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Advances and strategies to improve the performance of biodiesel in diesel engine

Avances y estrategias para mejorar el desempeño del biodiésel en motor diésel

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Abstract

The demand for diesel utilization in heavy-duty vehicles continues to increase worldwide. However, the potential use of alternative fuels such as biodiesel has disadvantages, such as lower calorific value and higher viscosity. For this reason, it is necessary to improve its properties to optimize combustion in the engine and reduce emissions. This research explores the various blends that can improve biodiesel utilisation through strategies and advancements that optimize diesel engine performance. Among the various strategies to improve biodiesel, we find the mixtures of different bio-oils (vegetable oils, pyrolysis oils, and used cooking oils), blends of biodiesel with alcohol and hydrogen, the use of biodiesel as a pilot fuel, emulsions of biodiesel with water, and the application of antioxidants, nanotubes, and nanoparticles to biodiesel. It is concluded that currently, biodiesel can be used through the dual combustion technique, where it acts as a pilot fuel representing 10% or 20% of the total fuel in the engine. This strategy allows for the promotion of other fuels (liquids and gases) in dual combustion to find the optimal blend that is the best option for the diesel engine.

Keywords: Biodiesel, engines, mixtures, oils, dual combustion, emulsions

Resumen

La demanda de diésel en vehículos pesados se incrementa cada año en el mundo. El posible uso de combustibles alternativos como el biodiésel tiene algunas desventajas como el menor valor calorífico y su mayor viscosidad, por esta razón se requiere mejorar sus propiedades, optimizando el comportamiento de la combustión en el motor y en la reducción de las emisiones. El objetivo del trabajo de investigación es explorar las diferentes mezclas que puedan ayudar a mejorar el uso del biodiésel a través de las estrategias y avances que se han generado con el propósito de beneficiar el desempeño del motor diésel. Entre las distintas estrategias de mejoramiento del biodiésel están las mezclas de distintos bioaceites (aceites vegetales, de pirólisis y usado de cocina), mezclas del biodiésel con alcohol, con hidrógeno, el biodiésel como combustible piloto, las emulsiones del biodiésel con agua y la aplicación del biodiésel con antioxidantes, nanotubos y nanopartículas. Se concluye que para poder usar actualmente el biodiésel se lo haría con la combustión dual, en donde este representaría el combustible piloto (10 % o 20 % del combustible total del motor). Con esta estrategia se puede impulsar a otros combustibles (líquidos y gaseosos) en la combustión dual, para que con el paso del tiempo se encuentre la mezcla óptima que sea la mejor opción para el motor diésel.

Palabras clave: biodiésel, motores, mezclas, aceites, combustión dual, emulsiones

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1. Introduction

From 2010 to 2040, the demand for the most used fuel in heavy-duty vehicles, diesel, is expected to increase by 85%, while the gasoline demand will decrease by approximately 10% [1]. As a result, the growing demand for energy in transportation focuses on diesel engines [2]. Unfortunately, the transportation sector worldwide is one of the main contributors to environmental pollution, generating 26% of greenhouse gas emissions [3]. Biofuels are considered carbon-neutral fuels, as plant crops easily absorb the CO_2 they produce through photosynthesis. Among the biofuels is biodiesel, which has a lower energy content than diesel. This is due to biodiesel's higher density, viscosity, specific fuel consumption, and NO_x emissions. These are some limitations that affect biodiesel.

However, the properties of biodiesel can be improved by applying metal-based additives, oxygenated additives, antioxidants, cetane improvers, lubricants, and cold flow property optimizers. The addition of alcohol [4] and the blend of diesel-alcohol with biodiesel result in the formation of diesterol. In the quest to improve the properties of biodiesel, many researchers have employed various methods, such as transesterification (Figure 1), oil heating, alcohol blending, and mixing with diesel or other alternative fuels [5]. Furthermore, renewable diesel has been obtained, which, unlike biodiesel, can be derived from lipids (oil or fat) as a raw material through a hydrodeoxygenation reaction with a catalyst at high temperatures and pressure [6]. This research aims to explore different blends that enhance the use of biodiesel through strategies and advancements that optimize diesel engine performance. The most critical factor for biodiesel production is the raw material used.

2. Blends with different oils

Several authors recommend blends of different oils (Tabla).

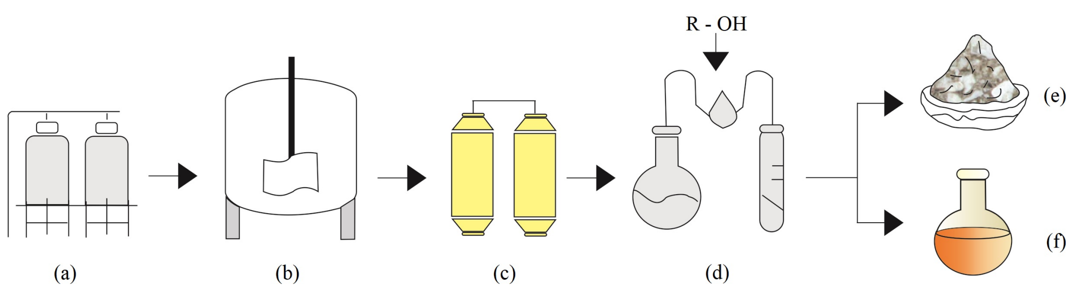

Figure 1. Transesterification process: (a) catalyst, (b) reactor with oil, (c) conditioning, (d) purification, (e) salts, and (f) biodiesel

Table 1. Evaluation of diesel engine performance using different bio-oils compared to conventional diesel

Type of bio-oil	Performance	Comments	Ref.
Soy methyl ester (SME) and yellow grease methyl ester (YGME)	Increase BSFC and YGME (12.2%) and GME (12.9%).	Both have a lower calorific value but exhibit good oxygenation, resulting in more efficient combustion.	[7]
Pithecellobium seed oil	BSFC increased.	There was a decrease in cylinder pressure, heat release rate, and exhaust temperature.	[8]
Orange peel oil	BTE improved at full load.	Reductions caused by low oil viscosity improve the complete combustion process.	[9]
PODE oil	BTE improved due to the type of oil used.	Due to the high oil-to-diesel blending ratio.	[10]

Type of bio-oil	Performance	Comments	Ref.
Palm oil	The output power decreased, and BSFC increased.	The use of oil with EGR caused a decrease in the release rate and generated fewer chemical reactions between the fuel and oxygen.	[11]
JOME	BTE increased, and BSFC decreased.	With the increase of EGR, the overall performance of the engine improved.	[12]
Mahua Oil	BSFC increased, and BTE decreased.	The engine efficiency decreased as the blending ratio of biodiesel increased.	[13]

Vallinayagam *et al.* [14] determined that a blend of 50% Kapok Methyl Ester (KME) and 50% pine oil was optimal in terms of performance and emissions. They observed a reduction in HC, smoke, and CO. However, the BTE of the blend was lower than diesel at low loads, although it was very similar to diesel at high loads. Singh *et al.* [15] determined that a blend of 70% Aamla oil and 30% eucalyptus oil reduces CO, HC, and smoke emissions, while NO_x is equivalent to diesel.

Kasiraman *et al.* [16] recommend a blend of 70% cashew shell oil and 30% camphor oil, which yields promising results, although it is still inferior to diesel. Dubey and Gupta [17] recommend a blend of 50% jatropha oil and 50% turpentine oil. This blend yielded the best results, significantly reducing NO_x, CO, HC, and smoke compared to diesel, especially under full-load conditions. Sharma and Murugan [18] recommend a blend of 20% tire pyrolysis oil and 80% jatropha oil. Table 2 shows the physicochemical properties of the biodiesel.

Table 2. Technical properties of various biodiesel types

Type of biodiesel	Density (kg/m^3)	Viscosity at 40 °C, cSt	Flashpoint (°C)	Cetane number	Calorific value (MJ/k)	Ref.
Pine oil	875,1	1,3	52	11	42,8	[14]
Pyrolysis oil	–	3,35	58	28	38,1	[18]
Orange oil	816	3,52	74	47	34,6	[9]
Mahua oil	960	24,58	232	–	36,1	[13]
Soybean oil	885	4,11	–	47,1	38,4	[19]
Used cooking oil	871	5,28	–	51	37,5	[20]
Rapeseed oil	886	6,18	–	59,3	40,8	[21]
Pongamia oil	870	6,79	–	> 48	38,8	[22]
Ceiba pentandra oil	880	1,9-6,0	–	47	–	[23]
Jatropha oil	874,3	4,34	130	52,7	42,67	[24]
Sunflower oil	880	4,3	148	54	40,76	[25]
Rice bran oil	880	–	–	56,3	39,54	[26]
Palm oil	870	–	–	56,5	38,84	[26]

3. Biodiesel-alcohol blend

Biodiesel's high viscosity, low volatility, and poor cold flow properties negatively affect combustion quality [19]. However, these characteristics can be improved by adding alcohol [27]. Fuel blends known as diesterol (composed of diesel, biodiesel, and ethanol) have demonstrated greater efficiency, improved performance, and lower emissions. This is because ethanol, with its high calorific value and low density compared to biodiesel, compensates for its deficiencies [28].

Additionally, ethanol has low viscosity and optimal cold flow properties, so when mixed with biodiesel, it helps reduce viscosity, increase volatility, and improve cold flow properties at low temperatures [29]. Table 3 presents the blend of ethanol and biodiesel and their emissions. The high oxygen content of ethanol can further reduce PM emissions in the mix with biodiesel [20]. The high cetane number of biodiesel compensates for the low cetane number of ethanol, thereby improving engine combustion [21].

The presence of biodiesel in the ethanol-diesel blend increases the cetane content and enhances the autoignition quality of the mixture [30]. Adding ethanol to the biodiesel-diesel blend improves overall physical properties such as evaporation and droplet size of the fuel mixture [22]. Tables 4 and 5 depict biodiesel blends with alcohols and their impact on engine performance.

Table 3. Emissions generation in the blend of biodiesel and ethanol

Emission reduction	Comments	Ref.
NO_x	Emissions can be reduced with the biodiesel-ethanol blend.	[31]
CO, NO_x and smoke	The reduction was due to the blend compared to pure biodiesel.	[32]
PM and NO_x	The blend exhibits a higher maximum heat release rate and maximum cylinder pressure than pure biodiesel.	[20]
HC, CO and soot	Diesterol reduces BSFC, and ethanol acts as an oxidant for soot.	[33]
NO_x	Diesterol exhibits a high heat of vaporization and reduces NO_x emissions.	[34]

Table 4. Emission generation in the blend of biodiesel with alcohols

Emission reduction	Type of alcohol	The reason	Ref.
PM	Butanol	BTE was increased by adding 20 % butanol to the biodiesel.	[35]
CO and HC	Butanol and Pentanol	Pentanol blended with biodiesel showed better engine performance.	[23]
NO_x and soot	n-Butanol	Applying higher injection pressure to the blend of butanol and biodiesel is a viable technique.	[36]
NO_x	DME	The maximum heat release rate decreases when blending biodiesel with DME.	[37]
PM	n-Petanol	Blending pentanol with biodiesel significantly reduces particle emissions.	[38]
NO_x, HC and CO	1-Petanol	The blend reduces emissions with a slight loss of BTE.	[39]
CO and HC	1-Octanol	Adding n-octanol improves BTE but increases NO_x.	[40]

Table 5. Impact of bio-oil and alcohol blends on engine performance and emissions

Composition of the blend	Emission reduction	Engine performance	Ref.
70% diesel, 20% Jatropha oil, and 10% ethanol, with an addition of 25 ppm of Al_2O_3 nanoparticles	HC, CO, NO_x and smoke	The maximum cylinder pressure and the maximum rate of heat release were reached closer to TDC.	[24]
40% diesel, 40% biodiesel, 10% vegetable oil, and 10% propanol.	NO_x	The blend exhibited the highest BSFC and lower NO_x, emissions, but it led to an increase in levels of CO and HC.	[41]
A blend of diesel, residual sunflower biodiesel, n-pentanol and n-hexanol	Various	By adding n-heptanol, both BTE and BSFC values improved.	[42]
A blend of 5% DEE and the remaining portion of soybean oil biodiesel and diesel.	CO	There was an improvement in BSFC. However, it is essential to note that adding more than 40% of DEE could lead to engine detonation.	[43]
20% ethanol and 80% sunflower oil biodiesel de girasol	CO and NO_x	With the blend, a higher thermal efficiency was achieved. However, when used at low speed, there is an increase in NO_x emissions.	[25]

Another option for biodiesel blending is using longer-chain higher alcohols, such as butanol and pentanol. These alcohols can be blended with biodiesel at proportions of up to 20% and with diesel in diesel engines without any alterations [44]. Babu *et al.* [44], determined that up to 29% of butanol blended with biodiesel can be added without causing any modifications to the engine, thereby improving the properties of biodiesel and optimizing the combustion of the blends.

4. Biogas and biodiesel blend

Biogas can be used in dual combustion as the primary fuel, with biodiesel serving as the pilot fuel. Sahoo [45] investigated the performance of dual combustion using biogas, obtaining a BTE of 16.8% and 16.1% for diesel and Jatropha biodiesel, respectively, compared to 20.9% for conventional diesel. Luijten and Kerkhof [46] analyzed synthetic biogas with a CO_2 variation from 30% to 60%, using a single-cylinder naturally aspirated diesel engine fueled with Jatropha biodiesel as the pilot fuel. They reported a slight variation in the engine's BTE when increasing the biogas energy proportion at high loads, while a significant BTE decrease was observed at low loads. Table 6 displays the engine performance with the blend of biodiesel, alcohol, and biogas.

5. Application of bio-oil with water

Using water-emulsified fuel in biodiesel (Figure 2) could reduce NO_x and PM emissions [47]. Additionally, a decrease in smoke has been observed, but there is an increase in fuel consumption, CO, and HC emissions [48]. Fuel emulsion also reduces wear and friction, and this decrease could be related to the presence of water, which results in lower temperatures and, therefore, less combustion wear [49]. Water emulsion increases BTE (brake thermal efficiency) by improving fuel atomization and evaporation, creating a microexplosion that forms a fine aerosol and enhances fuel vaporization. The continuous braking of water droplets in the emulsification process increases the evaporation surface area and ensures precise mixing, resulting in improved reaction and combustion efficiency [50]. Table 7 presents the results obtained in the application of biodiesel emulsions.

Table 6. Dual fuel blending with bio-oil and alcohol with biogas

Type of blend	Emission reduction	Engine performance	Ref.
Soybean biodiesel as the pilot fuel, and biogas	Soot	Biogas combustion with biodiesel shows good performance and a reduction in soot.	[51]
Methyl ester of rice bran oil with biogas	CO and HC	Rice bran oil biodiesel improved performance with biogas at a higher compression ratio.	[26]
Biodiesel was used as a pilot fuel with a 6% DEE supplement, while biogas was the primary fuel.	CO, HC and smoke	The blend improved the engine performance and reduced BSFC, but an increase in NO_x was observed.	[43]

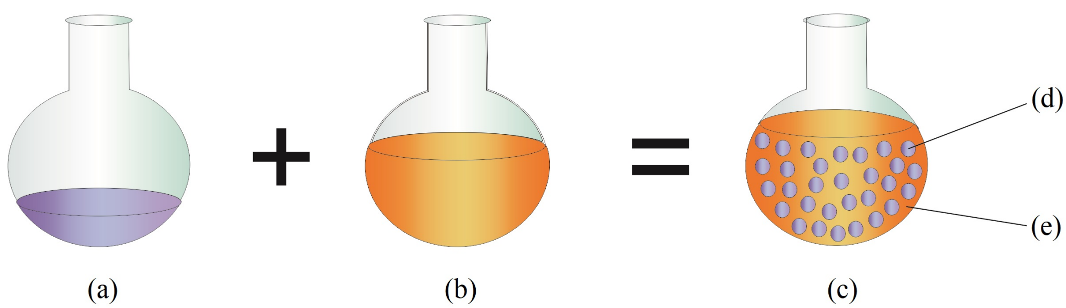

Figure 2. Emulsification phenomenon: (a) 30% water, (b) 70% fuel, (c) emulsion, (d) dispersed phase, (e) continuous phase.

Table 7. Application of bio-oils in emulsions

Emission reduction	Increasing emission	Engine performance characteristics	Ref.
CO and smoke	CO_2	The BSFC and BSEC increased with the emulsion, while the BTE remained unchanged.	[52]
NO_x and smoke	CO, CO_2 and HC	The use of diestrol-water microemulsions resulted in an increase in BSFC and a reduction in BTE.	[53]
NO_x and soot	CO	A biodiesel nanoemulsion was used, resulting in increased fuel consumption.	[54]
NO_x	HC, CO and smoke	The injection of 3 kg/h of water reduces NO_x emissions by 50% without any deterioration in engine performance.	[55]
Smoke	-	The BTE increased to 7.4% with the bio-oil emulsion from wood waste pyrolysis.	[56]
HC and smoke	-	The BTE increased to 7.3% with the emulsion of wood pyrolysis oil and Jatropha methyl ester.	[57]

6. Biodiesel blend with natural gas

Natural gas can be used in dual-fuel combustion as the primary fuel, while biodiesel is used as the pilot fuel. Paul *et al.* [58] utilized pongamia pinnata methyl ester (PPME) as the pilot fuel in a dual-fuel CI engine by adding natural gas. Biodiesel showed an improvement in BTE and a reduction in BSFC. The combustion was more complete, reducing CO and HC emissions, although there was an increase in NO_x emissions.

Tarabet *et al.* [59] determined that enriching natural gas with H_2 in a dual-fuel mode, using eucalyptus biodiesel as the pilot fuel improves engine performance and reduces emissions. On the other hand, the study conducted by Ryu [60] using vegetable oil (used cooking oil) as the pilot fuel in a DI Common Rail engine with natural gas, resulted in a power loss attributed to biodiesel due to its higher kinematic viscosity compared to diesel. Senthilraja *et al.* [61] conducted a study on combining seed methyl ester blends with diesel-ethanol enriched with CNG. They reported an increase in BSFC when increasing the concentration of the biodiesel-ethanol combination.

On the other hand, in the experimental studies conducted by Kalsi *et al.* [62], an RCCI engine was fueled with biodiesel using compressed natural gas mixed with hydrogen, resulting in significant improvements in BTE and reduction of smoke, HC, and CO.

7. Biodiesel and hydrogen blend

Since hydrogen is a carbon-free energy carrier, all carbon-based emissions such as HC, CO, H_2O, PM, and smoke decrease significantly in dual-fuel diesel engines under all loads [63]. The engine performance, as well as the engine behavior and its emissions with the blend of biodiesel and hydrogen, are presented in Tables 8 and 9, respectively.

Table 8. Engine performance with biodiesel and hydrogen blend

Type of blend	Engine performance	Ref.
Blending biodiesel with H_2 gas.	The blend reduces engine vibration and exhaust emissions, but biodiesel tends to generate noise.	[64]
Dual fuel with hydrogen and biodiesel.	With the blend, engine power was reduced from 190 g/Kwh to 104 g/Kwh, when switching from diesel to biodiesel.	[65]
A blend of diesel with Jatropha oil as biodiesel and 7% H_2 as pilot fuel.	With a 7% H_2 in the diesel/biodiesel blend, an increase in BTE was observed under full load conditions.	[66]
A blend of H_2 with jojoba oil methyl ester biodiesel as pilot fuel.	The thermal efficiency improved significantly, and the SFC was reduced.	[67]

Table 9. Engine performance and emissions with biodiesel and hydrogen blend

Emission reduction	Increasing emission	Engine performance	Ref.
CO and HC	NO_x	With a blend of palm oil biodiesel and 20% hydroxyl gas, fuel consumption is reduced compared to conventional biodiesel.	[68]
CO, HC and smoke	NO_x	With the blend of diesel and Jatropha oil as biodiesel, an increase in BTE was observed when adding 10% hydrogen H_2 to the blend.	[66]
NO_x	-	Stable engine performance was achieved with a blend of 20% biodiesel and 80% diesel, along with an additional 10% hydrogen H_2.	[69]
CO, HC and smoke	-	With the blend of waste cooking oil (WCO) emulsified with H2 as the primary fuel, superior thermal efficiency is achieved even at high power levels.	[70]
CH4	-	Emissions were reduced by blending 20% H_2 with biodiesel.	[71]

8. Biodiesel and antioxidants blend

Several studies have indicated that the addition of antioxidants reduces emissions. Among the phenolic antioxidants, TBHQ, BHA, and BHT are commonly used to control fuel degradation and improve biodiesel storage. These antioxidants help reduce NO_x emissions but may increase smoke, CO, and HC emissions [72].

Rashedul *et al.* [73] analyzed the effect of the antioxidant BHT in combination with Callophyllum biodiesel and found that BHT improves fuel stability, reducing NO_x emissions. Additionally, it increased braking power, achieved higher thermal efficiency (BTE), and reduced specific fuel consumption (BSFC). On the other hand, Ryu [74] conducted a comparative study of antioxidants using soybean oil biodiesel. It concluded that the effectiveness of antioxidants follows the order TBHQ > PrG > BHA > BHT > alpha-tocopherol. The study also revealed that using these antioxidants leads to a decrease in specific fuel consumption. However, commercial antioxidant additives are often expensive and produced from non-renewable materials, which has motivated the search for new low-cost alternative additives obtained from biomass or waste sources [75].

9. Nanoparticles in biodiesel

Adding nanoparticles to biodiesel improves its thermophysical properties, such as conductivity, mass diffusivity, surface-to-volume ratio, and physicochemical properties like kinematic viscosity, flash point, and pour point, among others [76].

Table 10 presents the engine performance with the mixture of nanoparticles and biodiesel. Carbon nanotubes (CNTs) have the potential to be used as additives in dual combustion to enhance the fuel and achieve improved results in terms of BSFC, BTE, and NO_x emissions. However, the issue of the lack of stability in the CNT mixture can be addressed by applying a fuel stabilizer or surfactant [77]. Table 11 shows the engine behavior with the blend of biodiesel and CNTs.

Mirzajanzadeh *et al.* [78] provide a detailed explanation of the use of nanoparticles. They synthesized a soluble hybrid nanocatalyst to improve engine performance. They added a compound of cerium oxide and multi-walled carbon nanotubes functionalized with amide groups to the blend of diesel and biodiesel. The results showed a reduction in CO, HC, NO_x, and soot emissions. Additionally, an improvement in engine performance and a decrease in fuel consumption were observed. However, caution must be exercised in using cerium oxide nanoparticles due to health risks such as cytotoxicity induction, oxidative stress, and lung inflammation [79]. Therefore, their use should be controlled. Replacing metal-based nanoparticles with non-metallic nanoparticles may be necessary as they are less toxic [80].

Table 10. Analysis of nanoparticles applied in biodiesel

Emission reduction	Type of nanoparticles	Engine performance	Ref.
CO and HC	TiO_2	In the blend of biodiesel (20%) and the remaining diesel with TiO_2, a decrease in BSFC and an improvement in BTE were observed. However, an increase in CO_2 and NO_x emissions was also observed.	[81]
CO, CO_2 and NO_x	Titanium nanoparticles	Adding titanium nanoparticles to the biodiesel blend reduces the BSFC, improves combustion and increases the BTE.	[82]
CO and HC	Nanometallic oxides	The blend of mahua oil biodiesel with nanoparticles in a CRDI engine reduces emissions.	[83]
NO_x, HC and smoke	Cerium oxides	The blend of 70% diesel, 10% castor oil biodiesel, and 20% ethanol, along with an addition of 25 ppm of cerium oxide, reduced the heat release rate and, consequently, the emissions.	[84]
CO and HC	Alumina nanoparticles	The blend of biodiesel with ethanol and alumina increased exhaust gas temperature and BTE, but it also caused an increase in NO_x emissions.	[85]
CO and NO_x	MgO and SiO_2	With the addition of nanoparticles to biodiesel, an improvement in engine performance and a reduction in emissions were observed.	[86]
HC, CO and NO_x	Cobalt oxide Co_3O_4	The addition of CoO_4 to Jatropha oil biodiesel improved combustion and reduced emissions by 75% during an engine load operation.	[87]
-	Copper oxide	Blending copper oxide (50 ppm) with 20% Mahua oil biodiesel and the rest diesel reduced incomplete combustion, improved BTE, and facilitated cold starting.	[88]

Table 11. Engine performance and emissions with the blend of biodiesel and applied carbon nanotubes (CNTs)

Emission reduction	Engine performance	Ref.
CO, HC and NO_x	A CNT blend was applied with a Jatropha methyl ester emulsion, resulting in an increase in BTE compared to pure biodiesel.	[89]
NO_x	The blend of biodiesel and CNTs increased the BTE.	[90]
CO, HC and soot	The blend of biodiesel and CNT (5% and 20%, respectively) improved the BTE and reduced the BSFC.	[76]
NO_x	The blend of biodiesel (neem oil methyl ester) with CNT increased the BTE, and due to the higher cetane number, the ignition delay was reduced, thereby improving combustion.	[91]
Soot	The combination of CNT, cerium oxide nanoparticles, and diesterol resulted in a highly efficient blend for combustion and a significant increase in engine performance.	[92]

A new alternative consists of using organic nanoparticles, such as coconut shells, which can be mixed with biodiesel and applied in diesel engines [93]. Table 12 presents the technical characteristics of the biodiesel ratio.

Table 12. Technical characteristics of biodiesel with nanoparticles

	Biodiesel + nanoparticles				
Properties	**Algae oil + TiO_2-$SiO_2$50**	**Mahua oil + ANP50**	**Soybean oil + alumina**	**Neem oil + CNT100**	**Jatropha oil + 100 CNT**
Density (kg/m^3)	817	827.5	-	889	899.4
Kinematic viscosity at a 40 °C (cSt)	3.03	3.37	3.37	4.28	5.76
Flashpoint °C	62.45	-	-	181	125
Cetane number	48	49.5	52	53	55
Calorific value (kJ/kg)	42,600	41,665	42,590	40,920	37,350
Reference	[81]	[83]	[85]	[91]	[89]

10. Conclusions

Due to the high production cost of biodiesel and some unfavorable properties, such as its low calorific value, high viscosity, and density compared to conventional diesel, it is crucial to implement strategies to increase its attractiveness. We have concluded that there are two promising alternatives for its future application. The first one is to find an appropriate blend that justifies the commercial use of biodiesel by optimizing its properties and performance. The second option is to use biodiesel as a component in fuel blends, using a proportion of 10% to 20% relative to the total fuel in the engine. This would allow for the application and promotion of other types of biofuels, such as gaseous fuels in dual-fuel diesel engines, opening new possibilities and contributing to greater sustainability in the transportation sector.

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