

The impacts of nanoscale silica particle additives on fuel atomisation and droplet size in the internal combustion engines: A Review

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ABSTRACT

The combustion process in compression ignition (CI) engines is complex and affects their efficiency and emission levels. Internal combustion engines (ICE) are being studied to find better ways to burn fuel and produce less pollution to meet the growing demand for these qualities. However, one intriguing avenue is the utilisation of nanoparticle additives, such as silica nanoparticles, to enhance fuel atomisation and droplet size. This study aimed to comprehensively review the impact of silica nanoparticle additives on fuel atomisation and droplet size in internal combustion engines. This review explores the researchers' underlying mechanisms and experimental techniques to determine nanoparticle fuel additives' overall impact on engine performance. The results achieved from the literature study indicated that incorporating these nanoparticles (following the engine design and fuel formulations) can enhance combustion efficiency and reduce exhaust emissions, thereby contributing to developing more sustainable transportation and power production systems.

1. INTRODUCTION

The greenhouse effect, air pollution, and detrimental exhaust emitted to the environment are strongly associated with increased petroleum fuel usage. Biodiesel fuels have been introduced to address the detrimental issues of petroleum use [1–4]. However, implementing these biodiesel fuels in compression

ignition engines (CI) has encountered notable difficulties, such as inadequate atomisation, low energy content levels, droplet size, density, and high viscosity. Consequently, biodiesel fuel utilisation is typically associated with higher fuel consumption, lower thermal efficiency, and increased nitrogen oxide (NO_x) emissions in CI engines [5]. These biodiesel fuel characteristics, such as inadequate

atomisation, can be dealt with by understanding the atomisation theory.

The theory of atomisation and droplet combustion involves several vital properties that affect the atomisation and combustion processes. These properties include the heat of combustion, thermal conductivity, viscosity, specific heat capacity, and latent heat of vaporisation [6]. Recent studies by fuel experts have shown that adding nanoparticles to biodiesel blends can enhance the performance and applicability of biodiesel [3][7–10]. The integration of nanoparticles is essential due to the unfavourable qualities of biodiesel, such as heat transfer rate, thermophysical properties, evaporation rate, calorific value, and other pertinent factors [7–9]. Nanoscale particle inclusion in biodiesel has been found to improve the combustion, performance, and regulation of CI engines' emission behaviours through the more significant interaction and chemical susceptibility of nanoparticles, which is assisted by the significantly larger surface-to-area ratio of the nanoparticles [7]. These enhancements have made biodiesels more attractive to become sustainable alternatives to conventional fuels [8][9]. From this perspective, numerous research papers in this field have showcased that nanoparticle inclusion into blended biodiesel fuels leads to lower emissions and better combustion characteristics, which is primarily attributed to the catalytic properties exhibited by nanoparticles [11–18].

In one of the investigations to evaluate the impact of nanoscale titanium dioxide (TiO_2) particles in a single-cylinder engine, Sadhik and Anand used an emulsion of water-diesel fuel water of 10% wt., diesel of 89.8% wt., and surfactant of 0.2% wt., and TiO_2 nanoparticles concentrations of 30, 60, and 90 ppm. It is reported that brake thermal efficiency (BTE) increased and emissions reduced with increased nanoparticle concentration compared to pure diesel fuel. Still, the blended fuel carbon content contributes to higher emissions [13]. However, adding nanoscale carbon particles into a biodiesel fuel blend decreased emissions of CO and HC, particularly at maximum loading of the engine, whereas at 50% and 75%, nitrogen oxide (NO_x) emissions were reduced, as stated by Hosseinzadeh-Bandbafha [19]. As a result, it enhances the use of combustion engines while conserving the environment.

Continued internal combustion engine (ICE) evolution is essential to meet the transportation and power generation demand while addressing environmental concerns [20]. Due to the need to enhance engine efficiency and reduce engine emissions, researchers have focused on finding innovative additives, such as silica nanoparticles, to improve the combustion process by improving fuel atomisation and controlling droplet size in next-generation internal combustion engines [21]. Fuel

atomisation is essential in the combustion process, which involves converting liquid fuel into a fine droplet mist to facilitate efficient mixing with air [22]. It significantly impacts combustion efficiency, emissions, and overall performance of the engine [23]. In particular, droplet size affects fuel-air mixing, evaporation rate, and subsequent combustion characteristics.

Furthermore, silica nanoparticles possess distinctive physical and chemical properties, enhancing fuel atomisation and droplet size control [24]. The larger surface area and thermal stability of nanoparticles increase the opportunities for fuel-air interaction, resulting in improved combustion efficiency; the catalytic reaction of silica nanoparticles enhances complete combustion, reducing harmful pollutant emissions [12]. The nanoscale catalytic reaction can be experimentally modelled using some techniques.

Tomar and Kumar investigated the experimental and computational modelling of the fuel atomisation and droplet size distribution in a CI engine fuelled with diesel, biodiesel, and blends in the presence of silica nanoparticles. Experimental studies employed advanced imaging techniques such as high-speed imaging and laser diffraction to observe and analyse the fuel atomisation process and droplet size distribution under different concentrations of silica nanoparticles [25]. The spray and atomisation properties of various alternative fuels with commercial diesel fuel were investigated by assessing droplet sizes and particle distributions using a laser-based device and measuring the cone angle and spray tip penetration with high-speed imaging [26]. High-speed imaging allows for the visualisation and detailed examination of the atomisation process, providing information about fuel breakup into droplets. On the other hand, laser diffraction enables droplet size distribution measurement by analysing light scattering patterns produced by the droplets [27]. In the same manner, Ehteram et al. utilised high-speed imaging as well as laser light scattering techniques in their study of droplet generation by striking an air jet onto a liquid surface in a penetrable manner, the penetrating gas caused periodic upward movement of fluid strands drawn into the area of high-speed with pressurised gas jet and then transformed into small droplets through atomisation process [27]. The fuel atomisation process was simulated using computational fluid dynamics (CFD). This numerical modelling tool enables the modelling of the complex interactions between fuel and air, considering factors such as fuel injection, airflow, and combustion [28].

Additionally, Lee et al. used experimental approaches involving Mie scattering, laser-induced fluorescence (LIF) and phase doppler anemometry (PDA) along with CFD models to examine the nozzle holes of an injector to determine their effect on spray generation and

movement of air; four holes with distinct designs and umbrella angles were utilised to analyse the impact on fuel distribution, entrainment of air, velocity of cross-flow and turbulence. They reported that a symmetrically configured nozzle formed isolated clusters of fuel vapour and an asymmetrical configuration promoted coherence in the vapour cloud and that the spray plumes in-between distance had a more significant impact compared to the nozzle hole symmetry. The spray plumes' in-between distance influenced the coherency of the turbulence, fuel vapour cloud, cross-flow velocities, and fuel-to-air ratio; spray plumes that were closer together had increased interaction [29]. The CFD simulations analysed the spray plumes and provided valuable information regarding the fundamental processes involved in fuel atomisation and the regulation of droplet sizes [30].

The incorporation of silica nanoparticles as additives in the simulations provides an understanding of the anticipated influence of the nanoscale additives on combustion and engine performance as well as fuel atomisation. However, there is still limited research and overviews on the behaviour of silica nanoparticles towards the atomisation of engine fuel and how this atomisation affects engine performance. Therefore, this study aims to comprehensively assess how nanoscale silica particles affect fuel atomisation and droplet size in advanced internal combustion engines. Thus, the results from different researchers are studied and highlight how various nanomaterial additives can improve combustion efficiency and reduce emissions due to improved atomisation and droplet size. This can help create greener and more efficient internal combustion engines, leading to more suitable transportation and power generation systems. The challenges, areas of limited knowledge, and future research avenues in this field are also highlighted.

2. OVERVIEW OF NANOMATERIAL ADDITIVES

Due to the need to enhance the efficiency and performance of ICEs, nanomaterials have been extensively utilised as fuel additives. These additives can improve combustion characteristics, reduce emissions, and enhance fuel stability when incorporated into fuel formulations. [13][24–25]. These additives include carbon nanotubes, metal nanoparticles, metal oxide nanoparticles, and nanocatalysts.

2.1. Carbon Nanotubes

Numerous studies have been undertaken to assess the effect of incorporating nanoscale particles into blends of diesel-biodiesel fuels on operational efficiency and engine emissions. Among these nanoparticles, carbon nanotubes have emerged as promising additives for fuel

enhancement to optimise engine performance while simultaneously minimising emissions [31]. In an investigation that was conducted by Hossein et al., a test on the CI engine's exhaust emissions and performance when powered by blends of diesel-biodiesel and carbon nanotubes (CNTs) in a single cylinder chamber was performed, and it was found that the addition of CNTs enhanced the engine performance at all speeds as a result of decreased viscosity and improved atomisation. Similarly, CNTs lowered specific fuel consumption and exhaust emissions [32]. The carbon nanotubes can be combined with metal nanoparticles to create nanocomposites with enhanced properties that can positively impact the characteristics of biodiesels.

2.2. Metal Nanoparticles

Metal nanoparticles, such as ferric chloride (FeCl_3), platinum (Pt), palladium (Pd), and gold (Au), facilitate more efficient fuel oxidation and improve combustion rates. They enhance the oxidation of CO and HC, which results in the pollutants [33]. These metal nanoparticles are used as catalysts in fuel additives. In a study by Kannan et al., biodiesel from waste cooking palm oil was catalysed by FeCl_3 . Results demonstrated a 6.3% BTE increase with 8.6% BSFC reduction and lower NO_x emissions despite drastically elevated CO₂ emissions. However, when compared to a non-fuel-borne catalyst at high injection pressures (280 bar), all emissions are reduced due to the shorter ignition delay and the increase in the heat release rate [34]. One notable benefit of ferrofluid is its unique ability to be extracted from exhaust gas, setting it apart from other additives [35]. Furthermore, metal nanoparticles can be used as catalysts, and their oxide (metal oxide) nanoparticles are also used as fuel catalysts.

2.3. Metal oxide nanoparticles

Being fuel additives, metal oxide nanoparticles that include cerium oxide (CeO_2) and titanium dioxide (TiO_2) are commonly used as catalysts. They mainly donate oxygen, enabling CO oxidation and absorbing oxygen to facilitate the reduction of NO_x, thus improving combustion efficiency and reducing emissions [36]. Additionally, nanoaluminium is used as metal oxide nanoparticles in some systems. Jones et al. prepared a complex system with many components to better understand ethanol combustion and the nano aluminium (n-Al) oxidation process in one study. They found nearly a linear correlation between an increase in heat released from the combustion of ethanol with higher n-Al concentrations and an increase in the volumetric heat of combustion (HoC) [37]. The metal oxide nanoparticles can further be classified as nanocatalysts that can be improved and applied in biodiesel blended diesel fuel.

2.4. Nanocatalysts

Bio-diesel-fed engines can maximise emission reduction and enhance performance by utilising heterogeneous or homogeneous catalysts [38]. Mirzajanzadeh et al. used a soluble nanocatalyst made of 90ppm cerium oxide nanoparticles (CeO₂-NPs) to examine its impact on amide-functional multi-wall carbon nanotubes (MWCNT-amide) and identify the direct injection (DI) engine's performance and emissions powered by biodiesel (B20) blended diesel fuel. An overall improvement in the combustion process and performance and reduced emissions were exhibited due to the catalyst's large surface area [39]. Similarly, in a bid to reduce emissions in DI engines, Sarvestani et al. conducted a study in which magnesium cation was integrated into ferric oxide to synthesise an active nanocatalyst (Mg_{0.25}Fe_{2.75}O₄) with a high Oxygen Storage Capacity (OSC) [40]. Compared with the base diesel fuel, it was revealed that the improved nanocatalyst displayed exceptional efficacy in minimising exhaust emissions in particulate matter (PM), HC, and CO [40]. The addition of the above nanomaterial additives into biodiesel fuels has been noted to affect CI engine combustion positively. This is because of their impact on the internal atomisation of fuel as well as the size of the spray droplets during the operation of the engine.

3. FUEL ATOMISATION AND DROPLET SIZE

Combustion efficiency is greatly affected by the size of the fuel droplet produced during atomisation. These droplets' diameter and size distribution, which the Sauter generally characterises mean diameter (SMD), directly impact the engine's combustion, overall performance and emissions. SMD is typically utilised in determining atomisation quality in combustion applications because it is required for several processes, such as mass transfer, droplet penetration, and heat transfer. SMD refers to a hypothetical uniform droplet set with the same total volume and surface area as the actual droplet set. This can be calculated by using the definition in Equation 1.

$$SMD = \sum N_i D_i^3 / \sum N_i D_i^2 \dots\dots\dots 1)$$

where N and D symbolise the number of droplets and droplet diameter, respectively [41].

SMD and other techniques have been employed in several studies. Qavi et al. used a method with high spatial precision, that is, shadowgraph imaging technique (SIT) as well as flow burning (FB) technique, to capture the cumulative distribution of droplet size and compute the SMD to investigate the spray properties of viscous renewable jet fuel. All methods, including particle image velocimetry (PIV), SIT, and Weber number estimates,

demonstrated effective (finer) atomisation due to a substantial secondary droplet disintegration towards the spray's outer edge, resulting in overall combustion performance improvement [42]. This finer atomisation is affected by the existence of nanoparticles in the fuel.

2.4. Secondary atomisation

Nanoparticle addition enhances the rate at which fuel breaks down into smaller droplets and promotes thorough combustion. Fuel mixtures that incorporate nanoparticles are more likely to ignite than pure diesel. Including nanoparticles improves the atomisation process alongside fine spray droplets (secondary atomisation), resulting in faster combustion [43]. In a study conducted by Hoang, it was found that the primary process responsible for secondary atomisation predominantly relied on micro-explosions, which enable the development of smaller droplets, which shortens the time required to prepare the fuel mixture before ignition [3]. The fuel and air mixing improvement is supported by the presence of concentrated nanoparticles within the small-sized droplets. This leads to enhanced efficiency of chemical reactions because of the fraction of surface and volume that allowed for better mixing. Additionally, nanomaterials, driven by their disruptive behaviour and ability to cause micro-explosions, have demonstrated an active role in promoting the secondary atomisation process, particularly during phases of injection and combustion [3].

Furthermore, Nyashina et al. studied how fuel droplet micro-explosive atomisation is affected by factors such as the environment, the economy, and comparative performance indicators compared to coal. The results indicated an improved fuel droplet atomisation and the relative performance indicator of slurry. Notably, experiments with slurry droplets of about 2 mm in diameter showed intense micro-explosion [44]. Meanwhile, in their study, Sardemir et al. recorded improved engine performance due to better atomisation, where corn oil methyl-ester was mixed with diesel fuel at 210 and 230 bar injection pressures. Likewise, peak in-cylinder pressure and heat release rate increased slightly under heavy loading and high pressure. This is mainly ascribed to fuel-improved atomisation at more significant injection pressures, which resulted in smaller droplet sizes [45].

The nature of micro explosion determines the size of the droplets. A study conducted by Anh Tuan Hoang shows nanomaterials' ability to actively induce secondary atomisation through enhanced disruption behaviour and micro explosions. This secondary atomisation occurs during the injection and combustion phases, as depicted in Figure 1. The combustion efficiency improved due to enhancement in fuel-air mixing and quick evaporation.

The initial breakdown of the fuel occurs during the injection phase in conditions characterised by high pressure and temperature. Fuel droplets are scattered with considerable force into a rapidly moving environment during this phase [3].

The spray progression for three types of fuel, one conventional diesel, one manufactured biodiesel fuel, and one blended biodiesel nanofuel, respectively, is depicted in Figure 2. This figure indicated the comparison performed with injection pressures that vary from low (40–50 MPa) to high (100–150 MPa), focusing on the length of penetration and cone angle. The droplet distribution is more elevated in blended nanofuel at low injection pressures than in pure diesel and biodiesel.

However, the penetration is longer in the diesel/and biodiesel fuel than in the nano fuel, as in Figure 2(a). Conversely, Figure 2(b) represents the effect on the spray development process at high injection pressure influenced by the ratio of biodiesel blending. When the spray development process is evaluated, the research indicates that biodiesel mixing ratios have a minimal effect. As a result, spray tip penetration of fuels incorporated with biodiesel is comparable to that of ordinary diesel fuel that has not been diluted [50]. However, for better spray tip penetration, the fuel can be incorporated with nanoscale materials, and silica nanoparticles are one of the best candidates for improving fuel performance in internal combustion engines.

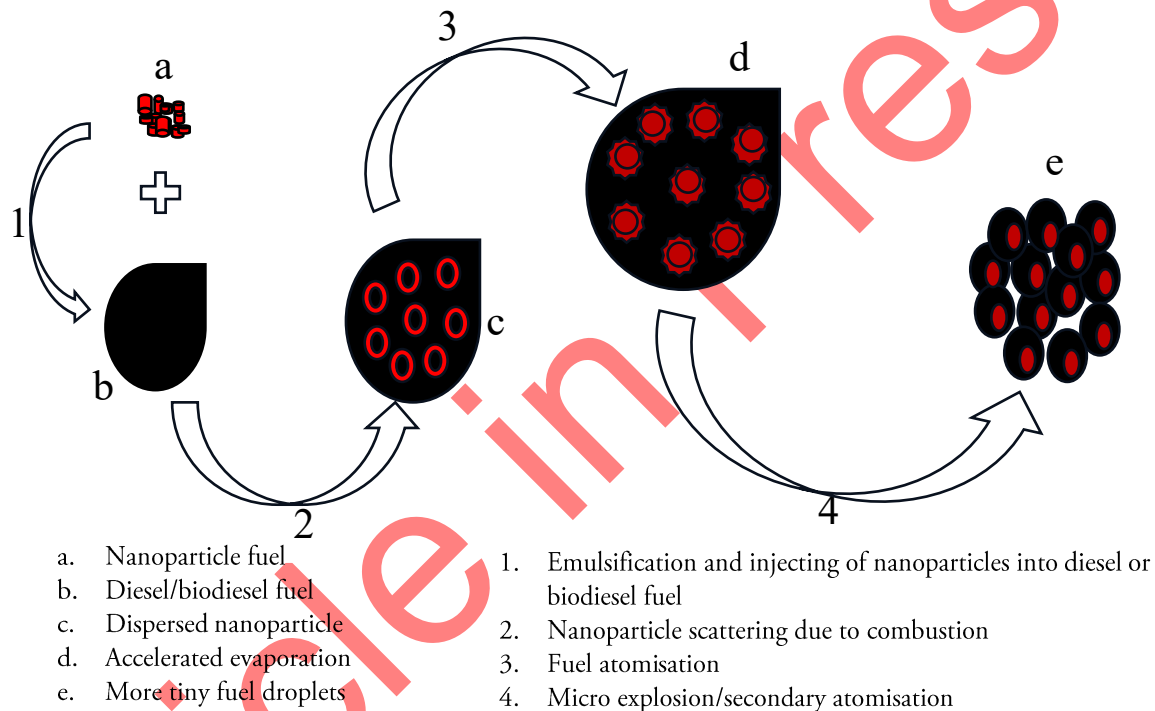


Figure 1. Enhanced/secondary fuel atomisation using nanomaterials (NM) [3][46–49]

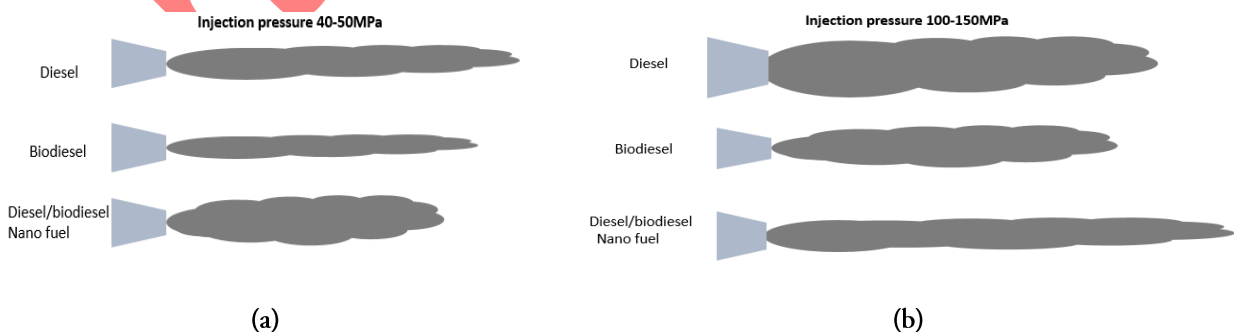


Figure 2. The profile of injection spray on various fuels at ambient pressure. (a) 40–50 MPa. (b) 100–150 MPa [50–54].

4. NANOSCALE SILICA

Nanoscale silica (SiO_2) particles are used as fuel additives to improve fuel efficiency and combustion characteristics. They possess unique physicochemical properties, including high surface area, thermal stability, and dispersibility. Adzim performed a study that indicated positive results while testing the incorporation of metal oxide nanoparticles in biodiesel fuel in a diesel engine. This enhancement reduces the ignition delay period, increasing the engine combustion and thermal efficiency. Conversely, silicon-based nanoparticles also exhibit promising characteristics and positively impact engine performance in diesel engines [55]. These silica nanoparticles are obtained by employing several techniques, including sol-gel.

4.1. Synthesis and characterisation of nanoscale silica

Various methods can be utilised to synthesise tiny silica particles on a nanoscale level. These include flame synthesis, the microemulsion technique, hydrothermal synthesis, mechanical milling, and the sol-gel method. Additionally, studies highlight techniques available to modify and enhance the functionality of these particles, such as co-condensation or grafting processes [56]. Some studies have highlighted the modification techniques.

In one of the studies, Ren et al. synthesised silica nanoparticles while employing the Stober method along with microchannel microwave (MM) and microchannel mixed (MC) alongside tetraethyl orthosilicate (TEOS) and ammonium hydroxide (NH_4OH) as the raw

materials. After several particle examinations, which included SEM, XRD, FTIR, and DLS, an amorphous silica structure of nanoparticle size between 15 and 300nm (for the MC process) and 30–350nm (for the MM process) was obtained at Polydispersity index (PDI) value between 0.05 and 0.2 [57]. Similarly, Mahalingam et al. utilised rice husk ash and cetyltrimethylammonium bromide (CTAB) as the surfactant and precursor, respectively, in a Sol-gel approach that used microwaves, in which amorphous silica nanoparticles sized in the range of 80 to 100nm with spherical shapes were obtained [58]. Furthermore, Dongfang et al. also performed a nano-silica synthesis experiment in which they first constructed oil-water microemulsions that were used alongside isopropanol (IPA), pentanol, ammonium bicarbonate, and CTAB as the surfactants. The mesoporous silica nanoparticles (MSNs) obtained varied in pore sizes, shapes and uniform diameters, where the particle sizes range from 135 to 280nm with pores from 2.8 to 32.3nm [59].

Similarly, Kumar et al. obtained silica nanoparticles from Silicon by employing planetary ball milling for 45 hours, reducing silicon microparticles to a smaller size. Results show that particle sizes range from 30 to 100nm. They further applied these particles in the twin-cylinder diesel engine as nano fuel additives, improving its performance [60]. Additionally, more experimental studies have been conducted to manufacture nanoscale silica particles as additives in biodiesel fuel and other applications (Table 1).

Table 1. shows the synthesis methods of nanoscale silica particles.

Silica name	Method	PH	Precursor	Characterisation	Particle size	Ref.
Mesoporous (SBA-16)	Hydrothermal	Acidic	SCA	XRD, SEM, TEM, BET, FTIR	~37 nm	[60]
Si NPs	Hydrolysis and condensation	Acidic	TEOS	AAS and FESEM	100 nm and 2 μm	[61]
SiO_2 @PANI	Stober	Acidic	TEOS	XPS, TGA, SEM, TEM, ATR-IR	90-300nm	[62]
SiO_2	Precipitation	Acidic	Na_2SiO_3	FTIR, XRD, XRF and SEM	6269.3 nm at T25 and 3295.9 nm at T80	[63]
MSN	Sol-gel		TEOS	SEM, TEM, and N2-adsorption analysis	100-200 nm	[64]
MSNs	Aggregation and condensation	Acidic	TEOS	TEM	20-110 nm	[65]
SiO_2	Multipoint injection approach	Acidic	TEOS	UV-Vis, FESEM, and DLS	0.9-1.1 μm	[66]
SiO_2 NPs	Thermal combustion and precipitation	alkaline	Bamboo leaf	HRSEM, EDX, XRD, FTIR, and TGA	20nm	[67]
Silica NPs	Sol-gel	Acidic, alkaline	Cassava periderm	XRD, SEM, EDS, FTIR, TEM, and PSA	33.69 nm	[68]

However, as shown in Table 1, the synthesised silica nanoparticles can be applied as additives when blended with biodiesel fuels. These fuels have distinct properties depending on the ratio of the mixed nanoparticles. Table 2 elaborates on some of these properties of the conventional base fuel and the blended silica nanoparticle fuels [61–62]. These properties play a significant role in

the disintegration and atomisation of fuel, how the fuel spray is distributed, and how it evaporates during the operation of an internal combustion engine. To effectively determine how best silica nanoparticles can affect fuel properties, the fuel (incorporated with silica nanoparticles) atomisation behaviour must be understood.

Table 2. The properties of the SiO₂-biodiesel fuel blend [69–70].

Properties	Base fuel			MME-SiO ₂ fuel blend			
	Diesel	Mineral diesel	Methanol	MME20	MME20+ SiO ₄₀	MME20+ SiO ₈₀	MME20+ SiO ₁₂₀
Calorific value, MJ/kg	42			41.95	41.62	41.728	41.963
Viscosity, cSt	4.1			4.7	3.3	3.37	3.21
Density, kg/m ³	830	830	792	858	831	827.5	828
Cetane number	45	50.5	4.8	53	48	48.5	55
Pour point, °C	3.5			2	3	2.8	4
Flashpoint, °C	53	70	12	132	73	69	66

4.2. Properties of atomisation, spray, evaporation, and breakup of fuels containing SiO₂.

The combustion chamber receives liquid droplets in the form of a spray, and the combustion process heavily relies on the characteristics of droplet oxidation and vaporisation [63–64]. Therefore, in developing an efficient combustion system, the vaporisation rate, the duration of guidance, and the rate at which droplets burn are crucial factors to consider [65–67]. These factors affect nanofluid fuel combustion related to multiphase, multi-scale, and multi-component processes. Therefore, droplet vaporisation will be more complex. Due to increased disruptive tendencies and micro-explosion (as in Figure 1), nanomaterials have demonstrated their capacity to actively cause atomisation at the secondary level, particularly at the injection and combustion stages. Consequently, the enhanced blending of fuel and air, along with rapid evaporation, results in improved combustion efficiency, thereby facilitating the thorough combustion of fuel [68–69].

The injection process manifests fuel combustion in high-pressure and high-temperature environments, where fuel is initially broken down into minute particles. This occurs when the fuel droplets are forcefully dispersed into a rapidly flowing environment [70]. The volume of the nanomaterial found in the base fuel builds the resilience of the nanofuel mixture, consequently affecting the dynamics of droplet formation. In one study, integrating nanomaterials into the fuel droplets resulted in a higher droplet aerodynamic shear stress between them and the surrounding flow field, potentially leading to further

droplet breakage. As a result, the deformed shapes of the droplets further facilitated the secondary atomisation of these nano-sized fuel droplets [26]. Secondary atomisation involves the breakage of larger fuel droplets into tiny ones caused mainly by micro-explosion. This phenomenon consists of highly concentrated nanoparticles produced within relatively small water and fuel droplets. These nanoparticles facilitate improved fuel-air mixing as well as more effective reactions due to their high surface area-to-volume ratio [71]. The rise of uneven nucleation, which was predominantly observed on the droplet surface, was the essential process underlying the micro-explosion phenomena. Various nanoparticle additives can influence the droplets' evaporation.

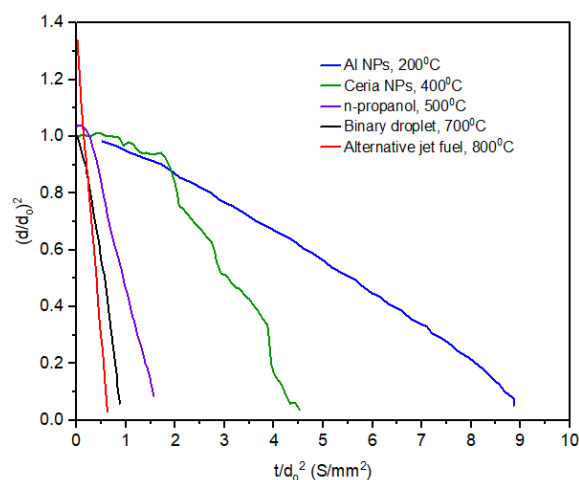
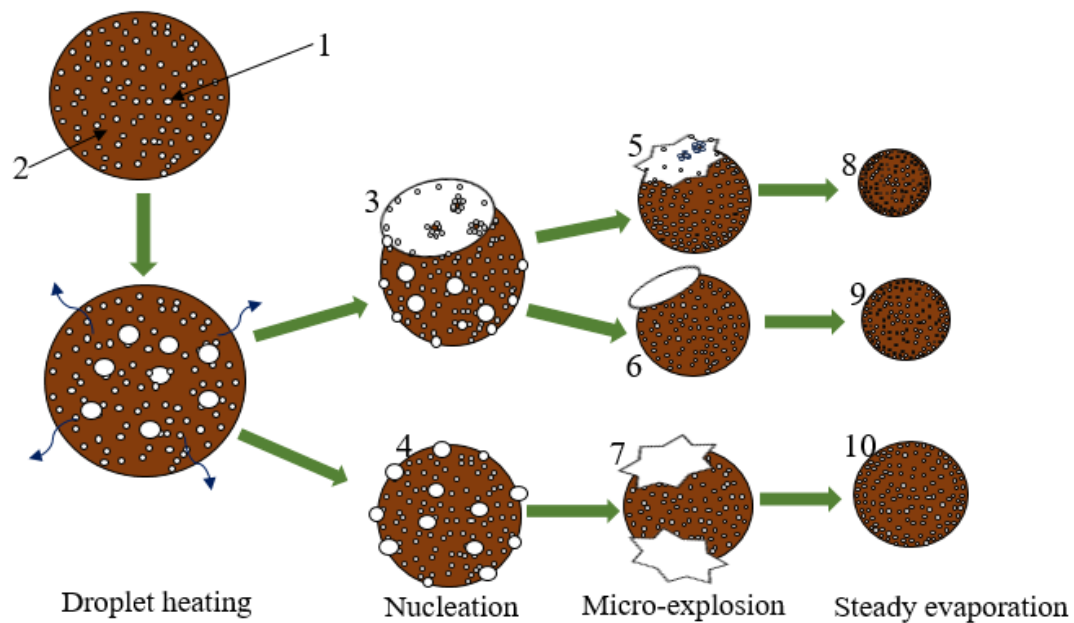


Figure 3. Droplet normalised square diameter evolution in nanofluid fuels at various temperatures [72–77].



- | | |
|---|------------------------------|
| 1. Nanoparticle | 6. Blow-off |
| 2. Diesel | 7. Weak micro explosion |
| 3. Homogeneous nucleation | 8. Smaller droplet, d_8 |
| 4. Heterogeneous nucleation | 9. Large droplet, d_9 |
| 5. Strong Micro explosion | 10. Larger droplet, d_{10} |
| $T_{3-5} > T_{amb}$, $T_{3-6} < T_{amb}$ | $d_8 < d_9 < d_{10}$ |

Figure 4. Nanofluid fuel droplets' mechanism of evaporation [72][78–81]

Several studies investigated the evolution of diesel droplets blended with various nanoparticles (NPs) at different temperatures in a typical gravity environment [72]. Figure 3 shows the addition of nano-additives can increase droplet longevity. However, bubbles and repeated micro-explosions accompany the evaporation process at higher temperatures (Figure 4). This consequently reduces the normalised square diameter due to the optimum delay time of explosion being reached.

Several studies show that the size of fuel droplets positively impacts the engine's performance due to micro explosion. Table 3 demonstrates how silica nanoparticle additives affect engine performance and combustion behaviour. Additionally, these additives are noted to impact the engine exhaust emissions, as given in Table 4.

Different SNP sizes have been experimentally explored to determine how atomisation affects diesel engine combustion and performance [82]. Results show silica nanoparticles possess unique physicochemical properties, including high surface area, thermal stability, and dispersibility for fuel atomisation and droplet size. These properties notably impact the engine's efficiency, combustion and emissions. This can further be analysed in the subsequent sections.

5. ENGINE COMBUSTION ANALYSIS

The combustion characteristics, regarded as the most essential aspects indicating the engine's combustion efficiency, greatly influence the engine's performance alongside emissions. Two key variables, pressure and heat release rates, are commonly employed to study combustion characteristics [83]. In one study, the superheated fuel droplets expanded upon ignition due to the high heat release rate caused by the nanomaterial's small size and high surface-to-volume ratio [75][84]. Due to its tiny size and high surface-to-volume ratio, diesel fuel's thermal conductivity increased. The thermal increase allowed further expansion, resulting in a microfuel explosion. Fuel droplets were further broken up by adding the micro-explosion effect, significantly reducing the ignition delay time [85]. This longer ignition delay causes the HRR and in-cylinder pressure to peak when the injection timing advances [82]. These variables are further elaborated on how they are affected by including nanoparticles in diesel/biodiesel blends.

5.1. Heat release rate (HRR)

Because the combustion's shorter ignition phase led the HRR to peak during this instant, nanoparticles most likely enhance the HRR [86–87]. According to the findings of Saravanan et al., the 50 ppm nanoblend fuel

resulted in the most incredible HRR value at 168.468 kJ/m³c, and this was ascribed to faster fuel combustion and a shorter time delay before ignition [88]. Likewise, Aalm analysed HRR using a 20% biodiesel and Fe₂O₃ alongside an Al₂O₃ nanoparticles mixture at different concentrations. This study found that increasing the nanoparticle dosage (despite their different concentrations) can improve the HRR [89]. Table 3 depicts that SNP inclusion in the fuel blend increases the HRR.

Similarly, Figure 5(a) indicates the decrease in HRR for various blends (including SNPs, biodiesel, and conventional diesel blends) at 100% load as a function of crank angle. Blended SNP fuels encourage complete combustion, preventing carbon deposits on the chamber walls. It was discovered that HRR is generated by blended fuel mixed with silica nanoparticles compared to pure diesel fuels or diesel/biodiesel fuel without nanoparticle inclusion. This rise in HRR is primarily due to SiO₂ or other nanoparticles, which are not generally found in biodiesel or diesel fuel. The actions aid HRR in raising the fuel before it enters the combustion chamber [34][90].

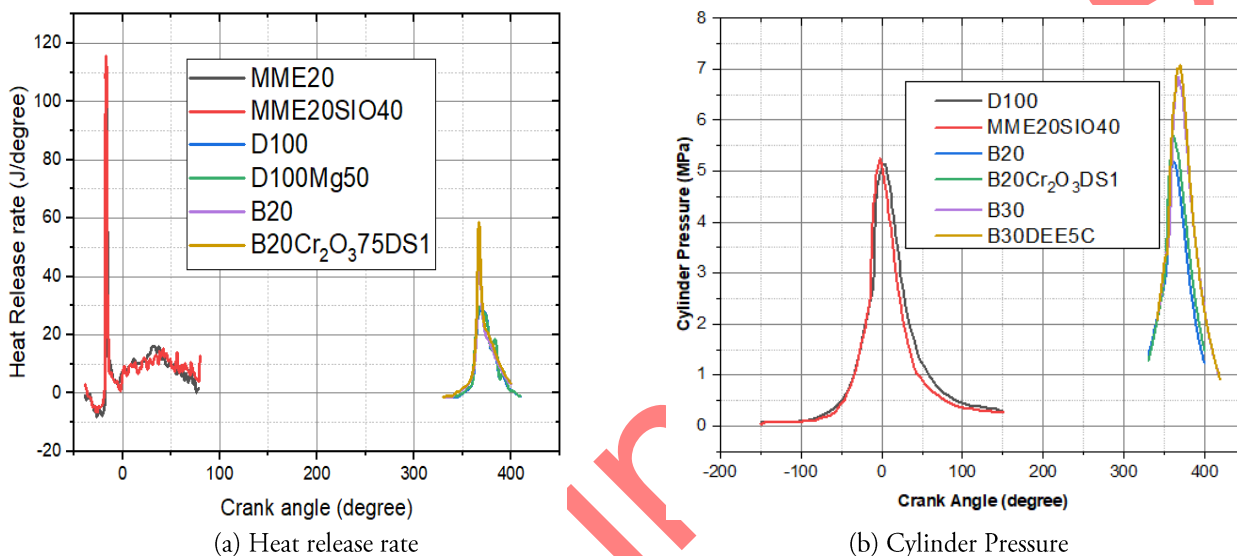


Figure 5. The variations in the heat release rate and in-cylinder pressure as a function of crank angle when nanoparticles are added into the diesel/biodiesel fuel [61].

Table 3. The impacts of SiO₂ nanoparticles fuel additives on combustion characteristics and engine performance.

Fuel	SiO ₂ , ppm	Combustion characteristics		Engine performance			Ref.
		HRR	PRR	Brake Power	BTE	BSFC	
MME20, MME20+SIO120	120	increase	increase	-	increase	decrease (compared to MME)	[69]
SBME25	25, 50, and 75	-	-	-	increase (3.48-6.39%)	increase (5.81-9.88%)	[90]
Si0.25, Si0.5, and Si0.75	0.25, 0.5, and 0.75 wt.%	-	-	decrease	increase (8.93%)	decrease (8.1%) (compared to base diesel)	[59]
Al ₂ O ₃ -SiO ₂ nano composite	21, and 60	-	-	increase (1.64%)	-	-	[91]
W/DS	0.1 wt.%	increase	increase (4%)	-	increase (14%)	decrease (37%)	[92]
B20SNP50, B20SNP75, B20SNP100	50, 75, and 100	-	-	decrease	decrease (31.91%)	decrease (0.388%)	[93]
D94W5S1-Si50	50	increase	increase	-	increase (2.6%)	decrease (3.7%)	[94]

Table 4. The impacts of SiO₂ nanoparticles fuel additives on engine emission

Fuel	SiO ₂ , ppm	HC	CO	NO _x	Smoke/soot	Ref.
MME20, MME20+SiO ₂ 120	120	decrease slightly compared to diesel	decrease slightly compared to diesel	increase	decrease slightly compared to diesel	[69]
SBME25	25, 50, and 75	decrease (20.56-27.5%)	decrease (1.9-17.5%)	increase (7.5-10.25%)	decrease (10.16-23.54%)	[90]
Si0.25, Si0.5, and Si0.75	0.25, 0.5, and 0.75 wt.%	decrease (20.63%)	decrease (28.57%)	decrease (27.3%)	increase	[59]
Al ₂ O ₃ -SiO ₂ nano composite	21 and 60	decrease	decrease	decrease	decrease	[91]
W/DS	0.1 wt.%	increase	increase	increase	increase	[92]
B20SNP50- B20SNP100	50-100	decrease (19.18%)	decrease (0.050%)	decrease (198.21ppm)	decrease	[93]
D94W5S1-Si50	50	decrease (69.69%)	decrease (64.28%)	decrease (52.52%)	decrease (29.32%)	[94]

5.2. Pressure release rate (PRR)

The incorporation of biodiesel and diesel fuel lengthens the delay time for ignition. It increases the accumulation at the premixed combustion phase, resulting in a quick combustion process and raising the peak cylinder pressure [36][91]. Muthusamy et al. observed, in their study, a tremendous peak pressure when a 20% mixture of Pongamia methyl ester (PME) and iron oxide nanoparticles' concentrations of 50 and 100 ppm were used to power an engine [92]. The in-cylinder pressure variation at full load conditions is depicted in Figure 5(b) when employing SiO₂ and other nanoparticles, diesel, and biodiesels. The graph shows the rise in the cylinder pressure when the nanoparticles are incorporated. The combustion process starts earlier by increasing the injection timing since the ignition delay time is reduced, and the biodiesel's injection pressure is raised. This phenomenon explains the higher cylinder pressure observed [93-94]. This pressure increase leads to a rise in torque production, indicating that torque generation at the instant of combustion is proportional to the combustion pressure [95].

6. ENGINE PERFORMANCE

The silica nanoparticles incorporated in biodiesel fuel have a more significant impact on engine performance. Some of the engine performance parameters, including specific fuel consumption and thermal efficiency, are highlighted in this section.

6.1. Brake-specific fuel consumption

The calorific content of the fuel and its combustion efficiency are some of the main factors that affect the specific consumption of fuel (BSFC). The increase in BSFC is influenced by a lower calorific value of the nanoparticle blended fuel in contrast with pure diesel fuel. According to several studies, BSFC is generally lowered when nanoparticles are integrated with diesel/biodiesel fuel, as shown in Table 3 [96]. A study conducted by Nour et al. found that blending JE20D diesel with ethanol increased the latent heat of vaporisation, assisting in heat absorption during combustion. In contrast, adding nanoparticles results in a more considerable calorific value and, thus, a lower BSFC when compared to pure diesel fuel [97-99]. SNPs in blended fuels promote superior combustion characteristics and increased atomisation, resulting in improved BSFC [13][100].

6.2. Brake thermal efficiency

According to Table 3, studies have shown the variations in brake thermal efficiency (BTE) when nanoparticles are included in the fuel blend. It is indicated the efficiency is enhanced significantly at full load. Nutakki et al. investigated the effect of MME-SiO₂ nano diesel fuel blends on combustion, engine performance, and engine efficiency in direct injection engines, discovering that higher SNP concentrations in the blends improve overall engine efficiency, with MME20-SiO₂ blends exhibiting a slightly higher BTE when compared to regular diesel fuel [61].

7. EXHAUST EMISSIONS

Several studies show that nanoparticle additives in biodiesel fuels impact the characteristics of the engine's exhaust emissions. Therefore, SiO₂ nanoparticles are discussed below, including how they affect the emissions of carbon monoxide, hydrocarbons, and nitrogen oxides, as well as the behaviour of smoke opacity.

7.1. Carbon monoxide

When compared to test fuel with standard fuel, lower carbon monoxide (CO) emissions are produced when using a nanoparticle fuel blend [101–102]. The improved fuel droplet evaporation rate associated with nanoparticle fuel blends can be ascribed to the reduction in CO emissions. This decrease is due to the enhanced combustion traits as well as the shorter ignition latency of the engine's test fuel [103–104]. The changes in CO exhausts for several fuel mixtures are illustrated in Table 4. It reveals that SiO₂ biodiesel mixes emit much less CO than pure diesel fuel. Iron oxide nanoparticles reduce ignition delay by boosting quick combustion reactions inside the cylinder. However, incomplete combustion and more significant CO emissions are found when SiO₂ is not used. A proper fuel-to-air ratio produces high-quality complete combustion, decreasing CO emissions [94].

7.2. Hydrocarbons (HC)

HC emissions are negligible, especially at low engine loads. However, as the load increases, HC emissions are detected. The variations in unburnt HC emissions, especially at full loads due to nanoparticle fuel mixture, are illustrated in Table 4. It is indicated from the studies that nanoparticle inclusion into fuel blends reduces HC emissions significantly [96][105]. The nanoparticles of SNPs in biodiesel blends act as catalysts with oxidising properties, enhancing the combustion process. This catalytic effect facilitates better flame propagation and lowers the activation temperature required for reducing carbon.

The presence of SiO₂ and other elements in biodiesel blends effectively restricts the emissions of unburnt HC. Notably, as the amount of SNPs in the blends increases, biofuels' high cetane number and oxygen content help significantly lower the amount of HC emissions [92][106]. This can further be elaborated in one of the studies conducted by Nour et al., where HC emissions were investigated at different engine loads. Results show that at low engine loads, that is, 0.11 MPa and 0.22 MPa, HC emission is insignificant but rises as the load increases (60%). This increase is due to factors such as a longer delay of ignition, cooling effect, and delayed combustion timing produced by increased engine load [97]. These

factors have been noted in including SNPs in the biodiesel blended fuel.

7.3. Nitrogen oxides (NOx)

The changes in NOx emissions for several fuel blends are presented in Table 4. From the studies, it is reported that these fuel blends constitute pure diesel and biodiesel blends with nanoparticle additives [69][107–108]. It is noted that the impact of SiO₂ nanoparticles on NOx exhaust is a complex process controlled by various factors. The engine's response time, combustion temperature, operating conditions, design features, and fuel quality are among these factors. SNPs-biodiesel emits more NOx than pure diesel due to its increased oxygen concentration [109–110]. As a result, NOx emissions are consistently increased when SiO₂ is added to the blend [61]. However, as highlighted in the section below, some research has been conducted to find out how NOx emissions could be minimised to boost engine performance.

Rao et al. used magnetite nanoparticles in a fuel blend, which enhanced the formation of additional oxygen to oxidise CO, whereby the levels of NOx were reduced due to the presence of the nanoparticle as the catalyst [111]. Similarly, Venu et al. determined the impact of utilising fuel incorporated with nanoparticles on NOx emissions. They found that NOx emissions were reduced marginally compared to standard diesel fuel at various engine loads [112]. Nanoparticles act as catalysts, providing additional oxygen that aids in the oxidation of CO, consequently lowering NOx levels. Moreover, the nanoparticle-enhanced fuel exhibited a higher HRR, reducing NOx emissions by facilitating more through combustion within the engine [69][113].

7.4. Smoke/soot opacity

Because of their heightened capacity to capture oxygen, SNPs have the potential to boost the oxidation of soot by utilising the existing oxygen molecules [62]. Table 4 demonstrates differences in smoke opacity of several fuel blends: plain diesel, pure biodiesel blend, and biodiesel blended with SiO₂ nanoparticles. Additionally, it is observed that a considerable reduction in smoke density is achieved when SiO₂ combined fuel is in contrast with pure diesel fuel. Although the smoke density increases for all blends at specific loads, higher quantities of SiO₂ additive lead to a subsequent decrease in density. The addition of SNPs improves ignition characteristics, reduces ignition delay, and increases the evaporation rate [114–115].

4. CONCLUSION

Silica nanoparticles play an essential role in nanotechnology because of their incredible properties, such as a mesoporous structure, large surface area, adjustable particle size and shape, and biocompatibility, which benefit various applications.

The particles produced are determined by the synthesis method used. According to the literature, SNPs are excellent additives for engine efficiency as well as regulated exhausts when added to biodiesel fuel. This comprehensive research thoroughly examined the techniques for manufacturing SNPs, the quality of fuels after adding SNPs, and how to use SNP additives in biodiesel-fueled diesel engines. The studies show substantial and notable results from using SNPs as fuel additives, as stated in the paragraphs below.

The incorporation of SNPs into biodiesel demonstrates a remarkable stability between the nanofuel molecules even at concentrations below 100 ppm. Also, it increases the oxygen concentration, enhancing fuel potential to improve engine performance and minimise emissions. This improvement is observed through the engine in-cylinder heat reduction. However, when biodiesel without SNPs is compared with that incorporated with SNPs, it is realised that heat release rate, BTE and brake power increase along with a reduction in BSFC in engines with biodiesel fuel blended with SNPs. Therefore, using SNPs provides favourable outcomes attributed to increased oxygen concentration, catalytic oxidation enhancement, micro-explosion, and effective atomisation by SiO₂-added biodiesel.

Catalytic oxidation and effective atomisation boost heat absorption in nano fuels with SNPs, reducing exhaust emissions of HC, CO, NO_x, and smoke opacity. Therefore, using SNPs (smaller than 100 nm in size) as biodiesel fuel additives is a novel and inventive method to boost combustion for better engine performance and reduced emissions. However, SNP fuel blends are not yet widely applicable to reduce PM emissions.

CONFLICTS OF INTEREST

The author declares that no competing financial interests could have appeared to impact the work.

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