Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI: 10.21474/IJAR01/23348
DOI URL: http://dx.doi.org/10.21474/IJAR01/23348

ISSN (O): 2320-5407
ISSN (P): 3107-4928

CONFERENCE PAPER

FUTURE FUELS FOR IC ENGINES: A REVIEW OF EMERGING PATHWAYS TOWARD NET-ZERO TRANSPORTATION

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Manuscript Info

Manuscript History
Received: 8 February 2026
Final Accepted: 10 March 2026
Published: April 2026

Key words:-
Hydrogen ICE, Ammonia fuel, Biofuels, Synthetic fuels, Net zero emissions, HCCI, RCCI, Dual-fuel engine, NOx control, Power-to-X

Abstract

Transportation is one of the biggest contributors to global greenhouse gas emissions, and some of its toughest sub-sectors - heavy trucking, maritime shipping, and aviation - depend on energy-dense fuels that batteries cannot replace on their own. This review takes a close look at the next generation of fuels for internal combustion engines (ICEs), covering hydrogen, ammonia, biofuels (ethanol and biodiesel), synthetic e-fuels, and compressed/liquefied natural gas. Building on a large-scale bibliometric study of more than 760 research articles published between 2012 and 2023 and drawing on supplementary workshop materials, the paper explores combustion behavior, emissions profiles, NOx control strategies, and the infrastructure required for each fuel pathway. It also discusses advanced combustion approaches, HCCI, RCCI, and dual-fuel operation, as key enabling technologies. Along the way, the review tackles the major hurdles: hydrogen storage challengesand combustion quirks such as backfire and knock; ammonia's stubborn resistance to ignition; the high cost of green hydrogen and synthetic fuels; and concerns about biofuel feedstock sustainability. The central conclusion is that no single fuel will do the job alone. Instead, a portfolio approach that matches multiple fuels with advanced engine technologies and well designed policy frameworks off ers the most realistic path toward net-zero transport emissions by mid-century.

Introduction:-

The Paris Agreement set a clear goal: keep global warming within 1.5–2 °C above pre-industrial levels. Meeting that target means decarbonizing every major sector of the economy, and transport is no small piece of the puzzle. It accounts for roughly a quarter of all global CO_2 emissions, and conventional fossil fuels - gasoline and diesel - still supply about 85% of the world's primary energy. Electric vehicles have made impressive strides in passenger cars, but they face serious limitations in long-haul trucking, international shipping, and aviation.

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These sectors need fuels that pack a lot of energy into a small volume, something batteries struggle to deliver. Together, these hard-to-abate segments make up about 30% of transport emissions and rank among the most difficult to clean up.This is where future fuels come into the picture. Hydrogen and its derivatives (ammonia, methanol), biofuels (ethanol, biodiesel), synthetic electro-fuels, and natural gas variants (CNG, LNG) have all been gaining momentum in research labs and policy circles alike. And the internal combustion engine itself is far from obsolete—it brings proven reliability, versatility, and relatively low cost compared to alternatives like fuel cells, making it a practical workhorse for the hydrogen and broader alternative-fuel transition. Getting to net-zero emissions by mid-century will almost certainly require a mix of fuel–engine combinations rather than betting everything on a single technology.This review pulls together insights from a major bibliometric study of hydrogen-fuelled ICE research (764 articles, 2012–2023), along with workshop materials covering the full range of future fuels. The goals are threefold: first, to survey what we know about each fuel's combustion properties, emissions, and technology readiness; second, to explore the advanced engine strategies that make these fuels viable; and third, to flag the key challenges and policy tools that will shape how the transition unfolds.

The Future Fuel Landscape:-

Hydrogen:-

Hydrogen stands out as perhaps the most exciting candidate for carbon-free ICE operation. When it burns, the only products are water vapor and a small amount of NOx—there is zero CO_2 at the tailpipe. It packs a remarkable 120 MJ/kg of energy (about 2.4 times that of gasoline by weight), and it offers a wide flammability range (4–75% in air), an exceptionally fast flame speed, and very low ignition energy. These characteristics make lean-burn operation straightforward, leading to high thermal efficiency and low NOx emissions when the equivalence ratio remains well below 1.The bibliometric data confirms that research on hydrogen-fuelled engines has picked up dramatically since 2012. The hottest topics include performance optimization, NOx emissions, combustion anomalies (backfire and knock), and dual-fuel diesel configurations. Hydrogen-enriched engines have been shown to outperform gasoline-only engines in brake thermal efficiency (BTE), with improvements of around 31% over gasoline baselines. The catch is that at stoichiometric or near-stoichiometric conditions, peak combustion temperatures can shoot past 2200 K, where thermal NOx formation via the Zel'dovich mechanism really takes off. Researchers have tackled this problem from several angles: exhaust gas recirculation (EGR), water injection, lean-burn strategies, and selective catalytic reduction (SCR).

Combustion anomalies remain a significant engineering headache. Backfire—when hydrogen ignites prematurely in the intake manifold during the suction stroke—can damage engine components and undermine reliability. Hydrogen's rapid burning rate also increases the likelihood of knock. The toolbox for dealing with these issues includes cold EGR to bring down in-cylinder temperatures, retarded spark and injection timing, water injection to cool hot spots, and carefully tuned intake valve timing. Researchers have found that delaying the intake valve opening to top dead center can effectively suppress backfire across the full speed range, even at richer equivalence ratios.Storage is another big hurdle. Hydrogen can be stored as a compressed gas at 350–700 bar, as a cryogenic liquid at 21 K, as a solid-state metal hydride, or chemically bound in molecules such as ammonia. Each option involves trade-offs between how much energy you can fit in a given volume, the energy cost of compression or cooling, weight, and price. Green hydrogen—produced by renewable-powered electrolysis—still accounts for less than 1% of global hydrogen production, and it costs between $2.50 and $5.00 per kilogram, well above grey hydrogen at roughly $1.50 per kilogram. The good news is that renewable energy costs keep falling and electrolyzer technology is scaling up, which should steadily narrow the gap.

Ammonia:-

Ammonia (NH_3) offers an intriguing alternative as a carbon-free fuel carrier. It can be made from nitrogen and green hydrogen, and it becomes liquid at just −33 °C at atmospheric pressure (or at moderate pressures at room temperature), making it far easier to store and transport than molecular hydrogen. Like hydrogen, burning ammonia produces no CO_2, and the world already has a vast fertilizer distribution network that could be repurposed for fuel logistics.That said, ammonia is a tricky fuel to work with. It burns slowly, needs a lot of energy to ignite, has a narrow flammability window, and scores poorly on the cetane scale—meaning it really struggles to auto-ignite in compression-ignition engines without some help. Dual-fuel approaches, using a small pilot injection of diesel or hydrogen to kick-start combustion, have shown real promise in overcoming these limitations. Japanese maritime projects have managed stable ammonia combustion in large two-stroke marine engines, and in 2024, the ammonia-fuelled tugboat Sakigake entered service as the world's first vessel of its kind. On the emissions side, NOx can come from both thermal mechanisms and the nitrogen bound in the fuel itself, so aftertreatment systems are a must.

Unburnt ammonia escaping from the exhaust (known as ammonia slip) is also a concern due to the compound's toxicity.

Biofuels: Ethanol and Biodiesel:-

Biofuels are the most commercially developed alternative fuels for ICEs today. Bioethanol, made by fermenting sugars or starches from crops or lignocellulosic waste, is routinely blended with gasoline at levels from E10 all the way up to E85 and beyond. Its high octane rating (around 108–110 RON) allows engines to run at higher compression ratios, and because the molecule contains oxygen, it promotes more complete combustion, resulting in lower CO and particulate emissions. The trade-off is that ethanol carries about two-thirds the energy of gasoline per liter, so you need more of it to get the same power output.

Biodiesel—fatty acid methyl esters made from vegetable oils, animal fats, or waste cooking oil—can step in for conventional diesel with minimal engine changes. Its higher cetane number indicates good auto-ignition quality, and its built-in oxygen helps reduce soot and CO. Some studies have noted a modest increase in NOx, likely due to changes in combustion timing and flame temperature. In practice, Scania's commercial ED95 ethanol trucks have shown CO_2 reductions of up to 90% compared with diesel while still meeting Euro VI pollutant limits—a strong proof of concept for biofuels in heavy-duty transport.

India's National Biofuel Policy has set ambitious targets: 20% ethanol blending in petrol (E20) by 2025 and 5% biodiesel in diesel by 2030. The country's ethanol blending program has already reached about 12%, drawing on feedstock from sugarcane, grain surpluses, and a growing number of second-generation plants that can turn agricultural waste like rice straw into fuel.

Synthetic Fuels (E-Fuels):-

Synthetic fuels are hydrocarbons produced from green hydrogen and captured CO_2, using processes such as Fischer–Tropsch synthesis or methanol-to-gasoline conversion. Their biggest selling point is that they are drop-in compatible: you can run them through existing engines, pipelines, and filling stations without any modifications. If the CO_2 feedstock comes from direct air capture or sustainable biomass, the lifecycle carbon footprint can get very close to net zero.

The downside is efficiency. Converting renewable electricity into a liquid fuel and back again currently wastes about half the energy along the way (round-trip efficiency sits around 40–50%), which makes e-fuels expensive—typically $5–10 per liter at today's pilot-plant scale. Even so, there is strong interest in sectors where going electric is not practical: aviation (synthetic kerosene), motorsport (Formula 1 plans to use 100% sustainable fuel by 2026), and the millions of legacy vehicles already on the road. The broader Power-to-X (PtX) framework captures these pathways, channeling surplus renewable electricity into hydrogen, which is then converted into methane, methanol, ammonia, or liquid hydrocarbons for a range of end uses.

Natural Gas (CNG/LNG):-

Compressed natural gas (CNG) and liquefied natural gas (LNG) occupy a useful middle ground as transitional fuels. They cut CO_2 emissions by roughly 20–25% compared with gasoline, virtually eliminate particulate matter, and reduce NOx. CNG is already a familiar sight in urban bus and taxi fleets, particularly in Indian cities like Delhi and Mumbai. A step further is hydrogen-enriched CNG (HCNG)—typically 18–20% hydrogen by volume—which has been trialed in Delhi's public bus fleet, delivering about 4% better fuel economy and a 70% reduction in CO2 emissions relative to straight CNG.

Natural gas is still a fossil fuel, though, and methane leaking from engines and supply chains can partly undo its climate advantage. A renewable alternative is biogas upgraded to pipeline-quality biomethane (compressed biogas, or CBG), which burns much like natural gas but with a far smaller carbon footprint.

Advanced Engine Technologies for Future Fuels:-

Getting the best out of future fuels means designing engines that can handle their very different combustion behaviors while achieving maximum efficiency and keeping emissions to a minimum. Three main strategies have attracted the most research attention.

Dual-Fuel Operation:-

Dual-fuel engines run primarily on a gaseous or low-reactivity fuel, with a small pilot injection of a high-cetane fuel (usually diesel) to light the fire. This approach is especially valuable for fuels that struggle to auto-ignite on their own—ammonia, hydrogen, and natural gas all fall into this category. In hydrogen–diesel dual-fuel mode, the hydrogen energy share (HES) can be tuned to find the sweet spot between cutting emissions and managing NOx. Research has shown that adding hydrogen to diesel engines can slash HC, CO, CO_2, and smoke by more than 50%, and applying EGR on top of that can rein in the resulting NOx increase. One study found that a 30% hydrogen share combined with 10% EGR achieved reductions of 38.4% in NOx, 27.4% in CO_2, 33.4% in CO, and 20% in particulate matter.

HCCI and RCCI Combustion:-

Homogeneous Charge Compression Ignition (HCCI) represents a fundamentally different way of burning fuel. A premixed lean charge auto-ignites throughout the cylinder simultaneously, resulting in very low peak temperatures that virtually eliminate both thermal NOx and soot. Efficiency gains of up to 30% over conventional spark-ignition engines have been demonstrated. The challenge, however, is control: because ignition timing depends on chemical kinetics rather than a spark plug or injector, it is hard to manage precisely.Reactivity-Controlled Compression Ignition (RCCI) was developed specifically to address this controllability problem. It uses two fuels with different reactivities—a low-reactivity fuel, like gasoline or ethanol, premixed in the intake, and a high-reactivity fuel, like diesel or biodiesel, injected directly to trigger and stage the combustion process. RCCI has achieved impressively low NOx and soot levels, along with thermal efficiencies above 50%, in laboratory conditions. It pairs particularly well with biofuel combinations such as ethanol–biodiesel, which could potentially enable fully renewable-fuel operation with minimal pollutant output.

Optimized Hydrogen Combustion Strategies:-

For engines designed specifically around hydrogen, lean-boosted direct injection has emerged as the leading configuration. Running at very lean equivalence ratios (0.2–0.5) with pressure boosting can push NOx levels to near zero while still maintaining competitive power output. Variable compression ratio (VCR) technology and optimized intake valve timing (delaying the intake valve opening to top dead center) have proved effective at preventing backfire and knock. When you combine direct injection, lean boosting, and multicycle variable valve timing (MCVVT), hydrogen engines can match or even exceed the efficiency of conventional diesels—and the only thing coming out of the exhaust is water.

Critical Challenges and Potential Solutions:-

The table below summarizes the main obstacles to widespread future-fuel adoption, along with the most promising solutions being explored.

Table 1. Summary of key challenges and potential solutions for future fuels in ICEs.

Challenge Area	Key Issues	Potential Solutions
Hydrogen Storage & Infrastructure	Low volumetric energy density; very few refueling stations; risk of steel embrittlement in pipelines; high energy penalty for compression and liquefaction	Solid-state storage (metal hydrides, MOFs); advanced cryogenic tanks; repurposing existing pipelines with new materials; government-funded station rollout
Combustion Anomalies	Backfire and knock in H_2 engines due to wide flammability range and low ignition energy; risk of engine damage.	Cold EGR; water injection; retarded spark/injection timing; optimized valve timing (IVO at TDC); direct injection; ammonia blending to increase ignition delay
NOx Emissions	Thermal NOx formation when temperatures exceed 2200 K; inherent trade-off with power output in lean operation	Lean-burn operation; EGR (up to 80% NOx reduction); water injection; SCR aftertreatment; multi-objective optimisation using machine learning
Green Fuel Costs	Green hydrogen at \$2.50–\$5.00/kg vs grey at ~\$1.50/kg; synthetic fuels at \$5–10/L; chicken-and-egg investment problem	Falling renewable energy costs, carbon pricing, economies of scale in electrolyzers, policy mandates, and subsidies
Ammonia Ignitability	Low flame speed; high ignition energy; narrow flammability range; toxic NH_3 slip	Dual-fuel with diesel/H_2 pilot; spark-assisted CI; higher compression ratios; catalytic aftertreatment for slip

Biofuel Sustainability	Food vs fuel competition; land-use change; lower volumetric energy content; cold-flow issues for biodiesel	2nd/3rd-generation feedstocks (waste, algae); cellulosic ethanol (e.g., rice straw); blending mandates with lifecycle assessments

Policy and Regulatory Landscape:-

Governments around the world are putting muscle behind the transition to cleaner fuels. The European Union has mandated a 55% cut in new-car CO_2 by 2030, with effectively zero tailpipe CO_2 required by 2035—though it has carved out an exception for vehicles running on certified carbon-neutral e-fuels. India's Bharat Stage VI norms (on par with Euro 6) took effect in 2020, and the country has pledged to reach net-zero emissions by 2070. Its National Biofuel Policy lays out phased targets for ethanol and biodiesel blending, while the National Green Hydrogen Mission (launched in 2023) channels significant public investment into green hydrogen production and end-use development.

Blending mandates have proved their worth in scaling up biofuel use: India's ethanol blending has climbed from negligible levels to around 12% in recent years. The SATAT (Sustainable Alternative Towards Affordable Transportation) initiative is pushing the production of compressed biogas from agricultural and municipal waste. Carbon pricing, low-carbon fuel standards (like California's), and direct subsidies for hydrogen infrastructure are further tools for closing the cost gap between old and new fuels. On the international stage, bodies such as the IEA, IRENA, and the IMO are hammering out standards for hydrogen refueling, ammonia bunkering, and lifecycle emission accounting.

Conclusions and Future Directions:-

If there is one takeaway from this review, it is that there is no silver bullet. No single future fuel can cover every transport application, every operating condition, and every regional context. Hydrogen delivers zero-carbon combustion and impressive thermal efficiency, but it comes with storage headaches, infrastructure gaps, and combustion quirks. Ammonia offers carbon-free energy and easier storage, but it needs help to ignite, and its toxicity demands careful management. Biofuels are commercially proven and compatible with existing infrastructure, yet feedstock sustainability and lower energy density put a ceiling on their scale. Synthetic e-fuels can drop right into legacy fleets and decarbonize them overnight—in theory—but they remain expensive and energy-hungry to produce. Natural gas bridges the gap for now, but it cannot deliver the deep emission cuts the world needs by mid-century.

The most realistic path forward is a portfolio strategy: matching each fuel to the applications where it performs best, while leveraging advanced combustion technologies—HCCI, RCCI, lean-boosted direct injection, and dual-fuel setups—to wring every bit of efficiency and emissions performance from each. Over the past decade, research has clearly shifted from basic performance testing toward sophisticated combustion and emission control strategies, increasingly aided by machine learning and multi-objective optimization.Looking ahead, the research priorities for the coming decade are clear: bring down the cost of green hydrogen and e-fuels through better electrolysers and cheaper renewables; develop robust, commercially ready HCCI/RCCI control systems for multi-fuel operation; sort out durability issues in hydrogen engines related to backfire, knock, and injector wear; improve ammonia combustion stability and NOx/slip management for marine and power applications; and build comprehensive lifecycle assessment frameworks that allow fair apples-to-apples comparisons across fuel pathways. With the right mix of research investment and smart policy, the internal combustion engine, far from being a relic of the past, can remain a vital and sustainable part of the global transport system through the net-zero transition and beyond.

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