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Mini review

A review of fuel additives' effects and predictions on internal combustion engine performance and emissions

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Abstract: In recent years, there has been an increasing interest in additives for fuel research in the field of internal-combustion engines. Many studies have been conducted to improve the performance and emissions of the engine. Many kinds of additives in the form of solids, liquids, and gases have been used. The objective of this review is to examine the effects of having additives on the performance and emissions of an internal combustion engine. Additives such as alcohol, hydrogen, and metal oxides are proven to be successful in improving performance or reducing emissions. Results from selected papers are discussed and summarised in a table. With the new developments in nanotechnology, many researchers have shown an increased interest in carbon-based nanoparticles such as multi-walled carbon nanotubes (MWCNT) and single-walled carbon nanotubes (SWCNT). Lately, with the discovery of graphene production techniques, graphene nanoplatelets (GNP) have also been applied as fuel additives. In addition to understanding the effects of the additives on the engine performance and emissions, researchers extended the research to predict the outcome of the performance and emissions. The experiments involving the predictions efforts are summarised in a table. From the summary, it is found that the prediction of the GNP as fuel additive effects to the performance and emissions has not yet been explored. This gap is an opportunity for researchers to explore further.

Keywords: diesel engine; engine performance; engine emission; fuel additive; graphene

1. Introduction

The internal combustion engine has become the foundation for vehicles, agriculture, and military operations as well as electricity generation. Acting as the heart of the vehicle, the internal combustion (IC) engine's function is to give the power that moves the vehicle. The engine itself is comprised of many elements and components, each of which has its own specific role. The primary component of the fuel is hydrocarbons. The composition and properties of it will determine its performance and emission results in the combustion process.

An internal combustion engine that runs on diesel fuel is known as a diesel engine. Diesel engines are commonly found in heavy-duty vehicles such as trucks, cars, and industrial transport that are used on the road. In comparison to S.I engines, C.I diesel engines have better fuel economy and reliability [1]. The excellent thermal efficiency of diesel engines is the primary reason for their vast range of applications, which include transportation, power generation, agricultural forms, and development domains [2].

In any case, compression ignition diesel engines emit massive volumes of pollutants (NOx, soot, CO, UHC, and particulate matter), posing serious health and environmental dangers [3]. The majority of these discharges result from non-ideal combustion cycles, such as fragmented fuel ignition, high temperature and pressing blending product responses, ignition of engine lubricating oil and additives, and burning of non-hydrocarbon diesel fuel components such as sulphur compounds and fuel added substances [4]. In terms of the environment, smoke emissions produced by diesel engines can cause both pollution of water and air, which significantly reduces visibility and contributes to global climate change [5]. It's a different scenario when it comes to health. Dizziness, headaches, and irritation of the eyes, nose, and mouth can occur after a brief exposure to high diesel exhaust emission levels [6]. Long-term exposure raises the risk of cardiovascular illness, cardiopulmonary disease, and respiratory disease, as well as lung cancer [7]. As a result of this, smoke emissions from diesel engines constitute a severe challenge that requires constant forecasting in order to keep them at a minimum, as well as other tactics such as fuel composition alteration, fuel additives, and other alternatives to manage smoke emissions [8].

Asia's rapid development has resulted in extremely high oil demand [9]. It is estimated that the world will consume 105 million barrels of oil per day in 2025 [10]. At this rate, the world is likely to run out of fossil fuels in the next 100 to 50 years [11]. Aside from that, the fuel price is extremely volatile [12]. Furthermore, fuel price fluctuations have a significant impact on economic, fiscal, and income patterns [13]. This is due to the fact that the fuel consumed in goods transportation has an impact on the price of goods [14].

With the conditions listed above, which include a mix of high emissions, high petroleum demand, volatile petroleum prices, and dwindling petroleum resources [15], it is well acknowledged that internal combustion engines must be more efficient [16]. To put it another way, the engine needs to consume less gasoline while producing more power [17]. The engine must also emit fewer pollutants. With these facts in mind, it's clear that we need to limit emissions from combustion engines [18]. As a result, a variety of studies have been done to improve performance and minimise emissions [19–21].

Alternative vehicle concepts such as electric vehicles and fuel cells are one way to cut emissions [22]. The less radical option involves employing a combustion engine but with alternative fuels such as biodiesel instead of pure diesel [23]. Another alternative is to add additives to the fuel that is currently being used [24]. The first application of fuel additives was to eliminate knocking in gasoline engines

in the early twentieth century [25]. Combustion modifiers, antioxidants, corrosion inhibitors, and deposit control detergents are all examples of fuel additives [26]. Furthermore, gasoline additives can be utilised for a variety of applications, including octane boosters, fuel injector cleaners, and fuel line antifreezes [27]. This study aims to assess the current state of fuel additives in diesel and gasoline engines. In addition to observing the impacts, the study's scope has been expanded to include predicting the outcomes of additive effects on engine performance and emissions.

2. Fuel additives in internal combustion engine

Currently, the transportation sector is primarily reliant on internal combustion engines, such as diesel and spark-ignition engines. Combustion engines are likely to remain the most important engine for the next 30 years. Every year, the global transportation sector consumes more and more energy. The use of fossil fuels is a major contribution to this fact. Internal combustion engines that run on fossil fuels provide a lot of power to the transportation sector. Despite advancements in alternative fuels, around 90% of people still use traditional fossil fuels, with only a small percentage using renewable fuels [28]. The demand for transportation, industrial, and research services is increasing every day as the world's population grows, resulting in a petroleum fuel shortage. The rapid depletion rate of petroleum fuel, as well as the impact of its emission gases on the environment, has become a major issue for people all over the world.

The literature suggested some popular additives that are in use. Hydrogen [29], CNG [30], LPG, ZnO [31], alcohols, methyl-esters [32], Mn_2O_3, Al_2O_3 [33], MWCNT [34], GO, and GNP are the latest additions to the list of materials used as additives. These additives can be classified into gaseous additives, liquid additives, and solid additives. These solid additives can be divided into metal and non-metal additives. This classification can be represented in Figure 1 below:
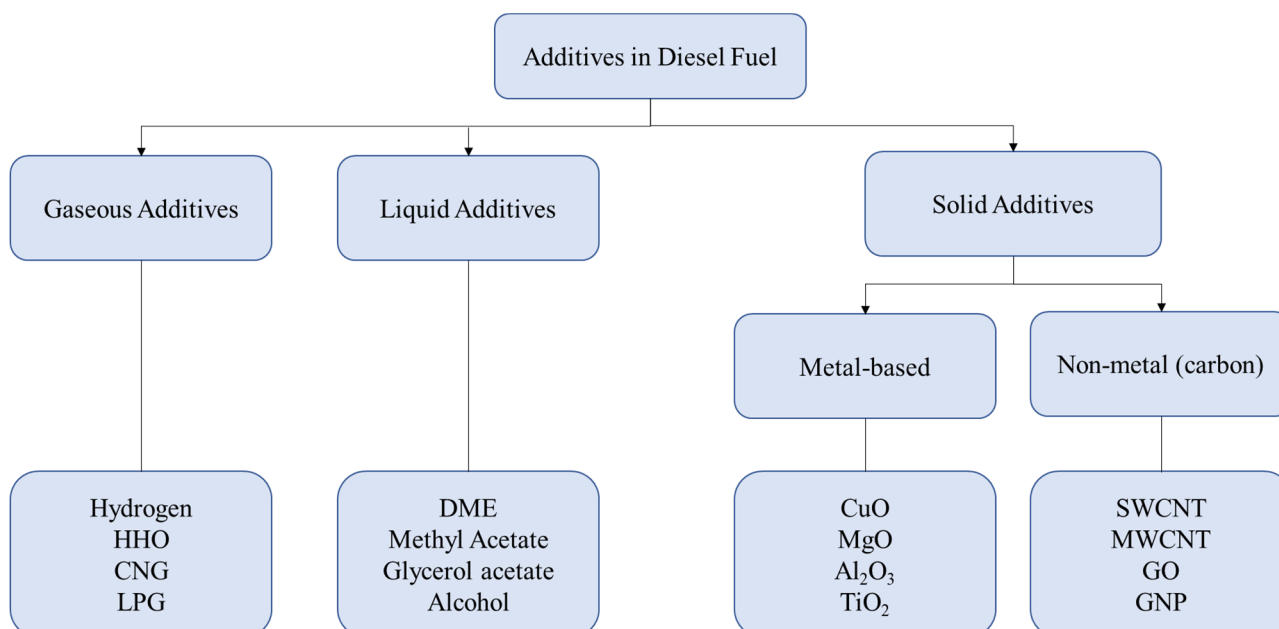

Figure 1. Classification according to different forms of additives.

To understand the subject, the properties of the fuel and additives are observed in detail. The properties of the base fuel (diesel or biodiesel) can be summarised in Table 1, while the properties of gaseous and liquid additives are presented in Table 2.

Table 1. Known roperties of base fuels (diesel and biodiesel) [28].

Properties Fuel/additive	CV [MJ/kg]	Density [kg/m^3]	Kinematic Viscosity [mm^2/s]	Flash point [°C]
pure diesel	44	825.96	3.96	72
Biodiesel Chlorella Vulgaris	38.7	860	3.7	124
honge biodiesel HB20	42.123	835	4.12	104

Table 2. Known properties of liquid and gaseous materials used as fuel additives [35].

Properties Fuel/additive	CV [MJ/kg]	Density [kg/m^3]	Kinematic Viscosity [mm^2/s]	Flash point [°C]
hydrogen	119.93	0.0838	110	-
methanol	20.30	790	0.59	12
ethanol	27	785	1.1	14
CNG	45.76	720	-	81.6

The carbon-based additives used are carbon nanotubes and graphene. The properties of the materials as in the Table 3 below:

Table 3. Properties of carbon materials used as fuel additives [36].

Properties Fuel/additive	CV [MJ/kg]	Density [g/cm^3]	Specific Surface Area (m^{2}g^{-1})	Thermal conductivity (kW/mK)
SWCNT		1.3–1.4	1315	1750–3800
Graphene	31.82	2.267	1598	5300

Many parameters can be used to measure the performance and emissions of a diesel engine. However, after researching many articles in the field, standard parameters used to evaluate engine performance are brake torque, brake power, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). Additionally, the emission parameters being observed are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and unburned hydrocarbons (HC).

3. Gaseous fuel additives

3.1. Effect of gaseous fuel additives on performance

In a study to determine the effect of hydrogen on diesel-biodiesel blend, Tayari [37] added different amounts of hydrogen mixtures to the engine. It was found that hydrogen improved the power performance. Torques in B20H10 and B10H10 were 10.6% and 8.4% higher than the biodiesel blends without hydrogen induction (B20H0 and B10H0). The engine's low power and torque are caused by

biodiesel's low heating value and high viscosity. Additional hydrogen to biodiesel improved the power and torque of the engine due to the faster rate of combustion caused by hydrogen. In another research by Ngang [38], the authors conclude that the torque of the diesel-LPG engine increases as the quantity of LPG fuel also increases. The findings strongly support the directly proportional relationship between the amount of LPG fuel introduced and the output torque of the diesel-LPG engine. The power output in the diesel-LPG mode of operation can be controlled by the amount of LPG introduced to the engine. Generally, increasing the LPG mass fraction yields more power. For example, the power of 60% LPG is higher than the power of 50% LPG.

In an experiment by Surya [29], hydrogen enrichment of biodiesel was observed. The fuel used was a honge biodiesel blend (HB20). The hydrogen enrichment was between 10–13 l/min. H-B20-A (Hydrogen 5 l/min + B20 + Al_2O_3 produced higher power of 6.4%. This combination also reduced specific fuel consumption by 2.72%. In a study to determine the effect of hydrogen on diesel-biodiesel blend, Tayari [37] added different amounts of hydrogen mixtures to the engine. It was found that hydrogen improved the BSFC performance. The average reductions of BSFC for B20H5 and B10H5 were 3.4% and 5.1% compared to the biodiesel blends without hydrogen (B20H0 and B10H0). Biodiesel with hydrogen led to more power generation and increased the combustion efficiency of the engine due to high calorific value and mass flow rate of hydrogen. An example experiment by Akcay [39] indicated that hydrogen addition reduced the BSFC. The result showed With H40 (hydrogen induction of 40 l/min), the BSFCs of diesel fuel tests were decreased by 11.1%, 12.5%, and 7.9%, respectively, for the engine loads of 40, 60, and 80 Nm, as compared with the pure diesel fuel tests. It is seen that BSFC generally exhibits a decrease with the increasing load for each fuel and hydrogen addition. As a result of the increase in the cylinder wall temperatures, the decrease in the ignition delay and, accordingly, the progress of the combustion, BSFCs showed decreasing tendencies [40]. For example, in an experiment using spark-ignition engine, Yilmaz [41] found that the BSFC of alcohol (methanol and ethanol) had been reduced after the induction of hydrogen. The addition of hydrogen reduced the BSFC by around 4% compared to the alcohol-gasoline blend. This is because the lower heating value of hydrogen is very high compared to gasoline. Hydrogen addition increases thermal efficiency and decreases BSFC [42].

The effect of hydrogen addition on thermal efficiency was carried out by Yilmaz [41] in an experiment with alcohol-gasoline in a spark-ignition engine. It was found that the BTE increased with the hydrogen addition. Experimentally, Gnanamoorthi [43] also shows a better BTE (increased by 30.65%) with the addition of hydrogen. Another finding from Tabar [44] is that the BMEP of CNG is 4–14% less than that of gasoline throughout all the engine speeds. CNG has a 10% lower indicated power. When compared to gasoline, CNG has a remarkable 11–39% lower fuel consumption [44]. Sonachalam [45] demonstrated that the brake thermal efficiency (BTE) is increased by about 3.7% at a flow rate of 4 liters per minute (LPM) of acetylene injection in RCCI combustion mode.

3.2. Effect of gaseous fuel additives on emissions

An analysis of fuel additive effects on engine emissions was carried out by Gnanamoorthi [43], and it indicated that the emissions of HC, CO, and CO_2 were reduced by 22.3%, 14% and 32.74% respectively with the addition of hydrogen. Similarly, another experiment by Selahaddin Orhan Akansu [46] pointed out that hydrogen produced fewer emissions, especially CO, CO_2, and HC. This happens because of the chemical composition of hydrogen, which does not have carbon and has high

thermal efficiency. However, the emission of NOx increased. The reason for that is the high temperature of the combustion. As argued by Yilmaz [41], the NOx emission has been reduced when hydrogen is introduced into the combustion. The reason for that is the low adiabatic flame temperature of the methanol. The addition of hydrogen by Surya [29] was successful in reducing the CO by 15.91%. However, this experiment produced higher CO_2 and NO_x by 22.37% and 37.68% respectively.

It was also reported by Yilmaz [41] that CO has been reduced with the addition of hydrogen. The fuel with the lowest CO emission was found to be G85M15H15, with a CO emission of 0.094%. On the other hand, CO_2 has been reduced with the addition of hydrogen. The lowest CO_2 emission was found to be 12.06% for G85M15H15 fuel. Another example, Sonachalam [45] found that acetylene addition to a diesel engine running with biodiesel shows significant decreases in polluting components such as smoke opacity, oxides of nitrogen (NOx), hydrocarbons (HC) and carbon monoxide (CO) are reduced by about 10%, 7.6%, 13.4% and 28.7%. As reported by [38], LPG addition reduced NOx and HC emission pollutants, despite the fact that the overall in-cylinder temperature increased. This demonstrates that adding LPG to a specific value allows for decreased emissions as long as the mixture remains lean. The ensuing increase in temperature and pressure is compensated for by the mixture becoming richer, cutting emissions and enhancing combustion efficiency.

Figure 2 is a bar chart depicting the various effects of gaseous fuel additives on engine emissions. In the graphic, the percentage value of hydrogen, CNG, and acetylene additions are compared to their base fuels, which are gasoline-ethanol blend, gasoline, and biodiesel, respectively.
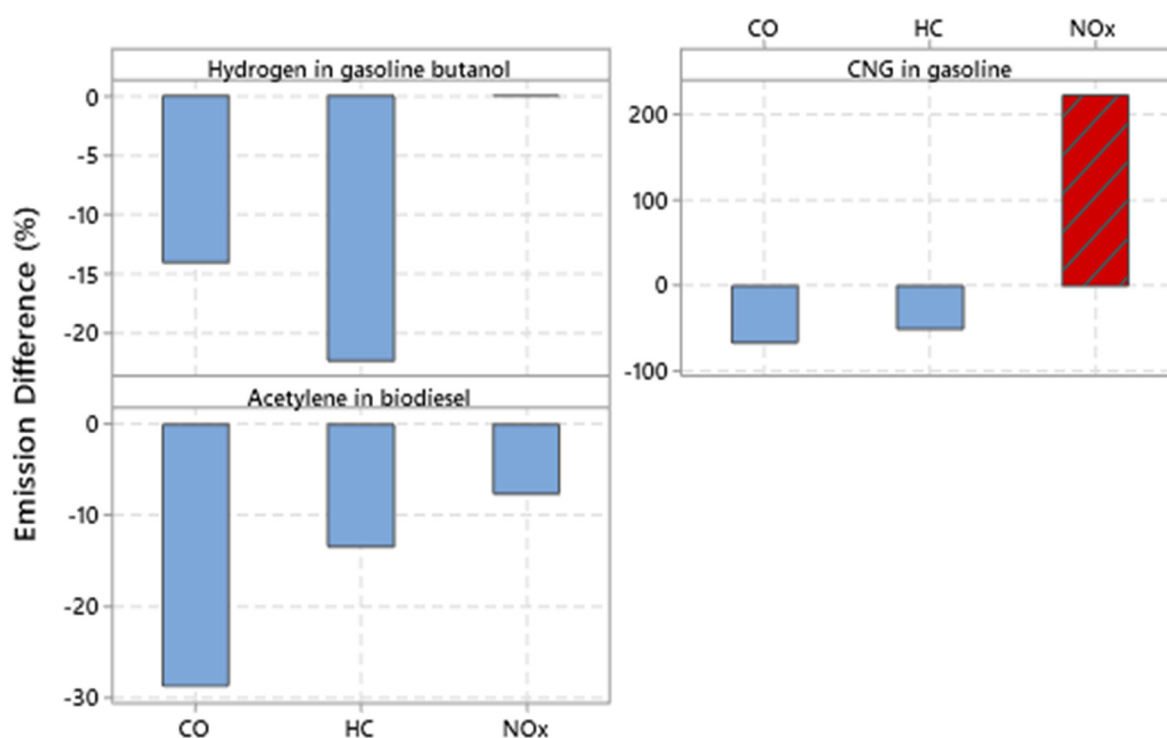

Figure 2. Emission differences of fuel with gaseous additives compared to base fuels.

4. Liquid fuel additives

4.1. Effect of fuel additives on performance

Several studies have been undertaken to investigate the impact of liquid additives on engine performance and emissions. Najafi [47] conducted an experiment to estimate the performance and exhaust emissions of a four-cylinder SI engine. The engine operates on the different mixing ratios of ethanol and gasoline blends. A mixture of gasoline and bioethanol derived from potato peels has been employed. 0%, 5%, 10%, 15%, and 20% have been employed. The mixture was called E0, E5, E10, E15, and E20. The engine performance and emissions from the mixture have been compared with the performance and emissions from 100% gasoline. The experiment found that using ethanol blends improved brake power, brake thermal efficiency (BTE), engine torque, and volumetric efficiency. On the other hand, the brake specific fuel consumption (BSFC) decreased. BSFC is defined as the energy consumed per unit power produced considering the calorific value of the fuel. Mohamed Nour [48] identifies the effects of pentanol/hydrous ethanol/diesel blend and octanol/hydrous ethanol/diesel have on compressed-ignition engine. The finding suggests that the addition of octanol to the hydrous ethanol/diesel blends achieves the lower BSFC at all loads.

A deeper investigation by Yesilyurt [49] was performed to compare the engine performance, combustion, and emissions of direct-injected diesel engines fuelled with diesel, with diesel-butanol blend, and diesel-pentanol blend. Yesilyurt reported that the blended fuels produced lower EGT and CO_2. However, more O_2 is produced. The reason for the observation was the higher oxygen content in the alcohol.

As highlighted by Godwin [50], gasoline blended with alcohol produced lower EGT compared to 100% gasoline. This is because gasoline has the highest calorific value and the lowest latent heat of vaporization, lean mixture formation, and flame propagation. This leads to an increase in cylinder temperature and more gasoline being used.

Another experiment using alcohol was conducted by S. Phuangwongtrakul [51] to study the engine performance. Brake torque and brake specific fuel consumption while a different mixing ratio of ethanol was investigated. The experiment proved that a proper ethanol-gasoline mixing ratio can improve engine torque output while reducing emissions. By adding pentanol to biodiesel, Yesilyurt [52] found the maximum BTE values of the diesel fuel and B20, and B20P5 were found to be at 22.75%, 21.82%, and 20.96% under 750 W engine load condition, respectively. This little change, however, can be considered insignificant.

4.2. Effect of liquid fuel additives on emissions

From the experiment by Najafi [47], the result showed that the amount of CO and HC had been reduced, but CO_2 and NO_x emissions were higher. This is supported by Dogan in 2017 [53] to identify irreversible processes using energy and exergy analyses. The fuels were blended in various proportions. E0 refers to 100 percent unleaded gasoline, while E10 refers to gasoline blended with 10% ethanol. E20 is ethanol with a concentration of 20%, and E30 is ethanol with a concentration of 30%. The fuel blends were then tested in gasoline engines at various speeds, loads, and under identical conditions for each fuel type. NOx levels were reduced as a result of the experiments and theoretical calculations.

One of the new exploratory investigations by Yesilyurt [49] is the exhaust emission characteristics

of a solitary chamber, direct-infusion diesel motor running on biodiesel/diesel/1-butanol and biodiesel/diesel/n-pentanol fuel blends. Yesilyurt found that alcohol blended fuels reduced NOx by 0.56%–2.65%, CO by 6.90%–32.40%, and smoke by 10.47%–44.33%. The authors expressed that higher alcohols, particularly n-pentanol, could be an efficient additive to diminish NOx emissions by thinking about the acquired outcomes.

In another major study, Uslu and Celik [54] utilised diethyl ether (DEE) blends with pure diesel to study the exhaust emission characteristics of a single-cylinder, direct-injection, and air-cooled diesel engine. An experiment was carried out at four engine speeds ranging from 1000 to 1600 RPM with 200 RPM intervals and four engine loads, which were 150, 300, 500, and 1000-watt halogen lamps. Diesel fuel was mixed with DEE0, DEE2.5, DEE5, DEE7.5, and DEE10, which contained 2.5%, 5%, 7.5%, and 10% by volume of DEE, respectively. According to the author's findings, DEE10 allows NO_x emissions to be reduced by 56%.

Another experiment was conducted by Dogan [53] to identify irreversible processes using energy and exergy analyses. The fuels were blended at different ratios. 100% unleaded gasoline is called E0, and gasoline blended with 10% ethanol is called E10. 20% ethanol is called E20 and 30% ethanol is called E30. The fuel blends then applied into gasoline engine with different speeds, under different loads and under the same conditions for each fuel type. The result from the experiments and theoretical calculations showed a reduction in carbon monoxide (CO).

In another major study done by Uslu and Celik [54], it was identified that DEE10 allows NO_x emissions to be reduced by 56% compared with diesel fuel, while CO emissions are reduced by about 45%. Dogan [53] conducted another experiment that focused on identifying irreversible processes using energy and exergy analyses. The fuels were mixed in various proportions. E0 refers to 100 percent unleaded gasoline, while E10 refers to gasoline blended with 10% ethanol. E20 is ethanol with a concentration of 20%, and E30 is ethanol with a concentration of 30%. The fuel blends are then applied to gasoline engines at varying speeds, under varying loads, and under the same conditions for each fuel type. Carbon dioxide levels were reduced as a result of the experiments and theoretical calculations (CO_2).

In the same vein, the experiments by Chao Chen [55] and Pinzi [56] found that the diesel/alcohol blend was able to reduce soot formation. This phenomenon might happen due to the high oxygen content in alcohol that helps in the burning of soot during combustion. A bar chart is plotted in Figure 3 to visualise the different effects of the liquid fuel additives on the engine emissions.
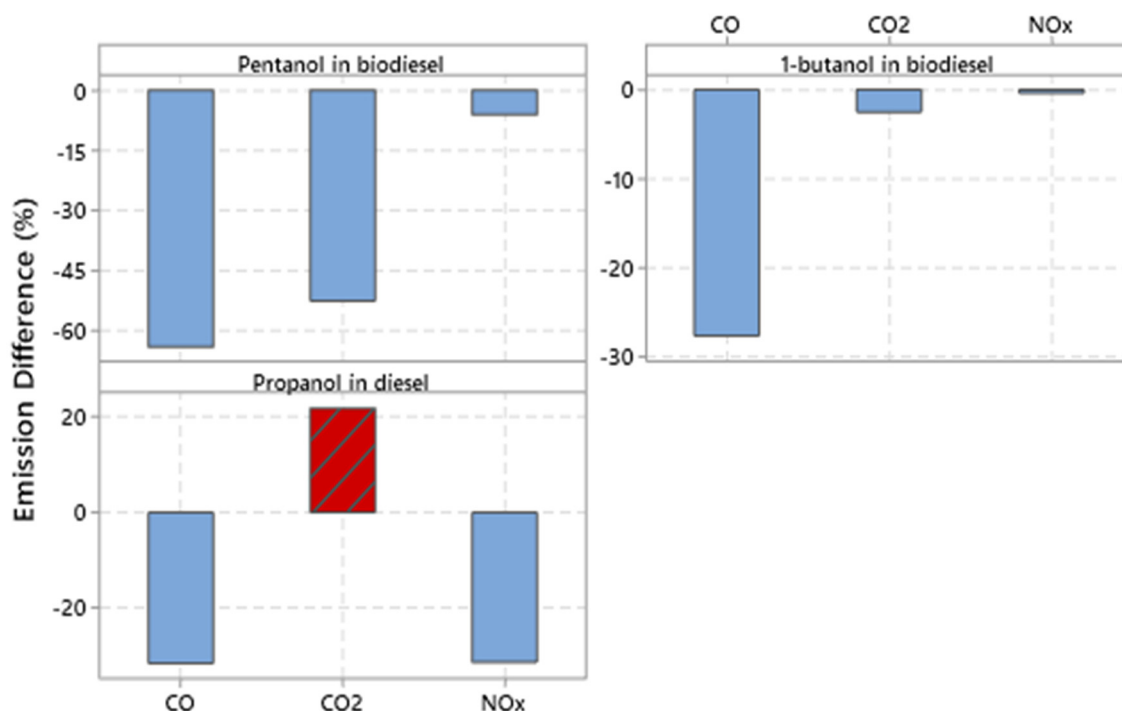
Figure 3. Emission differences of fuels with liquid additives compared to base fuels.

5.   Solid fuel additives

5.1. Effect of solid fuel additives on performance

Solid fuel additives are another important type of additive. Amirabedi [57] went above and beyond by incorporating Mn_2O_3 into the gasoline-alcohol mixture. She used gasoline that had been diluted with 10% ethanol. She then added 10 ppm and 20 ppm Mn_2O_3 as additional samples. The outcomes were very promising. In terms of efficiency, performance has improved. This is supported by Jayaraman's [58] findings, which investigate the effects of adding titanium oxide TiO_2 to a B20 blend in a CI engine. As a result, specific consumption has declined. At 25% load, B20 + 50 produces the lowest BSFC of 0.46 kg/kw-hr. At 18.16 kg load, the maximum BTE for B20 + 50 + EGR was 32.64 percent. The BTE of B20 with TiO_2 is higher than that of normal B20 because the TiO_2 improved combustion and released a high heat rate.

Jiangjun Wei [59] investigated the emission of CI engine operation with diesel-methanol blends using Aluminium Oxide Al_2O_3 as an additive. Among the highlights are reductions in BTE and BSFC of 3.6 and 3.7 percent, respectively. According to Örs [60], adding TiO_2 to biodiesel-butanol blends increased brake engine torque and power by 10.20 percent and 9.74 percent, respectively. BSFC, on the other hand, can be reduced by 27.73%. Amirabedi [57] discovered that the performance in terms of power and efficiency has improved. This finding is supported by Soner's findings [61]. In his experiment, adding 50 ppm of Al_2O_3 and CuO to diesel fuel resulted in increased engine power.

5.2. Effect of solid fuel additives on emissions

The research by Örs [60] showed that CO and HC have been reduced by around 14.96% and 34.39%, respectively. with the TiO_2 addition. However, the emission of CO_2 and NO was increased by 5.75% and 3.94%, respectively. Research by Amirabedi [57] achieved a 51.83% reduction of HC by using gasoline with 10% ethanol and 20 ppm Mn_2O_3 compared to that of baseline gasoline. This is achieved when the engine runs at full load and the speed is set at 2800 rpm. The CO was reduced by 24.09% with respect to the baseline gasoline fuel. However, CO_2 emissions increased by 13.27% in this experiment. Using aluminium oxide (Al_2O_3) as an additive, Jiangjun Wei [62] tested the emissions of a CI engine run with diesel-methanol blends. The results were lower CO and HC of 83.3% and 40.9%. However, the engine emitted a marginally higher NOX of 14.4%. A bar chart is plotted in Figure 4 to visualise the different effects of the solid fuel additives on the engine's emissions.
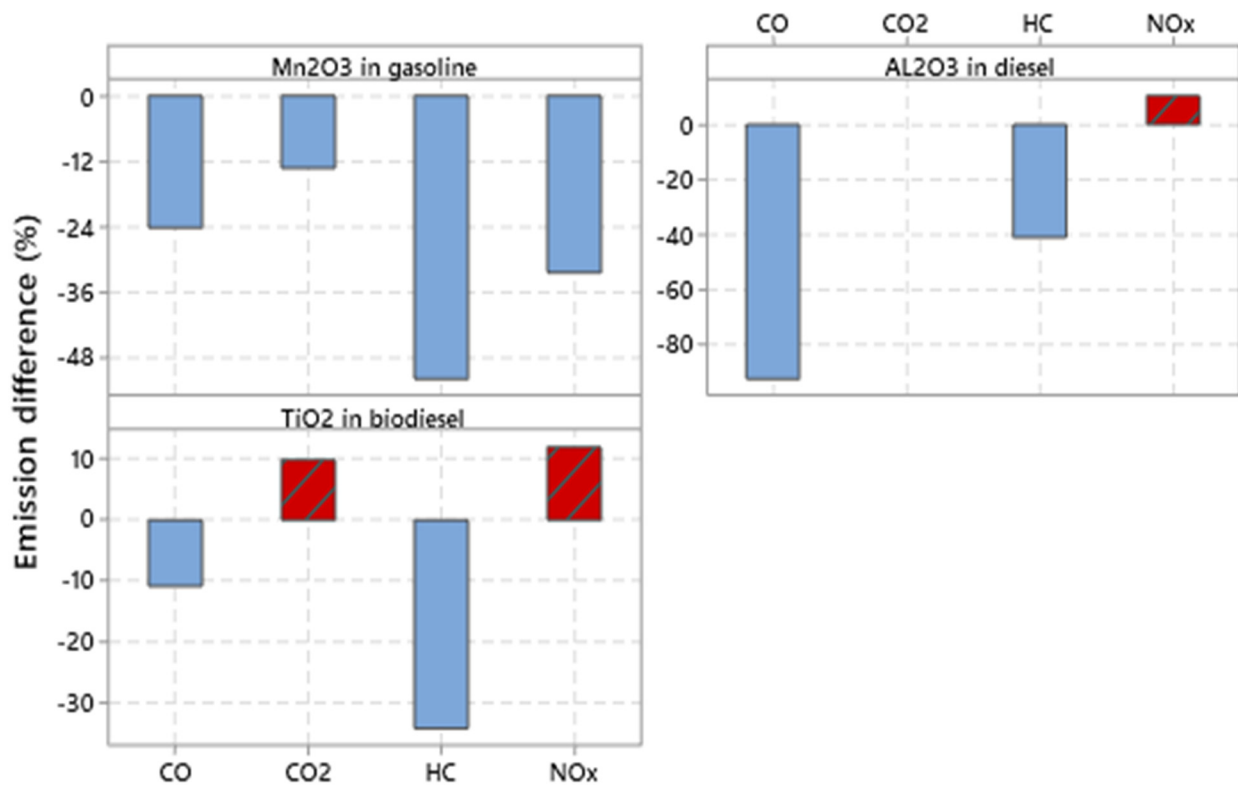

Figure 4. Comparison of emissions in percentage difference to base fuel with the addition of solid additives.

6. Carbon-based fuel additives

6.1. Effect of carbon-based fuel additives on engine performance

The section that follows discusses carbon-based fuel additives. This review focuses on carbon nanotubes and graphene. Heydari-Melaney [63] improved the performance of biodiesel-bioethanol mixtures by adding carbon nanotubes (CNT) and increasing torque, power, and BTE by 15.52%, 15.52%,

and 13.97%, respectively. BSFC, on the other hand, fell 11.73%. Similarly, Hosseini [64] used CNT as an additive in a CI engine that was powered by a diesel-biodiesel blend. The procedure for the experiment was carried out under full load with various blends and speeds. In his experiment, he discovered that the addition of CNT produced more torque than pure diesel fuel. He also discovered that power increased by 21.84% overall. BTE, on the other hand, was discovered to be decreasing from 1800 to 2800 rpm. This was caused by a decrease in volumetric efficiency. The addition of CNT reduced BSFC as well.

Gad [65] used carbon nanotubes and graphene nanosheets as fuel additives in B20 blends. CNTs and graphene nanosheets are mixed into B20 at concentrations of 25, 50, and 100 ppm to create fuel blends. Thermal efficiency for B20CNT100 and B20CNS100 improved by 8% and 19%, respectively, according to the results. In another significant study, Razzaq [66] investigated the use of graphene and dimethyl carbonate (DMC) as additives in biodiesel. The goal is to investigate the effects on performance and emissions. According to his observations, the BTE increased with a small amount of GNP. However, increasing the amount reduces the BTE. The reason for this could be due to the higher viscosity.

6.2. Effect of carbon-based fuel additives on engine emissions

In Hosseini's experiment [64], he discovered that under various conditions, the emission of a fuel blend with CNT additives was reduced by 40.38 percent when compared to neat diesel. In the case of CO_2, the average emission increased by 9.88 percent when all fuel blends with CNTs were compared to straight diesel fuel. The HC emissions of a fuel blend containing a CNT additive were reduced in general. In Gad's experiment [65], extremely large reductions in smoke thickness, CO, NO_x, HC, and with B20CNT100 are observed, which are 28 percent, 27 percent, 22 percent, and 28 percent, respectively. For smoke thickness, CO, NO_x, and HC, B20CNS100 obtained 54%, 47%, 44%, and 52%, respectively.

Tomar and Kumar [67] conducted a similar investigation using a single-cylinder four-stroke diesel engine (Kirloskar) and diesel-Schleichera Oleosa Biodiesel mixes with alumina nanoparticles and multi-walled carbon nanotubes. Based on their findings, the authors believe that the use of alumina and MWCNT-added substances could be an effective fuel reformulation strategy. NOx emissions decrease as a result of the presence of nano-added substances in D80B20C100 fuel, owing to the amazing spongy inclination of MWCNT nanoparticles.

Mei et al. [68] proposed a single-cylinder four-stroke air-cooled common-rail diesel engine operating at 3000 rpm with changing loads of 100%, 75%, 50%, and 25%. The authors used two different nanoparticles, CNTs and molybdenum trioxide (MoO_3), and mixed them with clean diesel at concentrations of 50 mg/L and 100 mg/L for each nanoparticle. According to the authors, CNTs have a greater potential than MoO_3 to reduce the entire estimated exhaust emission. CO, HC, NO_x, and smoke discharge from CNT100 were reduced by 9.6%, 11.4%, 8.9%, and 15.25%, respectively, when compared to the exhaust emission produced by Mo100, which is 6.8%, 7.5%, 5.2%, and 8.3%. The authors also stated that the results could be attributed to CNTs' superior heat conductivity and surface deficiency when compared to MoO_3.

In Heydari-Melaney [63] experiment where CNT was mixed into biodiesel-bioethanol mixtures, The CO and UHC reduced by 5.47% and 31.72%, respectively. However, NOx emission increased by 12.22%. According to Razzaq [66], an increase in HC emission was observed compared to that of

B30 with the addition of GNPs in biodiesel blends. However, if the concentration in GNP is increased further, the HC emissions are reduced significantly. The CO emission was also increased with the increasing engine speeds. This is valid for all tested blends. The reason for this observation is caused by the difference in air-fuel quantity entering the combustion chamber for different engine operating conditions. Normally, NOx emissions contributed to the high temperature in the cylinder. The high temperature oxidized the nitrogen which is the main component of air sucked by the engine. In Razzaq's experiment, the addition of GNPs in biodiesel blends reduced the NOx emission. This happens because GNP's presence improved the ID period.

Nivin Chacko [69] used GNP in an experiment that also showed a reduction in emissions, particularly NO. El-Seesy [70] discovered a reduction in emissions after using graphene nanoplatelets as an additive in jatropha biodiesel-diesel fuel. NOx, CO, and UHC emissions were reduced by 45 percent, 55 percent, and 50 percent, respectively. Another study by Debbarma discovered that adding 75 ppm of GNP to biodiesel improved engine performance, particularly BTE, BSFC, and combustion behaviour, especially at higher loads [71]. Figure 5 depicts a bar chart that depicts the various effects of carbon-based fuel additives on engine emissions.
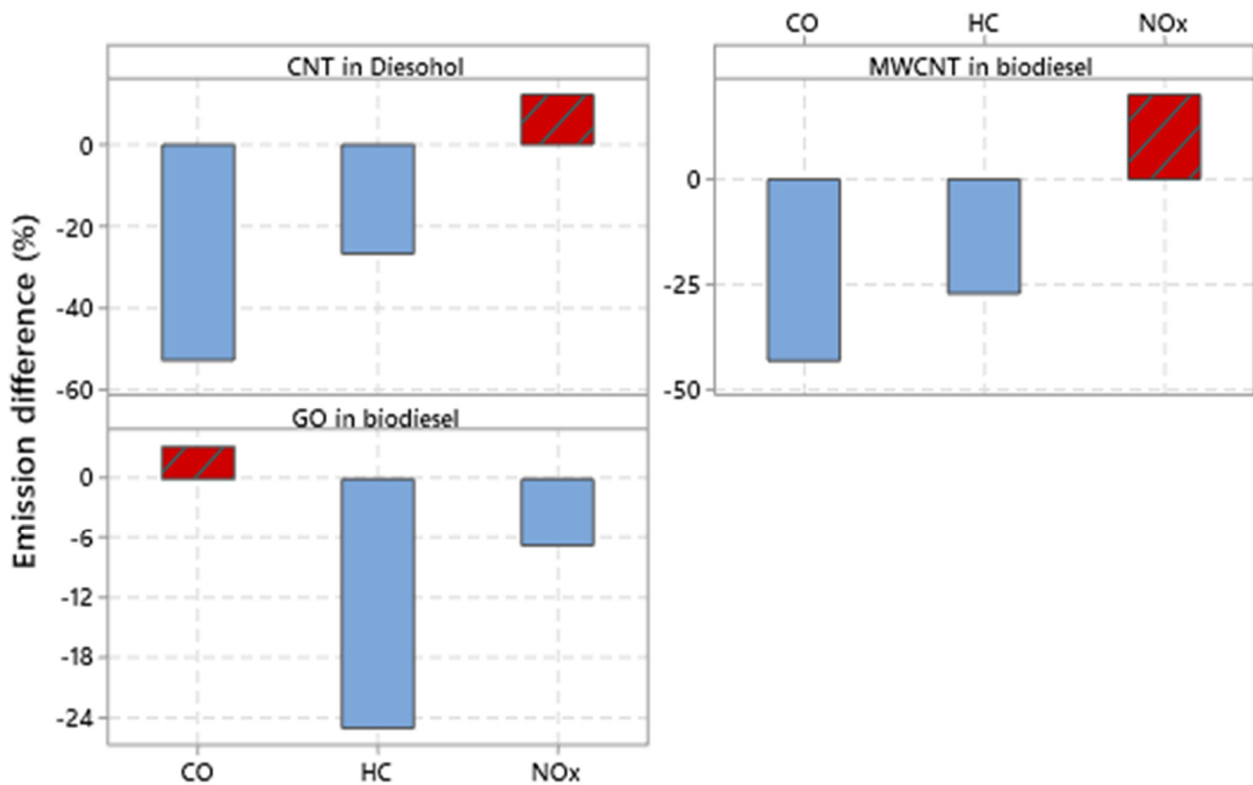

Figure 5. Comparison of emissions in percentage difference to base fuel with the addition of carbon-based additives.

In addition, a table to summarise the results from different experiments is depicted in Table 4 below:

Table 4. Effects of fuel additives on internal combustion engine performance and emissions.

Gaseous Additives

Ref.	Engine	Fuel	Additive	Method	Performance	Emissions
[29]	4-cylinder Diesel	B20	$Al_2O_3 + H_2$	Full load between 1200–2800 rpm	Power ↑ BTE ↑ BSFC ↓	CO ↓ CO_2 ↑ NO_x ↑
[37]	1-cylinder Diesel	B20	H2	Full load. Various speed	Torque ↑ Power ↑ BTE ↑	CO ↓ CO_2 ↓ HC ↓ NO_x ↑
[43]	1-cylinder Diesel	Diesel	H2	Constant speed 1500 rpm	BTE ↑	CO ↓ CO_2 ↓ HC ↓ NO_x ↑
[45]	1-cylinder Diesel	Biodiesel	Acetylene	1500 rpm Different loads	BTE ↑	CO ↓ HC ↓ NO_x ↓
[38]	4-cylinder diesel	diesel	LPG	different Speeds and loads	Torque ↑ Power ↑	HC ↓ NO_x ↓

Liquid Additives

Ref.	Engine	Fuel	Additive	Method	Performance	Emissions
[48]	1-cylinder Diesel	Hydrous ethanol-Diesel	Pentanol and Octanol	Different blends at different loads	Power ↓ BTE ↑ BSFC ↑	CO ↓ CO_2 ↓ NO_x ↓
[72]	1-cylinder Diesel	Diesel	Alcohol	Constant speed 2500 rpm. Different alcohol percentage.	BTE ↓	CO ↓ HC ↑ NO_x ↑
[52]	1-cylinder Diesel	Biodiesel	Pentanol	3000 rpm Different engine loads	BSFC ↑ BTE ↓	CO ↓ CO_2 ↑ NO_x ↓

Solid Additives (Metal-based)

Ref.	Engine	Fuel	Additive	Method	Performance	Emissions
[73]	1-cylinder Diesel	biodiesel	CuO	Various loads	BTE ↑ BSFC ↓	CO ↓ HC ↓ NO_x ↑
[62]	1-cylinder Diesel	Diesel-methanol	Al_2O_3	Constant speed 1400 rpm. Different loads	BTE ↑ BSFC ↓	CO ↓ HC ↓ NO_x ↑
[60]	1-cylinder Diesel	Waste Cooking Biodiesel	TiO_2	Various engine speeds. Full load	Torque ↑ Power ↑ BSFC ↓	CO ↓ CO_2 ↑ HC ↓ NO ↑

Solid Additives (Carbon-based)

Ref.	Engine	Fuel	Additive	Method	Performance	Emissions
[63]	1-cylinder Diesel	Diesohol (diesel + alcohol)	CNT	Full load at different rpm	Torque ↑ Power ↑ BTE ↑ BSFC ↓	CO ↓ CO_2 ↓ HC ↓ NO_x ↑
[67]	1-cylinder Diesel	Diesel & Diesel-biodiesel blend	MWCNT	Constant speed 1500 rpm. Different loads	BTE ↑ BSFC ↓	CO ↓ NO_X↓
[64]	1-cylinder Diesel	Diesel-biodiesel blend	CNT	Full load. Different blends and speed	Power ↑ Torque ↑ BTE ↓ BSFC ↓	CO ↓ CO_2 ↑ HC ↓ NO_X ↑
[66]	1-cylinder Diesel	Palm oil biodiesel	Graphene Oxide Nanoplatelets (GNP)	Varying engine speed. Different blends	BTE ↑ BSFC ↑	HC ↓ CO ↑ NO_X↓
[74]	1-cylinder Diesel	Jatropha biodiesel	Graphene Nanoplatelets (GNP)	Different Speeds, different loads, different fuel blends	BSFC ↓	CO ↓ HC ↓ NO_X ↓

7.   Prediction of the effects on performance and emissions

Further, the study extends to the prediction of the effects on the performance and emissions of a diesel engine. The articles with predictions or simulations of the effects are being studied. Different research articles with additional predictions on the additive effects on the performance and emissions are selected. The following is a table summary of the effects that additives have on performance and emissions.

In addition to understanding the effects the additive has on the fuels, the researchers go on further to predict the engine performance and emissions. The most popular method to predict the response of different factors in a study is called response surface methodology (RSM).

According to Table 5, no prediction research has been conducted on the effects of graphene additives on the performance and emissions of diesel engines. As a result, this is an opportunity for research to fill this gap.

Table 5. Predictions on the effects of fuel additives on engine performance and emissions.

No	Base fuel	Additives/blends	Parameters	Prediction Method	Software/Tool	Reference
Liquid Additives						
1	Waste plastic oil	ethanol	HC, CO, SFC	DOE with Full factorial design	Minitab	[75]
2	diesel	DME	BTE, BSEC	Double Weibe	-	[76]
3	diesel	higher alcohol additive (Decanol)	BSFC, BTE, CO, CO_2, HC, NO_x	ANN and RSM	Design Expert	[77]
4	diesel	pongamia methyl esters	BTE, UHC, NO_x	RSM	Minitab	[78]
Gaseous Additives						
5	diesel	CNG	BSFC, BTE, CO, CO_2, HC, NO_x	RSM	Minitab and Design Expert	[35]
6	diesel	LPG	BSEC, BTE	Fuzzy Logic	ANFIS	[79]
7	diesel	Hydrogen	CO, CO_2, HC, NO_x	DOE with Taguchi	Minitab	[80]
Solid Additives (Metal)						
8	biodiesel	NiO	BSFC NO_x, HC, CO	RSM	Design Expert	[81]
9	biodiesel	Alumina nanoparticles	BSFC, BTE, CO, NO_x	RSM	Design Expert	[82]
10	biodiesel	TiO_2, and Al_2O_3 nanoparticles	BSFC, BTE, CO, NO_x	RSM	Design Expert	[83]
Solid Additives (Carbon based)						
11	diesel and biodiesel	MWCNT	BSFC, CO, NO_x	RSM	Design Expert	[83]
12	diesel and biodiesel	MWCNT	BTE, BSFC, UHC, CO, NO_x	RSM	Design Expert	[84]
13	fusel oil	nano- biochar	Torque, Power, BSFC, BTE, CO, NOx	RSM	Design Expert	[85]

8. Conclusion and future recommendation

According to the review, many different types of fuel additives have been developed. Many additives were available in gaseous, liquid, and solid forms. Many solid materials are being considered as fuel additives as nanotechnology advances. Carbon-based nanomaterials have shown a lot of promise in terms of improved performance and lower emissions. New graphene materials have also been discovered and added to the list of additives; however, the depth of research is still insufficient. More information on various types of engines and configurations would aid us in establishing greater accuracy on this subject.

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Conflict of interest

The authors declare no conflicts.

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