



# Hydrogen and Ammonia Fuels for Spark-Ignition Engines: A Review of Carbon-Free Combustion

<sup>1</sup> Deepak Madhivanan, <sup>2</sup> Prakash Thiyagarajan

<sup>1</sup> Research Scholar, <sup>2</sup> Associate Professor

<sup>1</sup> Engine Testing Laboratory, Department of Automobile Engineering, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, 603203, Tamil Nadu, India

**Abstract:** The urgent need to decarbonize the transportation sector has intensified research into carbon-free alternative fuels, with hydrogen (H<sub>2</sub>) and ammonia (NH<sub>3</sub>) emerging as promising candidates for spark-ignition (SI) engines. This review comprehensively examines the combustion, performance, and emission characteristics of SI engines operating on hydrogen, ammonia, and their blends with gasoline. Hydrogen, characterized by its high flame speed and wide flammability limits, significantly enhances combustion completeness, leading to improved thermal efficiency and reductions in carbon-based emissions (CO, HC). However, its high adiabatic flame temperature exacerbates nitrogen oxide (NO<sub>x</sub>) emissions and increases knock propensity. Conversely, ammonia, while carbon-free, suffers from low reactivity, slow flame speed, and high ignition energy, often resulting in combustion instability and incomplete combustion. The combinational impact of hydrogen and ammonia, where hydrogen as a combustion stimulator effectively mitigates ammonia's poor combustibility, enabling stable lean-burn operation. Nevertheless, this strategy introduces a complex trade-off between minimizing unburned ammonia slip and controlling NO<sub>x</sub> and nitrous oxide (N<sub>2</sub>O) emissions. The review concludes that the successful integration of these fuels necessitates advanced engine management strategies including optimized injection systems (e.g., direct injection for hydrogen), advanced ignition technologies, and exhaust gas recirculation coupled with tailored after treatment systems to address nitrogenous emissions, paving the way for practical, high-efficiency, and ultra-low emission SI engines.

**Keywords:** Hydrogen, Ammonia, Spark-Ignition Engine, Dual-Fuel Combustion, NO<sub>x</sub> Emissions, Combustion Stability, Alternative Fuels.

## I. INTRODUCTION

The reliance on fossil fuels for transportation and power generation has raised concerns about global warming, air pollution, and energy security. Spark-ignition (SI) engines, widely used in the automotive sector, are under increasing pressure to adopt carbon-neutral fuels. Among potential candidates, hydrogen (H<sub>2</sub>) and ammonia (NH<sub>3</sub>) are gaining attention due to their renewable production potential and compatibility with existing engine technologies.

**Table.1 Carbon footprint in worldwide [1], [2]**

Country	Annual CO <sub>2</sub> or GHG Emissions (GtCO <sub>2e</sub> )	Share of Global Emissions (%)	CO <sub>2</sub> Emissions Per Capita (tone CO <sub>2</sub> / person)
China	15.9 GtCO <sub>2e</sub> (2023)	30.1 %	8.9 t (2022)
United States	6.0 GtCO <sub>2e</sub> (2023)	11.3 %	14.2 t (2022)
India	4.1 GtCO <sub>2e</sub> (2023)	7.8 %	1.89 t (2022)
European Union	3.2 GtCO <sub>2e</sub> (2023)	6.1 %	—
Russia	2.7 GtCO <sub>2e</sub> (2023)	5.0 %	11.4 t
Brazil	1.3 GtCO <sub>2e</sub> (2023)	2.5 %	2.22–2.15 t (2022)
Indonesia	1.2 GtCO <sub>2e</sub> (2023)	2.3 %	2.48 t (2022)
Japan	1.0 GtCO <sub>2e</sub> (2023)	2.0 %	8.66–8.4 t
Global total	—	—	4.4–4.8 t

**Table.2 Fuel properties of ammonia, hydrogen and gasoline, [3], [4], [5]**

Fuel Properties	Ammonia	Hydrogen	Gasoline
Molecular Formula	NH <sub>3</sub>	H <sub>2</sub>	C <sub>4</sub> to C <sub>12</sub> hydrocarbons
Molecular Weight (g/mol)	17.03	2.016	114
Carbon Content (% mass)	0	0	86-88

Hydrogen Content (% mass)	17.8	100	12-14
Lower Heating Value (MJ/kg)	18.6	119.93	42.7
Energy Density (MJ/L) - Liquid	12.7 (at 25°C, 10 bar)	8.5 (at -253°C)	32.0
Octane Number	110	130	91-98
Auto-Ignition Temperature (°C)	630	585	247-280
Density (kg/m <sup>3</sup> ) - Liquid at 25°C	608 (at 25°C, 10 bar)	70.8 (at -253°C)	750

### 1.1 Hydrogen and Ammonia as fuel in SI Engines

Hydrogen, with its high diffusivity and fast flame speed, can significantly improve combustion efficiency and reduce CO<sub>2</sub> emissions to zero. Ammonia, though less reactive, offers high volumetric energy density and can serve as a hydrogen carrier, making it attractive for large-scale storage and transport. A combination of hydrogen and ammonia could address the limitations of each fuel and provide a practical pathway toward sustainable SI engine operation.

The study demonstrates that hydrogen enrichment in a propane-fuelled SI engine significantly improves brake power, thermal efficiency, and combustion stability, especially under lean-burn conditions. It effectively reduces energy consumption and hydrocarbon emissions, though NO<sub>x</sub> emissions increase due to higher in-cylinder temperatures and volumetric efficiency decreases from fuel displacement. While eco-cost and fuel cost are lowered at optimal hydrogen flow rates, the overall operating cost remains slightly higher owing to hydrogen's market price. These results suggest that hydrogen is a technically viable and environmentally beneficial supplement to propane, provided cost barriers are addressed [6].

The simulation study confirms hydrogen's strong potential as a clean and efficient alternative to conventional SI engine fuels. At an equivalence ratio of 0.4 and 3000 rpm, hydrogen achieved the highest thermal efficiency, optimal cylinder pressure, and the lowest fuel consumption, while eliminating CO and HC emissions and drastically reducing CO<sub>2</sub>. However, elevated combustion temperatures led to persistent NO<sub>x</sub> emissions, indicating the need for effective mitigation strategies. Overall, hydrogen demonstrates superior performance and environmental benefits compared to gasoline and methane, making it a promising pathway for sustainable engine technologies [7].

The study highlights that spark plug positioning and ignition timing play a critical role in optimizing hydrogen-fueled SI engine performance. Relocating the spark plug closer to the exhaust port (SPP3) significantly improves brake power, BSFC, exergy efficiency, and reduces exergy destruction and specific exergy cost of shaft work. However, these gains come with the drawback of increased NO<sub>x</sub> emissions, which elevate the total cost rate. Overall, while engine modifications such as spark plug repositioning offer substantial performance and exergoeconomic benefits, effective NO<sub>x</sub> mitigation strategies are essential to balance environmental and economic impacts [8].

The study confirms that blending hydrogen with CNG in retrofitted SI engines effectively enhances combustion efficiency and lowers emissions, addressing key limitations of conventional CNG operation. A 40% hydrogen blend at lean conditions ( $\lambda = 1.4$ ) delivered notable improvements in efficiency and significant reductions in NO<sub>x</sub>, CO, and UBHC emissions, demonstrating the dual benefits of performance enhancement and cleaner operation. CFD analyses further validated that hydrogen's superior chemical reactivity is the primary driver of faster flame propagation and improved thermal efficiency. Overall, hydrogen-enriched CNG emerges as a practical and sustainable solution for reducing the environmental impact of single-cylinder engines used in rural power generation [9].

The study demonstrates that hydrogen stratification is an effective strategy to overcome ammonia's poor ignition and combustion performance in SI engines. Stratified combustion enhances IMEP, combustion stability, and early flame development, while achieving comparable performance to homogeneous combustion at significantly lower hydrogen blending ratios. It extends the stable operating boundary to as low as 2.5% hydrogen, reducing the dependency on high hydrogen fractions. Moreover, stratification lowers unburned NH<sub>3</sub> emissions and promotes in-cylinder NO<sub>x</sub> reduction reactions. Overall, hydrogen stratification offers a promising pathway for efficient and cleaner ammonia-fueled engine operation [10].

### 1.2 Hydrogen and Ammonia as a Dual fuel in SI engine

The study highlights that ammonia-hydrogen blends below 50% hydrogen enable stable premixed combustion, while 60% hydrogen addition improves thermal efficiency through spark-assisted compression ignition without knock. However, hydrogen ratios above 70% induce knocking, with severity linked to fuel reactivity and heat release rates. Optical diagnostics revealed that flame propagation strongly influences auto-ignition locations. Overall, optimizing hydrogen blending is crucial to balance efficiency gains and knock suppression in ammonia-hydrogen SI engines [11].

The Zero-1D simulation effectively evaluated combustion and emissions of NH<sub>3</sub>, H<sub>2</sub>, their mixtures, and isoctane in SI engines. An NH<sub>3</sub>/H<sub>2</sub> blend with about 20% H<sub>2</sub> was identified as the optimal compromise between efficiency, power, and NO<sub>x</sub> emissions. Water injections showed limited effectiveness, highlighting EGR as a more viable NO<sub>x</sub> control strategy. The Miller cycle further enhanced performance, particularly with synthetic carbon-free fuels [12].

Hydrogen addition to ammonia in marine SI engines enhances peak pressure, heat release, efficiency, and power while lowering unburned NH<sub>3</sub> emissions. NO<sub>x</sub> emissions stay stable near stoichiometry but rise sharply under lean conditions, whereas higher CR

improves efficiency and reduces NO<sub>x</sub> by about 10%. N<sub>2</sub>O emissions remain minimal (<20 ppm) across conditions. Kinetic analysis reveals distinct NO and N<sub>2</sub>O formation pathways depending on  $\lambda$  and flame location [13].

Ammonia shows potential as a zero-carbon fuel but faces challenges due to poor ignition and flame propagation. High compression ratio operation enables efficient pure ammonia combustion at low speeds and high loads, achieving up to 33.7% thermal efficiency. Hydrogen addition (2–16%) further improves load range and raises efficiency to 35.8%. Moreover, interactions between unburned ammonia and NO<sub>x</sub> at higher loads help reduce NO<sub>x</sub> emissions, supporting ammonia's viability as an engine fuel [14].

The study confirms that hydrogen addition effectively promotes ammonia combustion in SI engines, improving efficiency and power output. Raising the compression ratio from 14 to 16 significantly boosts brake power, thermal efficiency, NO<sub>x</sub>, pressure, and heat release while lowering CA<sub>10-90</sub> and exhaust temperature. Higher engine speed reduces volumetric efficiency, highlighting speed sensitivity. Optimal performance was achieved at 28°C<sub>A</sub> bTDC with 21% hydrogen, proving hydrogen's role as a reliable combustion enhancer for ammonia-fueled engines [15].

The study shows that liquid ammonia direct injection with hydrogen port injection enhances combustion performance in SI engines. IBTDC injection creates strong stratification, enriching hydrogen production and accelerating ammonia combustion. Optimized split injection and spark timing improve efficiency while lowering fuel consumption and emissions. Overall, NO, NH<sub>3</sub>, and N<sub>2</sub>O emissions are significantly reduced, with ITE reaching up to 44.3% [16].

The experimental study shows that higher compression ratios and hydrogen blending significantly improve flame development, combustion speed, brake power, and efficiency in ammonia-fueled SI engines. Although volumetric efficiency decreases with higher hydrogen fractions, BTE improves by up to 33%. Exhaust gas temperatures drop with increased hydrogen and CR, but NO<sub>x</sub> emissions rise due to higher peak temperatures. Hence, selective catalytic reduction (SCR) is recommended as a practical solution for NO<sub>x</sub> control in ammonia-hydrogen engines [17].

The study highlights ammonia as a practical hydrogen carrier for onboard storage, offering compact and low-cost solutions. Experimental results confirm that hydrogen addition is essential to enhance ammonia ignition and flame speed in SI engines. Engine performance improves with hydrogen blending, though it still lags behind conventional gasoline operation due to lower flame speed and intake dilution. Overall, ammonia-hydrogen fuelling shows promise for clean, carbon-free propulsion in range-extended vehicles [18].

Ammonia is a promising carbon-neutral fuel for ICEs but faces challenges such as poor flammability, high ignition temperature, and NO<sub>x</sub>/unburned NH<sub>3</sub> emissions. Strategies like co-combustion, engine modifications, and advanced combustion concepts improve its applicability. Ammonia decomposition and reforming, particularly via thermal, catalytic, and plasma-assisted methods, enhance H<sub>2</sub> availability for better efficiency and lower emissions. Recent progress in nickel-based catalysts further strengthens the potential of ammonia as a sustainable fuel solution [19].

The study demonstrates that metal ammine complexes offer a viable solution for safe ammonia storage in IC engine applications. Experimental results on a CFR engine show that an ammonia-hydrogen blend with 10 vol.% hydrogen achieves optimal efficiency and power. Compared to gasoline, higher compression ratios further enhance performance. However, due to elevated NO<sub>x</sub> emissions, SCR after-treatment is recommended for effective emission control [20].

The study confirms that hydrogen enrichment effectively overcomes ammonia's poor reactivity, significantly boosting torque, efficiency, and fuel economy. CFD results show reduced ignition delay and improved combustion completeness with higher hydrogen fractions. However, NO<sub>x</sub> emissions increase due to elevated combustion temperatures. An optimal hydrogen share of 29–39% achieves the best balance between performance and emissions, supporting ammonia-hydrogen dual-fuel engines as a viable carbon-free solution [21].

The study demonstrates that exhaust heat-driven ammonia cracking, combined with Injecting Jet Ignition (IJI), can significantly enhance ammonia-hydrogen engine performance. Optimal efficiency above 43.6% is achieved at specific  $\alpha$  values, while deviations reduce performance. Two effective strategies—low  $\alpha$  with high  $\beta$  and high  $\alpha$  with low  $\beta$ —offer improved power and reduced emissions. Overall, the findings provide theoretical guidance for optimizing ammonia-hydrogen engines under incomplete cracking conditions [22].

The study shows that combining hydrogen addition with oxygen enrichment effectively enhances ammonia combustion in IC engines. Higher oxygen concentration improves combustion stability, shortens duration, and increases IMEP, while ITE peaks before declining at excessive enrichment. Increasing ammonia proportion reduces NO<sub>x</sub> emissions and improves exergy efficiency under optimized oxygen levels. At 28% oxygen and 90% ammonia, the engine achieves peak IMEP (39.73%) and exergy efficiency (26.88%), supporting ammonia's practical application [23].

The study validates that ammonia decomposition products (H<sub>2</sub>-N<sub>2</sub> mixture) can effectively serve as ignition gas for jet ignition in ammonia engines. Compared to pure hydrogen, the mixture enhances jet penetration and ignition area, improving combustion stability. Optimal conditions with slightly lean mixtures achieved a maximum ITE of 44.2% while balancing heat loss and efficiency. NO<sub>x</sub> emissions showed a rise–fall trend with  $\lambda$ , with minimum values around 2796 ppm, highlighting optimized strategies for cleaner, efficient ammonia combustion [24].

Ammonia offers strong potential as a carbon-free fuel for ICEs but faces limitations due to its low burning rate. Hydrogen addition effectively enhances ammonia ignition, combustion speed, and overall engine performance. Research highlights the influence of

NH<sub>3</sub>/H<sub>2</sub> ratios on pressure, heat release, and emissions, showing clear trade-offs. Overall, hydrogen-assisted ammonia combustion is a promising pathway for sustainable SI engine development in a low-carbon future [25].

The study demonstrates that partial oxidation of rich ammonia–air mixtures inside the engine cylinder can generate hydrogen while producing useful work. Up to 6% hydrogen concentration in the exhaust and 40% of unburned fuel energy as hydrogen were achieved. Higher equivalence ratios and intake temperatures enhanced hydrogen yield and stability. This approach offers a catalyst-free, practical pathway for onboard hydrogen generation to support ammonia-fueled multi-cylinder engines [26].

### 1.3 Hydrogen, Ammonia and Gasoline in SI engine

Oral [27] investigated the combined use of ethanol and a hydrogen peroxide mixture in a single-cylinder spark-ignition (SI) engine operating at various speed conditions (1500–4000 rpm). The test fuels included pure gasoline (G100), a 5% ethanol blend (G5E), and these blends further enriched with H<sub>2</sub>O<sub>2</sub> produced from a prototype electrolytic generator. The study reported that the inclusion of H<sub>2</sub>O<sub>2</sub> notably enhanced engine torque, power output, and reduced specific fuel consumption compared with G5E alone. Moreover, the combined H<sub>2</sub>O<sub>2</sub> and ethanol enrichment led to significant decreases in CO and HC relative to pure gasoline. However, nitrogen oxide levels increased due to higher combustion temperatures. Overall, the results demonstrated that supplementing ethanol–gasoline blends with a small quantity of H<sub>2</sub>O<sub>2</sub> improves combustion efficiency and emission characteristics in SI engines.

Shang et al [28] explored the impact of hydrogen direct injection (HDI) on the combustion and emission characteristics of a spark-ignition engine operating with n-butanol/gasoline blends. It highlighted hydrogen's potential as a carbon-free additive capable of improving combustion efficiency in hybrid fuel engines. Results showed that a moderate n-butanol ratio (25%) enhanced combustion performance, while higher n-butanol proportions (75–100%) led to poorer atomization and vaporization, which were effectively compensated by increasing hydrogen addition (15–20%). The inclusion of hydrogen not only elevated brake mean effective pressure and improved heat release behavior but also shortened combustion duration and enhanced stability. Although HC, CO, and particulate emissions consistently declined with hydrogen enrichment, nitrogen oxide emissions rose due to higher combustion temperatures. Overall, the combined use of hydrogen and n-butanol demonstrated synergistic effects, enabling cleaner and more efficient combustion in gasoline engines.

Inbanaathan et al [29] examined the influence of hydrogen enrichment on the combustion, performance, and emission characteristics of a variable-speed spark-ignition engine fuelled with ethanol–gasoline blends. The research aimed to address the common issues of knocking and increased CO and HC emissions associated with higher ethanol blending in gasoline. Experiments were conducted using different ethanol proportions, focusing particularly on the E30 blend, combined with hydrogen injection durations of 2, 3, and 4ms at engine speeds ranging from 1200 to 1800 rpm. The results revealed that the E30 + H<sub>2</sub> combination with 3ms injection timing achieved superior combustion efficiency, higher engine performance, and lower CO and HC emissions compared to other blends. However, NO<sub>x</sub> emissions were elevated due to the more complete combustion process. The overall findings confirmed that hydrogen supplementation effectively improves the performance and emission behaviour of ethanol–gasoline engines, supporting its potential role in developing cleaner and more efficient flex-fuel engine systems.

Pan et al [30] focused on evaluating the influence of various hydrogen injection strategies on combustion behaviour and emission characteristics in a spark-ignition (SI) engine operating with gasoline port injection. Four configurations were compared: hydrogen direct injection (HDI) producing a stratified hydrogen mixture, hydrogen port injection (PHMD) forming a homogeneous mixture, split hydrogen direct injection (SHDI) creating a partially premixed mixture, and a baseline case without hydrogen addition. Results indicated that the hydrogen mixture distribution significantly influenced ignition timing, combustion rate, and overall engine efficiency. Among the tested strategies, the split direct injection method (PPHMD) achieved the fastest combustion rate and the highest brake thermal efficiency due to better control of mixture stratification. Although PHMD offered slightly lower efficiency, it demonstrated superior emission performance because of its uniform hydrogen distribution. The findings suggest that careful adjustment of hydrogen injection strategy can effectively balance combustion efficiency and emission reduction in SI engines.

Shang et al [31] investigated the influence of different fuel injection strategies on the combustion and emission behaviour of an n-butanol/gasoline spark-ignition engine equipped with a hydrogen direct injection system. Three injection modes—port injection (NGP), combined injection (NGPD), and combined injection with hydrogen enrichment (NGPH)—were tested under various n-butanol ratios. Results showed that both NGPD and NGPH modes enhanced combustion performance at low loads compared to NGP, with average increases in peak cylinder pressure of 5.58% and 11.63%, respectively. The combined injection approaches led to faster heat release, shorter combustion duration, improved power output, and greater combustion stability across all n-butanol ratios. In terms of emissions, both NGPD and NGPH modes significantly reduced HC and carbon CO levels, although nitrogen oxide emissions increased. Overall, the NGPH mode with 25% n-butanol demonstrated the best balance of combustion efficiency and emission control, confirming that hydrogen-assisted combined injection effectively compensates for the inherent limitations of n-butanol as a fuel.

X. Yu et al [32] compared the effects of homogeneous and stratified hydrogen addition on the combustion and emission characteristics of a gasoline/hydrogen dual-fuel spark-ignition engine equipped with hydrogen direct injection and gasoline port injection. Experiments were conducted under low-speed, low-load conditions across five excess air ratios. The findings revealed that brake thermal efficiency initially increased with the excess air ratio, peaking at 1.1 before declining. Hydrogen enrichment enhanced ignition stability accelerated the combustion rate, and improved efficiency, particularly under lean-burn conditions. Additionally, CO and HC emissions decreased due to more complete combustion, while NO<sub>x</sub> emissions increased because of higher in-cylinder temperatures. Between the two hydrogen distribution modes, stratified hydrogen injection provided faster flame development, shorter combustion duration, and lower cyclic variation compared to homogeneous mixing, thereby improving combustion stability and efficiency. However, this mode also resulted in slightly higher NO<sub>x</sub> and HC emissions due to increased

combustion temperature and wall quenching effects. Overall, stratified hydrogen injection demonstrated superior combustion performance, albeit with a minor trade-off in emission levels.

Akansu et al [33] experimentally evaluated the performance, combustion, and emission behavior of a spark-ignition engine fuelled with gasoline, gasoline–ethanol, and gasoline–ethanol–hydrogen blends. The addition of 20% ethanol to gasoline (G80E20) was found to deteriorate engine performance and emissions compared to pure gasoline. However, introducing hydrogen into the gasoline–ethanol blend significantly enhanced combustion efficiency, expanded the flammability range, and improved overall performance. The hydrogen-enriched blend reduced CO and HC emissions owing to more complete combustion, while NO<sub>x</sub> emissions increased due to higher in-cylinder temperatures. Overall, the results demonstrated that hydrogen supplementation effectively compensates for the drawbacks of ethanol blending in SI engines, leading to improved efficiency and cleaner combustion.

Purayil, Hamdan, et al [34] examined the influence of ethanol–gasoline and methanol–gasoline blends on the performance and hydrogen knock limit of a lean-burn spark-ignition engine equipped with in-cylinder liquid fuel injection and hydrogen port induction. The fuels, containing up to 50% alcohol by volume, were supplemented with hydrogen in incremental flow rates until knock onset. Results revealed that both ethanol and methanol blends increased the hydrogen knock limit, and further improvement was achieved through spark-timing retardation. However, these strategies led to reduced brake thermal efficiency, brake mean effective pressure, and peak in-cylinder pressure. The inclusion of alcohols increased cyclic variation, which was mitigated by hydrogen enrichment and spark retardation. Emission analysis indicated that ethanol and methanol reduced NO<sub>x</sub> and HC emissions but elevated CO levels, whereas hydrogen addition improved combustion stability and extended the knock resistance of the engine.

Purayil, Al-Omari, et al [35] analyzed the effect of varying gasoline injection pressure (GIP) influences engine performance and the hydrogen knock limit in a dual-fuel spark-ignition engine running on hydrogen–gasoline blends. The GIP was adjusted between 50 and 140 bar, with hydrogen supplied incrementally until knock onset at spark timings of 4° and 12° CA BTDC. Results demonstrated that higher injection pressures extended the hydrogen knock limit, allowing greater hydrogen flow rates before knocking occurred. However, increased GIP and spark retardation negatively impacted brake thermal efficiency, brake mean effective pressure, and peak in-cylinder pressure. Emission analysis revealed that CO<sub>2</sub> and NO<sub>x</sub> levels declined with increasing GIP, while CO emissions and cyclic variations rise. In contrast, hydrogen enrichment showed opposite behaviour, enhancing efficiency and combustion stability. Overall, the study highlighted the crucial balance between injection pressure and hydrogen enrichment for optimizing performance and knock.

Mohamed et al [36] explored the influence of valve timing and overlap on the performance, combustion, and emissions of a boosted direct-injection single-cylinder spark-ignition engine operating with gasoline and hydrogen. The results showed that optimized direct hydrogen injection effectively prevented backfire and hydrogen slip during positive cam overlaps, while also reducing pumping losses. Notably, hydrogen demonstrated the capability to serve as a direct replacement for gasoline without requiring modifications to cam profiles under high-load conditions. When operated under lean-burn conditions with an air–fuel ratio of 2.75, hydrogen achieved significantly higher thermal efficiency across various loads and maintained ultra-low NO<sub>x</sub> emissions. Overall, the study confirmed hydrogen's superior combustion stability, efficiency, and lower sensitivity to valve timing compared to gasoline, reinforcing its potential as a clean and efficient alternative fuel for spark-ignition engines.

Purayil et al [37] analysed the knock behaviour in a gasoline direct-injection engine operating with hydrogen–gasoline mixtures to better understand its impact on performance and stability. Hydrogen was supplied through the intake manifold, with its energy share increased incrementally up to 25%, while maintaining constant engine speed and power output for consistent comparison. The findings revealed that hydrogen enrichment intensified knock phenomena, characterized by greater in-cylinder pressure oscillations, higher sound pressure levels, and stronger engine vibrations compared to pure gasoline operation. Despite this, hydrogen addition reduced cycle-to-cycle variability, indicating more stable combustion. Emission-based knock diagnostics further confirmed that hydrogen–gasoline operation exhibited more pronounced knock tendencies than gasoline alone. Overall, the study highlighted both the challenges and potential of hydrogen enrichment, emphasizing the need for precise knock control strategies in hydrogen-assisted spark-ignition engines.

Duan et al [38] study evaluated the combined effects of methanol and hydrogen addition on the performance and combustion characteristics of a spark-ignition engine as a pathway toward carbon-neutral transportation. Four fuel blends were tested: pure gasoline (M0G100), 10% methanol–gasoline (M10G90), 30% methanol–gasoline (M30G70), and M30G70 with 7.5% hydrogen energy share. The results demonstrated that incorporating methanol and hydrogen significantly enhanced combustion efficiency and engine stability. Among all test fuels, the M30G70/hydrogen blend achieved the lowest coefficient of variation for both peak cylinder pressure and indicated mean effective pressure, indicating smoother and more consistent combustion. Additionally, this blend reduced fuel consumption by 14.3% and improved indicated thermal efficiency by 12.5% compared to pure gasoline. Carbon dioxide emissions were also substantially decreased, with reductions of 7.37%, 26.78%, and 33.27% for M10G90, M30G70, and M30G70/hydrogen, respectively. Overall, the synergistic use of methanol and hydrogen was found to be an effective approach to improve performance and reduce carbon emissions in gasoline engines.

Duan et al [39] study explored the feasibility of utilizing industrial by-product hydrogen (IPH), a carbon-free energy source generated during petroleum refining, as a fuel for spark-ignition (SI) engines to support carbon-neutral mobility. Engine performance and emission characteristics of IPH were experimentally compared with those of conventional gasoline. Results showed that combustion phasing parameters (CA<sub>10</sub> and CA<sub>50</sub>) advanced and then slightly retarded with increasing load when using IPH, while brake specific gas consumption decreased, and brake thermal efficiency improved notably. At loads of 2.5 and 5 bar, BTE increased by 15.39% and 11.58%, respectively, relative to gasoline operation. Although NO<sub>x</sub> emissions were somewhat higher due to elevated combustion temperatures, CO and HC emissions were reduced by over 90%, particularly under medium-load conditions. Furthermore, IPH combustion exhibited shorter duration and advanced timing, indicating enhanced combustion

efficiency. Overall, the findings confirm that industrial by-product hydrogen can serve as an efficient, low-emission alternative to gasoline in SI engines, offering significant potential for cleaner and more sustainable transportation.

Suresh [40] study examined the combined effects of ethanol and hydrogen enrichment on the performance and combustion characteristics of a lean-burn spark-ignition engine with a compression ratio of 10.5:1. Various ethanol–gasoline blends (E5, E10, E20, E30, and E40) were tested, and E10 was identified as the optimal blend based on performance metrics. Subsequent experiments evaluated the influence of 5% and 10% hydrogen addition (on an energy basis) to the E10 mixture. Results indicated that ethanol blending improved brake power by approximately 9% and brake thermal efficiency by around 7% compared to pure gasoline. The introduction of hydrogen further enhanced both parameters, particularly under lean conditions, extending the lean-burn limit to an equivalence ratio of 0.47 compared to 0.5 for E10 and 0.54 for gasoline. Hydrogen addition also promoted faster combustion and higher heat release rates while reducing cycle-to-cycle variations and hydrocarbon emissions. Overall, the synergistic use of ethanol and hydrogen significantly improved engine efficiency and combustion stability under lean-burn operation.

Pandey [41] study evaluated the effects of varying compression ratios and hydrogen enrichment on the combustion and emission behaviour of a spark-ignition engine fuelled with biobutanol. While butanol offers advantages over ethanol as an alternative fuel, its high latent heat and low heating value limit combustion efficiency. Tests conducted with different compression ratios (CR) and hydrogen additions revealed that brake thermal efficiency remained nearly constant at 90% butanol but improved notably with increased hydrogen concentration. Raising the CR to 15 and introducing up to 25–30% hydrogen shortened the flame development and propagation phases by 34% and 29%, respectively, while increasing peak pressure and heat release rate by about 12%. Combustion stability also improved, with a 21% reduction in the coefficient of variation. However, higher hydrogen shares led to combustion instability due to mixture stratification. Both peak cylinder temperature and  $\text{NO}_x$  emissions rose with CR and hydrogen addition, whereas CO and HC emissions generally declined because of enhanced combustion efficiency, with slight increases at high hydrogen levels attributed to local heterogeneity and fuel dissociation. Overall, hydrogen enrichment effectively compensated for butanol's combustion limitations, improving efficiency and stability with moderate trade-offs in  $\text{NO}_x$  emissions.

Yaman [42] study explored the effects of blending n-pentanol with unleaded gasoline on the performance, combustion, and emission characteristics of a spark-ignition (SI) engine. Tests were conducted on a single-cylinder, four-stroke, water-cooled, port-fuel-injected engine at a constant speed of 1600 rpm and variable loads (1–5 kW). Fuel mixtures containing 5%, 10%, 15%, and 20% n-pentanol by volume were compared with pure gasoline. Results indicated that n-pentanol addition enhanced brake thermal efficiency at all loads due to its inherent oxygen content, which promoted more complete combustion. The blended fuels exhibited higher in-cylinder pressures and heat release rates than gasoline, confirming improved combustion behaviour. In terms of emissions, HC, CO,  $\text{CO}_2$ , and NO levels were significantly reduced for all n-pentanol blends, while exhaust  $\text{O}_2$  concentrations increased.

Nathan Prasad et al [43] Investigation evaluated the effects of hydrogen enrichment on methanol-fuelled internal combustion engines to improve both performance and emission characteristics. Methanol, while renewable and clean, suffers from limitations such as low heating value and poor combustion stability issues that hydrogen addition can mitigate. Tests were conducted under wide-open throttle conditions with hydrogen enrichment levels between 5% and 20% in 2.5% increments across various engine speeds. Results showed that hydrogen supplementation markedly improved brake thermal efficiency (by 20–30%), increased brake power, and reduced brake specific energy consumption. However, excessive hydrogen addition beyond 12.5% led to reduced volumetric efficiency and a decline in performance. Emission analysis indicated substantial reductions in CO, HC, and  $\text{CO}_2$  levels (by 30–40%), although  $\text{NO}_x$  emissions increased slightly due to higher combustion temperatures.

Cong et al [44] study examined the combustion and emission characteristics of a hydrogen dimethyl ether (DME) spark-ignition engine to extend the operating range of homogeneous charge compression ignition (HCCI) combustion. Various DME blending ratios ( $\alpha\text{DME}$ ) were tested to optimize engine performance and reduce nitrogen oxide emissions. Results showed that blending DME initially extended flame development and propagation durations by up to 2°CA as  $\alpha\text{DME}$  increased to 3.0% but further increase to 3.4% shortened the propagation phase due to spontaneous high-temperature oxidation of residual mixtures. The addition of DME improved power output, with the indicated mean effective pressure rising by approximately 18.3%. Moderate DME fractions (<3.0%) caused slight cyclic variations, while overall combustion stability remained within acceptable limits. Importantly, DME addition significantly lowered  $\text{NO}_x$  emissions up to a 49.9% reduction compared to pure hydrogen operation though HC and CO emissions increased slightly due to incomplete oxidation.

Duraisamy [45] study explored the influence of dimethyl ether (DME) addition on the combustion characteristics of ammonia in a homogeneous charge compression ignition (HCCI) engine under ultra-lean conditions. Owing to its high reactivity and low autoignition temperature, DME was introduced as a combustion promoter to overcome ammonia's poor ignition properties. Experiments were conducted on a single-cylinder engine (compression ratio 16.4, 1000 rpm) using ammonia–air mixtures blended with 7–10% DME by volume at different equivalence ratios (0.3, 0.4, and 0.5) and intake pressures. Results showed that DME addition substantially reduced the intake temperature required for stable autoignition, leading to improved indicated mean effective pressure and thermal efficiency. Stable HCCI combustion was achieved across all test conditions, with ignition phasing (CA10, CA50, and CA90) advancing as equivalence ratio decreased due to higher intake temperatures. Both ringing intensity and cyclic variation remained low, confirming stable and smooth combustion.

## 2. Materials and Methods

### 2.1. About Hydrogen and Ammonia

Hydrogen and ammonia have gained considerable attention as potential alternative fuels for achieving sustainable and carbon-neutral energy systems. Hydrogen is characterized by its high gravimetric energy density, rapid flame propagation rate, and wide flammability limits, which make it an efficient fuel for spark ignition (SI) engines. Its combustion produces only water vapor, eliminating direct carbon emissions. However, hydrogen storage and transportation remain major challenges due to its low volumetric energy density and high diffusivity. Ammonia, in contrast, offers advantages in terms of storage and distribution, as it can be liquefied under moderate pressure and existing infrastructure can be adapted for its use. Additionally, ammonia acts as an effective hydrogen carrier, enabling easier handling and long-distance energy transport. Despite its low flame speed, high ignition energy requirement, and potential NO<sub>x</sub> formation, blending ammonia with hydrogen can significantly enhance combustion characteristics and overall engine performance. The complementary properties of hydrogen and ammonia thus make their combined utilization a promising pathway toward clean and efficient energy conversion in future internal combustion and power generation systems.

### 2.2. Purchase and usage

The procurement and utilization of hydrogen and ammonia as alternative fuels are gaining prominence in both research and industrial sectors due to their potential to decarbonize energy systems. Hydrogen is commercially available through various production routes such as steam methane reforming (SMR), water electrolysis, and biomass gasification. Among these, green hydrogen produced via electrolysis using renewable electricity is considered the most sustainable option, though it currently remains cost-intensive compared to conventional fossil-based methods. The cost of hydrogen largely depends on production technology, electricity prices, and distribution infrastructure. Hydrogen is typically supplied in compressed or liquefied form for use in fuel cells, internal combustion engines, and industrial applications.

Ammonia, on the other hand, is widely produced through the Haber–Bosch process by combining nitrogen from air with hydrogen derived mainly from natural gas or renewable sources. Its well-established global production and distribution network make ammonia more accessible and easier to handle compared to hydrogen. Ammonia can be stored and transported as a liquid under moderate pressure, providing a logistical advantage for large-scale energy applications. In energy systems, ammonia can be utilized directly as a carbon-free fuel in combustion engines or cracked to release hydrogen for subsequent use. The integration of hydrogen and ammonia in fuel applications provides a practical approach to achieving energy security and carbon neutrality while leveraging existing industrial infrastructure.

### 2.3 Port Fuel Injection System in Spark-Ignition Engines

Significant progress has been made in improving the combustion systems of spark-ignition (SI) engines to comply with tightening emission norms and fuel economy regulations [46]. For SI engines, the fuel–air mixture must be homogeneous before ignition, ensuring stable flame development and high combustion efficiency. Among several fuelling strategies, the Port Fuel Injection (PFI) system remains one of the most efficient and versatile for incorporating alternative gaseous fuels such as hydrogen and ammonia. In a PFI setup, a metered quantity of fuel is injected into the intake manifold where it mixes thoroughly with the incoming air stream before entering the combustion chamber [47].

PFI systems can be classified as single-point or multi-point injection types. In single-point injection, all cylinders share a common fuel injection point, whereas in multi-point systems, fuel is injected individually near each intake valve, improving mixture uniformity and reducing cycle-to-cycle variation. When hydrogen or ammonia is utilized, the gaseous fuel can be directed toward the intake valve through PFI while the liquid fuel typically gasoline or an alcohol blend may be supplied either via the same manifold or through direct injection (DI) into the cylinder. The combined configuration of hydrogen or ammonia DI with gasoline PFI has been reported to achieve higher in-cylinder pressure, enhanced brake thermal efficiency, and reduced brake specific fuel consumption. This improvement stems from increased in-cylinder turbulence, faster flame propagation, and superior volumetric efficiency.

The combustion characteristics depend strongly on the fuel's calorific value, ignition temperature, and chemical reactivity. Hydrogen's high diffusivity and rapid flame speed promote complete combustion, while ammonia's slow burning rate and high ignition energy demand can be compensated through hydrogen enrichment in the mixture. Such hydrogen–ammonia dual fueling in PFI systems has shown potential for achieving stable ignition and reduced carbon emissions. However, the elevated combustion temperature in DI configurations can increase NO<sub>x</sub> formation, whereas PFI systems generally offer lower NO<sub>x</sub> and hydrocarbon emissions due to better premixing and moderated flame temperatures. Conversely, excessive gaseous-fuel substitution may reduce volumetric efficiency, particularly when hydrogen or ammonia displaces a significant portion of intake air [48].

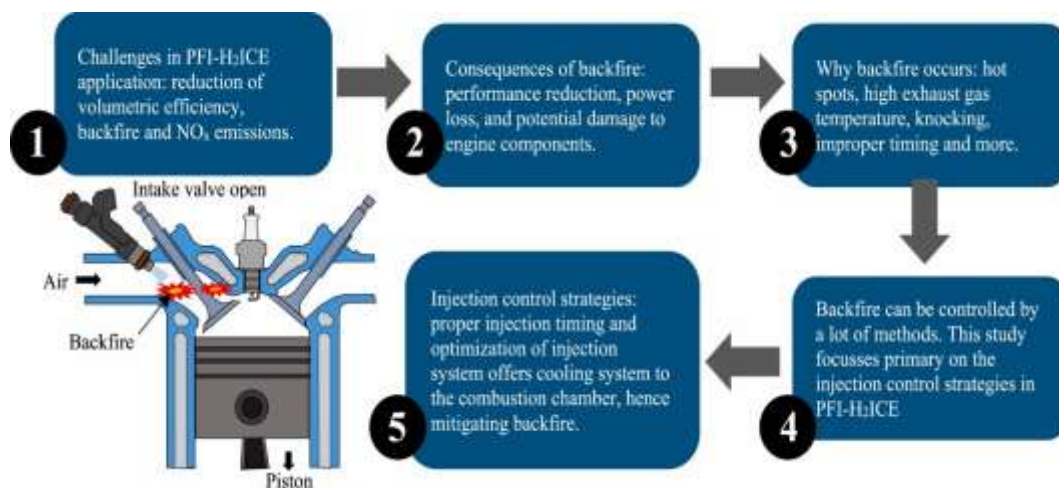


Fig 1. Port fuel Injection [49]

However, because hydrogen is injected into the intake port, it displaces a portion of the air due to its low density, leading to reduced volumetric efficiency and slightly lower engine performance. Despite this, hydrogen PFI offers smoother combustion, lower combustion temperature, and reduced emissions of nitrogen oxides (NOx) and unburned hydrocarbons (HC) compared to hydrogen direct injection (DI). Overall, hydrogen PFI provides cleaner combustion and simpler system integration, though it may limit power output due to air displacement effects and Table 3 present the PFI studies on hydrogen and gasoline in SI engine.

Table 3. Studies on Hydrogen–Gasoline Dual-Fuel Engines Using Port Fuel Injection (PFI)

Sl. No.	Authors (Year)	Engine Specifications	Air Intake System	Hydrogen Induction Method	Gasoline Induction Method	Key Findings
1	S. Wang et al [50]	1.6 L, 4-stroke	Naturally aspirated	PFI	DI	Improved cold-start characteristics; slight increase in NOx emissions.
2	Nguyen et al [51]	97 cc, 4-stroke	Naturally aspirated	PFI	Carburettor	Engine power output improved; reduction in HC emissions; rise in NOx and CO levels.
3	Shivaprasad et al [52]	338 cc, 4-stroke	Naturally aspirated	PFI	PFI	Brake thermal efficiency (BTE) and brake mean effective pressure (BMEP) increased; HC and CO emissions reduced; NOx increased.
4	EL-Kassaby et al [53]	1.3 L, 4-stroke	Naturally aspirated	PFI	DI	Enhanced thermal efficiency; reduction in NOx, CO, and HC emissions compared to pure gasoline mode.
5	Elsemary et al [54]	389 cc, 4-stroke	Naturally aspirated	PFI	Carburettor	Improved brake thermal efficiency; HC and CO emissions slightly higher due to incomplete combustion.

6	Ji et al [55]	1.6 L, 4-stroke	Naturally aspirated	PFI	DI	Decrease in BMEP observed; shorter combustion duration; moderate increase in NOx emissions.
7	Kim et al [56]	2.0 L, 4-stroke	Turbocharged	PFI	DI	Enhanced combustion stability between cycles; increased indicated thermal efficiency.

### 2.4 Hydrogen and Ammonia challenges and drawbacks in SI engine

Despite their strong potential as carbon-free fuels, both hydrogen and ammonia present several challenges when applied in spark ignition (SI) engines. Hydrogen, although highly reactive and efficient, suffers from storage and safety concerns due to its low volumetric energy density and high diffusivity, which increases the risk of leakage and pre-ignition. Its high flame speed and wide flammability limits can lead to abnormal combustion phenomena such as backfire, knocking, and flashback, requiring careful optimization of fuel injection timing and mixture control. Additionally, hydrogen’s lower energy content per unit volume demands modifications to the intake system and fuel supply components.

Ammonia, conversely, poses challenges related to its slow flame speed, high ignition temperature, and narrow flammability range, which result in poor combustion stability and reduced engine efficiency when used alone. The presence of unburned ammonia in exhaust gases raises toxicity and environmental concerns, while its combustion can lead to increased NO<sub>x</sub> emissions due to the high nitrogen content. Furthermore, ammonia’s low vaporization rate and high latent heat of vaporization can cause cold-start difficulties and incomplete combustion under lean conditions. Therefore, to achieve efficient operation in SI engines, strategies such as hydrogen–ammonia blending, advanced ignition systems, and optimized combustion chamber design are essential to overcome these inherent limitations and ensure stable, clean, and efficient performance.

### 3. Experimental Setup

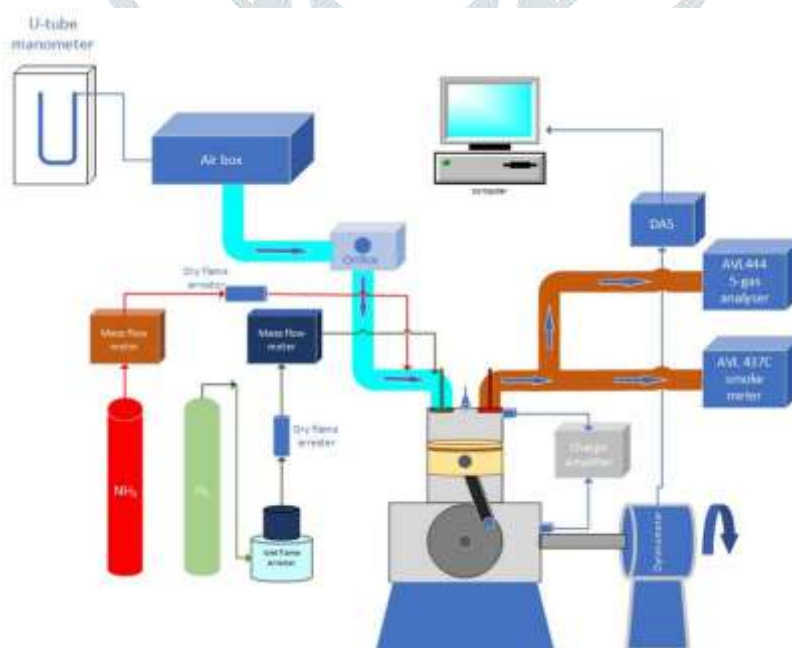


Fig 2. Schematic arrangements of the experimental setup

### 3.1 Research findings on SI engine operation with hydrogen and ammonia gaseous fuels in PFI mode

Numerous experimental investigations have been carried out using port fuel injection (PFI) systems in spark ignition (SI) engines to evaluate the combustion, performance, and emission behaviour of hydrogen and ammonia-based fuels. In the PFI configuration, the fuel is injected into the intake port, where it mixes with the incoming air before entering the combustion chamber. This approach ensures better fuel–air homogeneity, smoother combustion, and reduced cyclic variation compared to direct injection under specific operating conditions. Experimental studies using hydrogen in PFI mode have shown improved thermal efficiency, faster flame propagation, and lower carbon-based emissions. However, issues such as backfire and pre-ignition have been observed due to hydrogen's low ignition energy and high diffusivity, requiring careful control of injection timing and equivalence ratio.

When ammonia is used in PFI systems, researchers have reported challenges such as delayed ignition, incomplete combustion, and higher unburned ammonia emissions, primarily due to its low flame speed and high ignition temperature. Blending hydrogen with ammonia in PFI mode has been found to significantly enhance combustion stability, shorten ignition delay, and improve brake thermal efficiency while reducing unburned fuel emissions. These experiments demonstrate that optimized PFI strategies, including multi-fuel blending, variable ignition timing, and temperature intake control, are crucial for achieving efficient and stable operation of SI engines fuelled by hydrogen, ammonia, or their mixtures.

## 4. Results and Discussion

### 4.1 Combustion, Performance and Emission Characteristics of Hydrogen, Ammonia and Gasoline Dual-Fuel Engines

Recent investigations demonstrate that using hydrogen ( $H_2$ ) and ammonia ( $NH_3$ ) as co-fuels with gasoline significantly influences the combustion process. In hydrogen gasoline dual-fuel systems, the high diffusivity and flame speed of hydrogen facilitate faster ignition and more complete combustion, thereby reducing ignition delay and advancing the heat-release rate. However, the elevated flame temperature may exacerbate thermal  $NO_x$  formation unless suitably controlled by dilution or retarding spark timing. On the ammonia side, its inherent low laminar flame velocity, high auto-ignition temperature and narrow flammability limits pose significant barriers when deployed in internal combustion engines (ICEs) [57].

Besides, in the dual fuel operation with ammonia and hydrogen, hydrogen serves or stands as a combustion enhancer or stimulator owing to its phenomenal diffusivity, reduced ignition energy and predominant flame propagation. A recent review summarises that hydrogen addition not only accelerates combustion but also limits unburned ammonia slip, while facilitating lean operation of ammonia blends [58].

Among various studies, use of  $NH_3$ - $H_2$  under lean intake equivalence ratios (as low as 0.5) were achievable in a pre-chamber-ignited engine, with hydrogen-assisted ignition enabling acceptable indicated thermal efficiency and stable combustion. These results underscore the promise of hydrogen-assisted ammonia combustion but also highlight the need to optimise ignition devices, mixture preparation and chamber geometry to reduce residual unburned  $NH_3$  and  $N_2O$  formation [59].

Replacing gasoline energy with hydrogen or ammonia reduces  $CO_2$  emissions proportionally to the carbon content removed. Hydrogen addition typically reduces CO and unburned hydrocarbons because of leaner, more complete combustion. Ammonia contains no carbon, so it can reduce  $CO_2$  when substituted for gasoline; however, unburned  $NH_3$  (so-called “ammonia slip”) and incomplete oxidation byproducts may appear if combustion is incomplete [60].

Both hydrogen and ammonia influence  $NO_x$  formation but in different ways. Hydrogen's faster combustion and higher local temperatures tend to increase thermal  $NO_x$  unless dilution (EGR) or retarded timing is used. Ammonia combustion can form  $NO_x$  and also  $N_2O$  (a potent greenhouse gas) and may leave unreacted  $NH_3$  if combustion is incomplete; the net  $NO_x$  behavior depends on equivalence ratio, combustion temperature, and residence time. Studies show that blending hydrogen into ammonia mixtures can reduce unburned  $NH_3$  but may increase  $NO_x$  unless countermeasures (EGR, retarded timing, catalyst/aftertreatment) are applied [61].

Ammonia high ignition energy and low flame speed require either pilot fuels (e.g., small direct-injected gasoline or hydrogen pilot), hydrogen enrichment, higher compression ratios, pre-heating intake charge, or advanced ignition systems (plasmatron, laser, or high-energy spark) to maintain stable combustion. Hydrogen's flashback and pre-ignition risks are mitigated by injection strategy (port vs direct), careful injector placement, and intake/exhaust geometry changes [62]. The integration of hydrogen ( $H_2$ ) and ammonia ( $NH_3$ ) as fuels in port-fuel injected (PFI) spark-ignition (SI) engines significantly alters fundamental combustion parameters such as heat release rate (HRR) and in-cylinder pressure, which directly impact engine performance and efficiency.

#### 4.1.1 Heat Release Rate and In-Cylinder Pressure

The addition of hydrogen to gasoline generally enhances combustion characteristics due to hydrogen's high flame speed and wide flammability limits. At low to medium loads, this results in a more rapid heat release rate and a corresponding increase in peak in-cylinder pressure. The faster combustion duration reduces cyclic variation and improves thermal efficiency. However, at high loads, these same properties can lead to challenges. The elevated flame temperatures and increased pressure rise rates can induce engine knock and augment heat transfer losses, which can diminish or even reverse the efficiency gains observed at lower loads [63].

Hydrogen's high flame speed (300 cm/s), wide flammability limits, and low ignition energy lead to a significantly accelerated combustion process when blended with gasoline. Studies consistently report a substantial increase in the heat release rate (HRR) and a higher peak in-cylinder pressure compared to pure gasoline operation [64]. This is attributed to faster flame kernel development and rapid turbulent flame propagation. The combustion duration is notably shortened, which reduces cyclic variation and enhances stability, particularly under lean conditions [64]. However, a critical challenge is the increased propensity for abnormal combustion e

vents, including knock at high loads and backfire, especially in port-fuel injection (PFI) systems due to hydrogen's presence in the intake manifold.

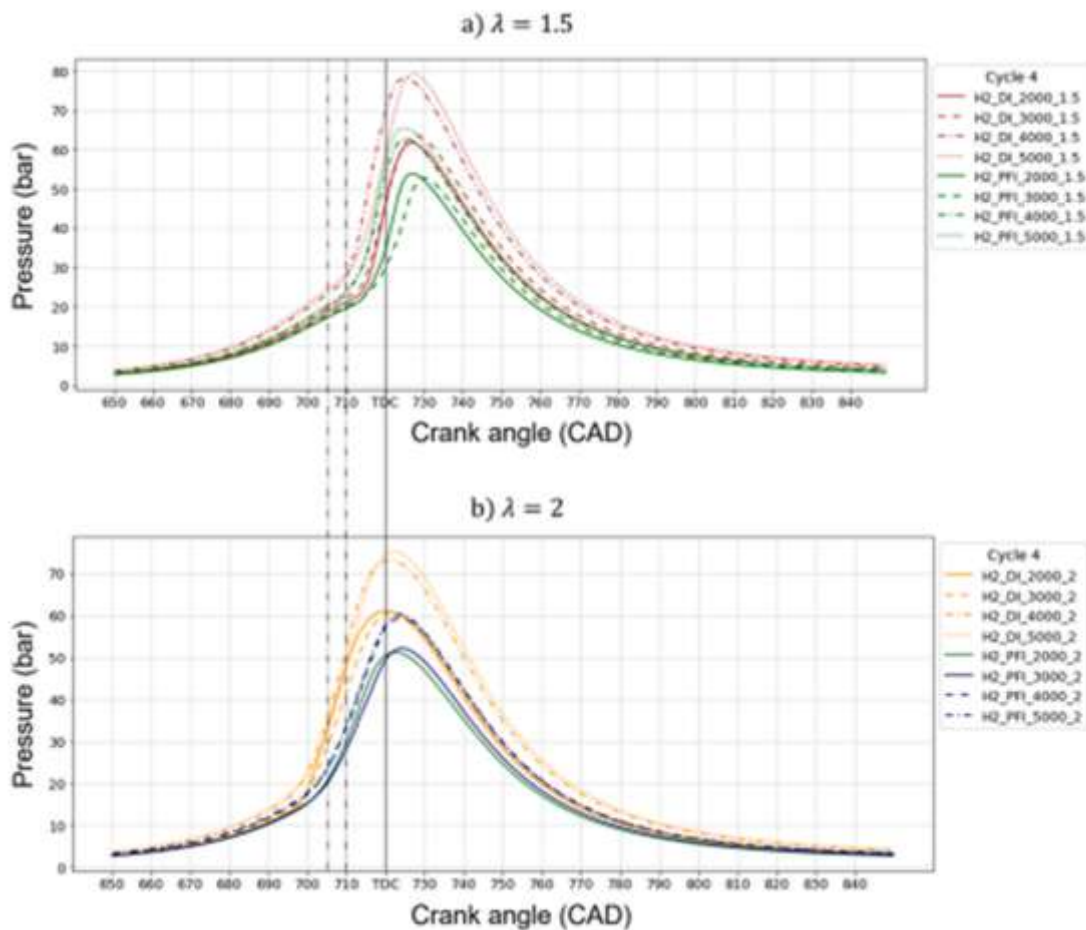
In contrast, ammonia's combustion in SI engines is characterized by its low reactivity and slow laminar flame speed. When used in a dual-fuel configuration with gasoline, increasing the ammonia energy share typically leads to a longer ignition delay, a slower heat release rate, and an extended combustion duration. This results in lower peak in-cylinder pressures and can lead to issues with incomplete combustion, misfire, and partial burns, especially at high substitution ratios. These factors contribute to increased heat transfer losses, which offset the theoretical efficiency benefits of its carbon-free combustion. To mitigate the slow-burning nature of ammonia, hydrogen is often introduced as a combustion catalyst. In such ternary blends (gasoline-NH<sub>3</sub>-H<sub>2</sub>), the presence of hydrogen markedly accelerates the flame propagation of the ammonia-air mixture. This synergistic effect sharpens the HRR profile, raises the in-cylinder pressure, and shortens the overall combustion duration, thereby improving stability and efficiency. This allows for higher levels of ammonia substitution while maintaining acceptable engine performance, although the optimal blend ratio is highly dependent on the specific engine design and operating conditions.

Ammonia acts as a combustion suppressant. Its low laminar flame speed (7 cm/s) and high resistance to auto-ignition result in a slower, more prolonged combustion event. Research indicates that with increasing ammonia energy share, the HRR profile becomes broader, the peak in-cylinder pressure decreases, and the combustion phasing needs to be advanced to compensate for the slow flame speed [65]. This often leads to increased combustion instability and a higher risk of incomplete combustion or misfire, especially at low loads and with high ammonia fractions (Wu et al., 2024).

Several investigations have examined the synergistic potential of hydrogen–ammonia fuel blends in internal combustion engines, particularly focusing on their combustion dynamics, performance trade-offs, and emission behaviour. A recent study [67] on hydrogen-fuelled engines highlighted the inherent challenges of low power density and irregular combustion, proposing the addition of ammonia as a moderating agent to control reactivity. The findings indicated that introducing varying proportions of ammonia into hydrogen effectively prolongs the flame development phase and reduces the peak heat-release rate, which in turn enhances combustion stability and engine power output. However, the slower reactivity of ammonia caused a marginal decrease in thermal efficiency. The study further revealed that while NO<sub>x</sub> emissions remained largely unaffected by ammonia content, they increased with delayed ignition timing, illustrating a clear trade-off between combustion efficiency and emission control in hydrogen–ammonia dual-fuel systems.

Complementary research [68] investigated ammonia–hydrogen premixed flames in spark-ignition engines under turbulent flow conditions. The results demonstrated that lean mixtures exhibit more wrinkled flame structures compared to stoichiometric or rich mixtures, signifying higher flame instability at low equivalence ratios. The inclusion of hydrogen improved overall flame reactivity and combustion completeness by enhancing the turbulent-to-laminar burning velocity ratio. Moreover, hydrogen significantly influenced the NO formation mechanisms, resulting in an inverse NO concentration distribution across flame fronts due to altered chemical reaction pathways. Further experimentation [69] explored performance enhancement in ammonia-fuelled engines through combined hydrogen enrichment and elevated intake air temperatures (476–551 K). At an intake temperature of 476 K, a 30% hydrogen blend achieved the highest power output, with controlled combustion knock intensity of approximately 2 MPa/°CA. This optimized mixture reduced unburned ammonia emissions and improved overall combustion stability, marking a crucial step toward zero-carbon fuel applications in spark-ignition engines. In another related investigation [70], hydrogen ammonia mixtures were evaluated in a high-pressure common-rail engine operating at 1800 rpm under dual ignition modes and nine hydrogen blending ratios (10–90%). The results revealed that ammonia addition increases ignition delay and flame development duration but reduces the rate of in-cylinder pressure rise. Although the engine maintained stable performance with optimized ignition timing, NO emissions increased with higher ammonia fractions, confirming ammonia's combustion-inhibiting influence in hydrogen-dominant mixtures. Overall, blending hydrogen with ammonia enhances combustion reactivity, stabilizes lean-burn operation, and modifies NO formation chemistry key factors in achieving efficient and clean spark-ignition combustion.

Figure.3 illustrates the pressure–crank angle diagrams, signifying that the impact of mixture leanness on combustion characteristics for a hydrogen-enriched fuel. At  $\lambda=1.5$  demonstrates a robust combustion event with a high peak pressure rise rate, indicative of efficient, fast combustion. In contrast, at  $\lambda=2$  reveals a substantial degradation in combustion quality, characterized by a lower peak pressure, a broader, slower pressure rise, and a later phasing. This progression visually underscores the combustion stability limits of ultra-lean operation, where increased charge dilution leads to slower flame propagation and reduced thermal efficiency.



**Fig.3** Comparison of in-cylinder pressure traces for a hydrogen-enriched fuel at different air-fuel equivalence ratios  $\lambda=1.5$  to  $\lambda=2$  demonstrates the impact of rate of pressure rise [71].

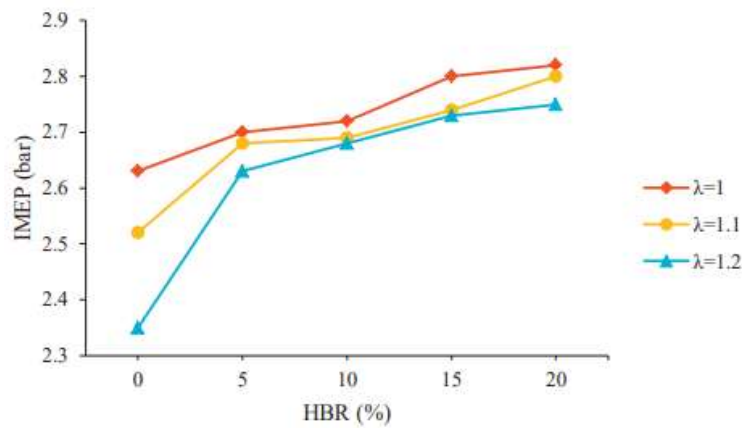
#### 4.1.2 Impact on Engine Performance and Efficiency

The variation of HRR and in-cylinder pressure influenced brake thermal efficiency (BTE). Hydrogen enrichment in various fuel systems consistently shows efficiency improvements, primarily attributed to its fast combustion kinetics. For instance, in hydrogen-diesel dual-fuel operation, significant BTE gains are reported at high loads, with one study noting an increase from 24.95% for base line diesel to 28.1% with hydrogen induction, due to enhanced heat-release characteristics [72]. However, these gains are more modest at low loads where lean, low-temperature conditions can lead to incomplete oxidation.

The trade-offs with energy density are also evident. While methanol-gasoline blends (e.g., M20) can exhibit comparable or slightly improved BTE due to improved combustion quality, they suffer from a higher brake-specific fuel consumption (BSFC) due to methanol's lower heating value. Supplementing such blends with hydrogen has been shown to recover some of the lost efficiency by enhancing flame speed and reducing ignition delay, particularly at low loads [73].

However, at high loads, efficiency gains can diminish due to knock-limiting spark retard and increased heat losses from higher in-cylinder temperatures [74]. For ammonia, the BTE generally decreases with its concentration due to slower combustion and higher heat loss. However, with hydrogen assistance, the BTE of ammonia-gasoline blends can be restored to levels comparable to, or even exceeding, neat gasoline in optimized conditions [75].

Figure.4 illustrates the relationship between hydrogen blending and combustion stability is quantified in the figure, which plots indicated mean effective pressure (IMEP) against hydrogen blending ratio (HBR) across various air-fuel equivalence ratios ( $\lambda$ ). For a given lambda value, the coefficient of variation (COV) of IMEP demonstrates a clear decreasing trend as the HBR increases, confirming hydrogen's potent effect on enhancing combustion stability. Furthermore, the graph reveals that a higher HBR enables stable engine operation at progressively leaner conditions (increasing  $\lambda$ ), effectively extending the lean-burn limit. This underscores the critical role of hydrogen enrichment in facilitating robust ultra-lean combustion, a key strategy for achieving high efficiency and low  $\text{NO}_x$  emissions.



**Fig.4** The impact of hydrogen enrichment on combustion stability  $\lambda$  values, increasing the hydrogen blending ratio consistently reduces the COV of IMEP [76]

#### 4.1.3 Emission Characteristics

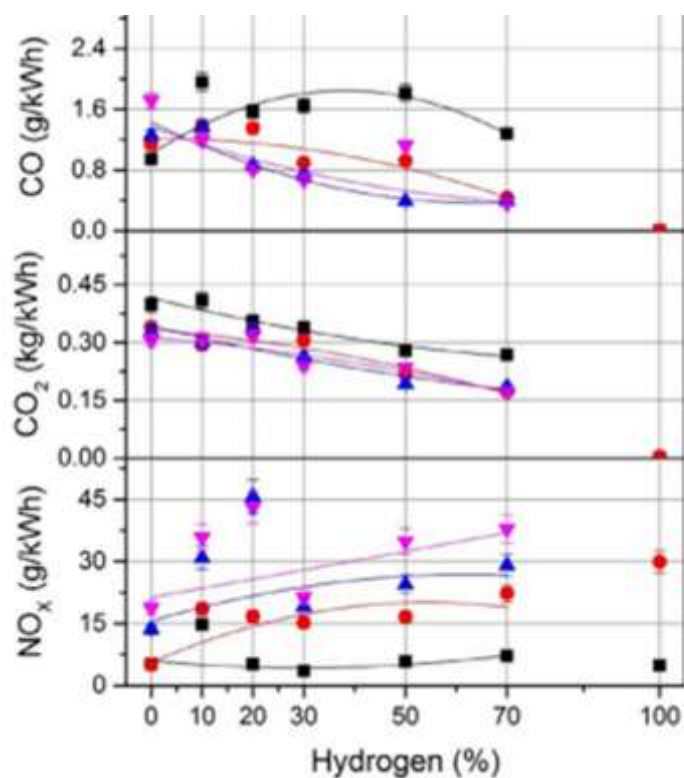
The emission profiles of hydrogen and ammonia are distinct from those of hydrocarbon fuels. The combustion of hydrogen with gasoline typically leads to a significant reduction in CO and unburned hydrocarbons (HC) due to the absence of carbon in the fuel and a more complete oxidation process. Particulate matter emissions are also notably lower. A major challenge, however, is the increase in nitrogen oxide ( $\text{NO}_x$ ) emissions, a consequence of elevated adiabatic flame temperatures. This necessitates the use of mitigation techniques such as cooled EGR or lean-burn strategies.

As a carbon-free molecule, ammonia eliminates  $\text{CO}_2$  and soot emissions from the combustion event itself. Its emission challenges are nitrogen-based. Poor combustion can lead to ammonia slip (unburned  $\text{NH}_3$ ), and the fuel-bound nitrogen can be converted into nitrogen oxides ( $\text{NO}_x$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ), a potent greenhouse gas. In hydrogen ammonia dual fuel operational mode, hydrogen's combustion helps to reduce the unburned ammonia slip. Furthermore, the diffusion effect of ammonia facilities moderate peak flame temperatures [77].

In hydrogen-ammonia dual-fuel operation, hydrogen's role in improving combustion completeness helps reduce unburned ammonia slip. Furthermore, the dilution effect of ammonia can help moderate peak flame temperatures, potentially curbing  $\text{NO}_x$  formation compared to pure hydrogen combustion. Ultimately, the net  $\text{CO}_2$  benefit of using these alternative fuels is contingent upon minimizing unburned fuel losses, managing the energy overhead for fuel production and handling, and controlling the formation of non- $\text{CO}_2$  greenhouse gases like  $\text{N}_2\text{O}$ .

Emissions challenge is twofold. First, the fuel-bound nitrogen can be converted into both  $\text{NO}_x$  and nitrous oxide ( $\text{N}_2\text{O}$ ), the latter being a potent greenhouse gas with a global warming potential 300 times that of  $\text{CO}_2$  [36]. Second, incomplete combustion leads to "ammonia slip," which is an environmental and toxicity concern. Research shows that hydrogen addition can effectively reduce ammonia slip by improving combustion completeness but may concurrently increase  $\text{NO}_x$  emissions due to higher flame temperatures, creating a delicate optimization problem [78]. Advanced after-treatment systems are deemed essential for managing these nitrogenous emissions.

Figure.5 illustrates the emission trade-offs associated with hydrogen enrichment are clearly demonstrated by the trends in CO,  $\text{CO}_2$ , and  $\text{NO}_x$  emissions across a range of hydrogen blending ratios. Carbon monoxide (CO) and carbon dioxide ( $\text{CO}_2$ ) emissions exhibit a consistent and sharp decline as the hydrogen percentage increases, a direct result of carbon displacement and more complete combustion. Conversely, nitrogen oxide ( $\text{NO}_x$ ) emissions show a characteristic peak at intermediate hydrogen concentrations (around 20-50%), driven by elevated combustion temperatures before being suppressed at very high hydrogen levels under ultra-lean conditions. This data underscores the critical challenge of optimizing the hydrogen blend to simultaneously minimize carbonaceous pollutants while mitigating the formation of nitrogen oxides.



**Fig.5** Trends of CO, CO<sub>2</sub> and NO<sub>x</sub> emissions as a function of hydrogen energy share [79]

#### 4.1.4 Combustion Stability and Ignition Strategies

Achieving stable combustion with these alternative fuels often requires specialized ignition and injection strategies. Ammonia's high ignition energy demand can be addressed through pilot fuels (e.g., direct-injected gasoline or hydrogen), hydrogen enrichment, elevated compression ratios, or advanced ignition systems such as plasma or laser ignition [60]. For hydrogen, the risks of flashback and pre-ignition are mitigated through precise injection strategies such as direct injection to avoid premature mixing in the intake port and careful design of the intake system.

Figure.6 illustrate the interaction between injection strategy and ignition timing is critically illustrated by the relationship between the direct injection ratios and indicated thermal efficiency. For an advanced ignition timing ( $-8^{\circ}$  CA BTDC), thermal efficiency initially rises with an increasing direct injection ratio, likely due to enhanced charge cooling and improved volumetric efficiency. However, a clear optimum exists, beyond which further increasing the direct injection ratio leads to a decline in efficiency, potentially due to over-leaning or insufficient mixture preparation time. In contrast, under significantly retarded ignition timings ( $-2^{\circ}$  CA BTDC), the benefits of direct injection are substantially diminished, resulting in lower overall efficiency and demonstrating that the optimal direct injection ratio is highly dependent on the chosen combustion phasing.



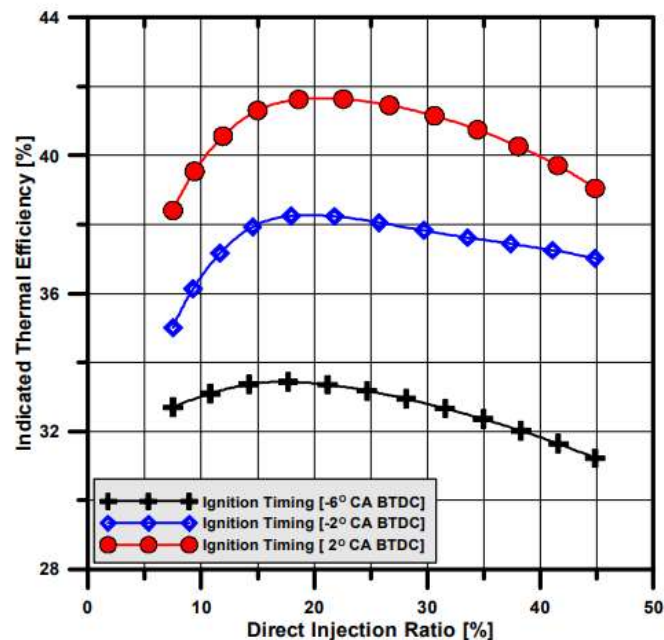


Fig.6 Combined effect of direct injection ratio and ignition timing on thermal efficiency[80]

The injection methodology plays a crucial role. Port fuel injection (PFI) creates a homogeneous mixture that benefits hydrogen's fast-burning nature but increases backfire risks. A combination of direct injection for one fuel (e.g., hydrogen or gasoline) and PFI for the other (e.g., ammonia) can create beneficial charge stratification and help manage abnormal combustion. For ammonia, which may require vaporization, PFI systems sometimes need intake air heating or a reactive pilot fuel to ensure reliable ignition [81].

#### 4.2 Implementation Strategies and System Architecture

Effective deployment of hydrogen–gasoline and ammonia–hydrogen–gasoline dual-fuel systems rests on several key architectural and control strategies. Fuel delivery and mixture preparation: For hydrogen–gasoline systems, dual injection (hydrogen DI + gasoline PFI/GDI) offers control of stratification, combustion phasing and knock mitigation.

Ignition enhancement for ammonia blends: As pure ammonia combustion suffers from slow flame speed, ignition systems must be enhanced (pre-chamber ignition, multi-spark, plasma-assisted ignition) and hydrogen or other promoters added to compensate. Dilution control and mixture stratification: EGR systems, intake heating/cooling, and deliberate stratification (e.g., hydrogen pilot jets) are required to tailor combustion temperature, flame speed and pollutant formation. After-treatment integration: For ammonia-based systems the risk of  $\text{NH}_3$  slip and  $\text{N}_2\text{O}$  emissions means that dedicated catalytic systems (e.g., SCR, ASC) must be considered early in the engine/fuel system design. Thermal management and knock mitigation: Particularly for hydrogen gasoline systems at high loads, knock risk increases due to hydrogen's high reactivity; controlling intake charge temperature, using direct injection of hydrogen and retarded spark may be required.

#### 5. Future study for reduction of $\text{NO}_x$ from hydrogen and ammonia

While hydrogen and ammonia present a pathway to carbon-neutral combustion, their utilization in SI engines introduces significant challenges regarding nitrogen oxide ( $\text{NO}_x$ ) emissions. Future research must, therefore, pivot towards innovative and integrated strategies that move beyond conventional mitigation techniques. A primary focus should be on the development of advanced combustion strategies that inherently suppress  $\text{NO}_x$  formation. For hydrogen engines, this entails a deeper investigation into ultra-lean burn ( $\phi < 0.5$ ) regimes coupled with high levels of exhaust gas recirculation (EGR). The combined effect of lower peak combustion temperatures from excess air and inert gases can dramatically reduce thermal  $\text{NO}_x$ . Research is needed to define the stability limits of such dilute mixtures and develop advanced ignition systems, such as multi-point laser or turbulent jet ignition, to ensure robust flame propagation. Similarly, for ammonia, future work should explore stratified-charge combustion via direct injection, where a locally rich ignitable mixture near the spark plug ensures stability while the overall cylinder charge remains lean, thereby curbing  $\text{NO}_x$  [82].

A second critical avenue for future study lies in the optimization of ammonia-hydrogen blending strategies and their synergistic interaction with after treatment systems. The addition of hydrogen to ammonia is essential for improving combustion stability but exacerbates  $\text{NO}_x$  formation due to increased flame temperatures. Future research must systematically map the  $\text{NO}_x$  trade-offs across the entire blend spectrum (e.g., from 5% to 30% hydrogen by energy fraction) under different engine loads and speeds. This should be coupled with the development of dynamic, real-time blend ratio control algorithms that minimize  $\text{NO}_x$  at the source. Furthermore, the unique composition of ammonia engine exhaust potentially containing significant slip of unburnt  $\text{NH}_3$  presents a novel opportunity. Research must intensify on Passive Ammonia Selective Catalytic Reduction (PA-SCR), where the engine-generated ammonia slip is used directly as a reductant over an under-floor SCR catalyst, effectively turning a pollutant into a de- $\text{NO}_x$  agent [65].

Finally, a holistic approach integrating machine learning (ML) and adaptive control systems represents the frontier of low-NO<sub>x</sub> engine management. The complex, non-linear relationships between injection timing, blend ratio, EGR rate, and ignition parameters make NO<sub>x</sub> prediction and control a prime application for ML. Future studies should focus on developing high-fidelity digital twins of the engine, trained on extensive experimental data, to enable model predictive control (MPC). These systems could proactively adjust engine operating parameters in real-time to maintain optimal conditions for low NO<sub>x</sub>, even during transient cycles. Validating these integrated control strategies, which harmonize in-cylinder combustion techniques with tailored after treatment management, will be crucial for deploying practical, high-efficiency, and ultra-low emission hydrogen and ammonia SI engines [83].

## 6. Conclusion

The integration of hydrogen and ammonia as co-fuels with gasoline in spark-ignition engines presents a complex yet promising pathway toward decarbonization, characterized by distinct trade-offs in combustion behavior, performance, and emissions. Hydrogen's role is primarily that of a combustion enhancer; its high reactivity significantly improves flame speed, shortens combustion duration, and increases thermal efficiency, particularly under lean conditions. However, these benefits are counterbalanced by a heightened propensity for abnormal combustion and a sharp increase in thermal NO<sub>x</sub> emissions due to elevated in-cylinder temperatures.

In contrast, ammonia acts as a combustion suppressant, its slow flame speed and high ignition energy leading to prolonged combustion and potential instability. While it offers the crucial advantage of being a carbon-free fuel, its use introduces a new set of nitrogen-based emissions challenges, including ammonia slip, NO<sub>x</sub>, and the potent greenhouse gas N<sub>2</sub>O. The synergistic combination of hydrogen and ammonia emerges as a highly effective strategy, where hydrogen acts as a reactivity booster, enabling stable and efficient combustion of ammonia that would otherwise be impractical. Ultimately, the successful implementation of these alternative fuels hinges on a system-level approach. No single fuel or simple blend offers a panacea. Future development must focus on optimized, adaptive engine strategies that intelligently manage injection timing, blend ratios, and advanced ignition systems. This must be coupled with robust after-treatment solutions specifically designed for nitrogenous species. The path forward lies not in choosing between hydrogen and ammonia, but in engineering their synergistic potential to achieve a practical balance between high efficiency, stable operation, and ultra-low emissions for the carbon-neutral SI engines of the future.

Combustion control strategies must be adapted for these alternative fuels. The use of exhaust gas recirculation (EGR) for NO<sub>x</sub> suppression, while effective, has a pronounced negative effect on BTE when using hydrogen or ammonia. The reduced oxygen concentration from EGR slows flame propagation, which is particularly detrimental for the already slow-burning ammonia, and can lead to instability and misfire at high EGR rates.

## Data Availability

This review article does not involve the generation of any new data. All data and findings are sourced from previously published articles and cited within this review article.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Reference

- [1] Z. Yu, S. Mingshan, and Y. Shanshan, "Comparison of Greenhouse Gas Emissions Per Capita Per Year Among Countries Considering Methane Emissions," *Earth Sciences*, vol. 9, no. 5, p. 219, 2020, doi: 10.11648/j.earth.20200905.18.
- [2] Q. Wu, Y. Chen, C. Huang, L. Zhang, and C. He, "Carbon emission peaks in countries worldwide and their national drivers," *Carbon Research*, vol. 4, no. 1, Dec. 2025, doi: 10.1007/s44246-025-00195-8.
- [3] X. Hu, J. Li, J. Pan, R. Zhang, H. Wei, and G. Shu, "On combustion and emission characteristics of ammonia/hydrogen engines: Emphasis on energy ratio and equivalence ratio," *Fuel*, vol. 365, p. 131183, 2024, doi: <https://doi.org/10.1016/j.fuel.2024.131183>.
- [4] C. S. Mørch, A. Bjerre, M. P. Gøttrup, S. C. Sorenson, and J. Schramm, "Ammonia/hydrogen mixtures in an SI-engine: Engine performance and analysis of a proposed fuel system," *Fuel*, vol. 90, no. 2, pp. 854–864, 2011, doi: <https://doi.org/10.1016/j.fuel.2010.09.042>.
- [5] S. Frigo and R. Gentili, "Analysis of the behaviour of a 4-stroke Si engine fuelled with ammonia and hydrogen," *Int J Hydrogen Energy*, vol. 38, no. 3, pp. 1607–1615, 2013, doi: <https://doi.org/10.1016/j.ijhydene.2012.10.114>.
- [6] S. Demirtürk, H. Gürbüz, and H. Akçay, "Effect of port-injected hydrogen on performance, emissions, and operating costs in a propane-fueled SI engine under lean-burn conditions," *Int J Hydrogen Energy*, vol. 177, p. 151538, 2025, doi: <https://doi.org/10.1016/j.ijhydene.2025.151538>.
- [7] R. Islam, S. M. Asiqur Rahman, M. Rajin Islam, M. Rakibul Islam, M. R. Ahmed, and M. R. I. Sarker, "Performance and Emission Analysis of Hydrogen and Conventional Fuels in PFI SI Engines Using CONVERGE 3.0," *Next Energy*, vol. 9, Oct. 2025, doi: 10.1016/j.nxener.2025.100404.
- [8] H. E. Gülcan and H. Gürbüz, "Effect of spark plug position and ignition timing on performance, exergy, exergoeconomic, environmental, and enviro-cost in a hydrogen-SI engine," *Appl Therm Eng*, vol. 278, Nov. 2025, doi: 10.1016/j.applthermaleng.2025.127400.
- [9] P. S. Varma and M. Mittal, "Experimental and numerical investigations to study the effects of hydrogen enrichment on a retrofitted CNG SI engine operating at a low load condition," *Fuel*, vol. 392, p. 134914, 2025, doi: <https://doi.org/10.1016/j.fuel.2025.134914>.

- [10] J. Li, R. Zhang, L. Wang, G. Shu, H. Wei, and J. Pan, "Hydrogen stratification improving ammonia combustion and emission performance in SI engines," *Energy Convers Manag*, vol. 344, Nov. 2025, doi: 10.1016/j.enconman.2025.120332.
- [11] J. Li, R. Zhang, X. Mao, L. Wang, H. Wei, and J. Pan, "Ammonia and hydrogen blending effects on knocking characteristics in an optical SI engine," *Fuel*, vol. 385, p. 134067, 2025, doi: <https://doi.org/10.1016/j.fuel.2024.134067>.
- [12] P. Guibert, K.-H. Tran, S. Sebai, M. Perceau, and S. Guilain, "Numerical simulation of predictive combustion and NOx emissions for different ammonia/hydrogen fuels in SI engine using zero-1 dimensional thermodynamic modeling," *Int J Hydrogen Energy*, vol. 143, pp. 500–512, 2025, doi: <https://doi.org/10.1016/j.ijhydene.2025.03.007>.
- [13] Y. Liang *et al.*, "Effects of hydrogen volume fraction, air fuel ratio, and compression ratio on combustion and emission characteristics of an SI ammonia-hydrogen engine," *Energy*, vol. 308, p. 132858, 2024, doi: <https://doi.org/10.1016/j.energy.2024.132858>.
- [14] T. Zhu, X. Yan, Z. Gao, Y. Qiu, L. Zhu, and Z. Huang, "Combustion and emission characteristics of ammonia-hydrogen fueled SI engine with high compression ratio," *Int J Hydrogen Energy*, vol. 62, pp. 579–590, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2024.03.035>.
- [15] M. H. Dinesh and G. N. Kumar, "Experimental investigation of variable compression ratio and ignition timing effects on performance, combustion, and Nox emission of an ammonia/hydrogen-fuelled Si engine," *Int J Hydrogen Energy*, vol. 48, no. 90, pp. 35139–35152, 2023, doi: <https://doi.org/10.1016/j.ijhydene.2023.05.219>.
- [16] Z. Lin *et al.*, "Numerical investigation of ammonia-rich combustion produces hydrogen to accelerate ammonia combustion in a direct injection SI engine," *Int J Hydrogen Energy*, vol. 49, pp. 338–351, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2023.07.281>.
- [17] M. H. Dinesh, J. K. Pandey, and G. N. Kumar, "Study of performance, combustion, and NOx emission behavior of an SI engine fuelled with ammonia/hydrogen blends at various compression ratio," *Int J Hydrogen Energy*, vol. 47, no. 60, pp. 25391–25403, 2022, doi: <https://doi.org/10.1016/j.ijhydene.2022.05.287>.
- [18] S. Frigo and R. Gentili, "Analysis of the behaviour of a 4-stroke Si engine fuelled with ammonia and hydrogen," *Int J Hydrogen Energy*, vol. 38, no. 3, pp. 1607–1615, 2013, doi: <https://doi.org/10.1016/j.ijhydene.2012.10.114>.
- [19] T. Prodkornburee, P. Promhuad, S. Sittichompoo, B. Sawatmongkhon, and K. Theinnoi, "A comprehensive evaluation of ammonia reforming methodologies for hydrogen production for promoting ammonia as a low-carbon fuel in internal combustion engines," *Int J Hydrogen Energy*, vol. 168, p. 151083, 2025, doi: <https://doi.org/10.1016/j.ijhydene.2025.151083>.
- [20] C. S. Mørch, A. Bjerre, M. P. Gøttrup, S. C. Sorenson, and J. Schramm, "Ammonia/hydrogen mixtures in an SI-engine: Engine performance and analysis of a proposed fuel system," *Fuel*, vol. 90, no. 2, pp. 854–864, 2011, doi: <https://doi.org/10.1016/j.fuel.2010.09.042>.
- [21] H. Song, K. Ju, and J. Park, "Numerical analysis on engine performance and combustion characteristics for ammonia-hydrogen dual-fuel engine," *Int J Hydrogen Energy*, vol. 170, p. 151137, 2025, doi: <https://doi.org/10.1016/j.ijhydene.2025.151137>.
- [22] J. Yu, Q. Liu, S. Liao, and Y. He, "Effects of ammonia supply distribution rate and cracking degree on combustion-emission in ammonia-hydrogen combination engine with IJL," *Appl Therm Eng*, vol. 280, Dec. 2025, doi: 10.1016/j.applthermaleng.2025.128467.
- [23] G. Xin, Y. Xu, H. Zhu, S. Feng, and X. Chen, "Enhancing the ammonia energy proportion of ammonia hydrogen internal combustion engines through oxygen enriched combustion strategy," *Int J Hydrogen Energy*, vol. 172, p. 150603, 2025, doi: <https://doi.org/10.1016/j.ijhydene.2025.150603>.
- [24] Q. Sun, Y. Qi, Z. Lin, Y. Liu, W. Zhu, and Z. Wang, "Combustion and emission characteristics of an ammonia-hydrogen engine using hydrogen-nitrogen jet ignition," *Energy*, vol. 328, p. 136544, 2025, doi: <https://doi.org/10.1016/j.energy.2025.136544>.
- [25] W. Tutak, "Co-combustion of ammonia and hydrogen in spark ignition engines - State-of-the-art and challenges," *Int J Hydrogen Energy*, vol. 80, pp. 188–205, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2024.07.163>.
- [26] S. A. Reggeti, S. P. Kane, and W. F. Northrop, "Hydrogen production in ammonia-fueled spark ignition engines," *Applications in Energy and Combustion Science*, vol. 14, Jun. 2023, doi: 10.1016/j.jaecs.2023.100136.
- [27] F. Oral, "Effect of using gasoline and gasoline-ethanol fuel mixture on performance and emissions in a hydrogen generator supported SI engine," *Case Studies in Thermal Engineering*, vol. 55, p. 104192, 2024, doi: <https://doi.org/10.1016/j.csite.2024.104192>.
- [28] Z. Shang *et al.*, "Synergic effect of hydrogen and n-butanol on combustion and emission characteristics of a hydrogen direct injection SI engine fueled with n-butanol/gasoline," *Int J Hydrogen Energy*, vol. 49, pp. 945–956, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2023.09.213>.
- [29] P. V. Inbanaathan *et al.*, "Comprehensive study on using hydrogen-gasoline-ethanol blends as flexible fuels in an existing variable speed SI engine," *Int J Hydrogen Energy*, vol. 48, no. 99, pp. 39531–39552, 2023, doi: <https://doi.org/10.1016/j.ijhydene.2023.03.107>.
- [30] S. Pan, J. Wang, and Z. Huang, "Effects of hydrogen injection strategy on the hydrogen mixture distribution and combustion of a gasoline/hydrogen SI engine under lean burn condition," *Int J Hydrogen Energy*, vol. 47, no. 57, pp. 24069–24079, 2022, doi: <https://doi.org/10.1016/j.ijhydene.2022.05.197>.
- [31] Z. Shang *et al.*, "Comparative study on effects of injection mode on combustion and emission characteristics of a combined injection n-butanol/gasoline SI engine with hydrogen direct injection," *Energy*, vol. 213, p. 118903, 2020, doi: <https://doi.org/10.1016/j.energy.2020.118903>.
- [32] X. Yu *et al.*, "A comparative study on effects of homogeneous or stratified hydrogen on combustion and emissions of a gasoline/hydrogen SI engine," *Int J Hydrogen Energy*, vol. 44, no. 47, pp. 25974–25984, 2019, doi: <https://doi.org/10.1016/j.ijhydene.2019.08.029>.
- [33] S. O. Akansu, S. Tangöz, N. Kahraman, M. İ. İlhak, and S. Açıkgöz, "Experimental study of gasoline-ethanol-hydrogen blends combustion in an SI engine," *Int J Hydrogen Energy*, vol. 42, no. 40, pp. 25781–25790, 2017, doi: <https://doi.org/10.1016/j.ijhydene.2017.07.014>.
- [34] S. T. P. Purayil, M. O. Hamdan, S. A. B. Al-Omari, M. Y. E. Selim, and E. Elnajjar, "Influence of ethanol-gasoline-hydrogen and methanol-gasoline-hydrogen blends on the performance and hydrogen knock limit of a lean-burn spark ignition engine," *Fuel*, vol. 377, p. 132825, 2024, doi: <https://doi.org/10.1016/j.fuel.2024.132825>.

- [35] S. T. P. Purayil, S. A. B. Al-Omari, and E. Elnajjar, "Experimental investigation on the influence of gasoline injection pressure on the hydrogen knock limit and performance of a hydrogen–gasoline dual fuel engine," *Int J Hydrogen Energy*, vol. 81, pp. 1385–1393, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2024.07.281>.
- [36] M. Mohamed, A. Biswal, X. Wang, H. Zhao, and J. Hall, "Experimental investigation for enhancing the performance of hydrogen direct injection compared to gasoline in spark ignition engine through valve timings and overlap optimization," *Fuel*, vol. 372, p. 132257, 2024, doi: <https://doi.org/10.1016/j.fuel.2024.132257>.
- [37] S. T. P. Purayil, S. Al-Omari, and E. Elnajjar, "Comparative analysis of knock intensity in spark ignition engines using gasoline and hydrogen–Gasoline blends," *International Journal of Thermofluids*, vol. 28, p. 101309, 2025, doi: <https://doi.org/10.1016/j.ijft.2025.101309>.
- [38] X. Duan, X. Chu, R. Wang, Z. Chen, F. Zhou, and T. M. M. Abdellatif, "The performance and emissions characteristics of the gasoline spark ignition engine fuelled with green and renewable methanol and hydrogen," *Renew Energy*, vol. 240, p. 122184, 2025, doi: <https://doi.org/10.1016/j.renene.2024.122184>.
- [39] X. Duan *et al.*, "Performance analysis and comparison of the spark ignition engine fuelled with industrial by-product hydrogen and gasoline," *J Clean Prod*, vol. 424, p. 138899, 2023, doi: <https://doi.org/10.1016/j.jclepro.2023.138899>.
- [40] D. Suresh and E. Porpatham, "Influence of high compression ratio and hydrogen addition on the performance and emissions of a lean burn spark ignition engine fueled by ethanol-gasoline," *Int J Hydrogen Energy*, vol. 48, no. 38, pp. 14433–14448, 2023, doi: <https://doi.org/10.1016/j.ijhydene.2022.12.275>.
- [41] J. K. Pandey and G. N. Kumar, "Study of combustion and emission of a SI engine at various CR fuelled with different ratios of biobutanol/hydrogen fuel," *Int J Hydrogen Energy*, vol. 48, no. 72, pp. 28222–28234, 2023, doi: <https://doi.org/10.1016/j.ijhydene.2023.04.031>.
- [42] H. Yaman and M. K. Yesilyurt, "The influence of n-pentanol blending with gasoline on performance, combustion, and emission behaviors of an SI engine," *Engineering Science and Technology, an International Journal*, vol. 24, no. 6, pp. 1329–1346, 2021, doi: <https://doi.org/10.1016/j.jestch.2021.03.009>.
- [43] B. S. Nuthan Prasad, J. K. Pandey, and G. N. Kumar, "Effect of hydrogen enrichment on performance, combustion, and emission of a methanol fueled SI engine," *Int J Hydrogen Energy*, vol. 46, no. 49, pp. 25294–25307, 2021, doi: <https://doi.org/10.1016/j.ijhydene.2021.05.039>.
- [44] X. Cong, C. Ji, and S. Wang, "Investigation into engine performance of a hydrogen-dimethyl ether spark-ignition engine under various dimethyl ether fractions," *Fuel*, vol. 306, p. 121429, 2021, doi: <https://doi.org/10.1016/j.fuel.2021.121429>.
- [45] G. Duraisamy and C. Mounaïm-Rousselle, "Ammonia-DME blends in homogeneous charge compression ignition engine," *Fuel*, vol. 405, p. 136463, 2026, doi: <https://doi.org/10.1016/j.fuel.2025.136463>.
- [46] J. L. Santos, C. Megías-Sayago, S. Ivanova, M. Á. Centeno, and J. A. Odriozola, "Functionalized biochars as supports for Pd/C catalysts for efficient hydrogen production from formic acid," *Appl Catal B*, vol. 282, p. 119615, 2021, doi: <https://doi.org/10.1016/j.apcatb.2020.119615>.
- [47] A. Kalwar and A. K. Agarwal, "Overview, Advancements and Challenges in Gasoline Direct Injection Engine Technology," in *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector*, A. P. Singh, N. Sharma, R. Agarwal, and A. K. Agarwal, Eds., Singapore: Springer Singapore, 2020, pp. 111–147. doi: 10.1007/978-981-15-0368-9\_6.
- [48] M. Aghahasani *et al.*, "Numerical Study on Hydrogen–Gasoline Dual-Fuel Spark Ignition Engine," *Processes*, vol. 10, no. 11, 2022, doi: 10.3390/pr10112249.
- [49] A. H. Khalid *et al.*, "Hydrogen port fuel injection: Review of fuel injection control strategies to mitigate backfire in internal combustion engine fuelled with hydrogen," *Int J Hydrogen Energy*, vol. 66, pp. 571–581, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2024.04.087>.
- [50] S. Wang, C. Ji, and B. Zhang, "Starting a spark-ignited engine with the gasoline–hydrogen mixture," *Int J Hydrogen Energy*, vol. 36, no. 7, pp. 4461–4468, 2011, doi: <https://doi.org/10.1016/j.ijhydene.2011.01.020>.
- [51] D. Nguyen, Y. Choi, C. Park, Y. Kim, and J. Lee, "Effect of supercharger system on power enhancement of hydrogen-fueled spark-ignition engine under low-load condition," *Int J Hydrogen Energy*, vol. 46, no. 9, pp. 6928–6936, 2021, doi: <https://doi.org/10.1016/j.ijhydene.2020.11.144>.
- [52] K. V. Shivaprasad, S. Raviteja, P. Chitragar, and G. N. Kumar, "Experimental Investigation of the Effect of Hydrogen Addition on Combustion Performance and Emissions Characteristics of a Spark Ignition High Speed Gasoline Engine," *Procedia Technology*, vol. 14, pp. 141–148, 2014, doi: <https://doi.org/10.1016/j.protcy.2014.08.019>.
- [53] M. M. EL-Kassaby, Y. A. Eldrainy, M. E. Khidr, and K. I. Khidr, "Effect of hydroxy (HHO) gas addition on gasoline engine performance and emissions," *Alexandria Engineering Journal*, vol. 55, no. 1, pp. 243–251, 2016, doi: <https://doi.org/10.1016/j.aej.2015.10.016>.
- [54] I. M. M. Elsemary, A. A. A. Attia, K. H. Elnagar, and A. A. M. Elaraqy, "Experimental investigation on performance of single cylinder spark ignition engine fueled with hydrogen-gasoline mixture," *Appl Therm Eng*, vol. 106, pp. 850–854, 2016, doi: <https://doi.org/10.1016/j.applthermaleng.2016.05.177>.
- [55] C. Ji, X. Cong, S. Wang, L. Shi, T. Su, and D. Wang, "Performance of a hydrogen-blended gasoline direct injection engine under various second gasoline direct injection timings," *Energy Convers Manag*, vol. 171, pp. 1704–1711, 2018, doi: <https://doi.org/10.1016/j.enconman.2018.06.112>.
- [56] J. Kim, K. M. Chun, S. Song, H.-K. Baek, and S. W. Lee, "Hydrogen effects on the combustion stability, performance and emissions of a turbo gasoline direct injection engine in various air/fuel ratios," *Appl Energy*, vol. 228, pp. 1353–1361, 2018, doi: <https://doi.org/10.1016/j.apenergy.2018.06.129>.
- [57] C. Engines, "A Review of Current Advances in Ammonia Combustion," 2023.
- [58] C. Tornatore, P. Sementa, and F. Catapano, "Ammonia–Hydrogen Dual-Fuel Combustion: Strategies for Optimizing Performance and Reducing Emissions in Internal Combustion Engines," *Energies (Basel)*, vol. 18, no. 12, 2025, doi: 10.3390/en18123159.
- [59] S. A. Reggeti and W. F. Northrop, "Lean ammonia-fueled engine operation enabled by hydrogen-assisted turbulent jet ignition," *Front Mech Eng*, vol. 10, no. March, pp. 1–9, 2024, doi: 10.3389/fmech.2024.1368717.

- [60] S. T. P. Purayil, M. O. Hamdan, S. A. B. Al-Omari, M. Y. E. Selim, and E. Elnajjar, "Review of hydrogen-gasoline SI dual fuel engines: Engine performance and emission," *Energy Reports*, vol. 9, pp. 4547–4573, 2023, doi: <https://doi.org/10.1016/j.egyr.2023.03.054>.
- [61] V. Sharma, A. Panesar, G. de Sercey, and S. Begg, "A Review of Ammonia Combustion and Emissions Characteristics in Spark-Ignition Engines and Future Road Map," Jan. 01, 2025, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/en18010041.
- [62] Y. Qi, W. Liu, S. Liu, W. Wang, Y. Peng, and Z. Wang, "A review on ammonia-hydrogen fueled internal combustion engines," *eTransportation*, vol. 18, p. 100288, 2023, doi: <https://doi.org/10.1016/j.etrans.2023.100288>.
- [63] E. Nadimi, G. Przybyła, D. Emberson, T. Løvås, Ł. Ziółkowski, and W. Adameczyk, "Effects of using ammonia as a primary fuel on engine performance and emissions in an ammonia/biodiesel dual-fuel CI engine," *Int J Energy Res*, vol. 46, no. 11, pp. 15347–15361, 2022, doi: 10.1002/er.8235.
- [64] T. Su, C. Ji, S. Wang, X. Cong, and L. Shi, "Improving the combustion performance of a gasoline rotary engine by hydrogen enrichment at various conditions," *Int J Hydrogen Energy*, vol. 43, no. 3, pp. 1902–1908, 2018, doi: <https://doi.org/10.1016/j.ijhydene.2017.11.175>.
- [65] K. P. S. U. T. M. Proniewicz, "Ammonia as carbon free fuel for internal Combustion engine driven Agricultural vehicle (ACTIVATE)," pp. 1–23, 2022.
- [66] Y. Wu, J. Hu, Y. Lin, P. Chen, G. Chen, and Z. Wang, "Experimental study of ammonia energy ratio on combustion and emissions from ammonia-gasoline dual-fuel engine at various load conditions," *Journal of the Energy Institute*, vol. 117, p. 101868, 2024, doi: <https://doi.org/10.1016/j.joei.2024.101868>.
- [67] G. Xin, C. Ji, S. Wang, H. Meng, K. Chang, and J. Yang, "Effect of different volume fractions of ammonia on the combustion and emission characteristics of the hydrogen-fueled engine," *Int J Hydrogen Energy*, vol. 47, no. 36, pp. 16297–16308, 2022, doi: <https://doi.org/10.1016/j.ijhydene.2022.03.103>.
- [68] W. Yang, K. K. J. Ranga Dinesh, K. H. Luo, and D. Thevenin, "Direct numerical simulation of turbulent premixed ammonia and ammonia-hydrogen combustion under engine-relevant conditions," *Int J Hydrogen Energy*, vol. 47, no. 20, pp. 11083–11100, 2022, doi: <https://doi.org/10.1016/j.ijhydene.2022.01.142>.
- [69] B. Wang, H. Wang, B. Duan, C. Yang, D. Hu, and Y. Wang, "Effect of ammonia/hydrogen mixture ratio on engine combustion and emission performance at different inlet temperatures," *Energy*, vol. 272, p. 127110, 2023, doi: <https://doi.org/10.1016/j.energy.2023.127110>.
- [70] C. Ji *et al.*, "Effect of ammonia addition on combustion and emissions performance of a hydrogen engine at part load and stoichiometric conditions," *Int J Hydrogen Energy*, vol. 46, no. 80, pp. 40143–40153, 2021, doi: <https://doi.org/10.1016/j.ijhydene.2021.09.208>.
- [71] F. Musy, R. Ortiz, I. Ortiz, and A. Ortiz, "Hydrogen-fuelled internal combustion engines: Direct Injection versus Port-Fuel Injection," *Int J Hydrogen Energy*, vol. 137, no. February 2024, pp. 925–938, 2025, doi: 10.1016/j.ijhydene.2024.07.136.
- [72] M. R. Dahake and D. N. Malkhede, "Experimental investigation of performance and emissions of CRDI diesel engine in dual fuel mode by hydrogen induction and diesel injection coupled with exhaust gas recirculation," *Mater Today Proc*, vol. 46, pp. 2814–2819, 2021, doi: 10.1016/j.matpr.2021.02.653.
- [73] S. Sarikoç, "Effect of H<sub>2</sub> addition to methanol-gasoline blend on an SI engine at various lambda values and engine loads: A case of performance, combustion, and emission characteristics," *Fuel*, vol. 297, no. February, p. 120732, 2021, doi: 10.1016/j.fuel.2021.120732.
- [74] Z. Liu, L. Zhou, L. Zhong, and H. Wei, "Enhanced combustion of ammonia engine based on novel air-assisted pre-chamber turbulent jet ignition," *Energy Convers Manag*, vol. 276, p. 116526, 2023, doi: <https://doi.org/10.1016/j.enconman.2022.116526>.
- [75] C. Lhuillier, P. Brequigny, F. Contino, and C. Mounaïm-Rousselle, "Experimental study on ammonia/hydrogen/air combustion in spark ignition engine conditions," *Fuel*, vol. 269, p. 117448, 2020, doi: <https://doi.org/10.1016/j.fuel.2020.117448>.
- [76] X. Yu *et al.*, "Effects of hydrogen direct injection on combustion and emission characteristics of a hydrogen/Acetone-Butanol-Ethanol dual-fuel spark ignition engine under lean-burn conditions," *Int J Hydrogen Energy*, vol. 45, no. 58, pp. 34193–34203, 2020, doi: 10.1016/j.ijhydene.2020.09.080.
- [77] M. Alnajideen *et al.*, "Ammonia combustion and emissions in practical applications: a review," *Carbon Neutrality*, vol. 3, no. 1, 2024, doi: 10.1007/s43979-024-00088-6.
- [78] J. Li, R. Zhang, L. Wang, G. Shu, H. Wei, and J. Pan, "Hydrogen stratification improving ammonia combustion and emission performance in SI engines," *Energy Convers Manag*, vol. 344, no. March, 2025, doi: 10.1016/j.enconman.2025.120332.
- [79] S. M. V Sagar and A. K. Agarwal, "Knocking behavior and emission characteristics of a port fuel injected hydrogen enriched compressed natural gas fueled spark ignition engine," *Appl Therm Eng*, vol. 141, pp. 42–50, 2018, doi: <https://doi.org/10.1016/j.applthermaleng.2018.05.102>.
- [80] M. Elkelawy and H. A.-E. Bastawissi, "Numerical Study on the Hydrogen Fueled SI Engine Combustion Optimization through a Combined Operation of DI and PFI Strategies," *Energy Power Eng*, vol. 05, no. 08, pp. 513–522, 2013, doi: 10.4236/epe.2013.58056.
- [81] A. Kiss, B. Szabó, K. Kun, and Z. Weltsch, "Prediction of Efficiency, Performance, and Emissions Based on a Validated Simulation Model in Hydrogen-Gasoline Dual-Fuel Internal Combustion Engines," *Energies (Basel)*, vol. 17, no. 22, Nov. 2024, doi: 10.3390/en17225680.
- [82] H. Wang, B. Wang, C. Yang, D. Hu, B. Duan, and Y. Wang, "Study on dual injection strategy of diesel ignition ammonia/hydrogen mixture fuel engine," *Fuel*, vol. 348, p. 128526, 2023, doi: <https://doi.org/10.1016/j.fuel.2023.128526>.
- [83] J. Kodavasal, A. A. Moiz, M. Ameen, and S. Som, "Using machine learning to analyze factors determining cycle-to-cycle variation in a spark-ignited gasoline engine," *Journal of Energy Resources Technology, Transactions of the ASME*, vol. 140, no. 10, pp. 1–9, 2018, doi: 10.1115/1.4040062.