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Assessment of gasoline engine performance and emissions powered by different gasoline-water ammonia blends: A Review

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A B S T R A C T

As a result of a large number of diseases due to environmental pollution resulting from emissions and fast energy depletion. Many researchers resorted to methods to produce a mixture that can be used as fuel and fight these issues. In this work, a mini review was concluded through previous studies to highlight and investigate the effect of using water ammonia solution on the characteristics of IC engines with a special focus on gasoline engines. The main findings showed decreased engine performance because ammonia has a lower calorific value and energy density. Also, most of the previous contributions highlighted a significant reduction in CO_2 and CO emissions for all loads. Using ammonia solution increased NOx emissions slightly.

1. Introduction

The world's use of primary energy has substantially expanded in recent decades due to rapid economic expansion and population growth. Around the world, the three main energy sources continue to be coal, oil, and natural gas. Burning fuels such as coal, oil, and natural gas emit pollutants like volatile organic compounds, CO_2, CO, SO_2, and NOx [1-4]. Several alternative fuel-vehicle combinations are being studied to reduce greenhouse gas emissions and put a limit on the use of fossil fuels. An encouraging, carbon-free fuel is ammonia. Ammonia is a colourless gas consisting of one nitrogen atom and three hydrogen atoms. Also, it is hygroscopic and easily dissolved in water and humidity, pure. Ammonia is corrosive, nevertheless, because of its alkaline characteristics. Despite this, it is among the industrial chemicals that are most frequently produced globally.

The agricultural sector uses more than 75% of the ammonia produced as fertilizer. Ammonia can also be used as a working fluid in a refrigeration cycle. Ammonia is also frequently used in household cleaning products. The amount of ammonia produced globally is depicted in Figure 1. [5-7]. The amount of ammonia produced and consumed is expected to rise rapidly. Global ammonia production will reach 1.2 billion metric tons in 2050 and continue to grow tremendously. There will be roughly 8.2 times as much ammonia produced in 2020. An economic cycle of ammonia from production to utilization is presented in Figure. 2 [7].

Ammonia can be used as fuel for ICE (internal combustion engines) [8-14]. Since it is liquid at around 9 bars at ambient temperature and has a smaller volume and requirement for lightweight, affordable tanks, it may be stored onboard more conveniently than hydrogen [6]. In addition, liquid ammonia has 1.77 times the volume of hydrogen [15].

The two most popular engines used are compression ignition (CI) engines and spark ignition (SI) engines, which employ various methods to ignite

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and consume the fuel. When compared to the other categories, each offers many advantages and disadvantages. It is important to point out that ammonia, when used for combustion, has some side effects (challenges), such as high ignition temperature, low flame velocity, and slow chemical kinetics. Since there are increasing research efforts to minimize the impacts and improve the combustion, performance, and emissions parameters. Many fuels are used in IC engines, as shown in Table 1 [16-21]. Also, the use of ammonia in research started clearly in 2010, as shown in Figure 3, as there are a few studies, and interest in it increased at the beginning of 2020 [22].

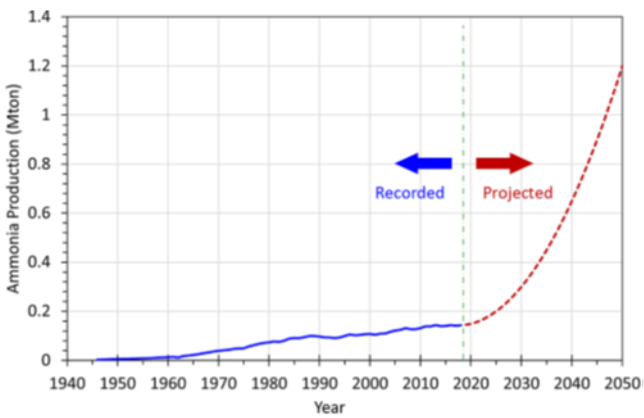

Figure 1. Production rates of ammonia globally [7]

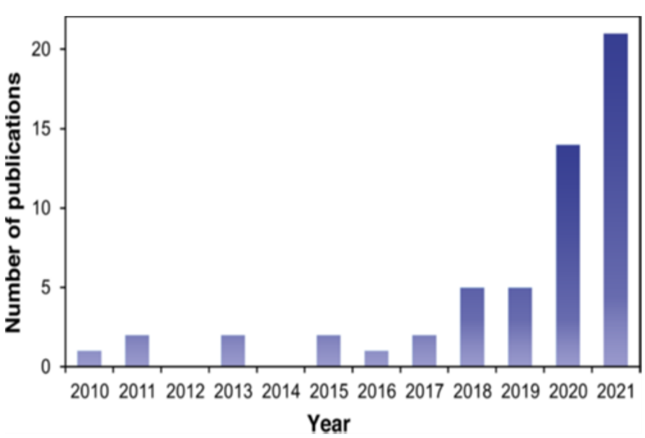

Figure 2. The number of publications about ammonia research that have been published every year since 2010 [22]

Ammonia is a carbon-free energy source because it contains hydrogen; however, it has a lesser heating value than gasoline or diesel (DF) [23]. In CI engine, ammonia and engine fuel co-combust. This approach uses two supply systems, one for alternate fuel that is frequently injected into the intake manifold and one for supply to the engine cylinder [24, 25]. Additionally, ammonia is extremely simple to store as a liquid or gas and can simply be liquefied and stored at 300 K ambient temperature and around 10 bar of pressure [12, 26]. The use of ammonia in diesel engines has also been researched using a variety of approaches, even though it has a high self-ignition temperature [27]. Better volumetric efficiency is achieved with liquid-phase ammonia induction because the ammonia cools the input mixture [28].

Generally clear shortage studies of using NH_3 as a fuel in internal combustion engines experimentally and numerically, as well as prominently, a little research effort on the use of ammonia solution in spark ignition engines, so the object of this study aims to review how employing various proportional blends of water ammonia solution (WAS) and gasoline fuel (GF) will affect the SI engine's performance. Since an apparent shortage of the use of ammonia solution in IC engines in IRAQ, this article aims to review the recently published articles in this field. It opens the door to investigate the effect of using ammonia solution on the characteristics of diesel and gasoline engines experimentally and theoretically.

2. Previous studies

2.1. Effect of using NH_3 and WAS on the characterize of diesel

Currently, solutions of ammonia or ammonia with diesel fuel (DF) in CI engines attract researchers' attention. In contrast, Sahin et al. [29] conducted experimental investigations to see how the amount of ammonia solution (25 percent ammonia with 75 percent diesel fuel DF) used in a small diesel engine's performance and emissions were impacted by DF. A carburetor fed water ammonia solution (WAS) to the engine manifold's intake air. The result showed that adding WAS increased the engine's overall effective efficiency under all operating situations. CO_2 emissions were decreased but NOx in the exhaust gas increased. In another investigation, Reiter et al. [9] explored how adding gas ammonia into the intake manifold might affect the CI engine's emissions and combustion characteristics. To produce continuous power in the working range of 40% to 60% of the input energy delivered by ammonia and to achieve the best fuel efficiency, they evaluated various ammonia/diesel ratios. According to the findings, NO emissions dramatically increase when ammonia energy makes up more than 60% of the overall energy, but soot emissions drop for larger ammonia ratios.

Pavlos. et al. [30] burned ammonia and diesel together in a dual-fuel system to reduce carbon-based emissions significantly. Because of the fuel-bound nitrogen, ammonia dual-fuel combustion currently has comparatively large unburned ammonia and NOx emissions. Thus, it has been suggested that utilizing several injection techniques will help reduce NOx and unburned ammonia emissions simultaneously. Aaron et al. [12] utilized ammonia and diesel fuel in a dual-fuel system. The combustion process started with injecting diesel fuel into the cylinder while ammonia vapor was pumped into the intake manifold. Results showed that as ammonia concentration increased, ignition delay also increased because ammonia burned at a lower temperature, and the peak cylinder pressure also dropped. To enhance combustion efficiency and lower exhaust ammonia emissions, direct ammonia with diesel injection strategies should be used to optimize combustion. Caneon et al. [31] used NH_3 as a primary fuel for CI engines operating in a dual fuel combustion mode with second fuels such (diesel, dimethyl ether, kerosene, and hydrogen), which were shown to be efficient for burning ammonia. The high auto-ignition temperature of ammonia requires secondary fuel in dual fuel mode for CI engines. According to this study, increasing the ammonia content of the fuel mixture decreased CO and CO_2 emissions and negatively impacted engine performance because ammonia has a lower calorific value and energy density.

The study of Ebrahim et al. [32] showed how to use ammonia as a primary fuel in a dual-fuel system with biodiesel. To start the combustion of the pre-mixed ammonia-air combination, a pilot dose of biodiesel is sprayed into the cylinder of a single-cylinder diesel engine that has been modified to inject ammonia into the intake manifold. The findings proved that ammonia could replace 69.4% of the energy from the biodiesel input; however, there was little reduction in the brake thermal efficiency.

Additionally, enhancing the ammonia decreased CO_2, CO, and HC emissions while increasing NOx emissions. Michal et al. [33] tested experimentally the burning of diesel fuel in a solution of water ammonia. A stationary single-cylinder dual-fuel diesel engine is used.

Three engine operation modes tested in the experiments, and a change in the WAS between 0% and 17%energy fraction at 60% load.
The combustion of DF and WAS led to a rise in the heat release rate and an extension of the ignition delay time and combustion time.

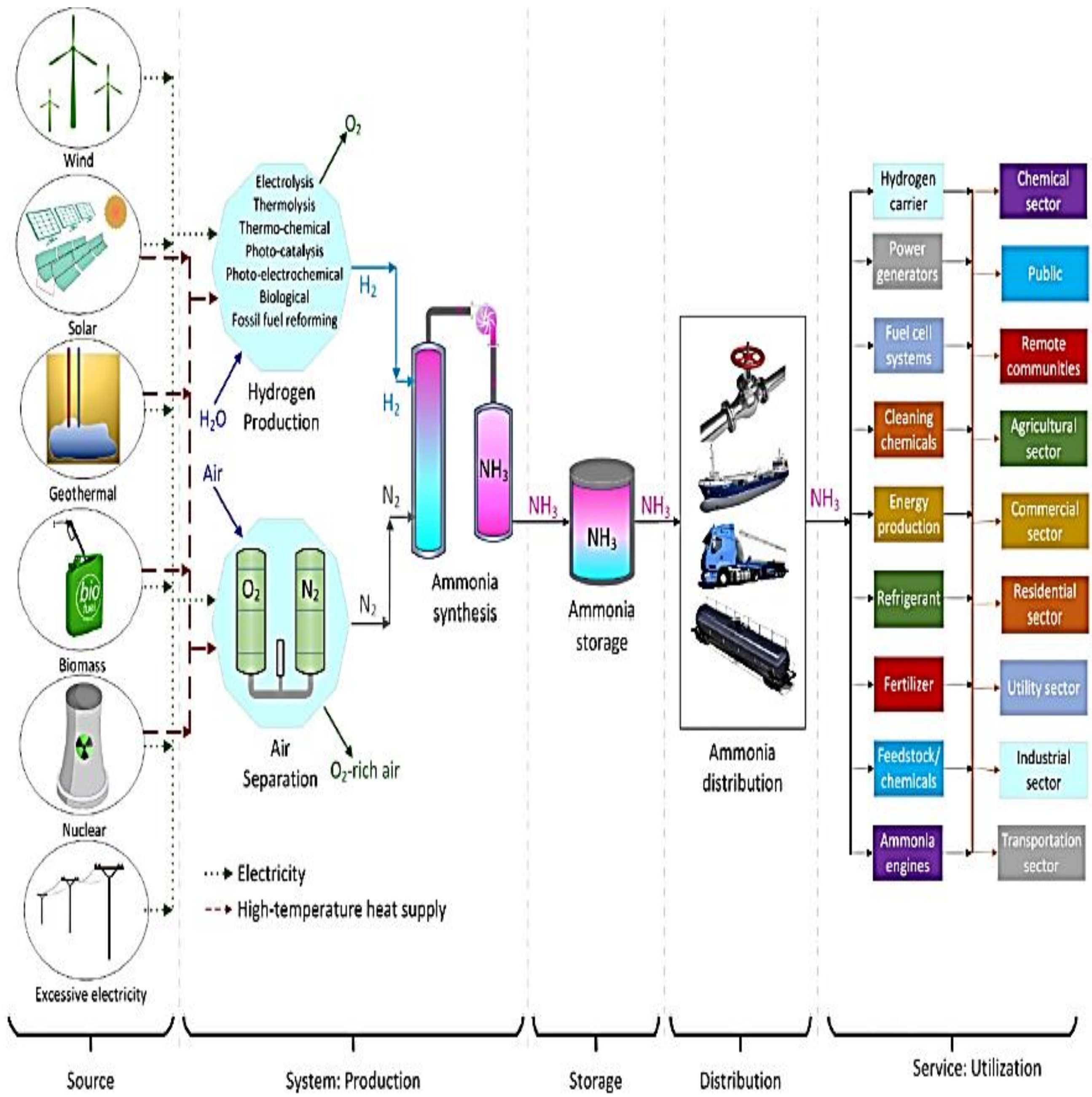

Figure 3. Ammonia life cycle from production to utilization [7]

Chatha et al. [14] studied the co-combustion of pure hydrogen and ammonia with diesel in the CI engine. The study used two engine loads in terms of indicated mean effective pressure (IMEP): 3 bar and 5 bar. Conventional diesel was injected into the cylinder to start combustion, whereas ammonia/air was injected into the intake manifold. According to the study, CO_2 emissions from diesel were reduced. Using NH_3 alone has shown to be more beneficial regarding engine stability and thermal efficiency. Borett et al. [34] established a dual-fuel combustion system by injecting diesel and NH_3 into the cylinder. The results presented an increase in power density and efficiency. According to the simulations, it is possible to precisely control the engine load when using direct injection of both fuels. Ryu et al. [35] developed practical methods for using ammonia in direct-injection CI engines by using three different mixtures in the experiments: 100% dimethyl ether (DME), 40% DME-60% NH_3, 60% DME-40% NH_3. The results demonstrated that engine performance declined as the ammonia concentration in the fuel mixture rose. As ammonia concentration increased, engine speed and power showed restrictions compared to 100% DME. Because NH_3 has a high resistance to auto ignition, the maximum timing for the greatest torque must be advanced with increased ammonia concentration in the fuel combination.

2.2. Effect of using NH_3 on the Performance of SI engine

Further studies on the use of ammonia in SI engines are addressed in the following lines. Shubham et al. [36] investigated how the direct injection of gaseous ammonia affects an SI engine's combustion properties and exhaust emissions. In this investigation, an air ammonia mixture with hydrogen was used. In the gaseous phase, hydrogen and ammonia are injected by electro-injectors. The results of the experiments supported the requirement for adding hydrogen to the air-ammonia mixture to speed up combustion. Only NOx is released into the atmosphere in small amounts, with a maximum of 1700 ppm at full load and 3000 rpm. It has been shown that ammonia/hydrogen combinations provide excellent fuel for SI engines. Shawn et al. [10] studied ammonia and gasoline in dual-fueled SI engines. Ammonia is delivered into the intake in the liquid phase. Gaseous ammonia induction with a combustion booster must be employed to limit ammonia emissions from the engine and obtain satisfactory combustion efficiency. When the ammonia and gasoline is working satisfactorily in terms of combustion stability and overall thermal efficiency, the engine-out exhaust emissions accurately reflect the proportioning of fuel content in the intake mixture. When ammonia is mixed with gasoline, standard oxygen sensors, and normal three-way catalytic converters can be used to control emissions, but the lean operation must be completely avoided.

Gross and Kong [37] explored the mixing of ammonia and dimethyl ether (DME) under high pressure. The DME is used to start combustion. The engine's injection system is modified to stop the fuel mixture from vaporizing. Results demonstrated that using ammonia limited engine load situations due to its higher auto-ignition temperature, poorer combustion rate, and longer ignition delays. The temperature and pressure of combustion is lowered. The CO, HC, and NOx emissions are increased. Ryu et al. [38] examined the impact of gaseous ammonia direct injection on engine output and exhaust emissions of dual-fueled gasoline-ammonia SI engines. The results showed that power increases based on the gasoline engine as the ammonia injection timing and duration are advanced and increased. Due to the low combustion efficiency of ammonia, direct injection of ammonia results in a minor reduction of CO_2 and CO for all loads and considerable rise in HC and NOx.

Yurttas et al. [39] used hydrogen-ammonia (H_2/NH_3) (70/30), hydrogen (100%), and gasoline. Different engine speeds and ignition timings have been experimentally analysed for two-cylinder SI engines. Investigations have been done on SFC, torque, power values, and CO, HC, and NO emission values. Ammonia and hydrogen have the benefit of not containing carbon, which prevents the engine from emitting carbon oxides. Farhad et al. [40] examined the effect of ammonia port injection on a gasoline/ethanol dual-fuel engine. An injector placed before the engine intake manifold injects ammonia into the system. The combustion process is numerically analysed using the basic frequently employed in the mathematical modelling of SI engines, the two-zone combustion model. Across the engine speed range, a considerable reduction in NOx emissions of about 50% was seen. The engine equivalent BSFC, CO, and HC emissions increased by (3%, 30%, and 21%, respectively, at the 10% NH_3 injection ratio.

Stefano et al. [41] focused on analysing the behaviour of a 4-stroke twin-cylinder SI engine that is fuelled by ammonia + hydrogen. An efficient electronic fuel injection system that injects ammonia and hydrogen in the gaseous phase is used in this experiment. The results of the experiments supported the necessity to accelerate combustion by adding hydrogen to an air-ammonia mixture, with ratios that are primarily dependent on load and less so on engine speed. The experimental findings showed that hydrogen must be added to air-ammonia mixtures to promote ignition and boost combustion velocity. Charles et al. [42] investigated a modern single-cylinder SI engine powered by gaseous ammonia/hydrogen/air mixtures at various hydrogen percentages, equivalency ratios, and intake pressures. The engine was created for gasoline direct injection. Ammonia is a particularly suitable fuel for SI engine operation, as evidenced by the significant power outputs that might be achieved with proposed efficiencies greater than 37%. Higher NOx and unburned NH_3 exhaust concentrations were also seen in fuel-rich and fuel-lean conditions, respectively.

Starkman et al. [43] conducted a similar experiment on a SI engine from Collaborative Fuel Research (CFR); at 1800 rpm and CR = 8:1, the lowest value of 4-5% by mass is recorded. The power output is further shown to benefit from raising the compression ratio and the cylinder wall temperature, and direct injection of liquid NH_3 is suggested as a further volumetric efficiency enhancement. However, the specific fuel consumption efficiency was inferior to those for operations with gasoline. The result showed that when compared to hydrocarbon at peak power, the specific fuel consumption when using ammonia is raised by a factor of 2 and 2-1/2 when compared to maximum economy. As long as small amounts of hydrogen are incorporated into the fuel flow, performance parameters such as those that are controlled by engine speed, spark timing, and manifold pressure are not significantly different with ammonia than with hydrocarbons. With ammonia, the indicated output is reduced to roughly 70%, but not more than 77%, of that with hydrocarbon. If the ammonia must be partially broken down before entering the cylinders, the theoretical 77% performance cannot be achieved.

Rui et al. [44] used a computational approach to evaluate the properties of ammonia-air combustion at elevated temperatures of typical SI engine operation (101.3-3424.8) kPa and (298-671) K. While the peak value of adiabatic flame temperature was assumed to be at stoichiometric condition, it was found that the laminar burning velocity peaked at an ammonia-air equivalency ratio of about 1.1. It was found that at larger compression ratios, ammonia was utilized more quickly. The final ammonia concentration is lower than the level concerned for ammonia-rich combinations in this investigation. Nitric oxide levels in the ammonia-rich mixture were lower, likely because of an oxygen deficiency.

Table 1. Comparison of IC engine fuels with ammonia [13-18].

Properties	Gasoline	Diesel	LPG	CNG	Hydrogen	Ammonia
Formula	C_8H_{18}	$C_{12}H_{32}$	C_3H_8	CH_4	H_2	NH_3
LHV MJ/Kg	44.5	43.5	45.7	38.1	120.1	18.8
Flammability (vol. %)	1.4-7.6	0.6-5.5	1.81-8.86	5-15	4-75	16.25
Flame- speed (m/s)	0.580	0.870	0.830	8.450	3.510	0.150
Auto ignition temp. (C)	300.0	230.0	470.0	450.0	571.0	651.0
Minimum ign. energy (MJ)	0.14	-	-	-	0.018	8
Flash point (C)	-42.70	73.80	-87.70	-184.40		-33.40
Octane no.	90-98	-	112	107	>130	110
Density (kg/m^3)	698.3	838.8	1898	187.2	17.5	602.8
Energy density (MJ/m^3)	31074	36403	86487	7132	2101	11333
heat of Vap. (kJ/kg)	71.780	47.860	44.40	104.80	00	1369
(Storage method)	(liquid)	(liquid)	(Comp. liquid)	(Comp. gas)	(Comp. gas)	(Comp. liquid)
(Storage temp. (C))	25.0	25.0	25.0	25.0	25.0	25.0
(Storage pressure(kpa))	101.3	101.3	850	24821	24821	1030

Table 2. Summary of studies on the use of ammonia in CI engines

References	Year	Fuel used	Inducting method	Main results
Reiter et al. [6]	2008	Ammonia with DF	Inducting gas ammonia into the intake manifold	NO emissions dramatically increase when ammonia energy makes up more than 60% of the overall energy, but soot emissions drop for larger ammonia ratios.
Chatha et al. [11]	2012	Diesel-NH_3-H_2	DF was injected into the cylinder, whereas ammonia/air was injected into the intake manifold.	CO_2 emissions reduced. Using NH_3 alone has shown to be more beneficial in terms of engine stability and thermal efficiency.
Borett et al. [31]	2017	Ammonia-Diesel	Direct injection of diesel and NH_3 into the cylinder	Increase power and efficiency. According to the simulations, It is possible to precisely control the engine load when using direct injection of both fuels.
Sahin et al. [26]	2018	WAS with DF	WAS fed to the engine manifold's intake air	Increased the engine's overall efficiency under all operating situations. CO_2 was decreased, but NO_x increased.
Pavlos et al. [27]	2020	Ammonia with DF	Using dual-fuel system	Excessive emissions of NOx and unburned ammonia.
Aaron et al. [9]	2021	Ammonia with DF	Ammonia vapor was delivered into the intake manifold	When ammonia concentration increased, ignition delay also increased. The peak cylinder pressure dropped.
Michal et al. [30]	2021	Diesel-WAS	DF should be directly injected into the engine's combustion chamber, and ammonia water should be injected into the suction manifold using a low-pressure injector.	Increase in the heat release rate and an extension of the ignition delay time and combustion time. Also, there is a decrease in CO emissions.
Caneon et al. [28]	2022	Diesel-DME+Ammonia	Dual-fuel system	Increasing the ammonia content decreased CO emissions but also negatively impacted the engine performance because ammonia has a lower calorific value and energy density.
Ebrahim et al. [29]	2022	Ammonia-air+biodiesel	Inducting ammonia into the intake manifold.	Ammonia can replace 69.4% of the energy from the biodiesel input. Decreased CO_2, CO, and HC emissions while increasing NO emissions.

Table 3. Summary of studies on the use of ammonia in SI engines

References	The year	Fuel used	Inducting method	Main results
Starkman et al. [40]	**1967**	Ammonia and hydrogen	Direct injection of liquid NH3 in the cylinder	Peak power was raised by a factor of 2. The indicated output is reduced to roughly 70%
Rui et al. [43]	**2003**	ammonia-air	the mixture was ignited into the flame	laminar burning velocity peaked at an ammonia-air equivalency ratio of about 1.1. For ammonia-rich combinations, the final ammonia concentration is lower than the level concerned
Shawn et al. [7]	**2009**	Ammonia and gasoline	Ammonia inducted through the intake manifold	stability of combustion and overall thermal effectiveness, and control emissions by using standard oxygen sensors and normal three-way catalytic converters
Gross et al. [34]	**2013**	Ammonia and DME	Direct injection into the cylinder	Longer ignition delay, increasing CO, HC, and NOx emissions.
Ryu et al. [35]	**2013**	Gasoline-ammonia	Direct injection into the cylinder	Power increases as the ammonia injection timing advances and increases. Reduction of CO_2 and CO for all loads
Stefano et al. [38]	**2013**	Ammonia and hydrogen	Electro-injectors are used to inject hydrogen and ammonia into the gaseous phase	, reduction of engine performance. Only NOx is released into the atmosphere in small amounts, with a maximum of 1700 ppm at full load and 3000 rpm.
Shubham et al. [33]	**2016**	A mixture of ammonia and hydrogen	Direct injection of gaseous ammonia and hydrogen	Only NOx is released in small amounts, with a peak of 1700 ppm at full load and 3000 rpm.
Yurttaş et al. [36]	**2016**	Hydrogen-ammonia	Inducting to the engine's intake port.	The highest efficiency and extremely low CO, HC, and CO2 emission levels were observed.
Charles et al. [39]	**2019**	ammonia/hydrogen/air mixtures	Direct injection Into cylinder	large power outputs, efficiencies higher than 37%, showing that NH3 is a very suitable fuel for SI engines with higher NOx and unburned NH_3 exhaust
Farhad et al. [37]	**2021**	Ammonia gasoline/ethanol	Ammonia inducted through the intake manifold	A reduction in NOx emissions of about 50% was seen. The engine BSFC, CO, and HC increased by 3%, 30%, and 21%, respectively, with a 10% ammonia ratio.

3. Summary

A study of previous research works revealed the following points:

1. Ammonia can be considered a promising substance that can be used as a fuel for IC engines to reduce exhaust carbon emissions.
2. Ammonia cannot be used alone, it must be used along with any hydrocarbon fuel such as hydrogen, gasoline, and diesel.
3. The engine performance decreased because ammonia has a lower calorific value and energy density.
4. Most of the previous contributions highlighted a significant reduction in CO_2 and CO emissions for all loads.
5. Using ammonia increases NOx emissions slightly.
6. Further research is recommended to study the use of GF blended with WAS experimentally and numerically.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

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