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Review Article

Using hydrogen as potential fuel for internal combustion engines: A comprehensive assessment

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Abstract. This comprehensive review explores the feasibility and potential of using hydrogen gas as a fuel for internal combustion engines, a topic of growing importance in the context of global efforts to reduce greenhouse gas emissions and transition towards sustainable energy sources. Hydrogen, known for its high energy content and clean combustion properties, presents a promising alternative to traditional fossil fuels. This paper examines the chemical properties of hydrogen and its benefits over conventional fuels, particularly focusing on the technological advancements and modifications required for compression ignition and spark ignition engines to efficiently utilize hydrogen. The review delves into the necessary engine design modification, fuel injection systems, combustion characteristics, and emission control technologies specific to both compression ignition and spark ignition engines. Furthermore, it addresses the environmental impacts, including reductions in greenhouse gases and other pollutants, and evaluates the economic implications, such as production costs and feasibility compared to other energy solutions. Key challenges associated with the storage, distribution, and safety of hydrogen are discussed, along with potential solutions and innovations currently under investigation. This paper aims to provide a thorough understanding of the current state of hydrogen as a promising fuel for internal combustion engines, guiding future research and development in this vital field.

Keywords: Emission reduction; Internal combustion engines; Alternative fuel; Hydrogen; Sustainability; Net-zero goal

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1. Introduction

Energy scarcity and greenhouse gas (GHG) emissions from fossil fuels are critical issues in contemporary environmental and energy policy discourse (V. G. Nguyen *et al.*, 2024a; Woertz *et al.*, 2014; Zhang *et al.*, 2023). Energy shortage presents major obstacles to economic stability, growth, and societal well-being. This issue is further exacerbated by depending on limited resources of fossil fuels such as coal, oil, and natural gas (Cherwoo *et al.*, 2023; Masuk *et al.*, 2021; Salah *et al.*, 2021). The likelihood of energy shortages increases as these resources get more difficult and costly to obtain, hence perhaps causing geopolitical conflicts and economic disturbance (Månsson, 2014). The burning and combustion of fossil fuels for generating energy is the largest source of anthropogenic GHG emissions (Hoang and Pham, 2021; X. P. Nguyen *et al.*, 2021a; Sirohi *et al.*, 2023). Carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), and other pollutants are the main sources of GHGs by the combustion of fossil fuel from industrial, transportation, and agricultural activities (V. N. Nguyen *et al.*, 2023; Olszewski *et al.*, 2023; Saikawa *et al.*, 2017). CO_2 emissions result primarily from the combustion process, while CH_4 is released during the extraction and transport of natural gas and oil and agricultural activities. NO_x emissions typically occur during the combustion of coal, oil, and other fossil-originated fuels (Hoang, 2018; Nouni *et al.*, 2021; Paramasivama *et al.*, 2024; Seyam et al., 2023). These GHGs contribute significantly to the greenhouse effect, where trapped heat in the Earth's atmosphere leads to global warming and climate change (Hansen and Sato, 2016; Kumar, 2018). The Intergovernmental Panel on Climate Change has repeatedly highlighted the link between fossil fuel combustion and rising global temperatures, increased frequency of extreme weather events, sea-level rise, and disruptions to ecosystems and biodiversity (IPCC, 2014; Stocker *et al.*, 2013). The persistence of GHGs in the atmosphere, particularly CO_2, which can remain for centuries, highlights the long-term consequence of current energy practices (Knutti and Rogelj, 2015). Addressing the dual challenges of energy scarcity and fossil

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fuel-emitted GHG necessitates a comprehensive multifaceted approach (Amponsah *et al*., 2014; Ren *et al*., 2020).

The connection between energy scarcity, fossil fuel-emitted GHGs, and the Sustainable Development Goals (SDGs) is profound and multifaceted (Trinh and Chung, 2023; Yu *et al*., 2022). Specifically, SDG 7 targets to ensure affordable, reliable, sustainable, and modern energy sources, while SDG 13 aims to take urgent actions to combat climate change. Addressing energy scarcity and reducing GHG emissions are pivotal in achieving these goals and advancing global sustainability (Razzaq *et al*., 2023; Wang *et al*., 2022). In many regions, the development of the economy, education, healthcare, and life quality could be hindered by the lack of reliable energy sources (IBRD/WB, 2018; Shyu, 2021). Therefore, transitioning from fossil fuels to renewables is critical for alleviating energy scarcity, reducing dependence on fossil fuels, and lowering GHG emissions (Han *et al*., 2024; Le *et al*., 2024a; V. N. Nguyen *et al*., 2024; Rathor *et al*., 2016; Sharma *et al*., 2022b). Indeed, utilizing various renewables could mitigate the issues of energy shortage and increasing pollutant emissions (Prempeh *et al*., 2024; Shadvar and Rahman, 2024; Ugwu *et al*., 2022). Indeed, the use of various renewable energy sources like biomass energy (Nguyen and Le, 2023; V. G. Nguyen *et al*., 2024b), solar energy (Afandi *et al*., 2022; Kian and Lim, 2023), wind energy (Hassoine *et al*., 2022; Marih *et al*., 2020), geothermal energy (Lee *et al*., 2019; Rudiyanto *et al*., 2023), biogas (Fransiscus and Simangunsong, 2021; Hadiyanto *et al*., 2023), syngas (Bui *et al*., 2024; Navid *et al*., 2020), biodiesel (Dong and Sharma, 2023; Hoang, 2021; Nguyen *et al*., 2022), bio-alcohol (Rahman *et al*., 2023; Yadav *et al*., 2024), and hydrogen (Al-Baghdadi *et al*., 2023; Noussan *et al*., 2020) have been reported in the literature to offer sustainable solutions that can be deployed in both urban and remote areas, enhancing energy access and security (Bawan and Al Hasibi, 2022; Said *et al*., 2022b). In addition, the emission of GHGs from fossil fuels is intrinsically linked to SDG 13, which calls for urgent actions to mitigate climate change (Iacobuţă *et al*., 2022). The negative impacts of climate change have been found to pose significant threats to human health, livelihoods, and biodiversity. Meeting the targets of SDG 13 requires a drastic reduction in GHG emissions, necessitating a global shift towards low-carbon energy systems (IEA; IRENA, 2019; H. Liu *et al*., 2022; Swardika *et al*., 2020). Additionally, improving energy efficiency, advancing carbon capture, energy storage technologies, and promoting sustainable consumption patterns, using no-emission electric vehicles, and fuel cells are essential strategies (Achmad *et al*., 2022; Cao *et al*., 2023; Ingried *et al*., 2022; Nguyen *et al*., 2021; Subramanian *et al*., 2021). Achieving net-zero emissions involves balancing the amount of GHGs emitted with the amount removed from the atmosphere, aiming for no net increase in atmospheric GHG levels (Gangadhari *et al*., 2023; Tan and Tan, 2022). This target is crucial for stabilizing global temperatures and preventing the most catastrophic effects of climate change. Obviously, strategies for obtaining net-zero goals include the increase in the renewable share in the global energy rate, enhancing energy efficiency, and developing and deploying carbon capture and storage technologies (Hoang *et al*., 2023c; Hong, 2022; Shaw and Mukherjee, 2022). Policymakers, researchers, and industry stakeholders must collaborate to implement these solutions, thereby addressing both the immediate and long-term challenges of energy scarcity and climate change (Hoang *et al*., 2021; T. H. Nguyen *et al*., 2024; X. P. Nguyen *et al*., 2021b). By fostering innovation, investing in clean energy infrastructure, and implementing supportive policies and regulations, stakeholders can drive the transition towards sustainable energy systems and net-zero emissions (Rodriguez *et al*., 2021; Shu *et al*., 2023). Collaborative international efforts are essential, as climate change and energy scarcity are global challenges requiring coordinated solutions. Progress in these areas not only supports the achievement of SDG 7 and SDG 13 but also contributes to broader sustainable development objectives, including poverty alleviation, economic growth, and environmental preservation (IEA, 2022; Thapa *et al*., 2023).

Hydrogen gas has emerged as a promising alternative fuel in the quest to mitigate energy scarcity and reduce GHG emissions. The transition from fossil-originated fuels to cleaner energy sources is critical for environmental sustainability and addressing climate change (J.O. Abe *et al*., 2019; John O Abe *et al*., 2019; Sharma *et al*., 2023). Hydrogen as a fuel is gaining prominence as can be observed by the increasing number of publications in this domain depicted in Figure 1 (Rueda-Vázquez *et al*., 2024).

Hydrogen as a fuel offers several compelling advantages for internal combustion engines (ICEs). It produces water vapor as the primary byproduct, eliminating CO_2 emissions and thus significantly reducing the carbon footprint of ICEs (Said *et al*., 2022a). Hydrogen can be generated from various resources like water, solar, wind, coal, biomass, and waste sources, which enhances energy security and accessibility, especially in regions lacking traditional fossil fuel resources (Chen *et al*., 2023; Hoang

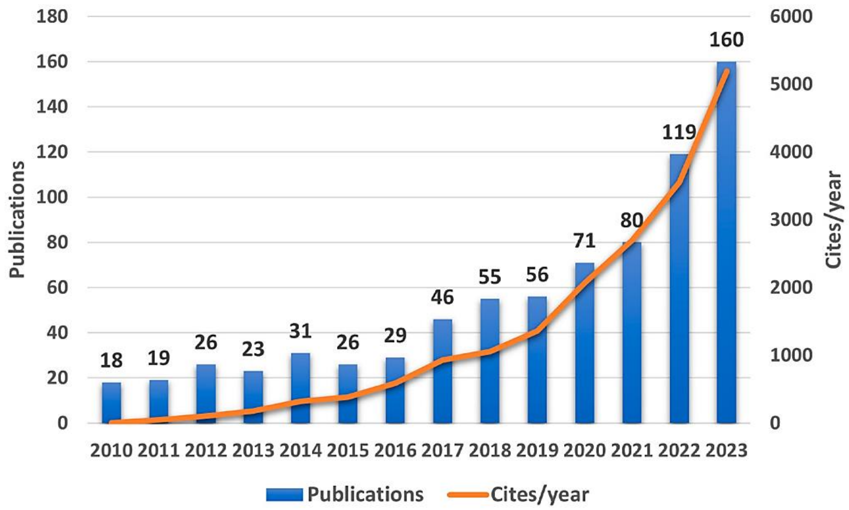

Fig. 1 Year-wise research publication in the domain of hydrogen as a fuel in dual-fuel mode (Rueda-Vázquez *et al*., 2024) (Permitted by MDPI)

et al., 2023b, 2023a, 2022c; Le *et al.*, 2024b; Minh Loy *et al.*, 2020; Rusdianasari *et al.*, 2023). This versatility aligns intending to ensure reliable and modern energy for all (Tan *et al.*, 2023). Hydrogen combustion in ICEs presents a feasible interim solution toward achieving net-zero emissions targets (Shi *et al.*, 2023). A comprehensive review paper on the use of hydrogen gas as fuel for ICEs is essential to consolidate existing research, identify gaps, and guide future investigations. Such a review will consolidate existing research on hydrogen-powered ICEs, providing a cohesive understanding of the current state of technology, challenges, and potential solutions. Key areas of focus should include hydrogen production and storage methods, necessary modifications for ICEs to efficiently burn hydrogen, performance and emissions characteristics, and safety considerations. Additionally, it should explore economic and policy frameworks that support the development and deployment of hydrogen technologies. Addressing these aspects will spur innovation, inform stakeholders, and contribute to the global transition towards sustainable energy systems, thereby supporting the achievement of broader environmental and energy security goals. This review will be invaluable to policymakers, industry leaders, and researchers in advancing hydrogen technology and solving the critical challenges of energy scarcity and climate change.

2. Hydrogen as a fuel for internal combustion engine

Hydrogen, the lightest and most abundant element, exhibits unique chemical properties that make it a highly attractive fuel for internal combustion engines (Lamas *et al.*, 2015). Its molecular form, H_2, is a colourless, odourless, and tasteless gas under standard conditions (Helen McCay, 2014). One of the most notable properties of hydrogen is its high energy content per unit mass; it has an energy density of approximately 120 megajoules per kilogram, which is nearly three times that of gasoline (Kovač *et al.*, 2021; Scovell, 2022). This high energy content translates to a significant potential for energy output, making hydrogen an efficient fuel. Additionally, the low energy density by volume of hydrogen in its gaseous state poses challenges for storage but also allows it to diffuse rapidly. Its wide flammability range, from 4% to 75% by volume in air, and low ignition energy make hydrogen highly combustible, which can enhance the efficiency of combustion processes in engines (SAKINTUNA *et al.*, 2007; Srinivasa Murthy and Anil Kumar, 2014). The stoichiometric air-fuel ratio for hydrogen is about 34.3:1, which is much higher than that of gasoline (14.7:1), indicating that much less hydrogen is needed to achieve optimal combustion. Hydrogen's flame speed is significantly higher than that of other common fuels, such as gasoline and natural gas, which leads to faster and more complete combustion (Algayyim *et al.*, 2024; Faye *et al.*, 2022). This property is advantageous for reducing the emission of unburned hydrocarbons and other pollutants. Furthermore, hydrogen combustion produces water vapor, reducing CO_2 emissions and thus contributing to a reduction in GHG emissions. Another key characteristic is hydrogen's high diffusivity, which enables it to disperse quickly in case of a leak, reducing the risk of accumulation and subsequent explosion (Matla *et al.*, 2024). However, hydrogen's reactivity, particularly its tendency to form explosive mixtures with air, necessitates careful handling and advanced safety measures in its storage and use (El-Adawy *et al.*, 2024). Despite these challenges, the favourable chemical properties of hydrogen, such as its high energy content, rapid combustion, and clean emissions, make it a promising alternative fuel for internal combustion engines, supporting the transition to more sustainable energy systems (Ayad *et al.*, 2024; Roy and Pramanik, 2024; Siadkowska and Barański, 2024).

The advantages of employing hydrogen in ICEs are substantial and multifaceted. It offers environmental, technological, and economic advantages (Faye *et al.*, 2022; Zhang, 2024). Firstly, hydrogen combustion results in water vapor as the primary byproduct, which dramatically reduces the emission of CO_2 and other harmful pollutants such as NOx, thereby contributing to improved air quality and mitigating climate change (Chintala and Subramanian, 2017; Li *et al.*, 2019). This makes hydrogen an attractive option for regions grappling with air pollution and stringent emission regulations (Serbin *et al.*, 2022). Moreover, the use of hydrogen in ICEs can leverage existing engine technologies and infrastructure, offering a transitional solution while the hydrogen fuel cell and electric vehicle technologies continue to evolve and become more economically viable (Deheri *et al.*, 2020; El-Shafie, 2023; Żółtowski and Żółtowski, 2015). This transitional aspect is crucial as it allows for the gradual integration of hydrogen into the energy system without the need for a complete overhaul of existing automotive manufacturing and fuelling infrastructure (Su-ungkavatin *et al.*, 2023). Furthermore, the adoption of hydrogen as a fuel can stimulate innovation and economic growth by creating new markets and job opportunities in the renewable energy and automotive sectors. It can drive advancements in related technologies such as hydrogen storage, transport, and fuelling infrastructure, fostering a holistic development of a hydrogen economy (Qureshi *et al.*, 2023; Sun *et al.*, 2023). The positive ripple effects include increased investment in research and development, enhanced technical expertise, and strengthened global collaborations aimed at tackling energy and environmental challenges (Qi *et al.*, 2023; WHITE *et al.*, 2006). In essence, hydrogen as a fuel for ICEs presents a compelling case for a cleaner, more sustainable, and economically robust future, addressing both the immediate need to reduce emissions and the long-term goal of transitioning to renewable energy sources (Sharma *et al.*, 2022a). Hydrogen as a fuel for ICEs offers several advantages over conventional fuels such as gasoline and diesel, making it an attractive alternative in the pursuit of reducing GHG emissions and enhancing energy sustainability (Dimitriou and Tsujimura, 2017). One of the most significant benefits of hydrogen is its clean combustion properties. When hydrogen is burned in an ICE, the primary byproduct is water vapor, which eliminates CO_2 emissions, a stark contrast to the significant CO_2 emissions produced by gasoline and diesel engines (Yip *et al.*, 2019). Additionally, hydrogen combustion results in negligible emissions of pollutants such as NOx and particulate matter, which are common byproducts of conventional fuel combustion and are harmful to both human health and the environment (Matla *et al.*, 2024; Purayil *et al.*, 2023). From an efficiency standpoint, hydrogen has a high energy content per unit mass compared to gasoline and diesel. This high energy density means that hydrogen can deliver more energy and potentially improve the fuel efficiency of ICEs (Bui *et al.*, 2021). However, this advantage is tempered by the challenges of hydrogen storage and distribution, as hydrogen is a low-density gas that requires high-pressure tanks or cryogenic temperatures to store in practical quantities (Manigandan *et al.*, 2023).

Also, economic considerations play a vital role in comparing hydrogen with conventional fuels. Hydrogen production and infrastructure development currently involve higher initial costs and technological advancements. The economies of scale are expected to reduce these costs over time (Brown *et al.*, 2013; Schüth, 2014). Conversely, the established infrastructure for gasoline and diesel means lower immediate costs, but ongoing environmental and health costs associated with their use are significant and often externalized (Gandhi *et al.*, 2022; Hughes and Agnolucci, 2012). Safety is another important factor; hydrogen has a wide flammability range and requires stringent safety measures in handling and storage, yet it dissipates quickly into the atmosphere in the event of a leak, reducing the risk of fire or explosion compared to liquid fuels which can pool and ignite (Guo *et al.*, 2024; Ustolin *et al.*, 2020). In conclusion, while hydrogen as a fuel for ICEs presents distinct advantages over conventional fuels in terms of emissions, energy content, and sustainability, it also faces challenges in storage, distribution, and initial economic viability. However, with ongoing research and development, hydrogen has the potential to play a crucial role in the transition to cleaner and more sustainable energy systems, offering a compelling alternative to conventional fossil fuels.

3. Compression ignition (CI) engines powered with hydrogen

Hydrogen has to satisfy specific criteria for oxygen content and minimum ignition energy to achieve combustion in ICEs. Still, hydrogen requires less energy to ignite and is more reactive than traditional fossil fuels. In an engine, igniting the hydrogen fuel mixture drives it to burn and expand within the combustion chamber, pushing the piston. Driven by this piston action, the crankshaft moves via the crank linkage, transforming chemical energy into mechanical energy, which is subsequently used for external work. With hydrogen replacing conventional fossil fuels, a hydrogen engine's operational mechanism essentially reflects that of a conventional internal combustion engine. Still, the engine has to be properly tuned to guarantee a seamless and effective operating cycle given the special qualities of hydrogen as opposed to gasoline and diesel (Ahmed *et al.*, 2020; Korakianitis *et al.*, 2010). The incumbent engines working on compression ignition design are primarily meant for diesel as fuel. The use of diesel as a fuel needs a unique fuel injection system including a fuel injection pump and injectors. These parts are designed to handle liquid fuel. Also, hydrogen being highly inflammable requires several design modifications to ensure safe and efficient operation (Chaurasiya *et al.*, 2022; Hoang *et al.*, 2022a; Kumar *et al.*, 2022).

Hydrogen requires a modified high-pressure direct injection system due to its low density and high diffusivity. This system needs proper mixing of hydrogen with air and precise control over the injection timing and duration. Wu et al. (Wu *et al.*, 2022) modified a Simpson 217 engine to run on hydrogen as a secondary fuel with neat diesel. The engine was installed with two gas regulators for managing the diesel and hydrogen flow rates for onward supply to injectors. A flame arrester was installed to prevent backfire. The hydrogen gas was injected into the cylinders using the venturi port. The findings showed that adding hydrogen improved engine performance by showing better BTE and lower fuel consumption levels. Vimalananth *et al.* (Vimalananth *et al.*, 2022) used a hydrogen-powered common rail diesel injection (CRDi) system-based diesel engine. The engine was installed with an exhaust gas recirculation (EGR) system. Three distinct hydrogen supply rates (3, 9, and 15 LPM) via the intake manifold were examined. Two distinct hydrogen induction using induction as well as injection approach were employed in this study. In this study,

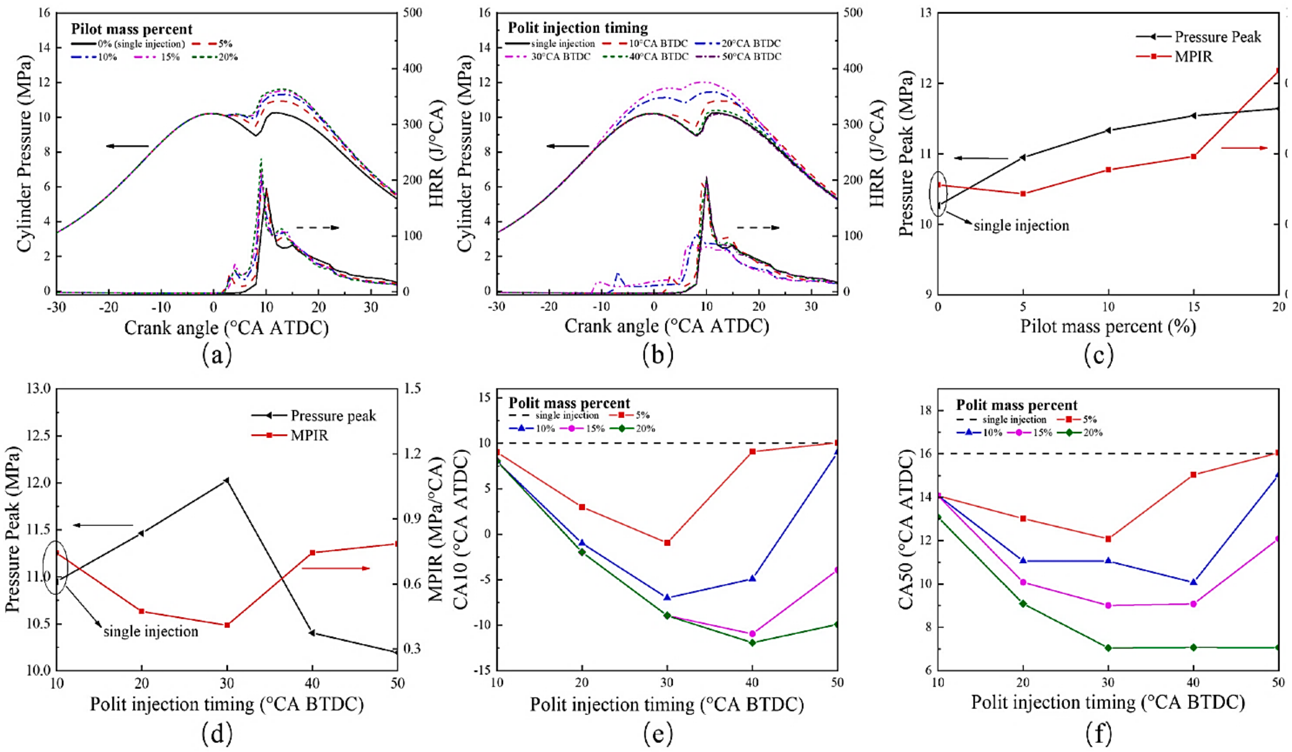

Fig. 2 Comparative effects of different liquid fuel injection techniques on the combustion properties (a) Pressure in the cylinder and HRR under various pilot mass %; (b) Pressure in cylinder and HRR under various pilot injection timings; (c) Pressure peak and MPIR under different pilot mass %; (d) Pressure peak and MPIR under different pilot injection timings; (e) Crank angle 10 degrees under different pilot mass % and timing of pilot injection; (f) Crank angle 50 degree under different pilot mass % and timing of pilot injection (Xu *et al.*, 2023) (Permitted by MDPI)

the thermal efficiency dropped initially but was improved at a larger percentage of hydrogen induction. Hydrogen addition lowered CO, HC, and smoke in both the approaches.

Since hydrogen has a higher auto-ignition temperature compared to conventional diesel, an advanced ignition system, potentially incorporating pilot injection of diesel or other fuels, is needed to initiate combustion (Hoang and Pham, 2020; Murugesan *et al.*, 2022; Tira *et al.*, 2014). Hydrogen combustion produces higher temperatures, necessitating enhanced cooling systems to prevent engine knock and maintain optimal engine temperatures. Park *et al.* (Park *et al.*, 2022) investigated the effects of altering the fuel injection timing in the case of hydrogen-powered engines in dual-fuel mode. From the standard fuel injection timing of 350 crank angle degrees (CAD) before the top dead center (BTDC), the fuel injection timing was retarded towards TDC. The engine efficiency as well as excess air ratio increased. The optimal ignition timing for achieving maximum torque was also improved. Also, an increase in engine torque was observed. Rahman *et al.* (Rahman *et al.*, 2011) investigated the diesel injection timing of a hydrogen-powered dual-fuel four-cylinder engine. During the compression stroke, hydrogen gas fuel is injected using sequential pulse injectors. Between 110° before BTDC and top dead center (TDC), the injection timing was changed. Whereas the equivalence ratio changed from 0.2 to 1.0, the engine speed changed from 2000 to 6000 rpm. The negative effects of the link between injection duration and ignition time were found and explained. The results showed a strong link between engine performance and optimal injection timing as well as between engine speed and air fuel ratio. The obtained results show that the ideal injection timing and engine performance depend much on the air-fuel ratio and engine speed. Xu *et al.* (Xu *et al.*, 2023) investigated the combustion mechanism of diesel-hydrogen dual fuel operation. Figure 2 depicts the effects of different pilot injection mass % and time on combustion parameters in a diesel/hydrogen dual-fuel engine. Increasing pilot mass from 0% to 20% with pilot injection set at 10° CA BTDC and main injection at 4° CA BTDC results in greater peak cylinder pressure and MPIR as illustrated in Figure 2a, c, e, f. The higher quantity of pilot injection diesel mixed with the hydrogen-air mixture increases the peak heat rate and combustion rate thereby improving cylinder pressure and HRR.

Pilot injection time (fixed pilot mass at 5% and main injection at 4° CA BTDC) is shown in Figures 2b, d, e, f. Although peak MPIR and HRR drop then rise, advancing pilot injection timing reduces then raises peak cylinder pressure. By reducing ignition delay, advancing injection timing 10–30° AC BTDC increases peak pressure. The pilot injection has little influence on the main injection beyond 30° AC BTDC (Xu *et al.*, 2023).

Liu et al. (Xiaole Liu *et al.*, 2023) explored the effects of hydrogen substitution rate on the engine performance using hydrogen in dual fuel mode. From Figure 3a-d it is clear that the PCP and HRR both rise with the increase of the hydrogen substitution rate under different loads. Under the condition of maximum hydrogen substitution rate, when the load is 30%, 50%, 70%, and 90%, the PCP goes up by 4.81%, 5.08%, 6.77%, and 6.81%, respectively, and, as the load increases, the PCP rises higher. With the hydrogen substitution rate rising from 0% to 15%, the cylinder's peak pressure went from 12.53 MPa to 13.38 MPa, and the peak HRR rose from 197 J/°CA to 228 J/°CA at a 90% high load.

Several important elements affect the combustion qualities and efficiency of CI engines running hydrogen. High flame speed of hydrogen reduces combustion time but effective combustion

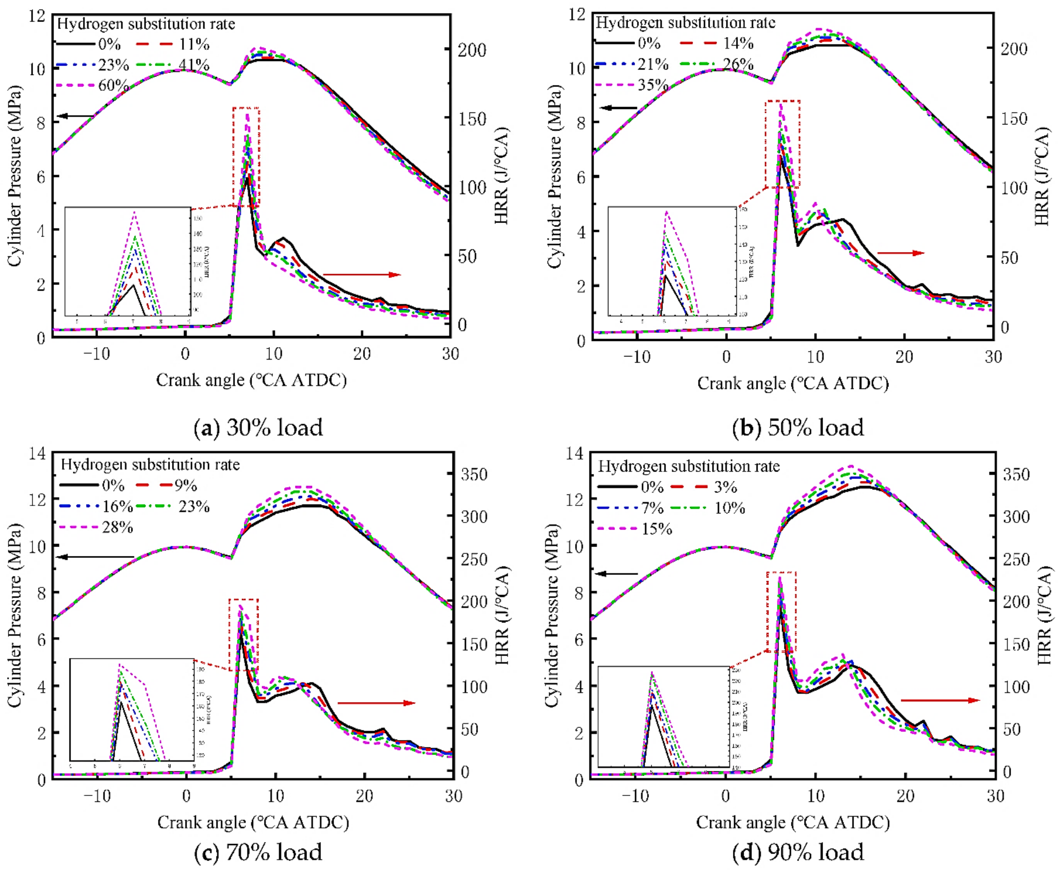

Fig. 3 Influence of hydrogen supply rate on HRR and pressure in the cylinder during combustion (Xiaole Liu *et al.*, 2023) (Permitted by MDPI)

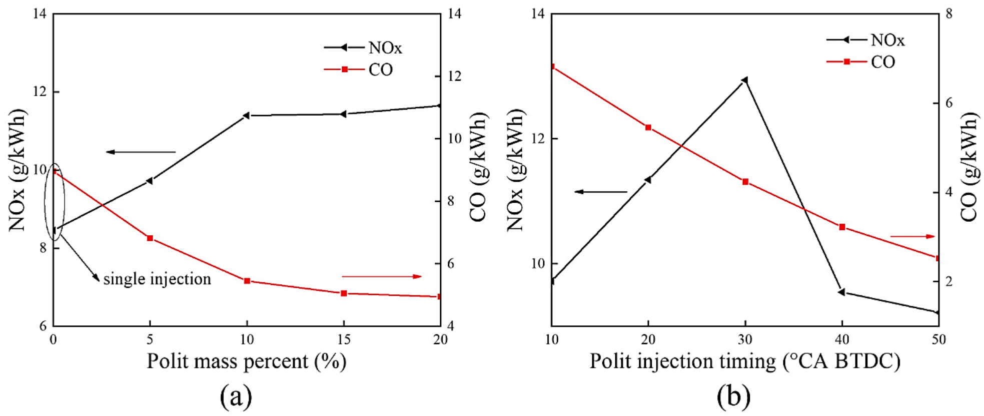

Fig. 4 Under several pilot injection techniques, (a) NOx and CO emissions; under different pilot injection times, (b) variations in NOx and CO emissions: Under varying pilot mass percentages (Xu *et al.*, 2023) (Permitted by MDPI)

results from this (Gao *et al.*, 2022; Saravanan and Nagarajan, 2009). Proper control is necessary to prevent knocking, as hydrogen can combust across a wide inflammability range, offering greater flexibility in engine control. Also, hydrogen needs less energy for ignition, improving cold start performance. An improved control of ignition is crucial to prevent backfiring and pre-ignition. The rapid diffusion of hydrogen offers a more homogenous air-fuel mixture, therefore lowering local hotspots during combustion. Although hydrogen burning produces little carbon emissions, the elevated combustion temperatures cause nitrogen oxides (NO_x) to develop. Reducing NO_x emissions calls for advanced after-treatment technologies. Xu *et al.* (Xu *et al.*, 2023) investigated the effects of hydrogen as a fuel in a hydrogen-diesel dual-fuel engine. Figure 4 shows how NOx and CO emissions change with pilot injection volume. As the percentage of pilot fuel mass increases, CO emissions drop while NOx emissions rise. This variation is attributed to greater distribution of ignition sources from increased pilot injection volumes as it improves combustion rates and general combustion efficiency, resulting in higher combustion pressure and temperature. As so, NOx emissions increase while CO emissions decrease. Under single injection mode, Figure 4a shows CO emissions are at their peak and mainly concentrated in the center of piston compression clearance. CO concentrations move towards the piston edge and combustion chamber pit as the pilot mass % increases. On the other hand, NOx emissions are lowest with a single injection and rise in concentration near the piston center at higher pilot fuel supply. Figure 4b depicts the effects of pilot injection timing

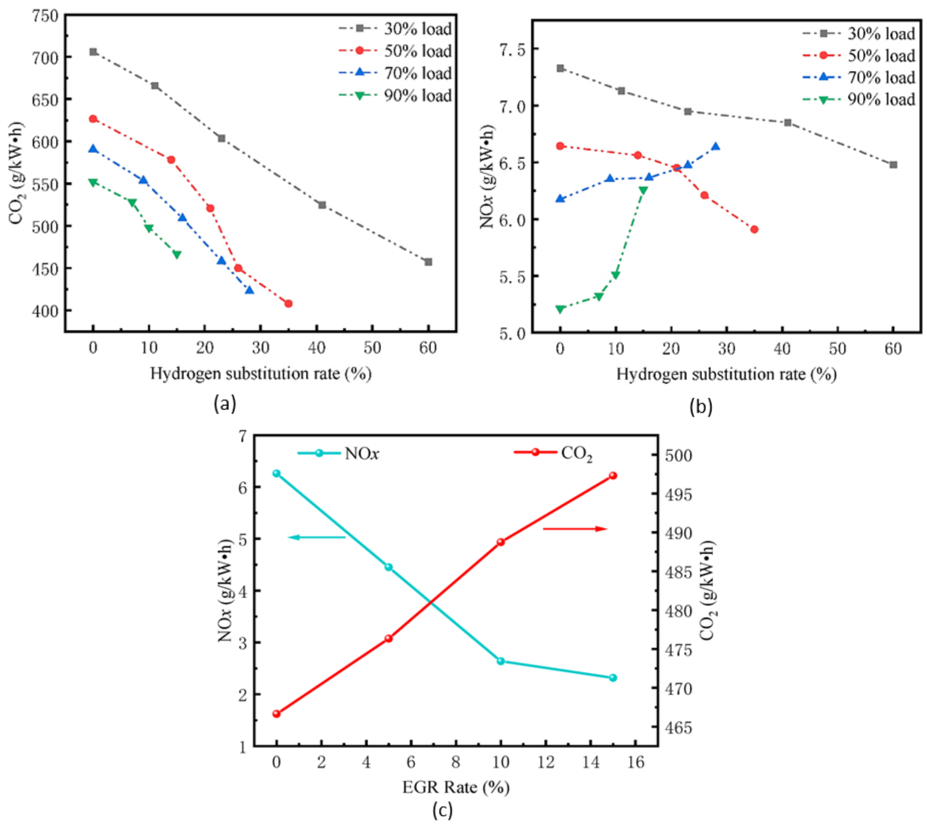

Fig. 5 Effects of (a) hydrogen substitution rate on CO_2 emission (b) hydrogen substitution rate on NOx emission (c) EGR rate on CO_2 and NOx emissions (Xiaole Liu *et al.*, 2023) (Permitted by MDPI)

Table 1
Recent investigations on dual-fuel (hydrogen + diesel) powered CI engine

Engine characteristics	Test conditions	Engine performance results	Engine emission	Ref.
Single-cylinder, 5.2 kW@1500 rpm, 661 cm3 displacement	Hydrogen supply rate 11%, 17%, 30%, and 42% energy fraction	BTE ↑; BSEC ↓; HRR ↑; PCP ↑	CO ↓; CO_2 ↓; NOx ↑; Smoke ↓	(Deb *et al.*, 2015)
Single-cylinder, 5.7 kW@1500 rpm, 661 cm3, displacement	Engine loads (2–12 kg), compression ratio 17.5:1	BTE ↑; BSEC ↓; BSFC ↓; PCP ↑ at full load	CO ↓; CO_2 ↓; NOx ↑; Smoke ↓	(Bose *et al.*, 2013)
Single-cylinder, 3.7 kW@1500 rpm, 553 cm3 displacement	Different engine power outputs (0–3.74 kW), CR 16.5:1, Hydrogen supply at 10 LPM	BTE ↑; HRR ↑	CO ↓; CO_2 ↓; NOx ↑; UHC ↑	(Saravanan *et al.*, 2007)
Four-cylinder, turbocharged, 48 kW, 1461 cm3 displacement	Various engine loadings (50–100 Nm), CR 18.25:1, hydrogen supply at 20 LPM and 40 LPM	BTE ↑; BSEC ↓; HRR ↑ PCP ↑ BTE ↓; BSEC ↑; HRR ↑; PCP ↑	CO_2 ↓; NOx ↓; UHC ↓ CO_2 ↓; NOx ↑; UHC ↑ at full load	(Yilmaz and Gumus, 2018)
Single-cylinder, 8 kW, 395 cm3	Engine speed @ 2200 rpm, CR 18:1, hydrogen supply at 0.15, 0.3, 0.45, and 0.6 LPM	BTE ↑; BSEC ↓; BSFC ↓	CO ↓; CO_2 ↓; UHC ↓; NOx ↓ Smoke ↓	(Demirci *et al.*, 2018)
Six-cylinder 260 kW@2200 rpm, 11967 cm3 displacement	Engine loads (20–100%), CR 18.5:1, hydrogen supply rate as 0.2, 0.4, 0.6, and 0.8 LPM	BTE ↑; BSEC ↑; BSFC ↑	CO ↓; CO_2 ↓; UHC ↓; NOx ↓	(Koten, 2018)
Seven-cylinder, 31.64 kW @ 80 rpm	hydrogen supply rate as 0 to 10% E/E	BTE ↓; BSEC ↑; BSFC ↓	CO_2 ↑	(Gholami *et al.*, 2022)
5.2 kW single cylinder engine 661 cm3, displacement	Different engine loading (30–100%), CR 17.5:1, hydrogen supply at 10 and 13 LPM	BTE ↑; BSFC ↓; HRR ↑; PCP ↑	CO ↓; CO_2 ↑; UHC ↓; NOx ↑; Smoke ↓	(Kanth *et al.*, 2020a)
3.5 kW single cylinder engine 661.5 cm3 displacement	Different engine loading (30–100%), CR 18:1, hydrogen supply 13 LPM	BTE ↑; BSFC ↓; HRR ↑; PCP ↑	CO ↓; CO_2 ↓; UHC ↓; NOx ↑; Smoke ↓	(Kanth *et al.*, 2020b)
10.3 kW@3000 rpm, single cylinder, 677 cm3 displacement	Different speeds of the engine (1500–2500 rpm), various engine loadings (5–25 Nm), CR 20.5:1, hydrogen supply rate as 21.4 to 49.6 LPM	BTE ↓; BSEC ↑; HRR ↑; PCP ↑	CO_2 ↓; NOx ↑; Smoke ↓	(Bakar *et al.*, 2022)
3.5 kW@3600 rpm single cylinder engine 296 cm3 displacement	Two speeds of speeds (3000, 3600 rpm), engine loads as 3 and 7 Nm, CR 20:1	BTE ↑; BSFC ↓	CO ↓; CO2 ↓; UHC ↓; NOx ↑	(Estrada *et al.*, 2022)
Single-cylinder 1300 cm3 displacement	Tested at 30% of engine load, speed as 2000 rpm, CR 17.5:1, hydrogen supply rate was 0 to 81% E/E	BTE ↓; PCP ↑	CO ↓; UHC ↓; NOx ↓; Soot ↑	(Karimi *et al.*, 2022)

BTE – Brake-thermal efficiency; BSFC - Brake specific fuel consumption; BSEC- Brake specific energy consumption; HRR – Heat release rate; PCP - Peak cylinder pressure

on CO and NOx emissions. Advancing pilot injection timing reduces CO emissions and first raises then lowers NOx emissions with a fixed pilot mass percent. By introducing more hydrogen mixture before TDC, advancing pilot injection time (10-30° CA BTDC) increases combustion rates, hence boosting in-cylinder combustion pressure and temperature and so lowering CO and increasing NOx emissions (Xu *et al.*, 2023).

The effect of different engine operating settings for a hydrogen-powered dual-fuel engine was investigated by Liu *et al.* (Xiaole Liu *et al.*, 2023). As seen in Figure 5a, CO_2 emissions under each engine load drop progressively as the hydrogen substitution rate rises; they drop when the load increases as well (Xiaole Liu *et al.*, 2023). The average decrease range of CO_2 is 20.2%, 21.9%, 17.7%, and 9.9%, respectively, when the load is 30%, 50%, 70%, and 90%, respectively, with an increase in hydrogen replacement rate. From Figure 5b, it is observed that NOx emissions drop in medium- and low-load locations whereas NOx emissions rise in high-load areas. The rate of hydrogen replacement shows a trend. NOx emissions fall with increasing load. The average increase in NOx is 4.54% and 9.53% respectively as the hydrogen replacement rate rises and the load reaches 70% and 90% respectively. As Figure 5c shows, the maximum cylinder pressure and mean temperature drop as the EGR rate rises. The maximum cylinder pressure at 5%, 10%, and 15% EGR rates lowers by 0.5%, 1.7%, and 3.7%, respectively, compared with the no EGR mode; the maximum average temperature drops by 0.8%, 1.1%, and 2.5%, respectively (Xiaole Liu *et al.*, 2023).

The high energy content of hydrogen improves thermal efficiency. Its rapid and efficient burning lets more energy be turned into work. Operating at lean air-fuel ratios, hydrogen increases fuel economy and reduces exhaust temperatures (Muralidhara *et al.*, 2022; Zhao *et al.*, 2020), which in turn extends engine life. The unique characteristics of hydrogen also help to enable effective engine operation, therefore lowering pumping losses and raising general engine efficiency (Yu *et al.*, 2017). Advanced combustion control techniques are essential to maximizing performance, with direct injection being a critical requirement (Manu *et al.*, 2021). Nonetheless, the great reactivity of hydrogen raises the pre-ignition risk, which can be reduced with exact control systems. Although hydrogen combustion generates almost zero carbon emissions, because of high combustion temperatures it can cause notable NO_x emissions (Du *et al*., 2017; Rahmani *et al*., 2023). Effective reduction of NO_x emissions has been demonstrated by strategies including water injection and exhaust gas recirculation (EGR) (Mohanasundaram and Govindan, 2021; Sathishkumar and Ibrahim, 2021). The modern catalytic converter is highly efficient in reducing emissions. Since hydrogen is highly flammable, safe storage is vital. With continuous developments needed to increase the safety and efficiency of storage technologies, hydrogen calls for high-pressure tanks and, in some circumstances, solid-state storage devices (Peschel, 2020). The recent studies and their outcomes in the domain of hydrogen-powered CI engines are listed below in Table 1.

4. Spark Ignition (SI) Engines powered with Hydrogen Fuel

Hydrogen-powered Spark ignition (SI) engines offer a potential substitute for conventional gasoline engines due to their combustion characteristics and low emission. The high energy density per unit mass of hydrogen fuel in comparison with gasoline can enhance SI engine performance (Molina *et al*., 2023; Özer, 2021). Its rapid flame speed results in quick combustion, thus helping to raise thermal efficiency. The large flammability range of hydrogen allows it to ignite a wide spectrum of air-fuel combinations, providing flexibility and more control under varying load situations (Bui *et al*., 2023). One major benefit of hydrogen as a fuel is clean burning with little amount of CO_2, CO, or hydrocarbons in the combustion process. This makes SI engines running on hydrogen more environmentally friendly, significantly reducing air pollution and greenhouse gas emissions (Cong *et al*., 2021; Nguyen *et al*., 2021). Higher levels of NO_x emissions can result from higher temperatures reached during hydrogen combustion. Modern after-treatment technologies such as SCR and EGR are necessary for efficient control of NO_x emissions (Huang *et al*., 2009; Solaimuthu *et al*., 2015).

Hydrogen's low ignition energy helps in easier ignition, though cold starts can still pose challenges owing to higher auto-ignition temperature. The low-ignition energy of hydrogen calls for careful control to prevent backfiring and pre-ignition. The high diffusivity of hydrogen helps to enhance air mixing, promoting more complete combustion and reducing hotspots in the combustion chamber (Gao *et al*., 2022; Subramanian and Salvi, 2016). More effective engine breathing made possible by fast hydrogen diffusion also helps to lower pumping losses and increase general efficiency. Using hydrogen in SI engines creates challenges (Hamzehloo and Aleiferis, 2013; Roy *et al*., 2011). The wide range of flammability and ease of ignition makes the distribution and storage of hydrogen particularly challenging. Practical hydrogen utilization depends critically on strong and safe storage solutions like high-pressure tanks and solid-state storage (Sagar and Agarwal, 2017; Subramanian and Salvi, 2016). Maximizing performance and lowering NO_x emissions depend on developing accurate control algorithms and better fuel injection systems. Several important modifications are needed for an SI engine to run effectively on hydrogen fuel to suit its special qualities and guarantee safe and efficient combustion. Molina *et al*. (Molina *et al*., 2023) investigated the effect of hydrogen combustion in SI engines. Corresponding with two distinct dilution circumstances, Figure 6a shows the in-cylinder pressure, and Figure 6b depicts the HRR for a spark timing sweep at the low-load point. Independent of the λ value, when the spark timing is advanced the pressure profiles rise and shift earlier in the compression stroke. Analysing the heat release rate profiles reveals a similar tendency parallel to the pressure profiles; they progress as the spark timing approaches the compression stroke, becoming somewhat narrower and showing increasing peak values.

Nguyen *et al*. (D. Nguyen *et al*., 2023) investigated the performance of hydrogen-powered engines in SI mode. Figure 7 depicts the combustion results for the study. Figure 7a displays volumetric efficiency concerning the excess air-fuel ratio (λ). Volumetric efficiency diminishes as the air-fuel ratio declines and a maximum of a 34% loss in volumetric efficiency is found under the stoichiometric circumstances ($\lambda = 1$) at the measured manifold air pressure, or 1 bar. Lower volumetric efficiency results since low density displaces air in the intake charge. On the other hand, as Figure 7b shows, the net indicated mean effective pressure (IMEP) rises with a declining λ, peaking at 5.2 bar. This is owed to the fact that at a fixed intake pressure, the mixture heating value rises with decreasing λ values. As seen in Figure 7c, the ITE (indicated thermal efficiency) peaks at around $\lambda = 2$ and begins to diminish on both sides of this excess air-fuel ratio. The ITE lowers when the mixture is richer that is, $\lambda < 2$ probably because of the increase in wall heat transfer losses. The cycle-by-cycle variations (COV) of IMEP are a major factor determining the combustion stability of the engine. A COV of less than 3% indicates a stable combustion.

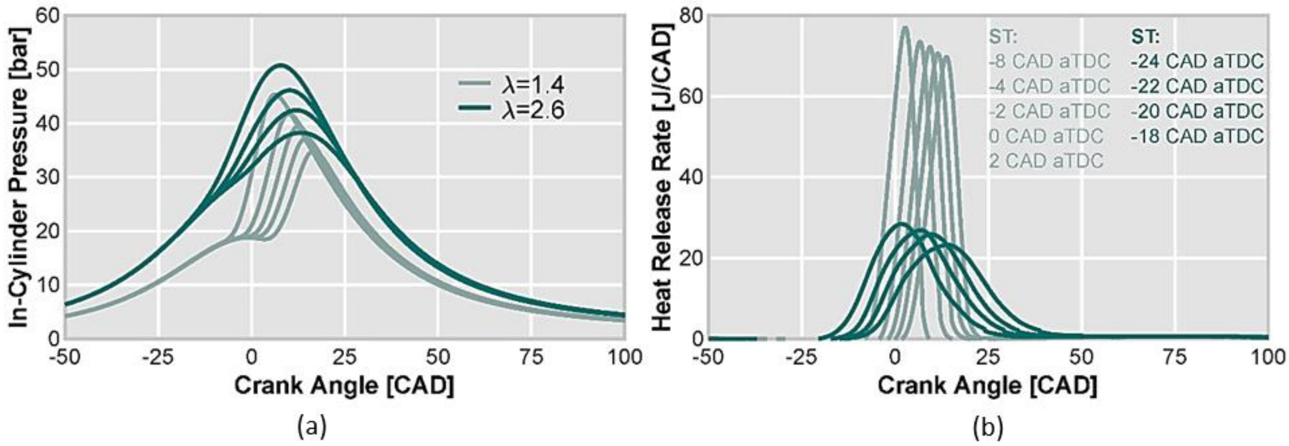

Fig. 6 Using the PFI system, (a) in-cylinder pressure and (b) HRR profiles at 1500 rpm engine speed and low-load situations are created showing changes with varied spark timing values for the two dilution settings (Molina et al., 2023) (Permitted by MDPI)

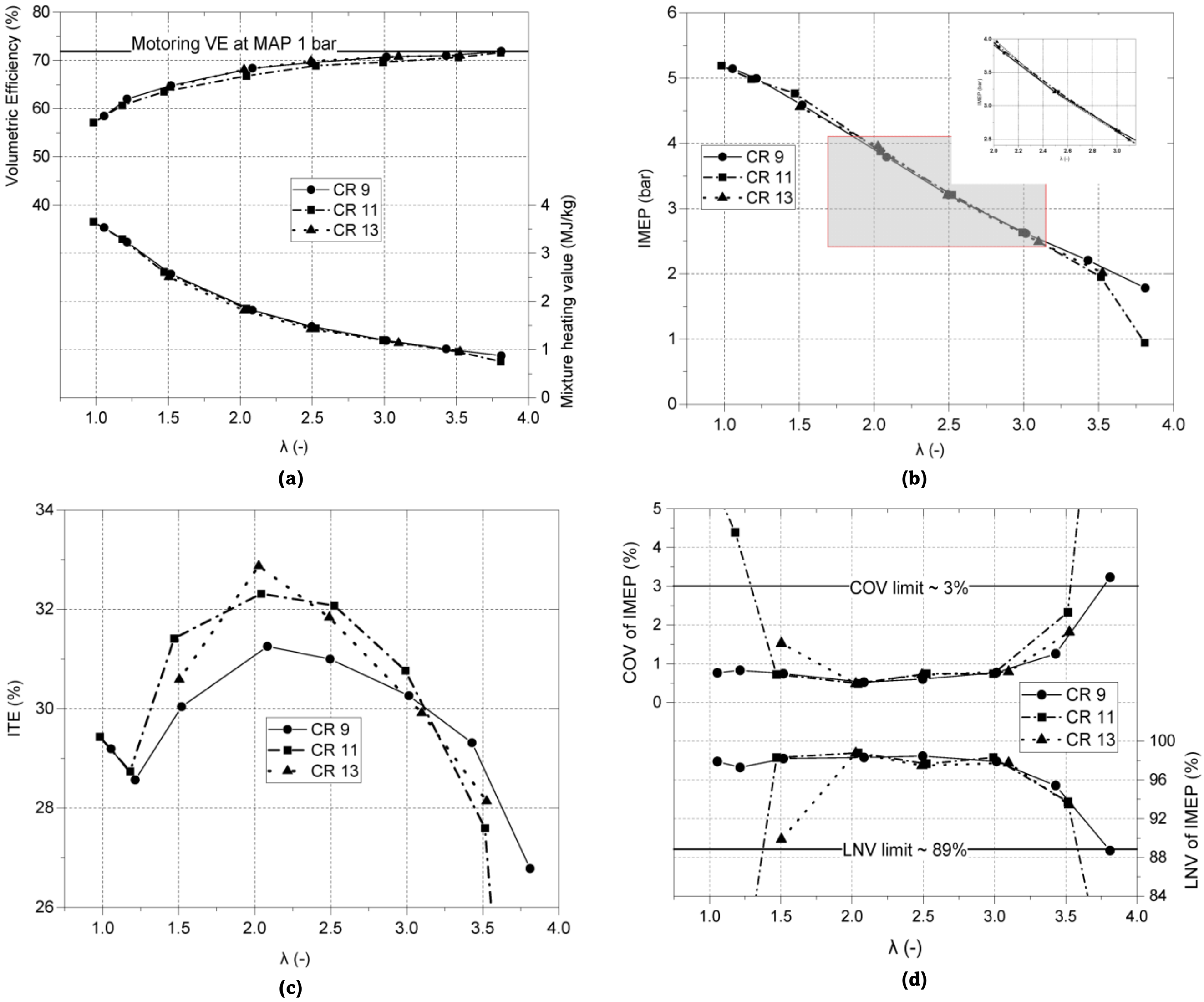

Fig. 7 At different CR the (a) Mixture heating rate and volumetric efficiency (b) Net indicated mean effective pressure (c) Indicated thermal efficiency (d) Coefficient of variation for IMEP (D. Nguyen et al., 2023) (Permitted by MDPI)

As shown in Figure 7d, the COV is less than 3% and implies strong combustion stability for almost all examined scenarios. At a compression ratio of 11, the COV values, however, rose noticeably with $\lambda < 1.5$ and $\lambda > 3.5$, implying unstable combustion.

Fuel injection system: Direct injection systems have to be either replaced or supplemented for conventional port fuel injection systems. Better control of the air-fuel mixture made possible by direct injection guarantees more efficient combustion and lowers the risk of pre-ignition and backfiring (Bui *et al*., 2022). Molina *et al.* (Molina *et al*., 2024) tested a medium-pressure direct injection system in a hydrogen-powered SI engine. Measuring two different engine loads under air dilutions as well as injection timing settings. From port fuel injection to direct injection, the data show rather significant efficiency gains, ranging from 0.6% to 1.1%. Low emissions and best performance depend on precise regulation of injection timing. Delaying the beginning of injection causes a 3.9% decrease in high load and a 7.6% decrease in low load compression power. Under both load situations taken into account, this yields up to 3.2% raise in the indicated specific consumption. In a novel approach, Li *et al.* (X. Li *et al*., 2024) employed a hole-in spark plug strategy for hydrogen induction in SI engines. The experimental results show that this novel approach had more marked effects in improving early flame propagation and supporting the establishment of stable flame nuclei than port injection, therefore extending the lean-burn limit significantly. Furthermore, it helped in the improvement of IMEP and BTE. However, this strategy also increased NOx, HC, and CO emissions.

Design of combustion chamber: The fast flame speed and high diffusivity imply hydrogen meaning that the combustion chamber has to be built to maximize complete mixing and reduce hot spots. Changes can call for changing the chamber's form and size, spark plug placement, and compression ratio. Since hydrogen burns quickly, lowering the compression ratio can help avoid knocking which is a common problem with this fuel. Basha *et al.* (Jeelan basha *et al*., 2023) explored a pre-chamber system in a hydrogen-powered SI engine. These pre-chamber layouts were investigated experimentally in an optical access, constant-volume combustion chamber. A high-speed camera running at 20000 fps caught the flame growth process; MATLAB handled the images to get quantitative data. Comparatively to the traditional SI system, the combustion

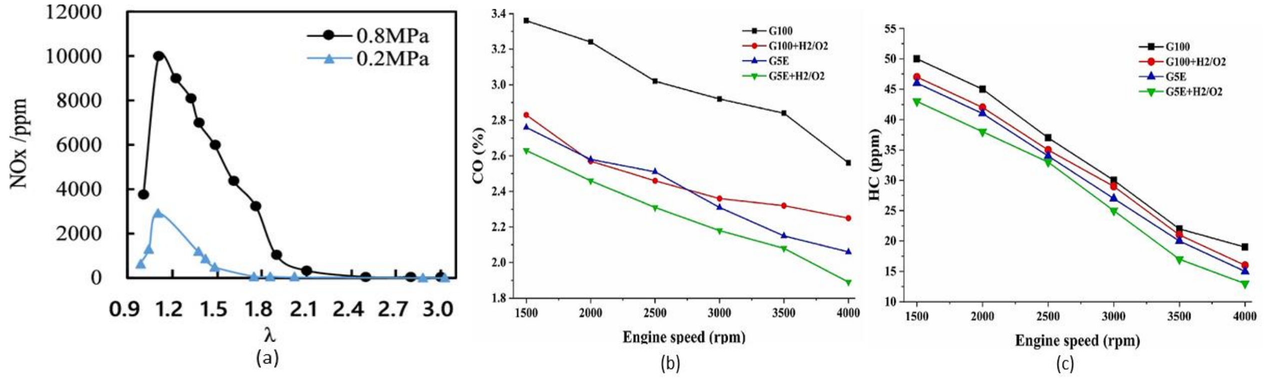

Fig. 8 Emission from hydrogen-powered SI engine (a) NOx emission in (Zhao *et al.*, 2024) (Permitted by ACS Omega); (b) CO emission and (c) HC emission (Oral, 2024) (Permitted by Elsevier)

properties of hydrogen-air mixtures using the pre-chamber system improved. However, the enhancement was more notable for ultra-lean mixtures. In a review article, Gultekin *et al.* (Gültekin and Ciniviz, 2023) brought out the effects of mixing ratio and combustion chamber geometry in the case of hydrogen-powered engines. The study led to the conclusion that the hydrogen energy ratio ought to range between 5 and 20% and that the combustion chamber should be built concerning the combustion properties. Liu *et al.* (Xinlei Liu *et al.*, 2023) used several strategies for hydrogen combustion investigations. It was reported that with a quite high indicated thermal efficiency, the PCC and SI modes were able to satisfy the EU VI regulatory limit of NOx emission. These two modes are more likely for pragmatic uses than the DF-PI and DF-DI modes as they just need one fuel supply system.

Ignition system: The ignition mechanism has to be able to manage hydrogen's fast and complete burning. Higher energy output igniting coils and advanced spark plugs could be needed. Multiple sparks plug per cylinder ensures perfect and consistent combustion, therefore lowering the possibility of misfires. Baş *et al.* (Duan *et al.*, 2023) investigated the effects of variations in spark plug gaps and different types of spark plugs on the performance and emission of hydrogen-powered engines. The results indicated that platinum and iridium spark plugs performed better than standard spark plugs. On the other hand, hydrogen enrichment may offset the loss even if methanol addition to gasoline fuel decreases performance. Park *et al.* (Park *et al.*, 2021) investigated the influence of spark plug conditions on engine performance. The engine was powered with port-injected hydrogen. Using a cold-type spark plug effectively reduced the backfire and raised the maximum torque to 101.7 Nm; yet the efficiency dropped as the combustion temperature rose and thus increased heat loss.

Engine cooling system: Hydrogen combustion creates high temperatures; hence a better cooling system is needed. To keep ideal running temperatures and avoid overheating, this can entail enhancing the coolant circulation of the engine, utilizing larger capacity radiators, and adding other cooling technologies including intercoolers. Balitskii *et al.* (Balitskii *et al.*, 2021) utilized nanoparticles in engine coolant to improve the cooling of engine heads in the case of hydrogen-powered engines. The study reported on boiling in engine cooling systems, the effect of nanoparticles on thermal conductivity, and their behaviors. At 90°C, using Al_2O_3 nanoparticles (0.75% concentration) in water raised thermal conductivity by 60%. Improved heat transfer, faster coolant flow speed, and more engine cooling efficiency follow from this increase. Bhutto *et al.* (Ahmed Bhutto *et al.*, 2024) employed a wall film cooling approach for a hydrogen-powered engine. The study reported that film cooling as one of the most efficient and sensible cooling techniques available for liquid fuel propulsion systems. The film cooling mechanism was investigated using a 3-D cooled injector in a 2-D configuration using CFD simulations. Analysing the mass fraction of species and the development of the film across the wall leading to the nozzle takes the front stage in the investigation. Calculations of temperature and mass fraction both with and without film cooling. It was reported that film cooling was 18% more effective compared to non-film cooling. These results improve knowledge of the film cooling processes and possible uses for them in liquid fuel engines.

Material: Hydrogen can embrittle some metals, hence materials utilized in the engine have to be carefully chosen for compatibility. To guarantee lifetime and durability, this could call for employing hydrogen-resistant alloys for important parts including fuel lines, injectors, and combustion chambers.

Safety Systems: Strong safety systems are very necessary given the great flammability of hydrogen. To stop and control leaks, one needs suitable ventilation systems, pressure-relieving devices, and leak-detecting sensors. Safely handling hydrogen storage and distribution depends on strict safety standards being followed (Guo *et al.*, 2024). Hydrogen has advantages in safety over other fuels because of its distinctive chemical and physical characteristics. For instance, hydrogen may swiftly escape into the air and is benign. However, gasoline might cling to the bottom of the car and not readily dissipated by volatilization, which would cause more catastrophic fire accidents (Swain, 2001). Compared to hydrogen direct injection engines, where it may be avoided, backfire is a major problem with hydrogen port fuel injection internal combustion engines. Along with numerous combustion-related aspects, hydrogen's inherent characteristics help to cause backfire in hydrogen port fuel injection engines. In hydrogen port fuel injection engines, hot patches in the combustion chamber are main causes of backfire. Backfire results from high-heat surface sources from soot particles burning on spark plugs igniting the hydrogen-air mixture during the intake stroke. Hot areas can also create super-knock, which would produce harmful pressure changes in the combustion chamber (Dai *et al.*, 2021; Khalid *et al.*, 2024).

Engine control unit tuning: The ECU must be modified to control the special combustion properties of hydrogen. This covers modifying air-fuel ratio settings, ignition timing, and fuel injection timing. Optimizing engine performance and emissions under different running circumstances may call for both advanced algorithms and their effective tuning with hardware

Table 2
Recent investigations on hydrogen-powered SI engine

Engine characteristics	Test conditions	Engine performance results	Engine emission	Ref.
Four cylinders, multi-point fuel injection (MPFI), 44.5 kW @ 6000 rpm, CR 9.4:1	Hydrogen supply rate 0% to 10% by volume	BTE ↑; BP ↑	CO ↓; HC ↓; NOx ↑	(Chitragar *et al.*, 2017)
Overhead valve, single cylinder, make-Honda	Hydrogen supply rate 24% to 49% by volume	BTE ↑; BP ↑; BSFC ↓	CO ↓; CO_2 ↓; NOx ↓; UHC ↓	(Elsemary *et al.*, 2017)
Direct injection, 4-cylinder, Port fuel injection, hydrogen injection pressure 6 bar	Hydrogen supply rate 0% to 10% by volume	BTE ↑; PCP ↑	CO ↓; NOx ↑; UHC ↑	(Shi *et al.*, 2017)
Single-cylinder, Port fuel injection, CR 11:1	Hydrogen-enriched compressed natural gas (CNG) in different ratios	BTE ↑ up for higher H_2 ratio but ↓ for 100% H_2; BSEC ↑ up for higher H_2 ration but ↓ for 100% H_2	CO ↑; CO2 ↓; UHC ↑; NOx ↓	(Verma *et al.*, 2016)
Four-cylinder engine but only one cylinder was used, displacement 399.5 cm^3, CR 10.5:1	hydrogen supply rate as 0 to 0.54 % volume	BTE ↑; PCP ↑	CO ↓; NOx ↑	(Lhuillier *et al.*, 2020)
4.4 kW @ 1500 rpm, single-cylinder engine lean burn SI engine, CR 17.5:1	hydrogen supply rate as 5 and 10% E/E	BTE ↑; BP ↑; PCP ↑	UHC ↓; NOx ↑	(Suresh and Porpatham, 2023)
2.1 kW, Single cylinder, four-stroke, displacement 272 cm^3, CR 6.5: 1	Different CR 4.5, 6.5, 7.2, EGR up to 25%, engine loading (30–100%), CR	PCP ↑ Higher HRR caused knocking. EGR helped in the reduction of HRR to suitable levels	-	(Salvi and Subramanian, 2022)
2.4L SI engine with 226 kW@4000 rpm fitted with supercharger	Engine speed at 2000 rpm and 3000 rpm. Engine torque was kept at 50Nm.	BP ↑; Coefficient of variation of IMEP ↓	NOx ↑	(Nguyen *et al.*, 2021)
Single cylinder VCR engine with 611.7 cm3 displacement, CR 4:1 to 18:1	Port fuel injection of hydrogen and different CR was examined	Higher PCP and advancement in knock point at higher CR. BTE ↑; BP ↓	CO ↑; UHC ↓; NOx ↓	(D. Nguyen *et al.*, 2023)
5.2 kW @ 1500 rpm, single-cylinder engine lean, CR 17.5:1, water-cooled, CR 10:1	Hydrogen content was varied between 0 to 30 % for the indicated biogas diesel mixture	PCP ↑; Coefficient of variation of IMEP ↓; Combustion duration ↓	UHC ↓; NOx ↑	(Bundele *et al.*, 2022)

(Verhelst, 2014). Martinez *et al.* (Martinez *et al.*, 2023) investigated a vehicle equipped with turbocharging to overcome the problem of reduced volumetric efficiency and consequent poor power in the case of H_2 in port fuel injection (PFI) engines. Although the issue of poor volumetric efficiency was reduced through turbocharging, ECU remapping was recommended by the searchers.

In an experimental investigation by Zhao *et al.* (Zhao *et al.*, 2024) electric turbocharger was employed to improve the performance of a hydrogen-powered SI engine. Figure 8 shows the change in NOx emissions with λ at 2000 r/min. NOx emissions climb greatly first as the air-fuel equivalence ratio (λ) rises before falling. The highest NOx emissions are around a λ of 1.1; yet NOx emissions decrease to less than 10 ppm when λ runs higher than 2.7, as depicted in Figure 8a. The combustion temperature, amount of oxygen, and long high-temperature duration define the formation of NOx emissions. Oral (Oral, 2024) investigated the performance of gasoline/gasoline-ethanol with an H_2 generator-aided SI engine. Figure 8b depicts that CO emissions were larger at low speeds at first and dropped with increasing speed. Gasoline alone produced the greatest value of CO emission at all engine speeds; mixes of gasoline + 5% ethanol + H_2/O_2 obtained the lowest value. At the greatest engine speed, one obtained the lowest CO emissions among whole test fuels. The addition of H_2/O_2 increasing combustion might be the cause of the CO drop. Examining Figure 8c shows that HC emission levels drop as the speed rises even if they are high rates at low engine speeds. Fuel combination HC emissions at all engine speeds are fewer compared to the use of gasoline solely. From gasoline fuel, the maximum HC was achieved; from the mixes of gasoline + 5% ethanol + H_2/O_2, the lowest HC. Adding H2 accelerates the rate of OH generation, therefore optimizing the fuel mixture's combustion and hence lowering HC emissions (Oral, 2024).

In summary, running an SI engine on hydrogen calls for thorough changes to the fuel injection system, combustion chamber design, ignition system, cooling system, and safety precautions. These changes guarantee consistent, safe, and effective hydrogen combustion, therefore optimizing the advantages of this clean fuel and minimizing possible problems. A summary of studies showing the effects of hydrogen-powered engines is shown in Table 2.

5. Challenges and Future Directions

5.1 Challenges in Hydrogen-Fueled CI and SI Engines

The unique qualities of hydrogen and CI engines' fundamental nature provide great difficulties for hydrogen-powered CI engines. One of the main problems is the poor energy density of hydrogen, which requires high-pressure storage systems adding weight and complexity to the vehicle architecture (J. Liu *et al*., 2022; Rivard *et al*., 2019). Because hydrogen's great flammability and wide flammability range raise safety issues, leak detection and prevention become vital. Moreover, the great diffusivity of hydrogen can cause embrittlement of engine components, therefore compromising their integrity and durability. This calls for the employment of specialist materials and coatings, which could complicate manufacturing processes and raise production costs (Naqvi *et al*., 2024; Sadeq *et al*., 2024).

A further major obstacle is hydrogen's higher-than-average diesel fuel autoignition temperature, which makes steady combustion in CI engines challenging (Falfari *et al*., 2023). Advanced ignition systems such as pilot injection of diesel or glow plugs often call for a higher ignition temperature to start combustion (G. Li *et al*., 2020). Though efficient, this dual-fuel strategy complicates engine design and control systems. Furthermore, limited quenching distance and quick flame speed of hydrogen might cause pre-ignition and backfire, so affecting the engine knock and maybe destroying the engine. Advanced engine management systems are necessary for the management of these combustion events as exact control over the fuel-air mixture and injection timing (De Simio *et al*., 2024; Su *et al*., 2018; Verhelst, 2001). Moreover, low lubricity of hydrogen could lead to wear and tear on engine parts, so new lubrication techniques are needed to guarantee engine lifetime. These obstacles taken together emphasize the need for ongoing research and development to solve the material, design, and combustion control problems in hydrogen-powered CI engines (Stępień and Urzędowska, 2021).

Spark ignition (SI) engines running on hydrogen fuel face several difficulties mostly related to the combustion properties of hydrogen and the modification needed for current engine designs. The poor volumetric energy density of hydrogen is one of the key problems; so, either more compression storage technologies or bigger fuel tanks are needed (Frigo and Gentili, 2013; Tahtouh *et al*., 2011). Particularly in vehicles where weight and space are major considerations, this presents major design and safety issues. Furthermore, the risk of leaks and fires is hydrogen's great diffusivity and tendency to create explosive combinations with air; hence, strong safety precautions and leak detection systems are needed (Urroz *et al*., 2023). The high flame speed of hydrogen makes it considerably more difficult to achieve proper combustion timing and avoid knock. Rapid pressure rises brought on by this fast flame speed can result in engine knock and maybe damage to components. Managing these calls for exact control of the air-fuel combination and sophisticated ignition mechanisms. Moreover, hydrogen's quenching distance is rather small, therefore it can readily ignite from hot places in the combustion chamber, causing pre-ignition and backfire (Giacomazzi *et al*., 2023; Ji *et al*., 2016). This calls for exact control of the engine's thermal management and the usage of materials resistant to high temperatures. Because hydrogen's lubricity is lower than that of other fuels, engine components may wear more, and new lubricants and coatings are therefore needed to guarantee engine durability. Furthermore, current spark ignition engines need to be greatly changed to fit hydrogen fuel in terms of fuel delivery system, ignition system, and combustion chamber architecture. These changes can be expensive and technically difficult; so, major research and development are needed to maximize engine performance and guarantee dependability (Anand and Debbarma, 2024; Frasci *et al*., 2023; S. Lee *et al*., 2022; Srinath *et al*., 2022).

5.2 Safety Concerns and Mitigation Strategies

Hydrogen-powered engines create special safety issues that need strict safety precautions and creative solutions. The great flammability and wide flammability range (4-75% in air) of hydrogen raises one of the main safety issues since it is easily ignited by mistake (Benim and Syed, 2015). Consequently, the priorities are stopping leaks and guaranteeing the integrity of the systems of storage and delivery. High diffusivity of hydrogen allows it to rapidly pass through materials and minor leaks can cause major safety concerns. Thus, strong leak detection systems and high-integrity seals are essential parts of the designs of hydrogen-powered engines (Dimos and Graaf, 2024; Sarıdemir *et al*., 2024).

Another major safety concern is hydrogen embrittlement, in which case hydrogen atoms seep into metal constructions and over time cause them to become brittle and break. For pipelines and high-pressure storage tanks especially, this is quite alarming. Materials choice becomes very important to mitigate this; employing alloys and composites resistant to hydrogen embrittlement will greatly improve safety (Campari *et al*., 2023; Dwivedi and Vishwakarma, 2018; Wetegrove *et al*., 2023). Furthermore, the application of surface treatments and sophisticated coatings can create a barrier preventing hydrogen access. Early embrittlement can also be found and addressed by utilizing regular inspection and maintenance procedures (Jia *et al*., 2023; X. Li *et al*., 2020).

Hydrogen stored under high pressure usually 350–700 bar poses further hazards. High-pressure storage systems have to be built to resist harsh environments and incorporate pressure-releasing mechanisms to stop disastrous breakdowns. Though they must be thoroughly tested to guarantee they can endure impacts and other pressures, these systems can make use of composite materials that mix strength and lightness (Arsad *et al*., 2023; Y. Liu *et al*., 2023). Another set of difficulties arises with the evolution of cryogenic storage, in which hydrogen is kept as a liquid at very low temperatures. These systems must be insulated to stop boil-off and have advanced handling techniques to control the very low temperatures (Ghaffari-Tabrizi *et al*., 2022; Morales-Ospino *et al*., 2023).

Rapid dispersion resulting from low molecular weight in the case of a hydrogen leak poses both a threat and a reducing mechanism. Although it spreads fast and lowers the concentration below flammable limits, this fast dispersion might cause hydrogen to accumulate in small areas and increase the explosion risk (Shu *et al*., 2021; Xie *et al*., 2015). In places where hydrogen is utilized or stored, ventilation systems are particularly essential since they guarantee any spilled hydrogen is rapidly diluted and distributed. Two good ways to reduce this risk include designing buildings with enough airflow and running sensors to track hydrogen content in real-time (S.-Y. Lee *et al*., 2022; Weber, 2006).

5.3 Engine Durability and Material Compatibility

Given its high diffusivity, hydrogen can cause metals to become brittle, especially in high-stress places like fuel injectors, combustion chambers, and exhaust valves. This phenomenon, sometimes referred to as hydrogen embrittlement, lowers the ductility and load-bearing capacity of the material, increasing its susceptibility to cracking and failure under operating circumstances (Q. Li *et al*., 2024; Saborío-González and Rojas-Hernández, 2018). Furthermore, low lubricity of hydrogen aggravates wear and tear on engine components, hence specific lubricants and coatings are developed to reduce friction and prolong component lifetime (Pardo-García *et al*., 2022). A further important problem is hydrogen's thermal conductivity, which affects engine component heat dissipation. The high combustion temperature of hydrogen calls for materials that can resist high temperatures without degrading. Internal combustion engines may not have enough thermal resistance from conventional materials utilized in them, which accelerates wear and lowers engine lifetime (Giacomazzi *et al*., 2023; Habib *et al*., 2024). To improve thermal stability and durability, advanced materials like ceramic products, composite materials, and high-temperature alloys are under investigation (Sadeq *et al*., 2024).

Also, the reactivity of hydrogen calls for careful thought on materials that come into touch with the fuel. Certain polymers and elastomers among non-metallic materials could break or become brittle in response to hydrogen, causing mechanical problems and leaks. Thus, guaranteeing the long-term dependability and safety of hydrogen-powered engines depends critically on compatibility testing and the use of hydrogen-resistant components (Ilyushechkin *et al*., 2023; Zheng *et al*., 2020). These elements highlight the need for continuous research and development to find and maximize materials that might resist the challenging circumstances of hydrogen combustion, therefore guaranteeing durability and efficiency in hydrogen-powered engines.

5.4 Infrastructure Development and Policy Support

Widespread acceptance of hydrogen-powered engines depends on infrastructure and governmental support developing (Hosseini and Butler, 2020). Production facilities, storage facilities, and distribution networks all together constitute a strong hydrogen infrastructure. Production of hydrogen now mostly depends on natural gas reformation, which releases greenhouse gasses (Almansoori and Shah, 2012; Lux *et al*., 2022). Sustainability depends on turning toward green hydrogen generation utilizing renewable energy sources. This shift calls for large expenditures on electrolyzers and renewable energy infrastructure (Al-Mahgari *et al*., 2023; Sharma *et al*., 2024). Because of its poor energy density, hydrogen storage presents further difficulties that call for creative storage methods including high-pressure tanks, cryogenic systems, or new materials like metal hydrides.

The practicality of hydrogen-powered vehicles depends critically on building a large-scale hydrogen refueling network. This network has to guarantee refilling convenience on par with conventional fuels, hence hydrogen refueling stations must be strategically placed on urban and highway sites (Neumann *et al*., 2022; Zhou *et al*., 2013). Development and acceptance of infrastructure depend on policy backing; it is therefore essential. By enacting advantageous policies such as tax incentives for buyers of hydrogen-powered vehicles, subsidies for hydrogen production and infrastructure, and strict emission rules supporting alternative energy sources, governments can be very important (Hoang *et al*., 2022b; Lou *et al*., 2019; Zhang *et al*., 2021). Leveraging both government backing and private sector innovation, public-private partnerships can help to enable significant undertakings.

6. Conclusion

This review highlights the possibilities of hydrogen gas as a fuel for internal combustion engines since hydrogen emerges as one of the promising substitutes for fossil fuels since it has great energy density and clean combustion characteristics. The required technical developments and changes needed for engines to use hydrogen are covered in this review. Key observations stress the requirement for engine design modifications, sophisticated fuel injection systems, and improved emission control technology. The environmental benefits of hydrogen are particularly noteworthy, as its use substantially reduces harmful emissions and greenhouse gases. The economic viability of hydrogen generation and related expenses is under close inspection in contrast to alternative energy sources. With an eye on constant innovation and possible solutions to these problems, the difficulties in hydrogen storage, delivery, and safety are also explored. The study offers a summary of current studies as well as case examples showing area advancement and prospects. Internal combustion engines powered by hydrogen show promise for effective and environmentally sustainable transportation. Supporting the broader goal of lowering greenhouse gas emissions and switching to sustainable energy sources, this comprehensive review seeks to direct further research and development. Advancing the use of hydrogen in internal combustion engines is crucial for creating a more sustainable future in transportation.

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