 %	-28.1 %	-24.7 %
		Al ₂ O ₃ , 60	+6.1 %	-19.5 %	-34.1 %



[79]	20 % rubber seed oil blended with 80 % diesel fuel (B20)	Al ₂ O ₃ , 10 Al ₂ O ₃ , 15 Al ₂ O ₃ , 20	+4.4 % +0.1 % -10.0 %		-13.3 % -8.3 % -6.7 %
[125]	80 % diesel and 20 % soybean biodiesel (B20)	80 % diesel, 15 % soybean biodiesel, 4 % ethanol, and 1 % isopropanol as a surfactant	+2.5 %	-	-12 %
[110]	20 % Poultry Litter Oil Methyl Ester + 80 % diesel	Al ₂ O ₃ , 30 mg/L	-5.4 %	+2.0 %	-26.6 %
[131]	75 % diesel and 25 % pongamia methyl ester (B25)	Al ₂ O ₃ , 50 Al ₂ O ₃ , 100	+6.7 % +18.0 %	-16.9 % -24.6 %	-16.7 % -20.0 %
[101]	Diesel	CeO ₂ , 25 (CDD) Graphite Oxide, 25 (GDD) Single Wall CNT, 25 (SDD)	+7.5 % -20.0 % +28.8 %	-	-6.8 % -12.5 % -17.5 %
[83]	Diesel	CeO ₂ , 50 CeO ₂ , 100	-2.4 % -5.4 %	-4.0 % -7.8 %	-15.1 % -18.4 %
[123]	LG025, 75 % by volume of diesel and 25 % of lemongrass oil	CeO ₂ , 50	-23.18 %	-16.58 %	-21.2 %
[31]	Jojoba methyl ester: diesel blended fuel (JB20)	MWCNT, 10 MWCNT, 20 MWCNT, 30 MWCNT, 40 MWCNT, 50	+0.2 % -11.5 % -1.0 % -5.7 % -1.6 %		-6.6 % -8.3 % -23.1 % -23.0 % -40.3 %
[34]	5 % n-butanol + 30 % jojoba methyl ester + 65 % diesel fuel	TiO ₂ , 25 TiO ₂ , 50	+0.4 % +15.0 %		-23.0 % -34.0 %
[34]	Jatropha Methyl Ester (JME)	Graphene Oxide, 25 Graphene Oxide, 50 Graphene Oxide, 75 Graphene Oxide, 100	-1.0 % -10.0 % -3.0 % +22.0 %	-	-33.0 % -33.0 % -33.0 % -33.0 %
[34]	20 % Jojoba methyl ester + 80 % diesel	Graphene nanoparticles (GNP), 25 GNP, 50 GNP, 75 GNP, 100	-25.7 % -6.5 % -13.6 % -18.0 %		-27.0 % -19.0 % -18.0 % -29.0 %
[30]	60 % Jatropha methyl ester and 40 % n-butanol fuel (JME60B)	GO, 50 GNP, 50 MWCNT, 50	-27.0 % -26.0 % -22.0 %		-50.0 % -50.0 % -50.0 %
[124]	Waste pyrolysis oil (WPO)	25 % WPO + 75 % Diesel + Al ₂ O ₃ , 25	-9.5 %	-28.5 %	-12.3 %
[81]	Diesel+ 20 biodiesel blends B20	- 50 ppm RuO ₂ 100 ppm RuO ₂	870 ppm 900 ppm 920 ppm 920 ppm		45 g/kWh 40 g/kWh 38 g/kWh 34 g/kWh
[111]	jojoba biodiesel blend (JB20)	- 25 ppm CuO 50 ppm CuO + 75 ppm CuO	- ↑ 0.4% than B20 ↑ 0.7% than B20 ↑ 1.8% than B20		↓ 5.18% than diesel ↓ 9.39% than diesel ↓ 12.17% than diesel ↓ 7.45% than diesel
[54]	Eichhornia Crassipes biodiesel	- 50 ppm TiO ₂ 100 ppm TiO ₂ 150 ppm TiO ₂	↓ 6.86% than diesel ↑ 3.05% than diesel ↑ 5.55% than diesel ↑ 8.06% than diesel		↓ 11.67% than diesel ↓ 24.56% than diesel ↓ 27.91% than diesel ↓ 31.8% than diesel
[121]	Sheep fat (SF) biofuel of 20 % volumetrically blended with conventional diesel fuel of 80 % (B20).	--- - 50 ppm ZnO 100 ppm ZnO	5.02 g/kWh 4.52 g/kWh 3.67 g/kWh 3.66 g/kWh		0.5 g/kWh 0.33 g/kWh 0.31 g/kWh 0.29 g/kWh
[102]	20 vol% palm-oil biodiesel in fossil diesel (B20)	25 ppm MWCNTs 50 ppm MWCNTs 100 ppm MWCNTs	↑ 21% than B20 ↑ 39.5% than B20 ↑ 13.5% than B20		↓ 11% than B20 ↓ 14.8% than B20 ↓ 4.7% than B20



[81]	Diesel+ biodiesel from Candle nut oils B20	-	450 ppm	/	
		25 ppm TiO ₂	496 ppm		
			452 ppm		↓ 8.1% than B20
		-	452 ppm	/	
		25 ppm TiO ₂	426 ppm		↓ 9.1% than B30
[56]	75% of diesel and 25% of biodiesel	-	6.2 g/kWh	/	
			/		↓ 6.23% than diesel
		150 ppm CeO ₂	6.09 g/kWh		↓ 14.3% than diesel
		150 ppm SiO ₂	4.29 g/kWh		↓ 29.25% than diesel
		+ 150 ppm TiO ₂	2.87 g/kWh		↓ 31.89% than diesel
[92]	B30(70%Dieseland30%Biodiesel)	B30	2.819		0.112
		B30+(100ppm)CarbonNanoTubes	2.708		0.136
		B30+(100ppm)TiO ₂	2.957		0.102
[35]	Butanol-Diesel blend (B20: 20% Butanol + 80% Diesel)	Diesel	-		
		B20 +30- Al ₂ O ₃	7.5%		31.2%
		B20 +50- Al ₂ O ₃	10.2%		34.5%
		B20 + 100-Al ₂ O ₃	12.37%		37.5%
[129]	Diesel75 %+25 biodiesel B25	25B25ZnO			16.6
		25B50ZnO			14.2
		25B100ZnO			13
		25B200ZnO			10.9
[114]	Diesel75 %+25 soybean biodiesel	Diesel			
		SBME25	431ppm	58.4	0.21
		SBME25ZnO25	443ppm	51.6	0.165
		SBME25ZnO50	455ppm	45.4	0.142
		SBME25ZnO75	466 ppm	49.2	0.16
[43]	Diesel	Diesel	451 ppm	57.2	88 ppm
	Lemongrass biodiesel	LGB + ZnO 50 ppm	482 ppm	79.5	58 ppm
		LGB + ZnO 100 ppm	475 ppm	77.4	52 ppm
		LGB + ZnO 150 ppm	431 ppm	65.7	48 ppm
		LGB + ZnO 200 ppm	375 ppm	90	73 ppm
		LGB + ZnO 250 ppm	294 ppm	98	58
[49]	25% soybean biodiesel in diesel	Diesel	420 ppm	48	79 ppm
		SBME25	440 ppm	62	89 ppm
		SBME25Ce-ZnO25	480 ppm	56	85 ppm
		SBME25Ce-ZnO50	520 ppm	48	80 ppm
		SBME25Ce-ZnO75	580 ppm	51	82 ppm
[36]	B30(70%Dieseland30%Biodiesel)	Diesel	2.78g/kWh		0.066g/kWh
		B30	3.1g/kWh		0.059g/kWh
		B30 + CNT	2.6g/kWh		0.076g/kWh
		B30 + TiO ₂	3.15g/kWh		0.047g/kWh
		B30 + Al ₂ O ₃	3.15g/kWh		0.05g/kWh
[134]	Biodiesel-diesel- propanol blend	Diesel	1580 ppm	62	78 ppm
		20% of Biodiesel + 80% of Diesel	1970 ppm	66	112 ppm
		CB20			
		20% of Biodiesel + 75% of Diesel+5% of Propanol CB20P5	2020 ppm	65	90 ppm
		CB20P5 ZnO40	2030 ppm	64	91 ppm
		CB20P5ZnO80	2050 ppm	64	108 ppm
		CB20P5ZnO120	2055 ppm	63	110 ppm
[94]	blend of Cotton Seed, Neem Oil, and Orange Peel Oil Biodiesel	Diesel	175 ppm		12 ppm
		B10ZnO30	215 ppm		22 ppm
		B10ZnO50	220 ppm		26 ppm
		B20ZnO30	160 ppm		15 ppm
		B20ZnO50	214 ppm		24 ppm
[58]	diesel + methyl ester biodiesel	DF	800 ppm		
		DCNT50	870 ppm		
		DCNT100	850 ppm		



		DCNT150	830 ppm	
		DZnO50	805 ppm	
		DZnO100	808 ppm	
		DZnO150	810 ppm	
[140]	Diesel + 20 % biodiesel	Diesel		25 %
		20B		23%
		20B50ZnO		16%
		20B100ZnO		14%
		20B150ZnO		13%
		20B200ZnO		10%
[3]	Diesel + 20 % biodiesel	Diesel	1300 ppm	55 ppm
		B20	1310 ppm	52 ppm
		B20+GO 90 ppm	1280 ppm	46 ppm
		B20+MgO 90 ppm	1200 ppm	44 ppm
		B20+MWCNT 90 ppm	1180 ppm	42 ppm
[82]	Diesel and Waste Cooking Oil Biodiesel	Diesel	830 ppm	50 ppm
		WCOB	800 ppm	41 ppm
		WCOB CZ50 (CuO Oxide with ZnO)	745 ppm	38 ppm
		WCOB CZ100	700 ppm	33 ppm

Nanoparticle adding into the mixture of diesel and biodiesel was recently appeared as a promising technique to reduce undesired exhaust emissions i.e., nitrogen oxides (NO_x), unburned hydrocarbons (HC) and smoke opacity. Nanoparticles, as flame promoters, can enhance oxidation and reduce ignition delay and the in-cylinder combustion processes. Their effectiveness is strongly amount dependent.

Nitrogen Oxides (NO_x)

NO_x production is deeply connected to the temperature of combustion and provides varying degree of sensitivity depending on how much oxygen there are as well as nanoparticles. With bound biodiesel mixtures made from grapeseed 100 ppm CeO₂ reduced NO_x emissions up to 12% as compared with base biodiesel [139]. Similar results were reported in neem biodiesel, where 50 ppm CeO₂ reduced NO_x from 10.8 to 9.4 g/kWh [122]. The NO_x reduction was also significantly aided by the presence of zinc oxide; 75 ppm of ZnO in *C. inophyllum* biodiesel decreased emissions by 10–15% via catalytic cracking and enhanced heat transfer [97]. Carbon nanotubes showed mixed results: moderate doses of 50–75 ppm decreased NO_x by 8–10% in diesel blends [96]; high dosages over than 100 pmm slightly increased nitric oxide (NO) due to high cylinder temperature. Slight but consistent reduction was achieved by aluminum oxide reducing NO_x by 5–7% at 40–60 ppm in Karanja biodiesel, with the relatively higher amounts offering little added benefit [6]. Titanium dioxide has also revealed promising results, since 100–200 ppm TiO₂ decreases NO_x emissions up to 9% in canola biodiesel blends [99]. Silver oxide promised dose dependent influence, as for low dosages (5 ppm), AgO reduced NO_x yet at amount over 20 ppm, enhanced combustion intensity resulted in increased NO_x emissions [23]. Collectively, all of these findings suggest that CeO₂ and ZnO reliably decrease NO_x at an appropriate dose level, whereas CNTs and AgO require careful control to avert counter-influences.

Smoke Emissions

Nanoparticles have also been effective in reducing smoke emissions, which primarily arise from incomplete combustion and poor fuel atomization in CI engines. By improving atomization and enhancing oxidation reactions, nanoparticle additives have demonstrated significant reductions in smoke opacity. In grapeseed and neem biodiesel blends, CeO₂ decreased smoke by 15–20% due to its oxygen-donating catalytic properties [108]. Similar

benefits were observed with ZnO, which reduced smoke by 12–18% at a amount of 75 ppm by promoting the oxidation of soot precursors [97]. CNTs also proved effective, lowering smoke by 10–15% at amounts of 50–75 ppm, although unstable dispersion at 120 ppm caused a slight increase in smoke emissions [96]. Al₂O₃ nanoparticles improved atomization and reduced smoke opacity by 8–12% when used at optimal dosages [6]. TiO₂ nanoparticles demonstrated reductions of up to 14% in canola biodiesel at 200 ppm [99]. AgO again showed notable results at very low amounts: 5–10 ppm led to reductions of around 10%, but its effectiveness diminished when the dosage exceeded 20 ppm [23].

Hydrocarbon (HC) emissions in compression-ignition (CI) engines

Hydrocarbon (HC) emissions in compression-ignition (CI) engines mainly create from imperfect combustion and fuel quenching in cooler areas of the combustion chamber. The addition of nanoparticles to biodiesel and its mixtures has consistently been shown to decrease HC emissions by improving oxidation reactions, shortening ignition delay and refining fuel with air mixing.

Cerium oxide (CeO₂) has shown promising outcomes due to its redox activity and oxygen-donating mechanism. Adding 100 ppm CeO₂ to grapeseed biodiesel reduces HC emissions by 20%, from 0.12 to 0.09 g/kWh. Catalytic activity and fuel volatility reduced ZnO-75 ppm by 15%. At 50–75 ppm, CNTs reduced HC emissions by 10–12%, but greater loadings caused agglomeration and lowered catalytic performance [96]. Aluminum oxide (Al₂O₃) reduced HC emissions by 8–10% in diesel Karanja biodiesel mixes [6]. Titanium dioxide (TiO₂) as a cause At 200 ppm, titanium dioxide (TiO₂) reduced canola biodiesel HC emissions by 12 wt% [99]. Silver oxide (AgO) reduced HC up to 15% via metal catalysis at 5 ppm, although its activity decreased with loading [23].

Synthesis

Nanoparticles increase oxidation and atomization to recover exhaust pollutants. The most efficient additions, CeO₂ and ZnO, reduce NO_x and smoke at moderate amounts (50-100 ppm). CNTs and AgO may work at low doses because large amounts increase emissions. Moderate promotion in Al₂O₃ and TiO₂. Nanoparticle type and dosage are critical for effective pollution abatement, fuel dispersion, and combustion performance.

A proportional data presentation shows nanoparticle performance changes with efficiency. CeO₂ at 100 ppm reduces HC and smoke emissions and regulates NO_x through oxygen buffering. At 75–100 ppm, ZnO is stable to HC, smoke, and NO_x. CNTs at 50–75 ppm reduce HC and smoke but have little influence on NO_x and stability issues at higher loadings. Using clay (Al₂O₃) at 40-60 ppm only slightly reduces emissions. TiO₂ at 100-200 ppm leads to significant smoke and HC reduction, but minimal NO_x reduction. HC and smoke reduction at 5–10 ppm with a reduced contribution to NO_x reduction, which is dosage sensitive, makes AgO intriguing. Table 6 shows relative trends.



Table 6. Comparison of Nanoparticles on Diesel/Biodiesel Emissions.

Nanoparticle	Optimum Amount (ppm/mg/L)	Influence on NOx Emission	Influence on Smoke Emission	Influence on HC Emission
Cerium Oxide (CeO ₂)	100	Reduced by up to 12%; oxygen buffering prevents excessive rise	Strong reduction (15–20%) due to oxygen release	Reduced up to 20% due to redox/oxygen mechanism
Zinc Oxide (ZnO)	75–100	Reduced 10–15% due to catalytic and thermal influences	Reduced 12–18%; improved oxidation of soot precursors	Reduced by ~15% at 75 ppm
Titanium Dioxide (TiO ₂)	100–200	Slight reduction (~9%) at moderate levels	Reduced by ~14% at 200 ppm	Reduced by ~12% at 200 ppm
Aluminum Oxide (Al ₂ O ₃)	40–60	Reduced 5–7% at optimum; negligible at higher doses	Moderate reduction (8–12%) via atomization	Reduced 8–10% in biodiesel blends
Carbon Nanotubes (CNTs)	50–75	Reduced 8–10% at moderate levels; increase at >100 ppm	Reduced 10–15% at moderate levels; agglomeration at higher doses	Reduced 10–12% at 50–75 ppm; limited at higher levels
Silver Oxide (AgO)	5–10	Reduced at 5 ppm; may increase at >20 ppm	Significant reduction (~10%) at 5–10 ppm; weaker beyond 20 ppm	Strong reduction (up to 15%) at low amount (5 ppm)

Influence of Nanoparticle Dosage on Normalized Fuel Characteristics and Engine Performance

The addition of nanoparticles to diesel and biodiesel blends has strong influences on the most important properties of fuel, as well as engine performance parameters. Cetane number, viscosity, calorific value and BTE may be reported in normalized mode by the ratios of values of nanoparticle blends to those of base diesel without nanoparticles in this study. This normalization allows for a convenient comparison of the influence of nanoparticles in various studies. However, it should be noted that because the emission were not normalized to any parameters might be noted that due to different kinds of data presentation (g/kWh, ppm, opacity % or relative reduction), the ratio based normalization was unreliable and would cause potential theoretical misinterpretation.

The outcome of nanoparticle dosage on significant fuel properties like cetane number, kinematic viscosity and calorific value are shown in Figs. 3–6. Generally, addition nanoparticles to diesel and biodiesel mixtures reliably advances ignition quality also having dependent influences on viscosity and calorific value.

Impact of Cetane Number

In Fig. 3, among all studied nanomaterials the cetane number of nano-fuel blends was enhanced by approximately 5–30% with respect to base fuel, where sign and degree of enhancement were determined by nanoparticle type and dosage. Two components, carbon nanotubes (CNTs) and titanium dioxide (TiO₂), showed the highest elevated cetane number ratios; greater than 1.3 normalized value at high dosage levels. These improvements are due to the increased catalytic influence of them enhanced heat transfer and promotion of the micromechanical explosion during combustion [31]. Other oxides as cerium oxide (CeO₂), aluminum oxide (Al₂O₃) and zinc oxide (ZnO) offering the continuous evolution up to 10–20%, essentially with the help of oxygen-buffering and oxidation-promoting functionalities [6,108,55]. Moderate, yet supportive influences of 5–15% were found for silver-based

additives, copper oxide (CuO), silica (SiO₂), and graphene nanoplatelets (GNPs) [68, 128, 144]. The increase is dose dependent; it increases with doses up to an optimal range of 100–150 ppm and then reaches a plateau because of the agglomeration of nano particles [75]. TiO₂ also showed good stability up to at least 300 ppm [146], indicating its potential as an ignition catalyst.

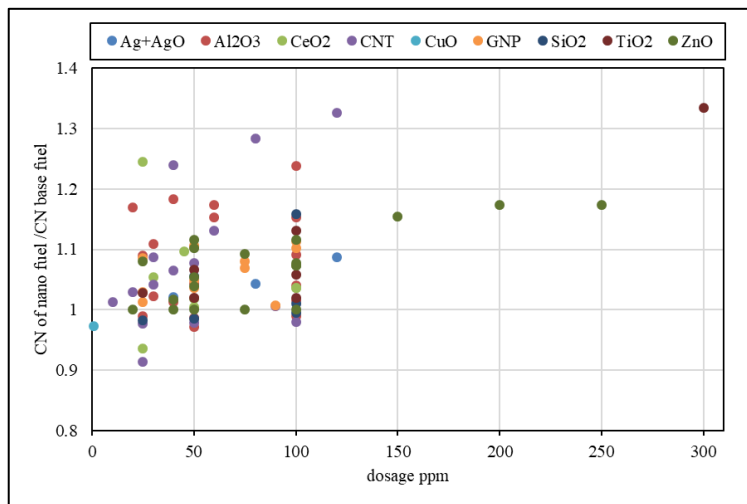


Fig.3. Normalize Cetane Number – nano material dosage.

Impact of kinematic viscosity

As shown in Fig. 4, the outcome of nanoparticles on viscosity was extremely material dependent. ZnO produced the severest rises, with viscosity ratios increasing from 1.0 at 50 ppm to roughly 1.31 at 250 ppm. ZnO dosages above 200 ppm considerably thicken biodiesel mixtures [43, 28]. Also, GNPs enlarged viscosity by 20–25% across 25–100 ppm, confirming earlier findings in *Jatropha* and diesel–biodiesel mixes [34]. In contrast, CeO₂ and CNTs usually kept viscosity close to base fuel, fluctuating within $\pm 10\%$, aligning with studies by [139] and [96]. Al₂O₃ presented mixed but modest shifts, infrequently reducing viscosity by up to 17% [6]. TiO₂ presented the most notable reduction, with viscosity ratios reducing to 0.71 at 300 ppm (about 29% decrease), consistent with results from canola biodiesel mixtures [99]. Ag/AgO and CuO kept values close to 1 (0.9–1.05), representing minimal influence [23, 105].

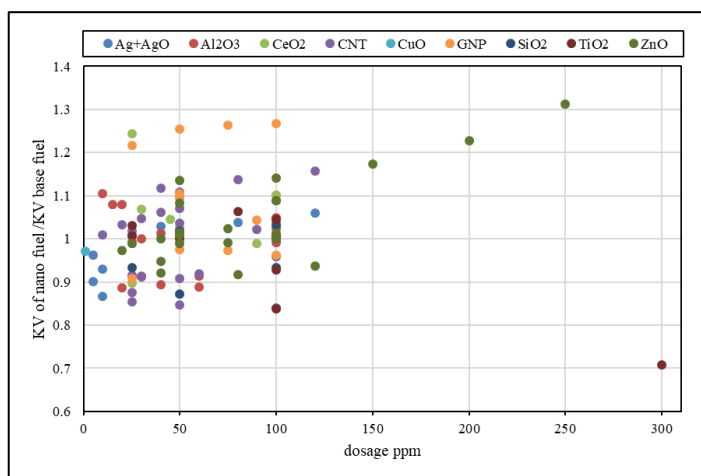


Fig.4. Normalize kinematic viscosity – nano material dosage.

Impact of Calorific Value

From Fig. 5, it can be seen that NP impacts on HHV tended to be marginal with the majority of additions lying within $\pm 5\%$ of base. The fact that the values in 25–100 ppm were close to unity for CeO_2 and CNTs indicated that their primary value lies in enhancing the energy release rather than energy content [139, 96]. CuO and GNPs both showed relatively stable outcomes with less than $\pm 5\%$ [105, 34]. A higher variability was observed Al_2O_3 , which could lead to a small increase in CV above unity (1.1), but could also reduce it by 12% at 25–50 ppm translates it according to [6,18]. The maximum enhancement was made by ZnO , being approximately 1.22 at 50 ppm and plateauing at higher doses in the vicinity of the baseline [118, 43]. Ag/AgO and SiO_2 remained neutral through the range that was investigated [23, 47]. These findings suggest that ZnO can potentially enhance calorific value at optimum doses.

Figures 3–6 display that addition nanoparticles offer a flexible way to develop ignition quality, viscosity behavior, and calorific value of diesel–biodiesel mixtures. CNTs and TiO_2 are mainly active at increasing cetane number, while ZnO and GNPs need careful content control due to their special influences on viscosity. ZnO also displays potential for improving calorific value.

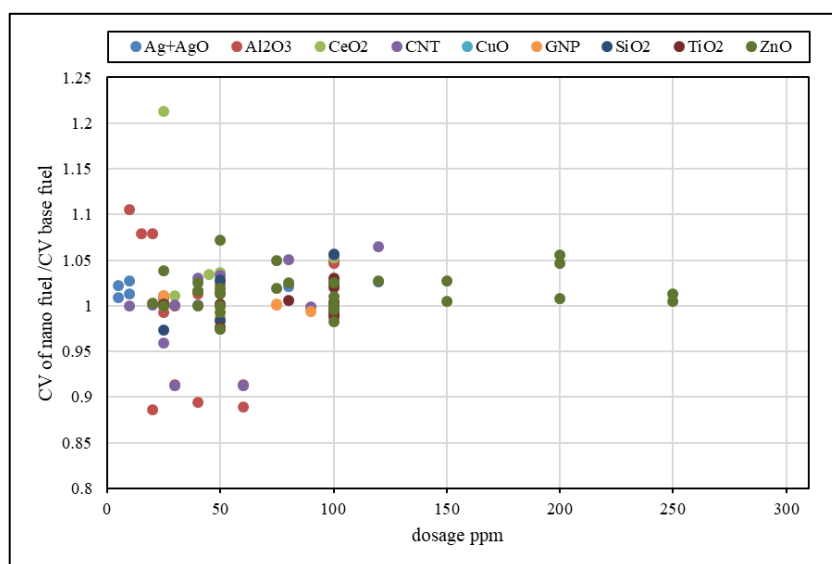


Figure 5. Normalize calorific value – nano material dosage.

Impact of BTE

Fig. 6 displays that normalized BTE expressively benefits from nanoparticle additives. Al_2O_3 demonstrated consistent enhancements, with normalized BTE ratios increasing to approximately 7.8% enhancement at 100 ppm [44, 131]. CeO_2 elevated normalized effectiveness by 5–10% across 50–100 ppm, aligning with earlier studies of BTE rises up to 36% with doping [68]. CNTs yielded the maximum improvements (10–15%) as *Jatropha* biodiesel blends improved from 35% to 40.2% [31]. TiO_2 developed normalized BTE by about 10–12% up to 100 ppm [26], while ZnO reached about 20–25% enhancement at 200 ppm before decreasing at higher dosages [97]. In contrast, CuO and SiO_2 accessible slight improvements, with ratios continuing near unity [105].

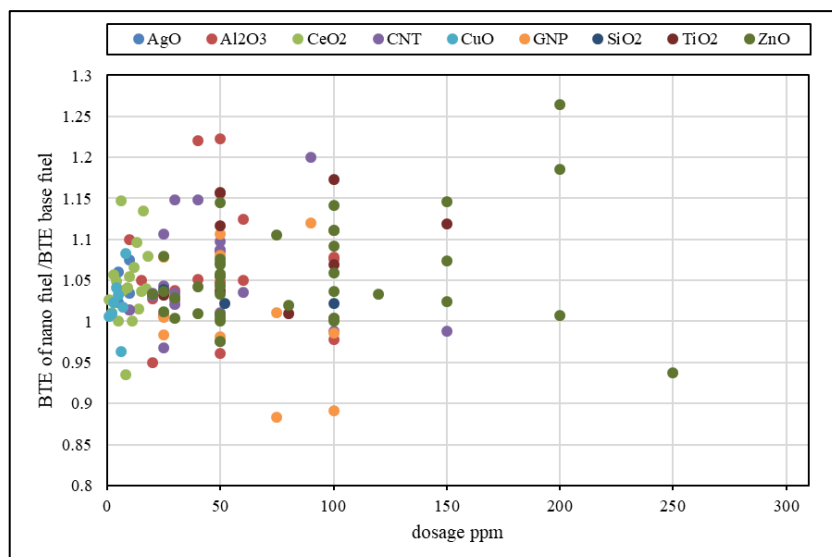


Figure 6. Normalize BTE – nano material dosage

Normalized data show that nanoparticles improve ignition quality, combustion stability, and energy conversion efficiency compared to basic fuel. CNTs, TiO₂, CeO₂, Al₂O₃, and ZnO are attractive additives, but dose optimization is crucial to balance performance gains with viscosity and calorific value fluctuations.

Conclusions

This study consolidates contemporary insights into the integration of nanoparticles within biodiesel formulations, emphasizing their capacity to overcome intrinsic limitations of conventional biodiesel and to advance global sustainable energy objectives. The incorporation of nanoparticles has been shown to enhance BTE by up to 20 % and reduce BSFC by 5–15 %, primarily through improved fuel atomization, shortened ignition delay, elevated heat release rates, and catalytic oxygen-donating mechanisms. Carbon nanotubes (CNTs) and multi-walled CNTs (MWCNTs) exhibit the most pronounced improvements in calorific value and ignition quality, rendering them ideal candidates for high power-density engine applications. The addition of CeO₂, ZnO, Al₂O₃, and TiO₂ nanoparticles significantly mitigates CO, HC, and smoke emissions, with CeO₂ demonstrating reductions in unburned hydrocarbons of up to 20 % via its redox cycling and oxygen-buffering functionality. While the influence on NO_x emissions remains composition-dependent, nanoparticle incorporation generally enhances key fuel characteristics—including cetane number and calorific value—while maintaining viscosity within ASTM D6751 limits at optimized amounts. Future research should prioritize the development of hybrid and multifunctional nanomaterials, optimization of nanoparticle dosage and surface chemistry, and establishment of standardized testing, life-cycle assessment (LCA), and regulatory frameworks addressing toxicity, safety, and environmental sustainability. The translation of nanoparticle-assisted biodiesel from laboratory research to commercial-scale implementation will necessitate coordinated efforts among materials scientists, combustion engineers, and environmental technologists. Ultimately, nanoparticle-enriched biodiesel represents a viable pathway toward low-carbon and high-efficiency energy systems, merging the renewability of biofuels with the catalytic

and thermal advantages of nanotechnology to enable cleaner and more sustainable transportation and industrial operations.

Nomenclature

Ag / AgO – Silver nanoparticles / Silver oxide

Al₂O₃ – Aluminum oxide nanoparticles

ASTM – American Society for Testing and Materials

BTE – Brake Thermal Efficiency

BSFC – Brake Specific Fuel Consumption (kg/kWh)

CI – Compression Ignition (engine)

CNTs / MWCNTs – Carbon Nanotubes / Multi-Walled Carbon Nanotubes

CO – Carbon Monoxide (emission)

CO₂ – Carbon Dioxide

CuO – Copper Oxide nanoparticles

CV – Calorific Value (MJ/kg)

FAME – Fatty Acid Methyl Esters (biodiesel molecules)

GHG – Greenhouse Gas

GO / GNPs – Graphene Oxide / Graphene Nanoplatelets

HC – Hydrocarbons (unburned, emission)

KV – Kinematic Viscosity (cSt)

MJ/kg – Mega Joule per kilogram (unit of calorific value)

NO_x – Nitrogen Oxides (NO, NO₂)

NPs – Nanoparticles

O₂ – Oxygen

PM – Particulate Matter (soot, smoke)

ppm / mg/L – Parts per million / milligrams per liter (nanoparticle amount)

TiO₂ – Titanium Dioxide nanoparticles

ZnO – Zinc Oxide nanoparticles


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