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Article

Combustion, Performance, and Emission Characteristics of Honge (Pongamia pinnata) Biodiesel Enriched with Carbon Nanotube-Based Nano-Additives: A Systematic Review with Particular Emphasis on Single-Walled Carbon Nanotubes

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Abstract: With the growing need for sustainable alternative fuels, biodiesel applications and nano-additives to optimize the performance of CI engines were the topics of interest. In the present study, a systematic review has been performed and the implications of combustion parameters, performance and exhaust emission reduction with the use of Honge (Pongamia pinnata) biodiesel and carbon based nano-additives in the CI engine with primary reference to SWCNTs (single walled carbon nanotubes) have been discussed. This involved a systematic literature review in the main electronic databases, reported, following PRISMA 2020 guidelines. Eleven experimental studies were published in the last seven years (2008-2025) and fulfilled the eligibility criteria and therefore were included in this study for qualitative synthesis.

Moderate Honge biodiesel blends (B20 – B40) show to be the best compromise in terms of engine performance and the emission characteristics. Typically these blended results demonstrated decreases in carbon monoxide (CO), hydrocarbon (HC), smoke opacity, and particulate matter (PM) while increases in biodiesel content were correlated with an increase in brake-specific fuel consumption (BSFC). Further, the combustion efficiency has been improved by the addition of these carbon based nano-additives such as carbon nanotubes (CNTs), multi-walled carbon nanotubes (MWCNTs), graphene, and SWCNTs, which enhanced fuel atomization, heat transfer, combustion oxidation reactions, brake thermal efficiency (BTE), compression ignition response, and heat release rate. Several drawbacks persisted, however, with higher nitrogen oxide emissions (NO_x). There was less evidence that addresses specifically SWCNT-enhanced biodiesel with only one eligible study considered for this. The present study confirms that the nano-enhanced Honge biodiesel fuel has a good potential for a sustainable fuel in CI engines, in general. More detailed, standardised research should be undertaken to achieve the best dosage of nanoparticles, determine the durability of the engine over longer periods and to enable the development of suitable NO_x mitigation measures for application.

Keywords: Pongamia pinnata; Honge biodiesel; carbon nanotubes; single-walled carbon nanotubes; compression ignition engine; engine performance; emissions; systematic review.

1. Introduction

1.1 Global Energy demand and environmental problems

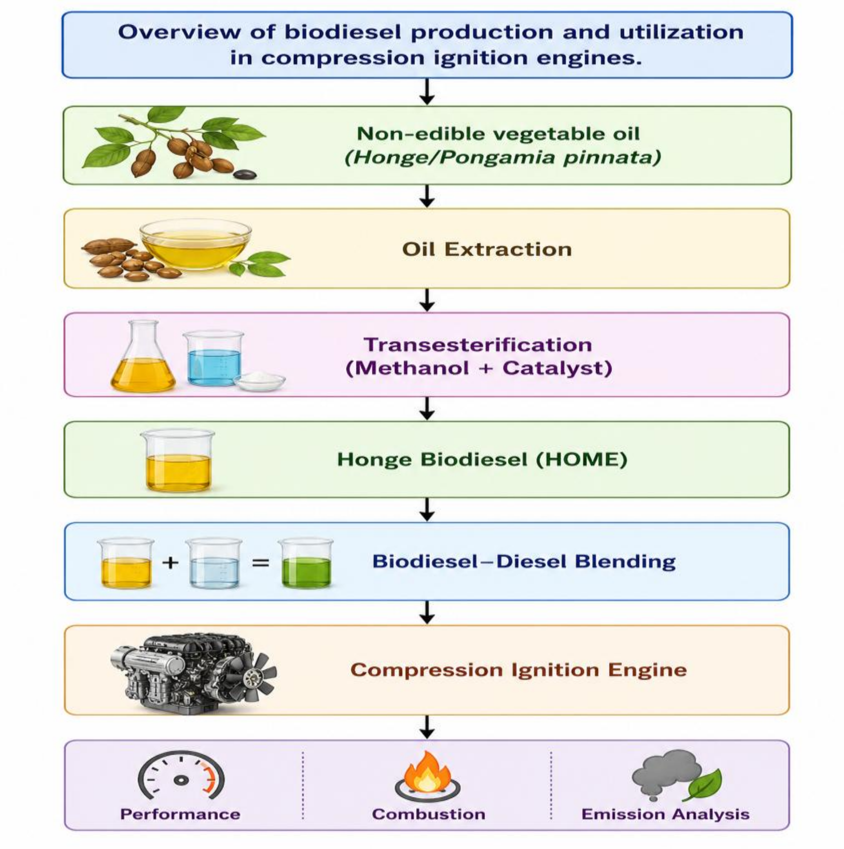
Here's one of the major realities of the world today, especially since it got used to being a highly industrialized, highly urbanized, and highly expanded transportation society, is that the world has exceeded its energy supplies -- and the transportation sector is particularly dependent on petroleum derived diesel fuel [1,2]. While diesel engines are known for their high thermal efficiency, longevity and fuel economy, their prevalence is leading to an increased amount of greenhouse gas emissions, meaning air pollution. Carbon dioxide, carbon monoxide, unburned hydrocarbons, nitrogen oxides, particulates and other pollutants that reduce air quality, human health and climate affect air quality due to combustion of diesel [3,4]. Global efforts towards carbon neutrality like the United Nations Sustainable Development Goals (SDGs) and international plans to reduce carbon emissions have boosted the need to pursue sustainable alternative fuels. Of the various alternatives workable biofuels have evolved as promising alternatives as they offer reduction of dependence on fossil-fuel utilization and make CI (compression ignition) engines less environment friendly [5].

1.2 Biodiesel is a sustainable alternative fuel

Biodiesel containing mono-alkyl esters of long-chain fatty acids is mainly prepared by transesterification reaction, whereby short chain alcohols are reacted with vegetable oils, animal fats or waste lipids containing lipids in the presence of a catalyst [6,7]. Biodiesel is one of the most studied alternative fuels, due to its renewable properties, biodegradability, low sulfur content, oxygen content and compatibility with conventional diesel engines. Oxygenated helps to support full combustion to lower the production of carbon monoxide, hydrocarbons, particulate matter and smoke [8,9]. Furthermore, biodiesel can be mixed in different concentrations with petroleum diesel and do not require extensive engine modifications, making it more feasible to use.

Although biodiesel offers the above benefits, it also has some inherent constraints limiting the extensive use of this fuel. Biodiesel typically has a higher viscosity and density, and lower calorific value, than petroleum diesel, as well as poorer cold-flow characteristics and oxidation stability. The above properties have a negative impact on the process of fuel atomisation, evaporation, combustion and engine performance, especially when operating under low ambient temperature conditions [10,11]. Moreover, the oxygen content of biodiesel can cause higher combustion temperature which leads to higher nitrogen oxide (NO_x) emissions. These challenges have led to significant research interests focusing on more sophisticated methods to modify both the properties of the fuel and the combustion process to enhance the combustion efficiency and to reduce the drawbacks of the use of biodiesel, mainly introducing nano-additive into the fuel.

Figure 1. Overview of biodiesel production and utilization in compression ignition engines.



1.3 Honge (Pongamia pinnata) biodiesel: Feedstock characteristics and its application in engines.

Karanja (Pongamia pinnata) is a non-edible leguminous tree that is widely used and is native to the tropical and sub-tropical regions that include India, Southeast Asia and Australia. It produces abundant amounts of non-edible oil which can be transformed into biofuels by transesterification, hence a good source of renewable energy without having any conflict with food production [12,13]. Furthermore, it can be found on less arable land, is drought resistant and does not need as much investment going into its agricultural process, which contributes to its potential as a sustainable biodiesel feedstock [14,15].

After transesterification Honge oil methyl ester (HOME) meets typically the requirements of EN 14214 and ASTM D6751, which are internationally recognized biodiesel standards. The use of transesterification oil results in lower viscosity and free fatty acid (FFA) content, and higher fuel quality and combustion properties, which can be used in a neat form as fuel or its blends in conventional compression ignition engines (CI) as compared to crude Honge oil [1,3,7]. Experimental testing and research have consistently shown that the blends of HOME, especially those containing a large percentage of B20-B40, generally allow a good balance between the engine performance and emission reduction. Earlier research has been conducted with better reported brake thermal efficiency, reasonable combustion properties and emission reductions of carbon monoxide, hydrocarbons, smoke opacity and particulate matters, compared to conventional diesel [16-18]. But higher biodiesel levels generally lead to increased fuel usage, decreased heating value and high nitrogen oxide (NO_x) emissions. The results show that while Honge biodiesel is an attractive alternative to conventional fossil fuel-based diesel fuels, there are still opportunities for further research and development to better understand its combustion efficiency and emissions characteristics to ensure that it can be used in the maximizing practical way [19,20].

Table 1. Physicochemical Properties of Honge Biodiesel Reported in Previous Studies

Property	Diesel	Honge Biodiesel (Typical Range)	ASTM D6751	EN 14214	Representative References
Density (kg/m³)	820–850	870–890	Report	860–900	Banapurmath et al.; Telgane et al.; Sureshkumar et al. [1,4,2]
Kinematic viscosity (mm²/s, 40°C)	2.0–4.5	4.5–5.5	1.9–6.0	3.5–5.0	Banapurmath et al.; Telgane et al. [1,4]
Cetane number	45–50	50–56	≥47	≥51	Sureshkumar et al. [2]
Heating value (MJ/kg)	42–43	37–39	—	—	Banapurmath et al.; Telgane et al. [1,4]
Flash point (°C)	60–80	160–225	≥93	≥120	Telgane et al.; Banapurmath et al. [4,1]
Fire point (°C)	70–90	170–230	—	—	Telgane et al. [4]
Oxygen content (%)	~0	10–12	—	—	Jose et al.; Banapurmath et al. [9,1]
Acid value (mg KOH/g)	<0.3	0.3–0.5	≤0.50	≤0.50	Telgane et al. [4]
Cloud point (°C)	Lower	Higher than diesel	Report	Report	Sureshkumar et al. [2]
Pour point (°C)	Lower	Higher than diesel	Report	Report	Banapurmath et al. [1]

1.4 Combustion, Performance and Emission Characteristics of Honge Biodiesel

Most of the combustion, performance, and emission properties of Honge biodiesel are controlled by its functional molecular structure, which contains the oxygen-containing functional group, and its physicochemical properties, which mainly includes the relatively high cetane number [21-23]. The combustion of biodiesel typically has a shorter ignition delay and stabler combustion because of its higher oxidation level, which contributes better complete fuel oxidation. This has led to biodiesel blends of various proportions having combustion properties that are equal to or superior to diesel in the optimized engine operating condition. However, higher concentration of biodiesel can increase the combustion time due to increased viscosity, reduced volatility and reduced fuel atomization ability [24,25].

Brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and volumetric efficiency are all commonly used methods to measure engine performance. There have been many experimental studies that concluded that B20–B40 blends can be used without any modifications while the greater percentage of biodiesel in the blend introduces higher BSFC due to its lower calorific value [26]. Biodiesel has generally a slightly less efficient volumetric result but has a higher combustion efficiency due to its oxygen composition which can partially compensate for the combustion efficiency loss [27].

Honge biodiesel has significantly cut down the emissions caused by incomplete combustion of fuels, such as carbon monoxide (CO), unburned hydrocarbons (HC), smoke opacity and particulate matter (PM), from an environmental viewpoint. However, higher in-cylinder temperatures and elevated levels of available oxygen often lead to high NO_x levels [28]. The above constraints and the lesser HV and viscosity of biodiesel have spurred research into more sophisticated modification strategies. Of these, nano-additives and some new materials have attracted special attention for use as combustion enhancers that can enhance engine efficiency without sacrificing the properties of traditional biodiesel fuels [29].

1.5 Nanotechnology in Biodiesel Fuels

The area of nanotechnology is coming up as a very promising solution to the several limitations of biodiesel fuels and therefore to improve their physicochemical properties and combustion characteristics [30]. The enhanced fuel atomization, higher evaporation rate, better air–fuel mixing and complete combustion by the use of nanoparticles is attributed to their high specific surface area, excellent thermal conductivity and catalytic activity. Due to this, a considerable number of studies have been reported that use nano-additives for improving brake thermal efficiency (BTE), reduce brake specific fuel consumption (BSFC), and decrease emissions of CO, HC, smoke and PM [31].

There are numerous classes of metallic and carbon-based nanoparticles which have been explored for biodiesel applications with aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), cerium oxide (CeO_2), zinc oxide (ZnO), graphene and carbon nanotubes (CNTs) [7,8]. These have garnered significant research and development interest, with carbon nanotube additives, in particular, single-walled carbon nanotubes (SWCNTs), exhibiting fascinating properties such as thermal conductivity, high specific surface area and promoting combustion kinetics. The properties outlined above made SWCNTs a potential addition to the fuel (Honge biodiesel) for the compression ignition engine for enhancing the combustion, performance and emission efficiencies [5-8].

Table 2. Common Nano-Additives Used in Biodiesel Research

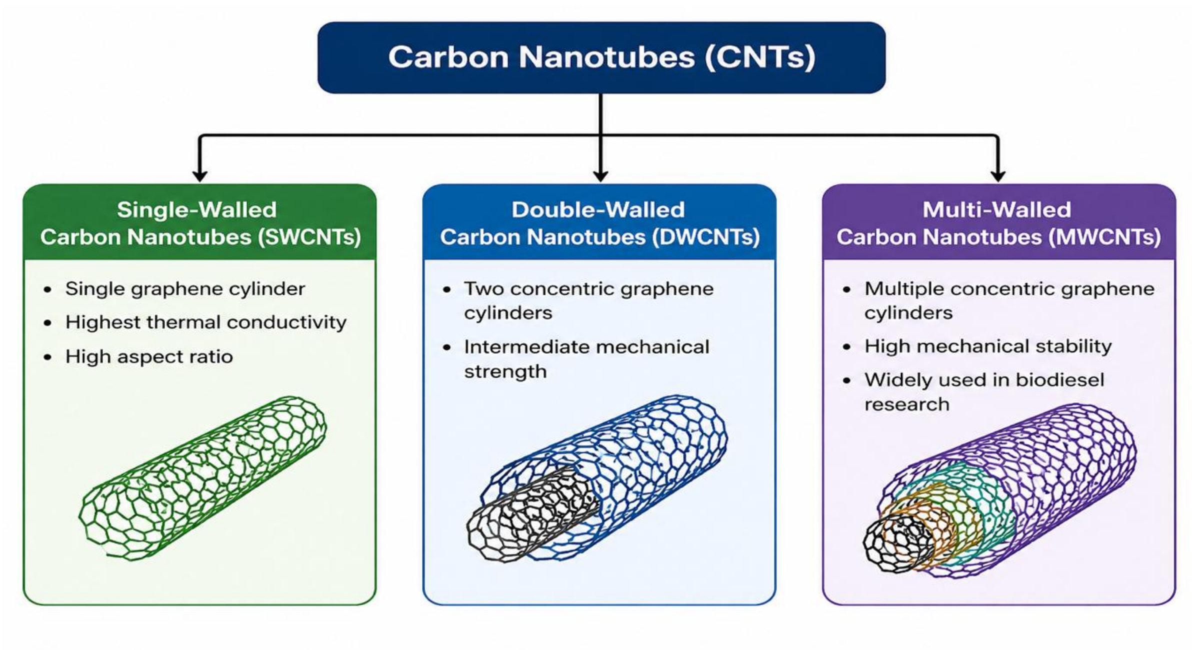
Nano-additive	**Typical concentration**	**Primary effect**	**Representative references**
Carbon nanotubes (CNTs)	25–100 ppm	Improved combustion efficiency, BTE, and emissions	Gad et al.; Vellaiyan; Rajpoot et al. [13,6,17]
Single-walled carbon nanotubes (SWCNTs)	**50–100 ppm**	**Enhanced heat transfer, fuel atomization, and combustion efficiency**	**Azarudeen et al. [27]**
Multi-walled carbon nanotubes (MWCNTs)	50–500 ppm	Improved combustion stability and fuel economy	Ooi et al.; Azarudeen et al. [16,27]
Graphene nanosheets	25–100 ppm	Enhanced heat transfer and combustion	Gad et al. [13]
Aluminium oxide (Al_2O_3)	20–60 ppm	Increased BTE; reduced CO, HC, and smoke	Soudagar et al. [10]

1.6 Carbon Nanotubes in Biodiesel Combustion

Carbon nanotubes (CNTs) have been a prime focus of attention owing to their outstanding thermal conductivity, high aspect ratio, mechanical strength, and catalytic activity, among the different carbon-based nano-additives [8,9]. From a structural point of view, CNTs are cylinders formed by the roll-up of sheets of graphene and they are classified as single-walled carbon nanotubes (SWCNTs), double-walled (DWCNTs), and multi-walled carbon nanotubes (MWCNTs). Such unique features lead to high heat transfer, fuel atomization in the combustion chamber and to the high speed of combustion reactions in compression ignition engines [12-15].

Past experimental research consistently shows the improved combustion, performance and emission parameters of biodiesel fuelled engines with CNT based additives. The reported benefits are an improvement in brake thermal efficiency, a reduction in brake specific fuel consumption, a reduction in ignition delay, higher heat release rate and peak cylinder pressure, and lower emission levels of CO, HC, smoke, and PM [30-32]. But, in some studies, the increase of nitrogen oxide (NO_x) emissions has been reported due to increase in the in-cylinder combustion temperature. Overall, the results showed that carbon nanotubes are a potential combustion enhancing nano-additives to biodiesel application.

Figure 2. Classification of Carbon Nanotube Nano-Additives Used in Biodiesel



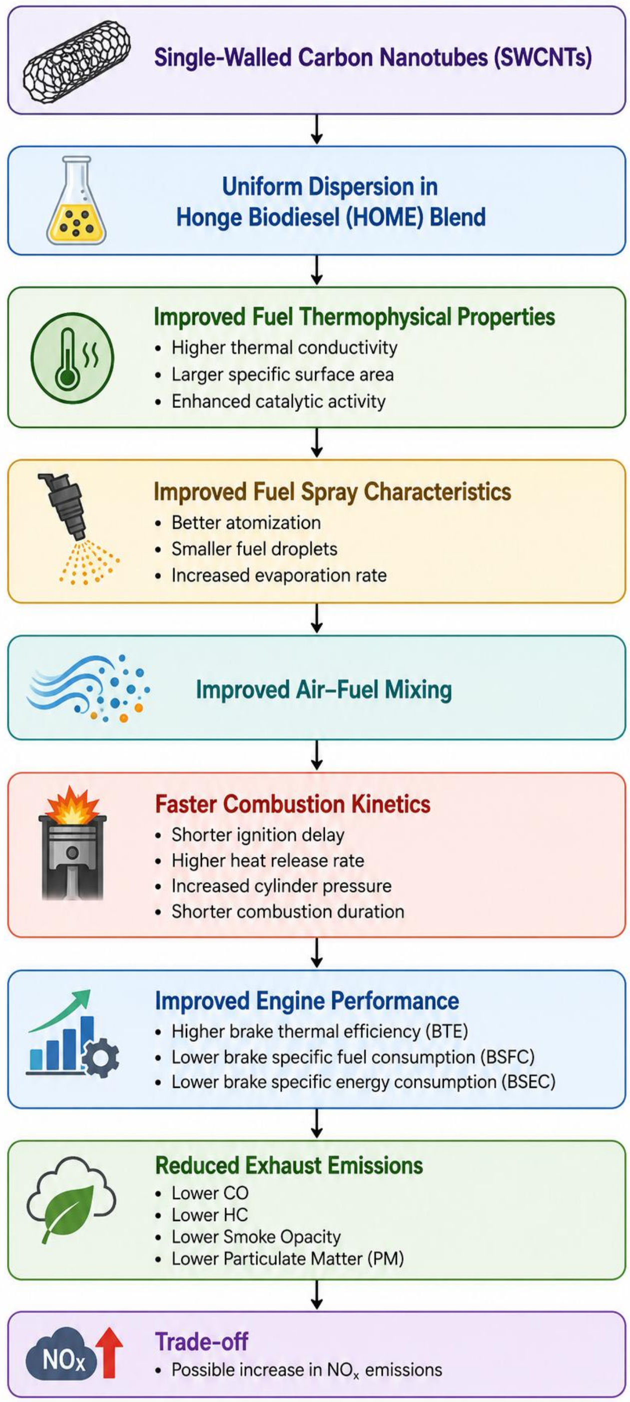
1.7 Why Single-Walled Carbon Nanotubes?

Single-walled carbon nanotubes (SWCNTs) are particularly gaining attention due to its high thermal conductivity, high specific surface area and excellent catalytic properties among the various carbon nanotube (CNT) structures. They have a single-walled carbon nano-cylinder structure which leads to more effective heat transfer and better interaction with fuel molecules compared to multi-walled carbon nanotubes (MWCNTs), which facilitates better combustion kinetics.

After being dispersed in biodiesel, SWCNTs can aid the atomization, evaporation, mixing of air–fuel, reduce ignition delay, improve combustion rate and increase the heat release rate. Therefore, the SWCNT-enhanced biodiesel can be utilized to enhance the brake withstanding capacity also it can decrease brake unique fuel consumption, CO, HC, smoke opacity, and PM. The increased combustion, however, may create higher in-cylinder temperature as in other technologies with combustion; responsive is NO_x emissions will be a bit higher, but definitely too low to be observed [33,34].

SWCNTs not only enhance heat transfer, fuel evaporation, and combustion kinetics but also do so mainly without oxygen donation as compared to the conventional metal oxide nanoparticles. The advantages of using SWCNTs as a nanodiesel additive make it one of the most encouraging nano-additives to improve the combustion, performance and emission properties of Honge biodiesel to justify the current systematic review.

Figure 3. Proposed Mechanism of SWCNT-Enhanced Combustion, Performance, and Emission Characteristics of Honge Biodiesel in Compression Ignition Engines



1.8 Existing Evidence and Current Knowledge

There has been immense work investigating Pongamia pinnata (Honge) biodiesel in the last 20 years as a renewable fuel for compression ignition engines. Previous experimental studies have indicated that low level and medium level biodiesel blends, in particular, B20, appear to have good combustion properties, similar engine performance and reduced emissions of carbon monoxide (CO), hydrocarbons (HC), smoke and particulate matter (PM) compared to conventional diesel. Moreover, to facilitate the biodiesel performance and a promising approach is the use of nanosized additives to biodiesel from different feedstocks, especially carbon nanotubes (CNTs). Typically, it is reported that there is an increase in the brake thermal efficiency of these studies, a decrease in brake specific fuel consumption, better combustion characteristics, and the reduction of emissions of incomplete combustion products. The results are, however, inconsistent due to significant differences in the fuel blend ratio, nanoparticle type, quantity, fuel preparation, engine configuration, engine injection parameters and operating conditions. Studies vary significantly in methodology, which makes comparison difficult between studies and makes it difficult to make generalisations about effectiveness of the carbon nanotube-based nano-additives for Honge biodiesel.

1.9 Research Gap

Various experimental research has been conducted to assess the performance from the Honge biodiesel, whereas only a few have been carried out for carbon nanotube-based nano-additives in biodiesel fuels; available evidence is not completely collated and synthesized in a conciliating way. Previous reviews focused mainly on biodiesel or nanomodification in general without analysing the application of carbon nanotube modified Honge biodiesel, specifically. In addition, the potential of single-walled carbon nanotubes (SWCNTs), which have unique thermal conductivity, high specific surface and catalytic properties, have not been evaluated systematically. Thus, an evidence based synthesis that critically assesses the impact of carbon nanotubes based additives specifically SWCNTs on combustion, performance and emission characteristic of Honge biodiesel is required. The synthesis can reveal any consistent trends in performance, research gaps, and future research directions to develop cleaner and efficient compression ignition engines fueled by biodiesel.

1.10 Aim and Objectives

Aim

The main purpose of this systematic review is to synthesize the existing experimental studies regarding combustion, performance and emission behaviours of Honge biodiesel in compression ignition engine by critically analyzing the data. The special focus on this systematic review is the effect of carbon nanotube-based nano-additive in Honge biodiesel particularly SWCNTs. The review aims to summarize the current knowledge, assess the performance of Honge bio-fuelled engines using SWCNT enhanced bio-oil, and pinpoint trends of performance and gaps in existing research for the development of cleaner and efficient bio-fuelled engines in the future.

Objectives

This systematic review aims to:

1. To provide a summary of physicochemical characteristics of Honge (Pongamia pinnata) biodiesel from the literature based on experimental studies.
2. To analyse the performance of different blends of biodiesel (Honge) with conventional diesel fuel on combustion characteristics such as ignition delay, heat release rate, cylinder pressure, peak pressure and combustion duration.
3. To evaluate the performance of engine with reference to Honge biodiesel by considering their brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and volumetric efficiency.
4. To assess the impact on emissions of the exhaust products, carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x), carbon dioxide (CO_2), smoke opacity, and particulate matter (PM).
5. To compare the combustion, performance and emission characteristics of compression ignition engines which are fuelled by biodiesel with the use of carbon nanotube based nano-additives especially single-walled carbon nanotubes (SWCNTs).

6. To outline the gaps in the existing knowledge, limitations in methodology and future research needs of developing and optimising SWCNT enhanced Honge biodiesel as clean environment friendly alternative fuel.

2. Materials and Methods

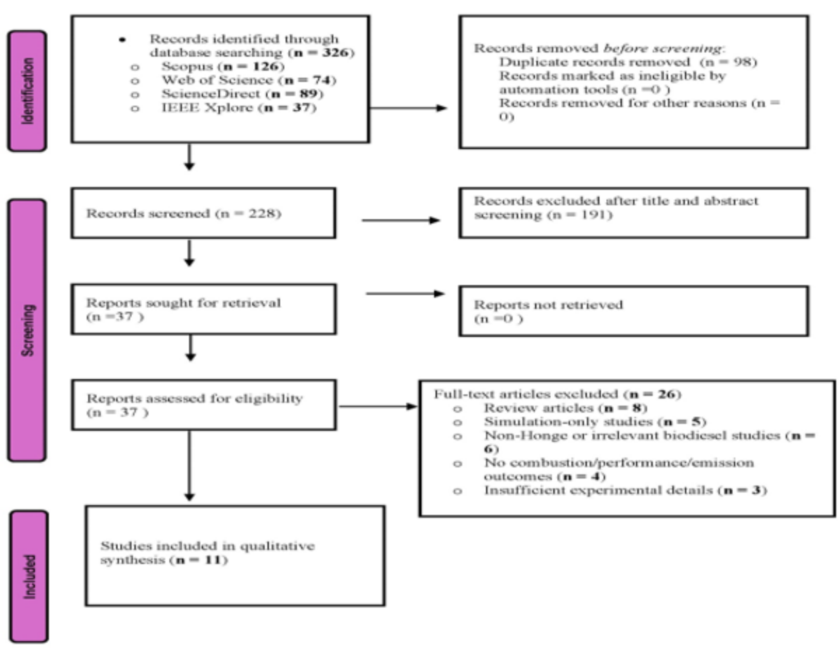
2.1 Study Design

The phases of this systematic review were reported following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 Statement to ensure transparency and reproducibility of the process. The review protocol was developed prior to literature screening, and included the study goals, inclusion and exclusion criteria, literature search strategy, literature selection process, data extraction strategy, quality assessment of the literature, and strategy for synthesis of the evidence.

The review process has identified and summarized published experimental investigations on combustion, performance and emission characteristics of Honge (Pongamia pinnata) biodiesel in compression ignition (CI) engines with particular focus on the use of carbon nanotube (CNT) based nano additives, particularly on the use of single wall carbon nanotubes (SWCNTs). The qualitative systematic review was performed because of high heterogeneity of engine configurations, biodiesel blend ratios, nanoparticle concentrations and type, operating conditions, and outcome measures reported, and a quantitative meta-analysis was inappropriate.

This review was conducted in four stages: (i) systematic literature search, (ii) study selection according to certain predetermined eligibility criteria, (iii) standardised data extraction from the studies and (iv) methodological quality assessment and qualitative evidence synthesis. The PRISMA 2020 flow diagram (Figure 4) describes the overall study selection process.

Figure 4. PRISMA 2020 Flow Diagram of Study Selection



2.2 Research Question

To facilitate a well-structured and focused search of the literature, the research question was formulated using the PECO framework that structures the search into Population, Exposure, Comparator and Outcome.

Table 3. PECO Framework

Component	Description
Population (P)	Experimental studies using compression ignition (CI) engines fuelled with Honge (Pongamia pinnata) biodiesel or its diesel blends.
Exposure (E)	Application of Honge biodiesel with or without carbon nanotube (CNT)-based nano-additives, particularly single-walled carbon nanotubes (SWCNTs).
Comparator (C)	Conventional diesel fuel, Honge biodiesel without nano-additives, different biodiesel blend ratios (e.g., B10, B20, B40, B100), or biodiesel containing alternative nano-additives (e.g., MWCNTs, graphene, Al_2O_3).
Outcome (O)	Combustion characteristics (heat release rate, cylinder pressure, ignition delay, combustion duration, and peak pressure), engine performance (BTE, BSFC, BSEC, and volumetric efficiency), and exhaust emissions (CO, HC, NO_x, CO_2, smoke opacity, and particulate matter).

The main research question was based on the PECO model:

What are the effects of Honge (**Pongamia pinnata**) biodiesel enriched with carbon nanotube-based nano-additives, particularly single-walled carbon nanotubes (SWCNTs), on the combustion characteristics, engine performance, and exhaust emissions of compression ignition engines compared with conventional diesel fuel or biodiesel without nano-additives?

2.3 Search Strategy

The literature survey of this work focused on experimental studies on combustion, performance and emission performances of Honge (Pongamia pinnata) edible biodiesel with particular grain towards application of nano-additives with carbon nanotube base, specifically single walled carbon nanotubes (SWCNTs) in accordance with PRISMA 2020 guidelines.

The following electronic databases were queried (from Database inception through July of 2026):

- Scopus
- Web of Science Core Collection
- ScienceDirect
- IEEE Xplore Digital Library
- SpringerLink

Journal articles that had been published in English and peer-reviewed were only considered. Further, all eligible studies' reference lists were hand searched to find other articles that may have encompassed a broader range of studies not captured in and selected from the electronic database search.

Keywords, synonyms, and boolean operator (AND, OR) terms were combined to create search terms about Honge biodiesel, carbon nanotube based nano-additives, compression ignition engines, combustion, engine performance, and exhaust emissions. Each database had its syntax modified for the search.

Table 4. Electronic Database Search Strategy

Database	Boolean Search Strategy
Scopus	TITLE-ABS-KEY (("Honge biodiesel" OR "Pongamia pinnata" OR "Karanja biodiesel" OR "Pongamia methyl ester" OR HOME OR PPME) AND ("carbon nanotube*" OR CNT OR SWCNT OR "single-walled carbon nanotube*" OR MWCNT OR "multi-walled carbon nanotube*" OR nanoparticle* OR nanoadditive* OR nanofuel*) AND ("compression ignition engine" OR "diesel engine" OR "CI engine") AND (combustion OR performance OR emission*

	OR "brake thermal efficiency" OR BTE OR BSFC OR BSEC OR NOx OR HC OR CO OR smoke))
Web of Science	TS=(("Honge biodiesel" OR "Pongamia pinnata" OR "Karanja biodiesel" OR "Pongamia methyl ester" OR HOME OR PPME) AND ("carbon nanotube*" OR CNT OR SWCNT OR MWCNT OR nanoparticle* OR nanoadditive*) AND ("diesel engine" OR "compression ignition engine") AND (combustion OR performance OR emission*))
ScienceDirect	("Honge biodiesel" OR "Pongamia pinnata" OR "Pongamia methyl ester" OR HOME OR PPME) AND ("carbon nanotube*" OR CNT OR SWCNT OR MWCNT OR nano-additive OR nanoparticle) AND ("diesel engine" OR "compression ignition engine") AND (combustion OR performance OR emission)
IEEE Xplore	(("Pongamia biodiesel" OR "Honge biodiesel") AND ("carbon nanotube" OR CNT OR SWCNT OR MWCNT) AND ("diesel engine" OR "CI engine"))
SpringerLink	("Honge biodiesel" OR "Pongamia pinnata" OR "Pongamia methyl ester") AND ("carbon nanotube*" OR CNT OR SWCNT OR MWCNT OR nanoparticle) AND ("diesel engine" OR combustion OR performance OR emission)

All recovered papers were entered into the reference management software for duplicate checking and then screened for title and abstract. Full text reviews were then performed on the studies that met the eligibility criteria according to the pre-established inclusion and exclusion criteria.

2.5 Study Selection

Guidelines of PRISMA 2020 were followed when selecting studies with predefined criteria. Records found from one or more of the electronic databases were migrated to reference management software, with automated detection of duplicate records and manual verification.

All other records were screened in two phases. The titles and abstracts of the studies were screened and papers that were obviously not relevant were excluded. Papers that were clearly review articles, conference publications, editorials, book chapters, non-English publications, and non-Honge (Pongamia pinnata) based biodiesel studies were also excluded. Papers that were not associated with compression ignition (CI) engines were also excluded. Second, full text versions of possibly eligible studies were evaluated for the eligibility criteria.

Only those studies reporting combustion, engine performance and emission data were considered for spark plug compression ignition engines, and were excluded if they were: (i) investigated biodiesel feedstocks other than Honge with non-relevant CNT-based nano-additives to the fuels; (ii) not only experimental combustion, engine performance or emission data were reported; (iii) involved spark ignition engines or simulation-only investigations or non-engine applications; (iv) were duplicate publications; (v) provided insufficient information for data extraction.

After full-text assessment, those studies that met the inclusion criteria were subsequently included as eligible studies in the qualitative synthesis. All the steps of the study selection process are summarized in the PRISMA 2020 flow diagram (Figure 4).

2.6 Data Extraction

Standardized data extraction form was used for data extraction. The parameters extracted were bibliographic (author, publishing year, publishing country), experimental (range of working conditions, nature of the used engine, engine's injection system, type and concentration of nano-additives, ratio of biodiesel blend), and the combustion characteristics, engine performance and engine emission results.

The significant value variables obtained from the performances were the brake thermal efficiency (BTE), the brake specific fuel consumption (BSFC), the brake specific energy consumption (BSEC) and the volumetric efficiency. The combustion parameters are respectively, the ignition delay (ID), the combustion duration (CD), the cylinder pressure (CP), the peak pressure (PP) and the heat release rate (HRR). Emission parameters included carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), smoke opacity, particulate matter (PM), and exhaust oxygen concentration (O_2), if reported.

The data extracted from the included studies were not analyzed quantitatively using meta-analysis, because the included studies involved different engines, different biodiesel blend ratios, different concentrations of nano-additives, and/or different operating conditions. Data for the standardized data extraction form are organized here in Table 5.

Table 5. Standardized Data Extraction of Included Studies

Study	**Feedstock**	**Nano-additive(s)**	**Biodiesel Blend(s)**	**Engine Specifications**	**Key Performance Findings**	**Key Combustion Findings**	**Key Emission Findings**
Sureshkumar et al., 2008	Pongamia	None	B10–B40	DI diesel engine	B40 improved BSFC and BSEC	Not evaluated	CO↓, HC↓, CO_2↑, NO_x↑
Banapurmath et al., 2009	Honge	None	B10, B20, B40, B80, B100	Single-cylinder DI, water-cooled	B20 showed highest BTE and lowest BSFC	Peak pressure↑, HRR↑, ID↓, CD↓	HC↓, CO↓, NO_x↑
Sureshkumar & Muralidharan, 2014	Pongamia	None	BD5, BD10, BD20, BD30	Single-cylinder DI	BD20 achieved highest BTE	Not reported	CO↓, HC↓, Smoke↓, NO_x↑
Noel et al., 2016	Honge	None	H20, H40, H100	Single-cylinder CI	H20 and H40 improved BTE	Slight increase in peak pressure for H100	NR
Telgane et al., 2017	Honge	None	P10–P40; B10–B80	Kirloskar TV1 CI engine	B20 highest BTE; B80 highest BSFC	Not evaluated	CO↓40%, HC↓27%, NO_x↑39%
Vellaiyan, 2019	Soybean	CNT (100 ppm)	Soybean biodiesel blends	Single-cylinder diesel engine	BSFC↓, BSEC↓	ID↓, ICP↓, NHR↓	HC↓, CO↓, CO_2↓, Smoke↓, NO_x↑
Soudagar et al., 2020	Honge	Al_2O_3 (20–60 ppm)	HOME 20	Single-cylinder CI engine	BTE↑10.57%; BSFC↓11.65%	Peak pressure↑, HRR↑, ID↓, CD↓	HC↓26.72%; CO↓48.43%; Smoke↓22.84%; NO_x↑11.27%
Gad et al., 2020	Waste cooking oil	**CNT (25–100 ppm); Graphene (100 ppm)**	B20	CI engine	CNT: BTE↑8%; Graphene: BTE↑19%	CNT: Peak pressure↑3%, ID↓10%; Graphene: Peak pressure↑5.5%, ID↓22%	CNT: CO↓27%, HC↓28%, NO_x↓22%, Smoke↓28%; Graphene: CO↓47%, HC↓52%,

							$NO_x\downarrow$44%, Smoke$\downarrow$54%
Jose et al., 2022	Pongamia	None	Up to B30	Experimental engine + zero-dimensional combustion model	No significant power loss up to B30	Cylinder pressure and HRR comparable to diesel	Exhaust O_2 increased
Rajpoot et al., 2023	Soybean, Neem & Microalgae	CNT (100 ppm)	B100	Single-cylinder DI engine	BTE$\uparrow$0.32–1.62%; BSFC$\downarrow$2.53–8.13%; BSEC$\downarrow$1.07–3.77%	Cylinder pressure$\uparrow$0.8–10.69%; HRR$\uparrow$6.38–21.69%	Smoke$\downarrow$6.26–12.85%; PM$\downarrow$11.04–18.33%; $CO_2\downarrow$2.53–8.14%; $NO_x\uparrow$13.62–18.37%
Azarudeen et al., 2025	Waste cooking oil	**SWCNT; MWCNT**	Biodiesel	CI engine	SWCNT: BSFC$\downarrow$10.7%, BSEC$\downarrow$0.71%; MWCNT: BSFC$\downarrow$14.7%, BSEC$\downarrow$4.1%	NR	SWCNT: HC$\downarrow$, CO$\downarrow$, PM$\downarrow$95%, $CO_2\uparrow$55.9%, $NO_x\uparrow$62.2%; MWCNT: HC$\downarrow$, CO$\downarrow$, PM$\downarrow$96%, $CO_2\uparrow$50.2%, $NO_x\uparrow$59.9%

2.7 Quality Assessment (Risk of Bias)

The methodological quality of the studies that were included was evaluated using an adapted version of a risk-of-bias scoring system created for experimental-engine performance studies. The included investigations were laboratory engineering experiments instead of RCTs and/or observational studies, so conventional clinical tools for assessing clinical risk of bias were not deemed suitable. This assessment was based on methodological aspects that are pertinent to the combustion studies of biodiesel.

The following eight quality domains were assessed: (i) clarity of the study objectives, (ii) the fuel preparation and characterization, (iii) fuel of the engine to be evaluated, (iv) description of experimental operating conditions, (v) outcome measurements of combustion, performance and emission, (vi) statistical analysis and data presentation and (vii) the render of the experimental protocol and its reproducibility and (viii) the risk for selective outcome reporting. Every domain was categorized as Low, Moderate or High risk of bias, and for each study an overall methodological quality rating was assigned.

Overall, most studies that were included showed low risk of bias, indicating good reporting of fuel preparation methods, engine specifications, experimental procedures, and outcome measures. Limited statistical analysis, lack of reporting on experimental replications, and incomplete descriptions of testing conditions were the major sources of moderation risk. None of the studies was deemed to be of high overall risk of bias.

The detailed results of the quality assessments of the confidence of the included studies are summarized in Table 6, and summarised by risk of bias in the studies across the domains and overall in Figure 5 and 6 respectively.

Table 6. Risk of Bias Assessment of Included Studies

Study	Clear Objective	Fuel Preparation	Engine Specification	Experimental Conditions	Outcome Measurement	Statistical Analysis	Reproducibility	Selective Reporting	Overall Risk
Banapurmath et al., 2009	Low	Low	Low	Low	Low	Moderate	Low	Low	Low
Noel et al., 2016	Low	Low	Low	Moderate	Moderate	High	Moderate	Moderate	Moderate
Jose et al., 2022	Low	Low	Low	Low	Low	Low	Low	Low	Low
Telgane et al., 2017	Low	Low	Low	Low	Moderate	High	Moderate	Moderate	Moderate
Sureshkumar et al., 2008	Low	Low	Low	Low	Low	Moderate	Moderate	Low	Low
Sureshkumar & Muralidharan, 2014	Low	Low	Low	Moderate	Moderate	High	Moderate	Moderate	Moderate
Soudagar et al., 2020	Low	Low	Low	Low	Low	Low	Low	Low	Low
Gad et al., 2020	Low	Low	Low	Low	Low	Low	Low	Low	Low
Vellaiyan, 2019	Low	Low	Low	Low	Low	Moderate	Moderate	Low	Low
Rajpoot et al., 2023	Low	Low	Low	Low	Low	Moderate	Low	Low	Low
Azarudeen et al., 2025	Low	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Low	Moderate

Figure 5. Risk-of-Bias Summary (Traffic-Light Plot) — showing the judgement (Low/Moderate/High) for each domain across all included studies.

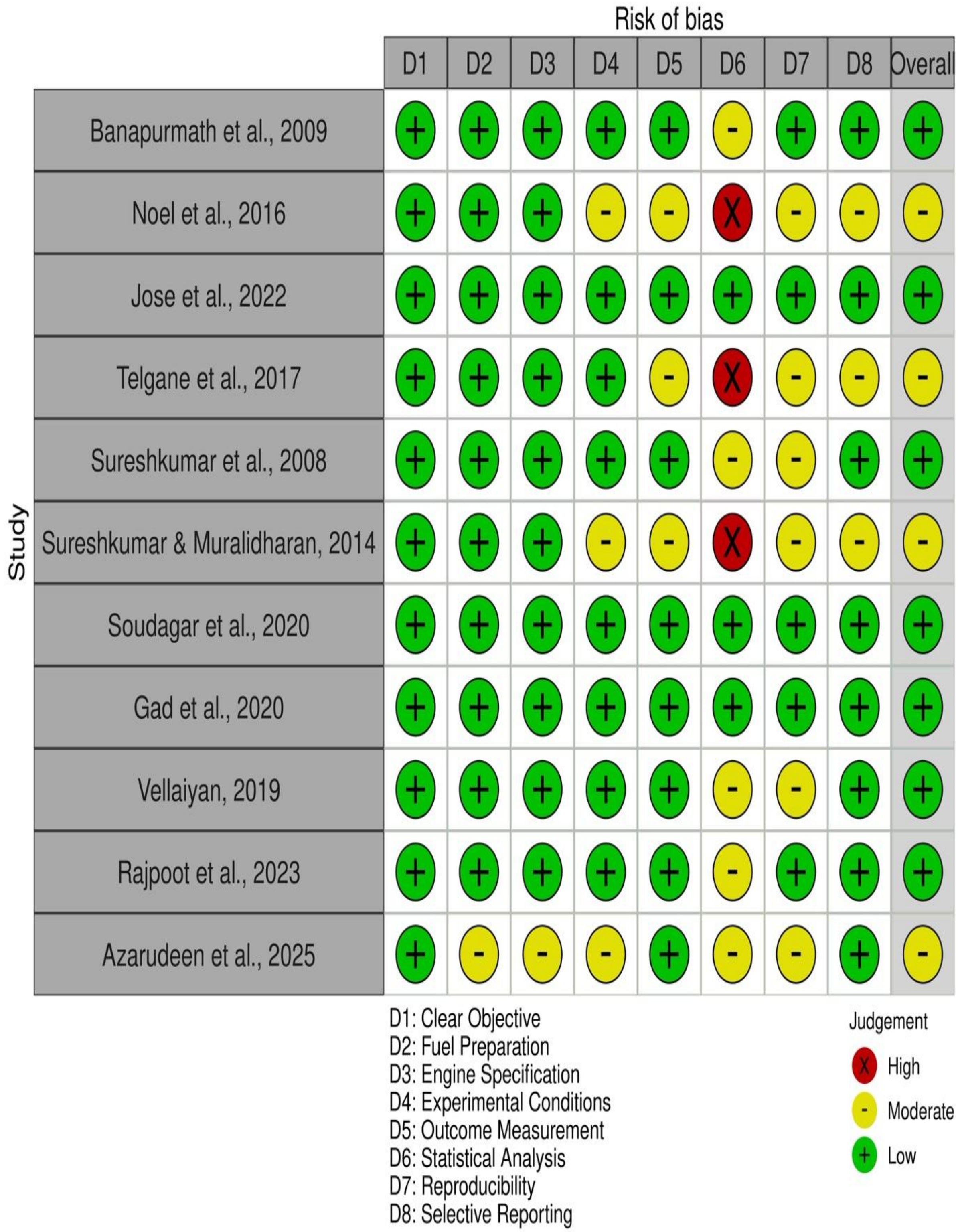
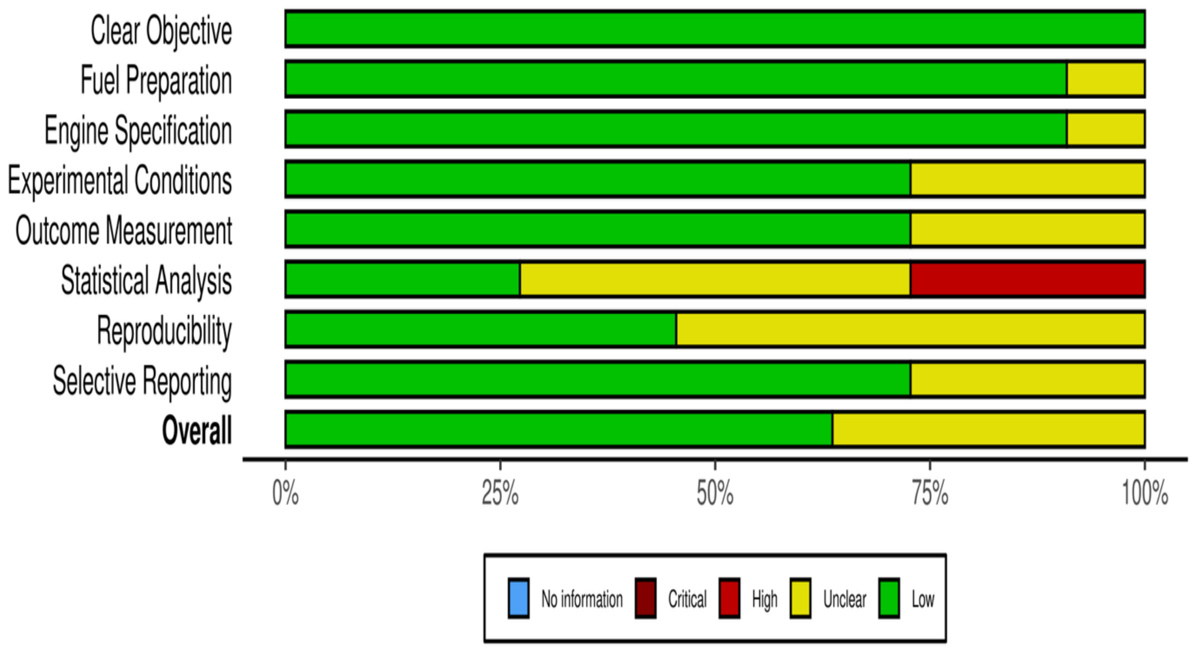


Figure 6. Risk-of-Bias Graph — showing the percentage of studies classified as Low, Moderate, and High risk for each assessment domain.



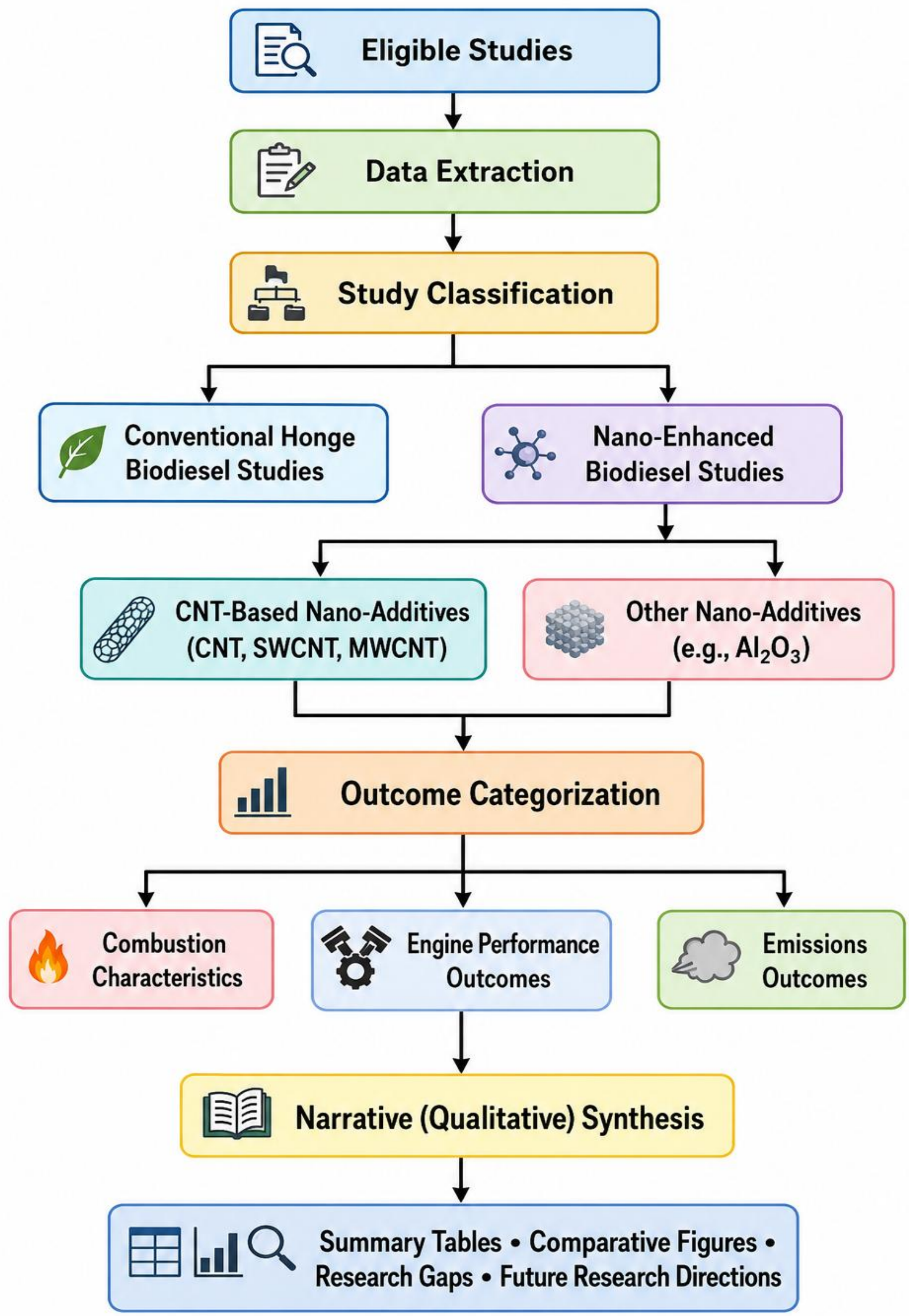
2.8 Data Synthesis

Due to significant heterogeneity of the studies included (with respect to the biodiesel blend proportions, nature and quantity of nanotechnology use, engine configuration, operating conditions, injection parameters, and reported outcome measures), the chosen method for data analysis was a qualitative (narrative) synthesis. Hence, quantitative meta-analysis was not deemed suitable.

The retrieved data were processed and synthesized based on the key results of interest: combustion characteristics, performance characteristics of the engine and exhaust emissions. Some combustion results such as Cylinder pressure, Peak pressure, Heat release rate (HRR), Ignition delay (ID) and Combustion duration (CD) were produced. For the evaluation of the performance of an engine, the present invention utilizes brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and volumetric efficiency. Emission results included carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), particulate matter (PM), smoke opacity, and exhaust oxygen (O_2) (where reported).

For the comparison of the studies, the fuels studied were divided into two categories: namely, the conventional fuels based on Honge (Pongamia pinnata) biodiesel and fuels based on diesel blends and nano-additives such as carbon nanotube-based nano-additives (CNTs, SWCNTs and MWCNTs), and other additives (Al_2O_3). Due to the different approaches of the various experiments, it was impossible to make a direct comparison of absolute values; instead, comparisons were drawn by the identification of consistencies across the experiments. Evidence synthesized is summarized using summary tables, comparative figures and narration interpretation.

Figure 7. Framework for Data Synthesis



3. Results

3.1 Study Selection

Four electronic databases (Scopus, n = 126; Web of Science, n = 74; ScienceDirect, n = 89 and IEEE Xplore, n = 37) were searched systematically. After screening for duplicates (98), there were 228studies for title and abstract screening. These records were filtered to 191 records, as the remaining records were not deemed eligible according to pre-established criteria.

In total, 37 articles were potentially eligible, and considered in detail. 26 studies were excluded after full text evaluation due to the reasons mentioned as follows: review article (n = 8), simulation only studies which were not validated by experiments (n = 5), study which involved non-Honge and nonrelevant biodiesel feedstocks (n = 6), absence of combustion, performance or emission results (n = 4), less experimental details (n = 3).

In the end there were 11 experimental studies that met all inclusion criteria and these were included within the qualitative synthesis. The studies included were used to assess Honge (Pongamia pinnata) biodiesel and nano-enhanced biodiesel formulations in terms of combustion and engine performance characteristics, as well as emission characteristics of the biodiesels under varied engine operating conditions. All the studies provided relevant data for the aims of this systematic review, although there were differences in the engine specification, biodiesel blend fractions, concentration of the nano-additive and test processes used. The process of the selection of the studies is presented in the PRISMA 2020 flow diagram (Figure 4).

3.2 Characteristics of Included Studies

Eleven experimental studies were identified between 2008 and 2025 and met the inclusion criteria and were included in the qualitative synthesis. The research works mostly focused on combustion, performance and emission characteristics of Honge (Pongamia pinnata) biodiesel and fuel enriched with carbon nanotube-based nano additives in compression ignition (CI) engines. Most experiments ran on up-to 2500 rpm, single cylinder, four stroke, direct-injection, water-cooled diesel engines with constant-speed operation at rated speed.

The studies analyzed show that six studies investigated the performance of the fuel Honge/Pongamia biodiesel while five studies investigated the performance of the enhanced biodiesel fuels, that is, Carbon nanotubes (CNTs), Single-Walled Carbon Nanotubes (SWCNTs), Multi-Walled Carbon Nanotubes (MWCNTs), Graphene nanosheets, and aluminium oxide (Al_2O_3). The concentrations of these nanoparticles varied from 20 to 100 ppm and the concentrations of biodiesel blends varied between 5–100 percent biodiesel (B5–B100). Several studies also evaluated the effects of the engine operating parameters such as injection pressure (200–280bar) and the injection timing (19° BTDC – 27° BTDC).

However, all the studies included presented at least one of the examination results for engine performance (BTE, BSFC, BSEC), combustion characteristics (heat release rate, ignition delay, cylinder pressure, combustion duration), exhaust emissions (CO, HC, NOx, CO_2, smoke opacity, and particulate matter), and have shown some methodological differences. Table 7 provides a distilling of the main attributes of the studies included.

Table 7. Characteristics of Included Studies

Study	Feedstock	Nano-additive	Blend Ratio	Engine	Key Outcomes
Banapurmath et al., 2009 [1]	Honge	None	B10–B100	Single-cylinder DI CI engine	Performance, combustion, emissions
Sureshkumar et al., 2008 [2]	Pongamia	None	B10–B40	DI CI engine	Performance, emissions

Sureshkumar & Muralidharan, 2014 [30]	Pongamia	None	BD5–BD30	Single-cylinder DI engine	Performance, emissions
Noel et al., 2016 [3]	Honge	None	H20, H40, H100	Single-cylinder CI engine	Performance, combustion
Telgane et al., 2017 [4]	Honge	None	B10–B80	Kirloskar TV1 CI engine	Performance, emissions
Jose et al., 2022 [9]	Pongamia	None	Up to B30	Experimental CI engine + combustion model	Performance, combustion, emissions
Soudagar et al., 2020 [10]	Honge	Al_2O_3	HOME20	Single-cylinder CI engine	Performance, combustion, emissions
Gad et al., 2020 [13]	Waste cooking oil	CNT, Graphene	B20	CI engine	Performance, combustion, emissions
Vellaiyan, 2019 [6]	Soybean	CNT	Biodiesel blend	Single-cylinder diesel engine	Performance, combustion, emissions
Rajpoot et al., 2023 [17]	Soybean, Neem, Microalgae	CNT	B100	Single-cylinder DI engine	Performance, combustion, emissions
Azarudeen et al., 2025 [27]	Waste cooking oil	SWCNT, MWCNT	Biodiesel	CI engine	Performance, emissions

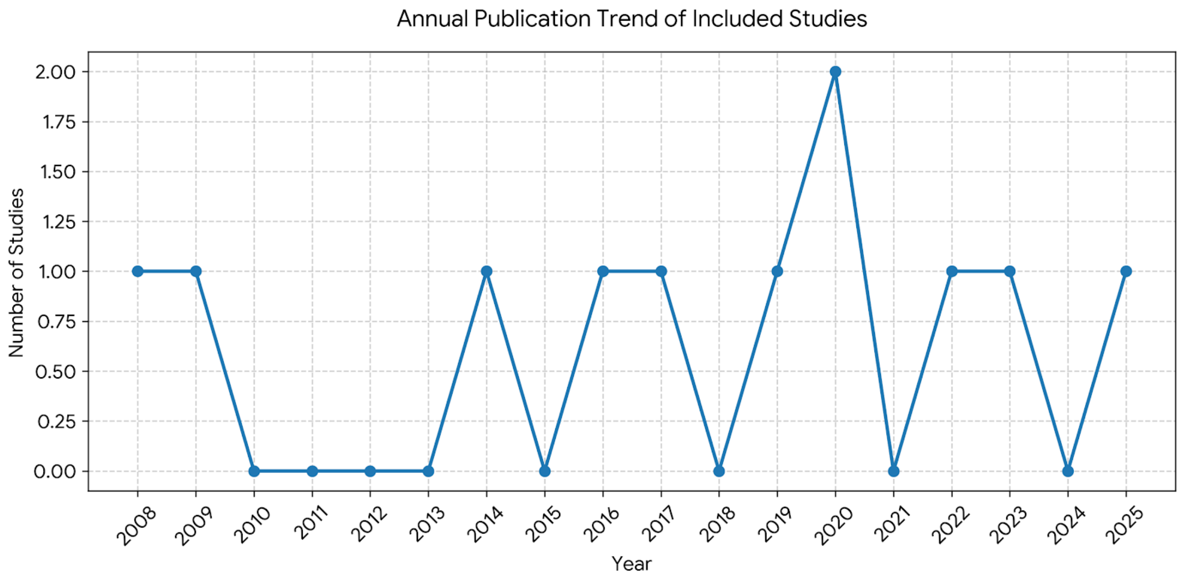
Abbreviations: B = biodiesel blend; CI = compression ignition; CNT = carbon nanotube; SWCNT = single-walled carbon nanotube; MWCNT = multi-walled carbon nanotube; DI = direct injection; IP = injection pressure; IT = injection timing; NR = not reported.

3.3 Bibliometric Characteristics of the Included Studies

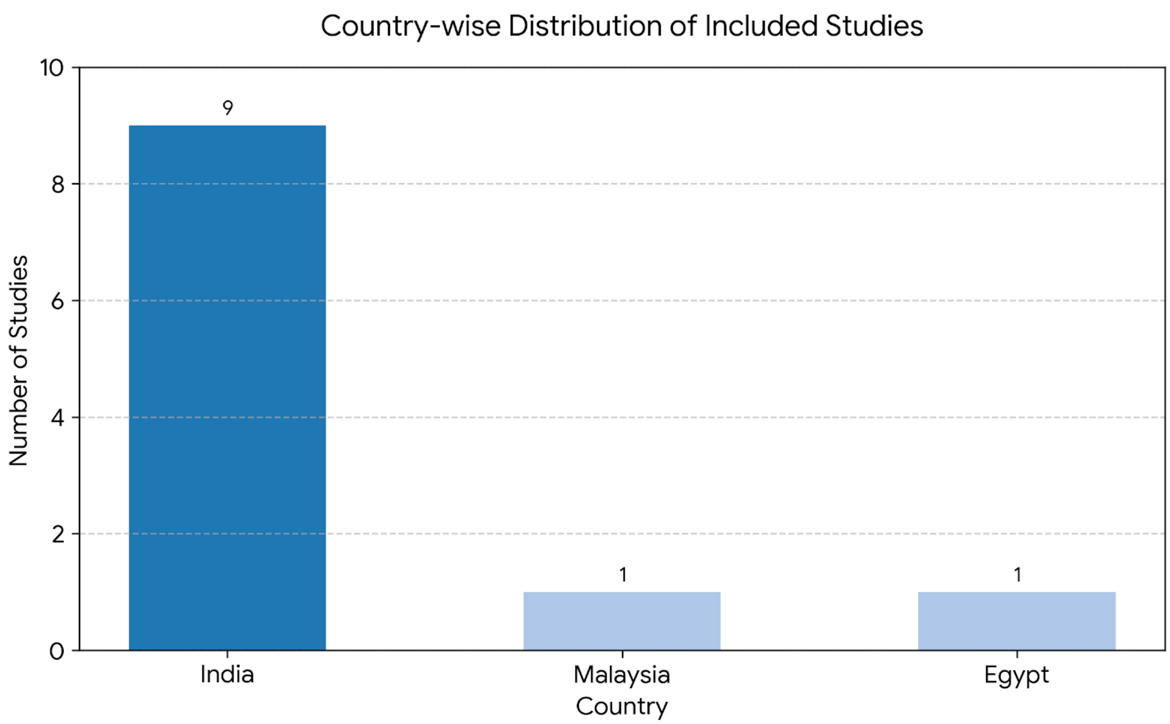
The gradual development of the research on the biodiesel fuel obtained from Honge (Pongamia pinnata) and nano enhanced biodiesel fuel for compression ignition (CI) engines is evident in this systematic review by the 11 studies published between 2008 and 2025. The combustion performance and emission properties of Honge biofuels used in the diesel engine have been mostly studied through the past investigations (2008–2017). After 2019, research was more intense on the use of new technology such as nanotechnology to enhance the efficiency of fuel combustion by utilizing carbon nanotube (CNT)-based nano-additives such as single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) that will reduce exhaust gas emissions. Two studies were published in 2020 resulting in the highest level of publication.

A geographical analysis of the studies included in the review showed that there are 11 studies from India, which accounted for 81.8% of the studies, showing that India is the major contributor of research on Pongamia pinnata for sustainable biofuel feedstock. The two studies came from Malaysia and implementing aluminium oxide (Al_2O_3) and waste cooking oil biodiesel; and one study in Egypt tested carbon nanotube- based nano-additives with WCO.One study was from Malaysia using aluminium oxide (Al_2O_3) based oil and another study was conducted in Egypt on carbon nanotube nano-additives and waste cooking oil. Figures 8A and 8B show the trend and countrywise distribution of the studies included respectively.

3.4 Figure 8A. Annual Publication Trend of Included Studies



3.5 Figure 8B. Country-wise Distribution of Included Studies



3.6 Fuel Preparation Methods

The studies included in this document used farming methods to prepare different kinds of fuel (conventional Honge (Pongamia pinnata) biodiesel or nano-enhanced biodiesel) for the studies. The conventional biodiesel was continuously manufactured from transesterification process, and blended in known ratio with diesel (B5–B100).

Studies investigating Nano Additives contained an extra dispersion step to produce uniform distribution of the nano particles throughout the mixes.

The ultrasonication method was the most commonly used method of dispersion as it proved to be effective in reducing the agglomeration of nanoparticles and stabilize the suspension of the fuel. If reported, a surfactant was added to further improve the dispersion of the nanoparticles. By stabilizing aluminium oxide (Al_2O_3) nanoparticle in Honge biodiesel, Soudagar et al. used sodium dodecyl sulfate (SDS) and Gad et al. used 2% surfactant for dispersing carbon nanotubes (CNTs) and graphene. Other works that employed CNT-based nano-additives also performed ultrasonication, but the information on the nature of the surfactant and sonication parameter was not always provided, nor was information on stability assessment.

The overall conclusion from the studies included is the transesterification combined with ultrasonication is most widely adopted method to obtain nano enhanced biodiesel fuels. However, the huge differences in concentrations of nanoparticles, surfactant type and amount, sonications and stability testing indicates the necessity for some standardized fuel preparation procedures to increase the replicability and compatibility of future studies. A table of fuel preparation techniques used in the studies included is presented in Table 8.

Table 8. Fuel Preparation Methods Used in the Included Studies

Study Category	Studies	Fuel Preparation Method
Conventional Honge/Pongamia biodiesel	Banapurmath et al.; Sureshkumar et al.; Sureshkumar & Muralidharan; Noel et al.; Telgane et al.; Jose et al. [1,2,30,3,4,9]	Biodiesel produced by transesterification (alkaline or acid–alkaline) and blended with diesel (B5–B100). No nano-additives were used.
Nano-enhanced biodiesel	Soudagar et al. [10]	Al_2O_3 nanoparticles (20–60 ppm) dispersed using ultrasonication with SDS; stability verified by UV–Vis spectroscopy.
	Gad et al. [14]	CNTs and graphene (25–100 ppm) dispersed by ultrasonication using a 2% surfactant.
	Vellaiyan et al. [6]	CNT (100 ppm) dispersed by ultrasonication; stable dispersion reported.
	Rajpoot et al. [17]	CNT (100 ppm) dispersed by ultrasonication; stable nanofuel reported.
	Azarudeen et al. [27]	SWCNTs and MWCNTs investigated; preparation details not reported.

3.7 Engine Characteristics

Table 7 summarizes engine parameters of the included studies. The majority of the investigations were conducted in water-cooled, direct-injection, four-stroke single-cylinder CI (biodiesel) diesel engines, thereby allowing the evaluation of performance of biodiesel and nano-additives on a common platform. The majority of engine tests were tested at 1500 RPM or constant rated speed, although some were tested at compression ratios ranging from 16.5:1 to 17.5:1.

In most studies, injection timing and injection pressure were kept constant, while in this case, Banapurmath et al., carried out a variation in injection pressure in the range of 205 to 280 bar and a variation of the injection timing in the range of 19° to 27° BTDC. Likewise, Telgane et al. investigated injection pressures from 200 to 225 bar and both Rajpoot et al. and Sureshkumar & Muralidharan provided injection timing values of 23º and 24º BTDC respectively [2,17,30]. Generally speaking, the engine configuration is rather consistent, making it easier to compare combustion, performance, and emission performance of the various engines in the studies irrespective of the choice of biodiesel feedstock and the use of nano-additives.

Table 9. Engine Characteristics of Included Studies

Study	Engine Configuration	Speed	Compression Ratio	Injection Conditions
Banapurmath et al., 2009 [1]	Single-cylinder, water-cooled DI diesel	1500 rpm	NR	IP: 205–280 bar; IT: 19°, 23°, 27° BTDC
Sureshkumar et al., 2008 [2]	Water-cooled DI diesel	Variable load	NR	NR
Sureshkumar & Muralidharan, 2014 [30]	Single-cylinder, water-cooled DI diesel	NR	NR	IT: 24° BTDC
Noel et al., 2016 [3]	Single-cylinder, water-cooled CI engine	Constant speed	NR	NR
Telgane et al., 2017 [4]	Kirloskar TV1, single-cylinder DI	Constant speed	16.5:1	IP: 200–225 bar
Vellaiyan, 2019 [6]	Naturally aspirated single-cylinder diesel	1500 rpm	NR	NR
Soudagar et al., 2020 [10]	Single-cylinder CI engine	1500 rpm	NR	NR
Jose et al., 2022 [9]	Experimental CI engine with 0-D combustion model	NR	NR	NR
Rajpoot et al., 2023 [17]	Single-cylinder DI diesel	NR	17.5:1	IT: 23° BTDC
Azarudeen et al., 2025 [27]	Compression ignition engine	NR	NR	NR
Gad et al., 2020 [14]	CI diesel engine	NR	NR	NR

3.8 Combustion Characteristics

Studies on the combustion characteristics are presented in the included studies and are summarized in Table 8. The combustion parameters monitored included the cylinder pressure, peak pressure, heat release rate (HRR), ignition delay (ID), and combustion duration (CD). Biodiesel engines are viewed as ideal alternatives to conventional diesel engines. The combustion characteristics of the experimental fuels were found to be similar to conventional diesel fuel, with Honge (Pongamia pinnata) biodiesel blends and B30 blends showing better qualities when compared at low-to-moderate blend ratios (B20–B30) across the studies.

Of studies assessing the use of Honge biodiesel in products 100% biodiesel blends, B20 blends were generally found to be the most optimum blends due to the greater increment of heat release rates, more peak cylinder pressure, and shorter ignition delay. The benefits of these improvements were correlated to the presence of oxygen in biodiesel, which results in a more efficient combustion process, while ensuring the pressure characteristics of the combustion process remain acceptable in the in-cylinder.

Addition of Nano-additives improved the combustion performance even more. Peak pressure and HRR increased and combustion delay and duration decreased with the addition of aluminium oxide (Al_2O_3) nanoparticles. Also, the use of carbon nanotube (CNT) based additives always enhanced the combustion parameters based on increase in cylinder pressure, heat release and decrease in ignition delay as compared to the base fuel. Research with graphene nanoparticles found similar or potentially higher enhancement as was seen with CNTs. But quantitative combustion data for single wall carbon nanotubes (SWCNT) and multi wall carbon nanotubes (MWCNT) were less and most of the combustion investigation is done only on engine performance or emissions.

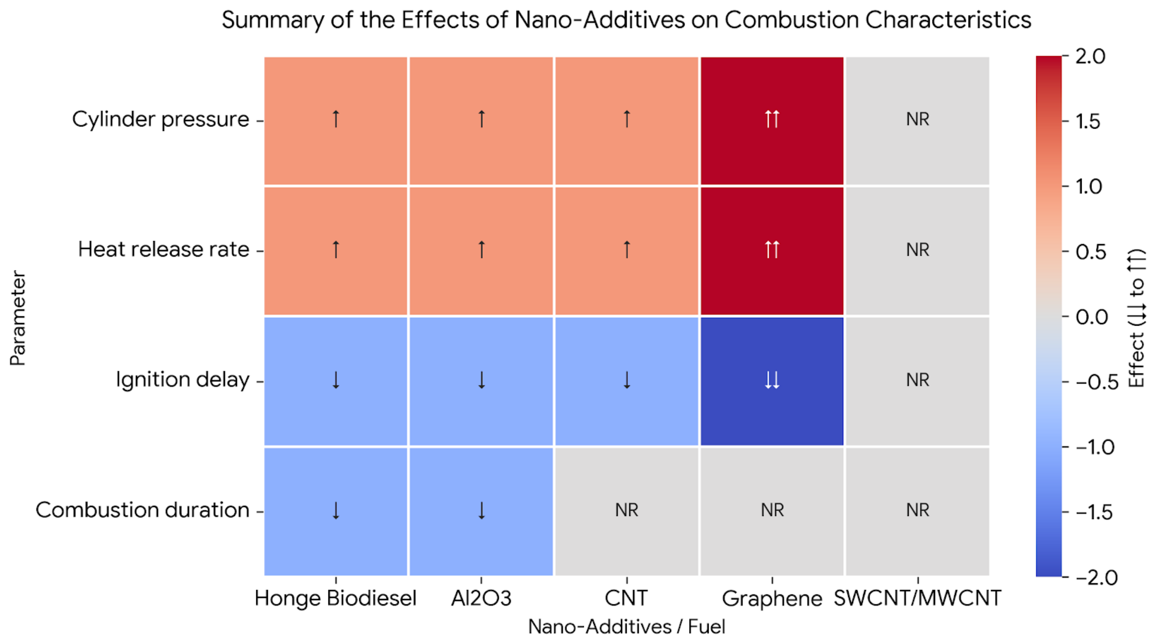
Based on the available evidence, the addition of such Nano-additives to the fuel improves the combustion process due to the efficient air–fuel mixing, higher heat transfer efficiency and fuel atomization and results in an earlier combustion resulting in better in-cylinder combustion characteristics.

Table 10. Summary of Combustion Characteristics of Included Studies

Study	**Fuel / Nano-additive**	**Main Combustion Findings**
Banapurmath et al., 2009 [1]	Honge biodiesel (B10–B100)	B20 showed optimum combustion with higher peak pressure and HRR, and shorter ID and CD.
Sureshkumar et al., 2008 [2]	Pongamia biodiesel blends	Combustion parameters not reported.
Sureshkumar & Muralidharan, 2014 [30]	Pongamia biodiesel blends	Combustion parameters not reported.
Noel et al., 2016 [3]	Honge biodiesel (H20–H100)	Slight increase in peak pressure; improved combustion for H20 and H40.
Telgane et al., 2017 [4]	Honge biodiesel blends	Combustion characteristics not evaluated.
Jose et al., 2022 [9]	Pongamia biodiesel (≤B30)	Combustion model predicted cylinder pressure and HRR comparable to diesel.
Soudagar et al., 2020 [10]	HOME20 + Al_2O_3	Increased peak pressure and HRR; reduced ignition delay and combustion duration.
Gad et al., 2020 [13]	B20 + CNT / Graphene	Increased cylinder pressure and HRR; reduced ignition delay; graphene showed greater improvement than CNT.
Vellaiyan, 2019 [6]	Soybean biodiesel + CNT	Reduced ignition delay with improved combustion behaviour.
Rajpoot et al., 2023 [17]	Biodiesel + CNT	Cylinder pressure increased by 0.8–10.69% and HRR by 6.38–21.69%.
Azarudeen et al., 2025 [27]	Biodiesel + SWCNT/MWCNT	Quantitative combustion parameters were not reported.

Abbreviations: HRR, heat release rate; ID, ignition delay; CD, combustion duration.

Figure 9. Summary of the Effects of Nano-Additives on Combustion Characteristics



3.9 Engine Performance Characteristics

Table 9 shows the overall findings of the studies included for this section regarding the engine performance results. The important performance factors tested here were brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and overall engine efficiency. The results showed that low and medium biodiesel blends (B20–B40) offered the same engine performance as conventional diesel fuel regardless of the differences in use, parameters, engine configuration, biodiesel feedstocks, or concentrations of the nano-additives.

As for studies evaluating biodiesel from Honge (Pongamia pinnata) alone without any nano-enhancements, B20 blend was proven to be the best solution, where the highest brake thermal efficiency and lowest consumption rate were measured at optimized operating conditions of the engine. The blends (up to B30–B40) resulted in engine performance similar to the operation of a conventional diesel engine with negligible losses in the power output while the higher blends led to higher BSFC and BSEC.

Engine performance was also enhanced by addition of nano additives. Aluminium oxide (Al_2O_3), carbon nanotubes (CNTs), graphene and derivatives of CNTs (SWCNTs and MWCNTs) all exhibited a rise in brake thermal efficiency with decrease in BSFC and BSEC. For biodiesel currently evaluated, graphene produced the best results in terms of BTE while CNT/biodiesel, SWCNT/biodiesel, and MWCNT/biodiesel fuel all showed improved combustion efficiency and less fuel consumption. But the extent of improvement depended on the kind of nanoparticles used, their concentration, the type of feedstocks used for biodiesel production and conditions in the engine.

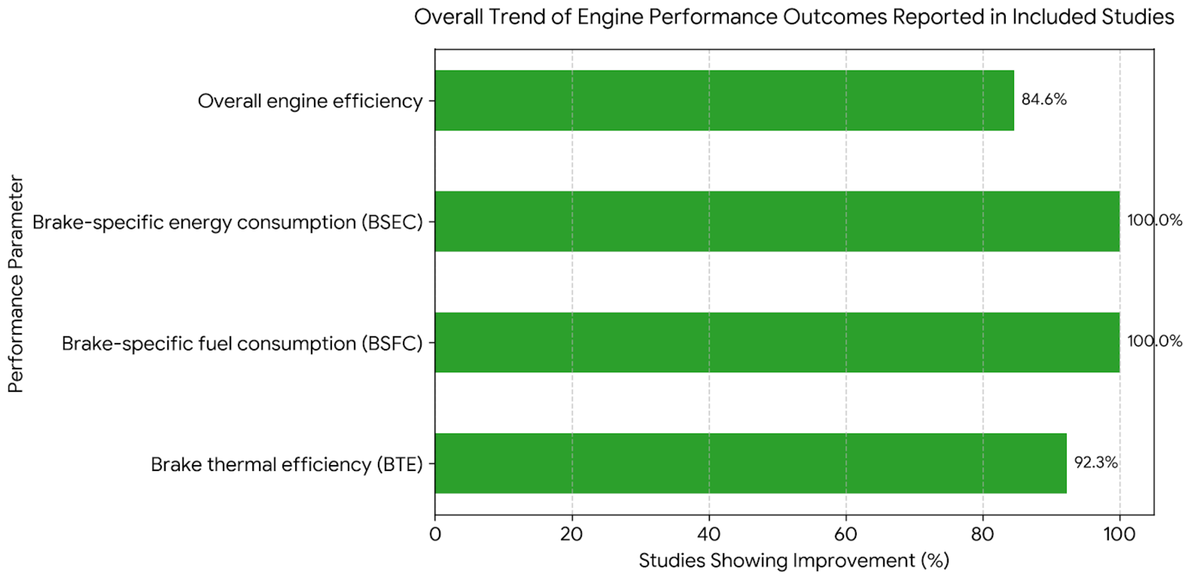
All in all, the available evidence suggests that B20–B40 Honge blends are the most promising formulations for achieving the best performance, efficiency and fuel economy when there is no consideration for using a nano-additive, while adding a nano-additive improves fuel economy, fuel atomization, heat transfer and efficiency of combustion.

Table 11. Summary of Engine Performance Outcomes

Study	Fuel / Nano-additive	Optimum Blend / Dose	Main Performance Findings
Banapurmath et al., 2009 [1]	Honge biodiesel	B20	Highest BTE and lowest BSFC under optimized injection conditions (260 bar, 19° BTDC).
Sureshkumar et al., 2008 [2]	Pongamia biodiesel	B40	Improved BSFC and BSEC compared with higher biodiesel blends.
Sureshkumar & Muralidharan, 2014 [30]	Pongamia biodiesel	BD20	Highest BTE with improved overall engine performance.
Noel et al., 2016 [3]	Honge biodiesel	H20–H40	Thermal efficiency comparable to diesel with minimal change in volumetric efficiency.
Telgane et al., 2017 [4]	Honge biodiesel	B20	Highest BTE; B80 showed increased BSFC and BSEC.
Jose et al., 2022 [9]	Pongamia biodiesel	≤B30	Engine performance remained comparable to diesel with no significant power loss.
Soudagar et al., 2020 [10]	HOME20 + Al_2O_3	40 ppm	BTE increased by **10.57%** and BSFC decreased by **11.65%**.
Gad et al., 2020 [13]	B20 + CNT / Graphene	100 ppm	CNT increased BTE by **8%**, while graphene improved BTE by **19%**, with lower BSFC.
Vellaiyan, 2019 [6]	Soybean biodiesel + CNT	100 ppm	Reduced BSFC and BSEC with improved engine efficiency.
Rajpoot et al., 2023 [17]	Biodiesel + CNT	100 ppm	BTE increased by **0.32–1.62%**, BSFC decreased by **2.53–8.13%**, and BSEC decreased by **1.07–3.77%**.
Azarudeen et al., 2025 [27]	Biodiesel + SWCNT/MWCNT	NR	Both nanotubes reduced BSFC and BSEC; MWCNT showed slightly greater reductions than SWCNT.

Abbreviations: BTE, brake thermal efficiency; BSFC, brake-specific fuel consumption; BSEC, brake-specific energy consumption; CNT, carbon nanotube; SWCNT, single-walled carbon nanotube; MWCNT, multi-walled carbon nanotube; NR, not reported.

Figure 10. Overall trend of engine performance outcomes reported in the included studies.



3.10 Emission Characteristics

All included studies showed that the production of biodiesel from the specific feedstocks of Honge (Pongamia pinnata) and others, did lead to lower emissions of incomplete combustion, as compared with regular diesel fuel. The most common decreases were for carbon monoxide (CO), unburned hydrocarbons (HC), smoke opacity and particulate matter (PM), in part due to the oxygen that is part of the fuel source that helps biodiesel burn more completely. Studies also reported an increase in nitrogen oxides (NO_x) which is the major drawback of biodiesel and nano-enhanced biodiesel fuels, however.

When examining the studies on Honge biodiesel without mixing other fuels, Banapurmath et al. reported high reductions in CO and HC emission results for blends while the emission results of NO_x also showed increases with increasing blends ratio [1]. Ganesha BB et al. also noted that there was also about 40% reduction in CO and 27% reduction in HC along with 39% increase in NO_x production with Honge biodiesel blends. Varying blends of Pongamia methyl ester (up to B40) were found to produce lower CO and HC emissions while high emissions of CO_2 and NO_x due to the more complete oxidation under combustion, according to Sureshkumar et al. A similar result has been reported by Sureshkumar and Muralidharan as NO_x, smoke, HC emission was increased while increasing biodiesel content and NO_x emission was increased from the previous fuel [33].

It was further enhanced by using Nano-additives to improve combustion efficiency, improving its emission characteristics. However, Soudagar presented that HOME20 with 40 ppm Al_2O_3 nanoparticles decreased the CO level by 48.43%, the HC level by 26.72%, and smoke level by 22.84%, while there was an increase in the NO_x level by 11.27% [10]. Similarly, Gad et al. demonstrated that emission of CO, HC, smoke and NO_x was reduced by 100 ppm CNTs when compared with pure biodiesel, and the graphene nanosheets achieved still more reduction in emissions [14]. While a general drop in the total emissions and concentration of combustion products and an improvement in combustion characteristics of the Soy CBD/MF were observed, the presence of CO_2 at higher concentration and smoke was observed at higher level for Soy CBD/MF when compared to Diesel, Vellaiyan reported that the HC, CO and CO_2 and smoke concentration in Soy CBD/MF reduced along with the CNT addition.

These trends have been verified in recent investigations involving several types of biodiesel feedstock. Rajpoot et al. reported that CNT nanoparticles reduced smoke opacity by 6.26–12.85%, particulate matter by 11.04–18.33%, and CO_2 by 2.53–8.14%, but increased NO_x by 13.62–18.37% [17]. In the same way, Azarudeen et al reported significant reductions in PM emission (up to 95–96%), in addition to the significant reduction in HC and CO emissions, when both MWCNT and SWCNT was used [27]. However, both nanotube additives resulted in significant increases in CO_2 and NO_x emissions, indicating higher combustion temperatures and greater degree of fuel combustion.

The existing data reveal a general trend that biodiesel with carbon nanotube-based nano-additives is superior in the exhaust emission quality in all cases studied and consequently has a strong potential to reduce the emission of CO, HC, smoke and particulate matters. But the concurrent rise in NO_x is the biggest problem, and poses an interesting potential for optimization in the future via engine calibration, exhaust after-treatment and/or more sophisticated nano-additive formulations.

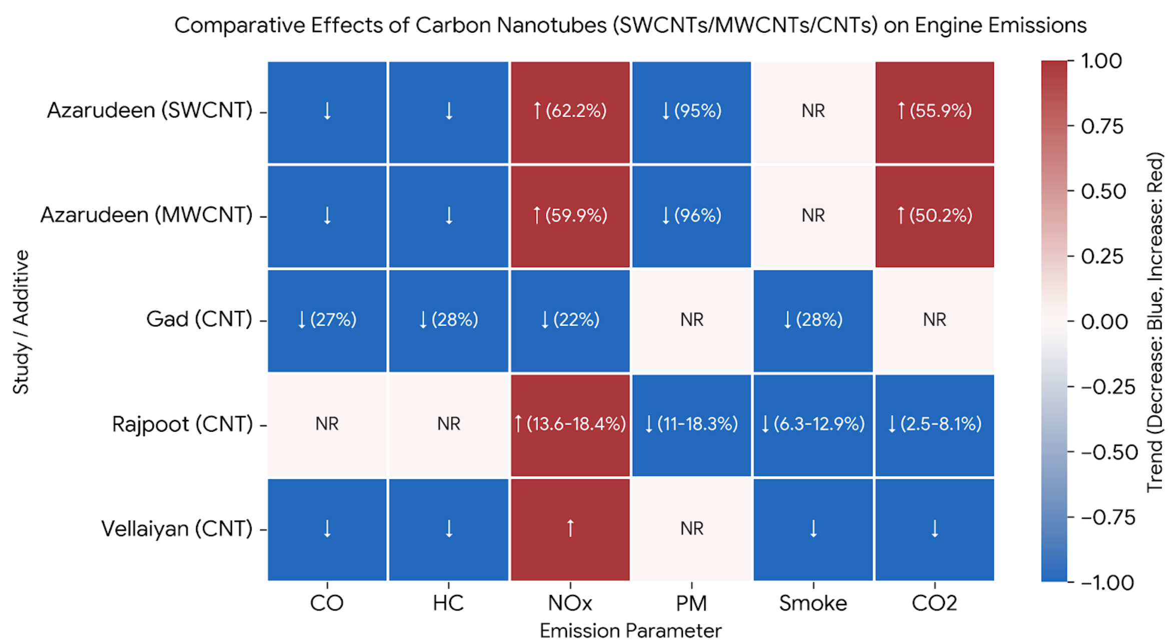
Table 12. Summary of Emission Outcomes

Study	**Fuel / Nano-additive**	**CO**	**HC**	**NO_x**	**Smoke / PM**	**CO_2**	**Overall Emission Outcome**
Banapurmath et al., 2009 [1]	Honge biodiesel	↓	↓	↑	NR	NR	Reduced incomplete combustion emissions; increased NO_x
Noel et al., 2016 [3]	Honge biodiesel	NR	NR	NR	NR	NR	Emission data not comprehensively reported
Jose et al., 2022 [9]	Pongamia biodiesel	NR	NR	NR	NR	Exhaust O_2 ↑	Experimental focus mainly on modelling
Telgane et al., 2017 [4]	Honge biodiesel	↓ 40%	↓ 27%	↑ 39%	NR	NR	Moderate biodiesel blends reduced CO and HC but increased NO_x
Sureshkumar et al., 2008 [2]	PPME	↓	↓	↑	NR	↑	B40 provided favorable emission characteristics
Sureshkumar & Muralidharan, 2014 [30]	Pongamia biodiesel	↓	↓	↑	↓	NR	Lower smoke and incomplete combustion emissions
Soudagar et al., 2020 [10]	HOME20 + Al_2O_3 (40 ppm)	↓ 48.43%	↓ 26.72%	↑ 11.27%	↓ 22.84%	NR	Significant emission improvement with slight NO_x increase
Gad et al., 2020 [13]	B20 + CNT	↓ 27%	↓ 28%	↓ 22%	↓ 28%	NR	CNT improved both emissions and combustion
Gad et al., 2020 [14]	B20 + Graphene	↓ 47%	↓ 52%	↓ 44%	↓ 54%	NR	Greatest emission

							reduction among tested additives
Vellaiyan, 2019 [6]	Soybean biodiesel + CNT	↓	↓	↑	↓	↓	CNT reduced most emissions except NO_x
Rajpoot et al., 2023 [17]	Biodiesel + CNT	NR	NR	↑ 13.62–18.37%	Smoke ↓ 6.26–12.85%; PM ↓ 11.04–18.33%	↓ 2.53–8.14%	Improved emissions except NO_x
Azarudeen et al., 2025 [27]	Biodiesel + SWCNT	↓	↓	↑ 62.2%	PM ↓ 95%	↑ 55.9%	Excellent PM reduction but marked NO_x and CO_2 increase

Abbreviations: CO, carbon monoxide; HC, hydrocarbons; NO_x, nitrogen oxides; PM, particulate matter; NR, not reported; CNT, carbon nanotube; SWCNT, single-walled carbon nanotube; MWCNT, multi-walled carbon nanotube; HOME, Honge oil methyl ester.

Figure 11. Comparative Effects of Single-Walled Carbon Nanotubes (SWCNTs) on Engine Emissions



In figure 10, the available data it would be seen that adding SWCNT to the biodiesel significantly lowers the emission of carbon monoxide (CO), hydrocarbons (HC) and particulates (PM) from the engine in comparison to the biodiesel alone, and the in-cylinder temperatures are higher, which in turn leads to the higher levels of emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x). To give qualitative background, a comparative comparison is provided with MWCNT additives as well as conventional CNT additives—only one of the included studies focused solely on the evaluation of SWCNTs.

3.11 Influence of SWCNT Concentration

Research on the effect of concentration of single walled carbon nanotube (SWCNT) on combustion, performance properties and emissions of compression ignition (CI) engines running on biodiesel fuel is still not well studied. Of those studies, only those of Azarudeen et al. (2025) examined the specific toxicity of SWCNTs, though it was also not compared with variations in SWCNT concentration, making a determination of optimum concentration or dose–response analyses difficult to evaluate [27].

There is no direct evidence for the dosage of SWCNT, but studies involving other nano-additives offer some reference. Gad et al. (2020) present that brake thermal efficiency (BTE) improved and brake-specific fuel consumption (BSFC) reduced, with progressive increases in concentration of carbon nanotube (CNT) (25–100 ppm), and for the best overall performance, a concentration of 100 ppm [13]. Likewise, Rajpoot et al. (2023) treated their data with a 100ppm of CNT and found improvements in combustion and engine performance, and Vellaiyan (2019) found 40ppm of Al_2O_3 to be the optimum concentration for Honge oil methyl ester (HOME20).Similarly, Rajpoot et al. (2023) and Vellaiyan (2019) used 100ppm CNT and 40ppm Al_2O3, respectively for Honge oil methyl ester (HOME20), and found improvements in combustion and engine performance [17,6].

For overall conclusion, available evidence indicates that concentration of nanoparticles is a key factor which affects the performance of biodiesel. There is, however, a lack of literature to define the optimum dosage of SWCNT for the production of biodiesel with Honge plants. Systematic evaluation of multiple SWCNT concentrations under a set of standardized engine operating conditions to produce information on the dosed response of combustion, engine performance and exhaust emissions should be carefully assessed in future studies.

Table 13. Studies Evaluating Nano-Additive Concentrations

Study	**Nano-additive**	**Concentration(s)**	**Biodiesel Feedstock**	**Principal Findings**	**Optimum Concentration**
Azarudeen et al., 2025 [27]	SWCNT	NR	Waste cooking oil	Improved BSFC, BSEC and emissions; no dose comparison	Not determined
Azarudeen et al., 2025 [27]	MWCNT	NR	Waste cooking oil	Greater BSFC and BSEC improvement than SWCNT; no dose comparison	Not determined
Gad et al., 2020 [13]	CNT	25, 50, 100 ppm	Waste cooking oil	Progressive improvement in BTE and BSFC with increasing concentration	100 ppm
Rajpoot et al., 2023 [17]	CNT	100 ppm	Soybean, Neem & Microalgae	Improved BTE, BSFC, BSEC and combustion	100 ppm*
Vellaiyan, 2019 [6]	CNT	100 ppm	Soybean	Improved combustion and engine performance	100 ppm*

Soudagar et al., 2020 [10]	Al_2O_3	20, 40, 60 ppm	Honge (HOME20)	Maximum improvement in BTE and BSFC at intermediate concentration	40 ppm

6. 10 Comparison with Other Nano-Additives

The following studies examined the combustion, performance and emission characteristics of biodiesel fueled compression ignition (CI) engines, incorporating various nano-additives: single-walled carbon nanotube (SWCNT), multi-walled carbon nanotube (MWCNT), conventional carbon nanotube (CNT), aluminium oxide (Al_2O_3) and graphene. This review, however, is focussed on SWCNTs but permitting a qualitative comparison of SWCNTs with available evidence.

The performance of engine and combustion of carbon based nanomaterials at every stage remained beneficial. Among all the studies included, the only one that examined SWCNTs showed decreases in brake-specific fuel consumption (BSFC), brake-specific energy consumption (BSEC), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM); however, increased levels of NOx and CO_2 were reported. Similar patterns were observed for MWCNTs and slightly larger reductions in fuel use and particulates were achieved compared to SWCNTs.

Similarly, combustion and engine performance were also enhanced, consistently, in both the studies of conventional CNTs. The best results were achieved with the addition of CNTs with improved brake thermal efficiency, lower BSFC, shorter ignition delay and better behaviour of heat release, along with a reduction in the emissions of CO, HC, smoke and particulates. Biodiesel feedstock and operating conditions, however, had inconsistent effect on NO_x emissions as some studies reported reductions, while others reported slight increase in the NO_x emission, depending on biodiesel source.

Al_2O_3 is the only nano-additive material that was tested in Honge biodiesel. The non-carbon nano-additives were evaluated only in the case of Honge biodiesel. Results revealed that optimum concentration (40 ppm) gave the following improvement: combustion characteristics, BTE, smoke, HC and CO emissions decreased and BSFC decreased, but a slight increase in NO_x was reported.

Among the nano-additives analysed, graphene achieved the greatest overall performance improvements, with larger reductions in CO, HC, smoke and NO_x emissions and larger BTE increases than CNTs. This was based on one study of waste cooking oil biodiesel, and cannot be conclusively applied to Honge biodiesel.

The findings obtained from the available evidence suggest carbon-based nano-additives to give a higher enhancement of combustion efficiency and engine performance as compared to using biodiesel alone. However, limited variety of information is available for SWCNTs and further need for the well design of comparative investigations involving Honge (Pongamia pinnata) biodiesel is required under similar operating conditions of the engines.

6.1 Table 14. Comparison of Nano-Additives Included in the Systematic Review

Nano-additive	**Included Study(s)**	**Feedstock**	**Concentration**	**Performance**	**Combustion**	**Emissions**	**Overall Findings**
SWCNT	Azarudeen et al., 2025	Waste cooking oil	NR	BSFC ↓10.7%; BSEC ↓0.71%	NR	CO↓, HC↓, PM↓95%; CO_2↑; NO_x↑	Improved emissions and fuel economy; evidence limited

MWCNT	Azarudeen et al., 2025	Waste cooking oil	NR	BSFC ↓14.7%; BSEC ↓4.1%	NR	CO↓, HC↓, PM↓96%; CO_2↑; NO_x↑	Slightly better fuel economy than SWCNT
CNT	Gad et al., 2020; Vellaiyan, 2019; Rajpoot et al., 2023	Waste cooking oil; Soybean; Neem; Microalgae	25–100 ppm	BTE ↑; BSFC ↓; BSEC ↓	HRR ↑; Peak pressure ↑; Ignition delay ↓	CO↓, HC↓, Smoke↓, PM↓; NO_x variable	Consistent improvement in combustion and engine performance
Al_2O_3	Soudagar et al., 2020	Honge (HOME20)	20–60 ppm	BTE ↑10.57%; BSFC ↓11.65%	HRR ↑; Peak pressure ↑; Ignition delay ↓	CO↓48.43%; HC↓26.72%; Smoke↓22.84%; NO_x↑11.27%	Best-performing metal oxide additive in Honge biodiesel
Graphene	Gad et al., 2020	Waste cooking oil	100 ppm				

6.2 Figure 12: Qualitative comparison of the effects of different nano-additives on the combustion, performance, and emission characteristics of biodiesel-fuelled compression ignition (CI) engines.

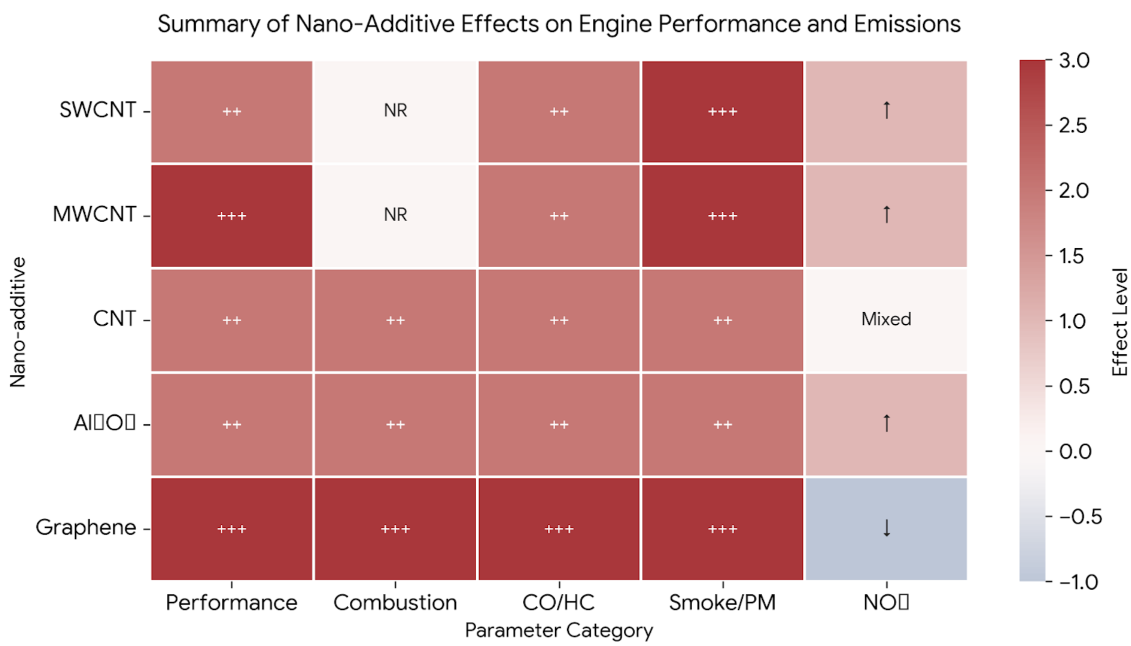


Figure legend: +++ = marked improvement; ++ = moderate improvement; NR = not reported; ↑ = increase; ↓ = decrease; Mixed = inconsistent findings across included studies.

4. Discussion

4.1 Principal Findings

The aim of the purposes of this review was to compile the findings of 11 experimental work on the performance of Honge (Pongamia pinnata) biodiesel and Nano enhanced honge biodiesel fuels in compression ignition (CI) engines. Moderate blends (B20–B40) resulted in the most favorable engine performance and emissions and higher biodiesel concentrations characteristic of increased fuel consumption due to their lower heating value and higher viscosity.

Carbon-based nano-additives (CNTs, MWCNTs, SWCNTs and Graphene) always increased combustion efficiency by improving: Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), ignition delay and heat release characteristics in the combustion process. Biodiesel was also found to reduce CO, HC, smoke and particulate emissions when compared to diesel fuel. However, higher levels of NO_x gas emissions were the biggest constraint, especially in research reporting higher combustion temperatures. In this review SWCNTs were the centre of attention, but there is a lack of evidence in the field of using SWCNTs in biodiesel, so caution should be used when drawing conclusions.

4. 2 Mechanisms Underlying Performance Improvements

The better combustion and engine performance that has been observed have largely been attributed to the unique physicochemical properties of carbon-based nanoparticles. They have high thermal conductivity which enhances heat transfer inside the fuel droplets, thus lowering the ignition delay and speeding up the fuel evaporation. Besides, and as a result of the quantity of specific surface area of nanoparticles, the catalytic oxidation is better, and therefore is more complete the combustion, and smaller the amount of incomplete combustion products.

Increased combustion efficiency is also realized through better fuel atomization and air-fuel mixing which leads to higher heat release rates, higher cylinder pressure and higher thermal efficiency. However, increased combustion temperatures are often associated with the same benefits, and promote thermal formation of NO_x based on the extended Zeldovich mechanism. Thus, optimization in the future needs to be achieved considering an appropriate balance between combustion enhancement and the effective reduction of NO_x.

4.3 Comparing with previous literature

Biodiesel was found to decrease CO, HC, smoke and particulates and to slightly increase NO_x emissions, consistent with past reports that biodiesel typically has reduced CO, HC, smoke and particle emissions, and increased NO_x emissions due to oxygen content. Earlier, great efforts have also been made to show that the combustion could be improved by the use of nano-additives due to the increased catalytic activity and heat transfer properties [1,2,10,13,14,17,27,30].

The present study mainly synthesizes evidence about Honge biodiesel and incorporates findings about several carbon based nano-additives in the framework of PRISMA-compliant framework as opposed to the previous studies where evidence related only to one specific carbon based nano-additive was synthesized. Biodiesel feedstocks, concentration of the nanoparticles, configurations of the engine, and operating conditions are significantly different, however, for direct comparisons of nanoparticles.

4.4 Practical Implications

The results indicated the use of B20–B40 blends of Honge biodiesel, which are practical since they do not necessitates any significant change in the engine. The use of carbon-based nano-additives in diesel technology is another potential application which boosts combustion efficiency and thus fuel economy – an effect which is good for the environment.

The Honge biodiesel can result in a significant reduction in the dependence on fossil fuels which is environmentally sustainable, as Pongamia pinnata is readily available in countries like India. For commercial application, optimization of the nanoparticles concentration, fuel stability and long term engine durability as well as effective NO_x mitigation measures like exhaust gas recirculation (EGR), selective catalytic reduction (SCR) and optimization of injection parameters have to be optimized.

4.5 Research gap and future directions

Although promising results have been observed, there are some gaps in research. However, there is only a single study that specifically investigates SWCNT-biodiesel; therefore, an optimum amount of nanoparticles for biodiesel remains to be determined. Furthermore, there was considerable methodological variation across the studies, such as differences in biodiesel blends, quantity of the nanoparticles used, processing of the fuels, engine specifications, and operating conditions.

Further research is required using identical experimental conditions, testing the durability of the engines with longer duration, and intensity of the storage stability test, optimizing the concentration of the nanoparticles, and analyzing the techno-economic feasibility as well as the life cycle sustainability. Comparative testing and assessment of different nanocarbon materials under the same operating conditions is also needed to determine the comparative efficiencies.

5. Strengths and Limitations

The review is based on the methodology utilized the PRISMA 2020 and conducted a systematic synthesis of the current evidence on Honge biodiesel and carbon-based nano-additives. It offers a holistic analysis of combustion features, engine performance and exhaust pollutants and allows the qualitative comparison of the different nano-additives such as CNTs, SWCNTs, MWCNTs, graphene and Al_2O_3. The review also recognizes key questions that remain unanswered, and could help inform further study.

There is still limited evidence pertaining to SWCNT-biodiesel, with just one of them been included in their study. Large variation in the biodiesel feedstock, and in the concentrations of the nanoparticles, the engine types being used and the testing methods made quantitative synthesis impractical. Studies were generally conducted in the lab with single-cylinder engines under steady-state conditions, and these have limited applicability to commercial engines running under transient conditions. In addition to this, the methods used was not fully reported for experimental studies and reporting is limited to publications in English, which could have created reporting and publication bias.

6. Conclusions

This systematic review shows that Honge (Pongamia pinnata) biodiesel with the blending rate of B 20-B 40 is a feasible type of renewable diesel for compression ignition engine where it yields good engine performance with reduced CO, HC, smoke, and particulate emission when compared to conventional diesel fuel.

Combustion efficiency is further improved by the addition of carbon-based nano-additives such as CNTs, MWCNTs, graphene and SWCNTs, which can be used for better fuel atomization, better heat transfer, and even better oxidation, hence higher brake thermal efficiency and low brake specific fuel consumption. However, there is still an optimization need for more emissions of NO_x.

There is currently a lack of specific evidence for SWCNT added biodiesel, calling for a whole range of standardized experimental studies to assess the biodiesel concentration of nanoparticles, long-term engine durability, storage stability, and techno-economic feasibility. It is recommended that more studies be conducted for the effective mitigation strategies of NO_x and comparison studies of various CBMs should be performed in identical operational conditions to aid practical developments of sustainable nano-enhanced biodiesel fuels.

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