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Potential for the use of SAF in internal combustion piston engines

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This review examines the feasibility of using Sustainable Aviation Fuels (SAFs) in internal combustion piston engines. It analyzes major SAF types and pathways, combustion and emission characteristics, material compatibility, certification frameworks, and economic considerations. The findings confirm that paraffinic SAFs (e.g. HEFA, FT) are suitable drop-in fuels for compression-ignition engines, offering lower emissions and compatibility with existing systems. Spark-ignition engines remain limited by octane requirements. The review concludes that SAF can significantly reduce environmental impact in piston-engine applications, though full deployment is constrained by cost, certification, and fuel availability.

Key words: *SAF, piston engines, HEFA, fuel compatibility, emissions*

1. Introduction

Sustainable Aviation Fuel (SAF) refers to non-petroleum-derived jet fuel components that can be blended with conventional jet fuel (Jet A/A-1) to reduce life-cycle carbon emissions [37]. While SAF has been developed primarily for turbine engines in aviation, there is growing interest in its applicability to internal combustion piston engines across aviation, automotive, and marine sectors. The main question is whether and how these renewable fuels can replace or supplement conventional gasoline, diesel, and avgas in piston engines without compromising performance or safety. This review addresses the feasibility of using SAF in piston engines, examining combustion characteristics, material compatibility, emissions, regulatory standards, and current developments. The goal is to summarize current knowledge and identify the pros and cons of SAF utilization in various piston-engine applications. In this review, we extend the SAF concept to include analogous renewable fuels for piston engines (such as renewable diesel and high-octane biofuels), recognizing that "SAF" in the strict sense usually refers to turbine fuel. The scope covers all internal combustion piston engines – spark-ignition (gasoline/avgas) and compression-ignition (diesel/jet fuel).

2. Overview of sustainable aviation fuels (SAF)

2.1. Definition and scope

SAF is defined by the aviation industry as a "drop-in" replacement for fossil jet fuel that meets the same technical specifications (after blending) but is produced from sustainable feedstocks [37]. SAF is chemically similar to kerosene (containing the same hydrocarbon range) so that, once blended and certified under standards like ASTM D1655 [3], it can be used in existing fuel systems and engines without modification. Importantly, to be recognized under ICAO's CORSIA program, SAF must also meet sustainability criteria (e.g. at least 10% life-cycle carbon intensity reduction and sustainable feedstock sourcing) [21].

Multiple production pathways for SAF have been approved or are under development, each yielding a fuel composed mainly of paraffinic hydrocarbons (alkanes) with properties akin to jet fuel [20, 40]. Table 1 summarizes the major pathways.

Table 1. Certified SAF pathways under ASTM D7566 (Annexes A1–A7) and their blend limits [5]

SAF type	Description
HEFA-SPK [1] Hydroprocessed Esters & Fatty Acids Synthetic Paraffinic Kerosene	Produced by hydrotreating vegetable oils, used cooking oil, animal fats, and other lipids to yield straight-chain and isoparaffinic hydrocarbons. Approved in 2011 with up to 50% blend limit [33]. HEFA is the most mature and widely used SAF pathway, chemically similar to hydrotreated vegetable oil (HVO) diesel.
FT-SPK [17] Fischer–Tropsch Synthetic Paraffinic Kerosene	Gasification of biomass or solid waste to syngas, followed by Fischer–Tropsch synthesis to produce hydrocarbons. Approved in 2009, 50% blend limit. FT-SPK contains zero aromatics and sulfur. An FT variant with added aromatics (FT-SPK/A) was approved in 2015 (50% limit) to provide aromatics for seal compatibility.
ATJ-SPK [24] Alcohol-to-Jet Synthetic Paraffinic Kerosene	Converts alcohols (such as isobutanol or ethanol from biomass fermentation) into jet-range hydrocarbons via dehydration, oligomerization, and hydrogenation. Approved in 2016 (isobutanol-derived) and 2018 (ethanol-derived) with up to 50% blend.
HFS-SIP [24] Synthetic Iso-Paraffins from Fermented Sugars	Produces a specific hydrocarbon (farnesane) from sugar via microbial fermentation and hydrogenation. Approved 2014 with a 10% blend limit.
CHJ (CH-SK) [36] Catalytic Hydrothermolysis Jet	Uses catalytic hydrothermolysis of fats/oils (a process akin to hydrothermal liquefaction) to produce jet fuel. Approved 2020, 50% blend limit.
HC-HEFA [17] Hydrocarbon-Hydroprocessed EFA from algae	A pathway using algal oils (e.g. Botryococcus braunii) to produce hydrocarbons. Approved 2020 with a 10% blend limit.

In addition to these neat blending components, ASTM allows limited co-processing of biogenic oils in petroleum refineries (up to 5% biogenic content in jet or diesel fuel) as an early route to introduce sustainable content.

2.2. Production technologies, feedstocks, distribution

SAF feedstocks range from lipid materials (e.g. waste cooking oil, tallow, camelina, or jatropha oil) for HEFA, to cellulosic biomass and municipal solid waste for gasification-to-FT pathways, to sugars or alcohols from corn, sugarcane, or lignocellulosic biomass for ATJ routes. Emerging routes also include Power-to-Liquid fuels using CO_2 and renewable hydrogen [24]. The flexibility of feedstocks and processes is a key advantage of SAF – it allows production of fuel from various waste streams or renewable resources, potentially offering 50–85% net greenhouse gas reduction compared to fossil jet fuel. However, different pathways yield fuels with different chemical compositions (e.g. all-paraffinic vs some cyclic content), which influences their compatibility and performance in engines. It should be noted that the "drop-in" requirement currently means SAF is used in blends (up to 50%) with conventional fuel to meet all specifications; neat 100% SAF is not yet certified for routine use in aviation due to certain properties discussed later [5] (Fig. 1).

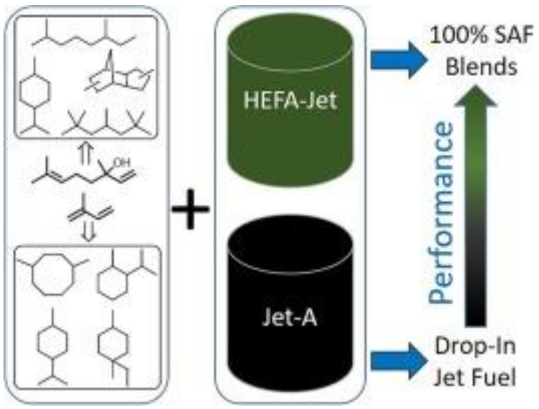

Fig. 1. Logistic path for SAF [29]

Prior to utilization in aviation applications, SAF must be blended with conventional Jet A fuel in accordance with ASTM D1655 certification standards [5]. In the case of co-processing within existing petroleum refineries, the resultant fuel can be seamlessly integrated into the current fuel supply chain, allowing for distribution via established infrastructure such as pipelines, fuel terminals, and road transport to end-user facilities, including airports. Similarly, SAF produced at standalone biorefineries is expected to be blended with Jet A at downstream fuel terminals before being conveyed to airports through traditional logistics channels, such as pipelines, tanker trucks, or barges (Fig. 2). Blending may occur either in proximity to or at a significant distance from the point of final use, depending on logistical efficiency. Importantly, fuel handling operations at airports remain unaffected, as only pre-certified, blended fuel is delivered through conventional means, thereby avoiding the need for on-site blending infrastructure, which would incur additional operational, personnel, and insurance costs. Consequently, upstream certification remains the industry-preferred approach to ensure compliance with stringent quality specifications [29].

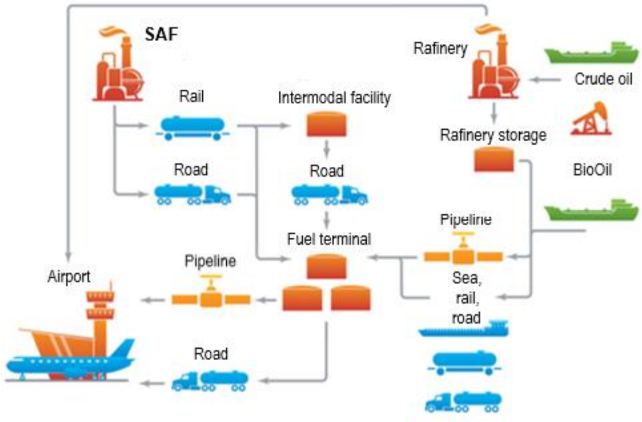

Fig. 2. Logistic path for SAF [29]

In land-based applications – particularly within the transport and defense sectors – comparable logistical frameworks can be implemented. Alternative fuels analogous to SAF, such as Hydrotreated Vegetable Oil (HVO), may be integrated into the existing diesel distribution infrastructure, including bulk storage facilities, fueling stations, and fleet refueling points, with only minimal modifications required [25]. Nonetheless, large-scale deployment remains dependent on regional regulatory approvals, the compatibility of storage tank materials, and the establishment of reliable fuel traceability systems to uphold certification standards. As in the aviation sector, centralized upstream blending and certification prior to distribution is considered the most effective strategy to facilitate supply chain integration and reduce implementation costs.

2.3. Current usage and trends

SAF usage in aviation, while still limited in volume, has been steadily increasing. Over 360,000 commercial flights have used SAF blends since 2021, at dozens of airports worldwide. Typical blend ratios are 30% or below in current airline trials, although the maximum allowed is generally 50%. Several national and industry initiatives (such as the U.S. SAF Grand Challenge and EU ReFuelEU mandate) aim to scale up SAF production to billions of gallons per year in the 2030–2050 timeframe (Fig. 3) [33].

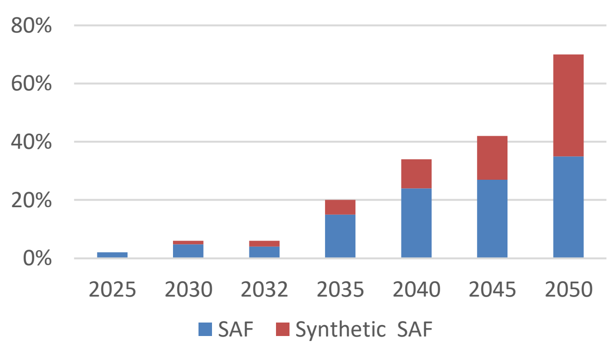

Fig. 3. Regulatory trajectory of minimum SAF blend mandates to support EU net-zero emissions target by 2050 [33]

For piston engines in aviation, the term "SAF" has not been applied in the same way – small aircraft mostly use avgas (a high-octane gasoline with lead) or, in some cases, jet fuel for diesel piston engines. Unleaded avgas formulations are being developed to eliminate lead, but these are typically petroleum-based and do not meet the sustainability criteria of SAF. Similarly, in road transport, "renewable diesel" (Hydrotreated Vegetable Oil – HVO) and other biofuels are being used as drop-in fuels for diesel engines, achieving significant CO_2 reduction. These renewable fuels are analogous to SAF and often come from the same production plants (e.g. a HEFA refinery can produce jet fuel and diesel cuts from the same process) [20]. In summary, SAF in the broad sense (renewable drop-in fuel) is already in use for diesel piston engines in some regions, and the technology and supply chains developed for aviation SAF can potentially benefit ground and marine fuels as well.

The projected fuel consumption and associated CO_2 emissions for international aviation between 2005 and 2050, as presented by ICAO, incorporate anticipated improvements in aircraft technology and air traffic management (ATM), as well as the potential deployment of sustainable aviation fuels (SAFs). These projections are illustrated in Fig. 4.

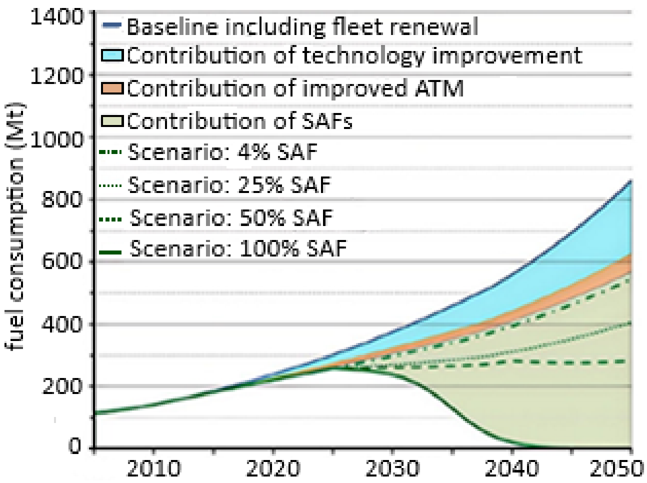

Fig. 4. Projected fuel use for international aviation according to the ICAO [9, 38]

2.4. Fuel standards and certification

2.4.1. Aviation fuel standards

The use of any fuel in certified aircraft engines is tightly governed by specifications and regulations. Jet fuel for turbines (and Diesel cycle piston aircraft) must meet DEF STAN 91-091 standard in Europe or ASTM D1655 (for Jet A/A-1) standard in the USA. SAF components are certified, which is effectively a supplement standard – once a SAF component is blended within allowed limits and meets needed requirements, it is re-identified as Jet A/A-1 fuel [20]. There are currently seven certified SAF pathways as described earlier, most with a 50% maximum blend limit. The ASTM committee is continuously reviewing data to potentially allow higher blends or new pathways; for instance, the ATJ blend limit was initially 30% and later raised to 50% after further testing. A major focus now is approving 100% SAF for future use – this will likely entail either a new ASTM specification or further annexes that include synthetic aromatic fractions to ensure a fully drop-in formulation [40]. Regulators like FAA, EASA, and ICAO are closely involved in this process through initiatives such as CAAFI (Commercial Aviation Alternative Fuels Initiative) and various demonstration programs.

For aviation spark-ignition piston engines, the relevant standard is ASTM D910 (the spec for 100LL leaded avgas) and ASTM D7547 (spec for unleaded avgas grades like UL91/UL94) [4, 6]. So far, no bio-derived avgas is certified under these standards. The unleaded avgas that is emerging (e.g., G100UL developed by GAMI, and Shell's proposed UL100) is still synthesized from petroleum in order to meet the strict volatility and high-octane requirements. These fuels aim to eliminate lead but are not necessarily lower-carbon. It's conceivable that in the future, an ASTM D7547 fuel could be formulated with some synthetic components (e.g. isopentane or ethanol-derived high-octane compounds) to be partially renewable. Such a fuel would need to go through engine testing and certification via FAA/EASA processes (e.g. Supplemental Type Certificates for each engine model, as G100UL is doing). The FAA has a broad initiative called EAGLE (Eliminate Aviation Gasoline Lead Emissions), targeting leaded avgas replacement by 2030 [16], which includes streamlining the testing of candidate unleaded fuels. While EAGLE's primary goal is lead removal, not directly carbon reduction, it could open the door to innovative fuel formulations, potentially including bio-based components.

2.4.2. Ground transport fuel standards

In the automotive world, standards are more accommodating to renewable drop-in fuels as long as they meet chemical property requirements. For diesel fuel, many countries allow a certain volume of biodiesel (FAME) blending (e.g. up to 7% in Europe's EN590 diesel). Paraffinic renewable diesel (HVO) is actually covered under a separate standard EN 15940 in Europe, which sets specifications for synthesized or hydrotreated paraffinic diesel fuels that contain essentially no aromatics [11].

Table 2. Key property ranges of EN 15940, EN 590, and ASTM D975 compliant fuel [11]

Parameter	EN 15940	EN 590:2013	ASTM D975
Cetane number	≥ 70.0	≥ 51.0	≥ 40
Density at 15°C [kg/m³]	765–800	820–845	–
Viscosity at 40°C [mm²/s]	2.00–4.50	2.00–4.50	1.9–4.1
Hydrocarbons (% m/m)	–	–	≤ 35
Polyaromatic	–	≤ 8	–
Aromatic	≤ 1.0	–	–
Olefin	≤ 0.1	–	–
Sulfur content [mg/kg]	≤ 5.0	≤ 10.0	≤ 15
Flash point [°C]	≥ 55	≥ 55	≥ 52
Lubricity HFRR at 60°C [μm]	≤ 460*	≤ 460	≤ 520
95% by volume distils at [°C]	≤ 360	≤ 360	282–338
CFPP [°C]	≤ –34	≤ –34	–
Ash content [% m/m]	≤ 0.01	≤ 0.01	≤ 0.01
Total impurity content [mg/kg]	≤ 24	≤ 24	–

* Including lubricating additives for use in vehicles approved for driving on the fuel according to the standard. CFPP: cold filter plugging point; HFRR: high frequency reciprocating rig.

EN15940 fuels (which include HVO and GTL) can be used in vehicles approved for them; notably, several major truck manufacturers (Volvo, Scania, Daimler) have endorsed HVO fuel for their engines with no changes required. In the US, ASTM D975 (diesel spec) doesn't distinguish HVO – if the fuel meets D975 properties, it can be used. Renewable diesel is fungible with fossil diesel, so it often just goes into the general diesel pool. Gasoline (EN228 or ASTM D4814) currently allows up to 10% ethanol; high-level ethanol or other high-octane components require special tuning but could be considered "alternative fuel" rather than drop-in.

2.4.3. Marine fuel standards

Marine fuels are governed by ISO 8217, which primarily covers heavy fuel oil and marine distillates [22]. There is no widely adopted standard for biofuels in marine use yet, but ISO 8217:2017 includes a mention that up to 7% FAME biodiesel may be blended into marine distillate (DMA) as long as it meets the requirements (similar to on-road diesel). Trials are being conducted with HVO in marine engines (replacing marine gas oil) as discussed in Section 8. For now, any high percentage of biofuel for marine use is handled case-by-case with engine manufacturer guidance. The International Maritime Organization (IMO) has set targets for GHG reduction in shipping, which is encouraging experimentation with drop-in biofuels as well as novel fuels like methanol, ammonia, etc. Within that, HVO is attractive for its plug-and-play nature (no sulfur, cleaner burn, usable in existing diesel ship engines), but availability and cost are limiting factors [30].

2.4.4. Certification and regulatory approvals

Whether in air, road, or sea, introducing a new fuel requires ensuring safety and compatibility. In aviation, this is formalized through fuel approval (ASTM specs) and, in many cases, additional certification by the airframe/engine manufacturer and regulators. For example, when SAF blends were first used on commercial flights, OEMs like Boeing and Airbus had issued technical approvals and worked with airlines on demonstration flights [8]. Now, any engine certified for Jet A can use SAF blends up to the approved limit without further modifications or approvals [40], since the fuel is considered Jet A once it meets D1655. For piston aircraft using Jet-A (diesel) engines, the same logic applies – those engines can run on SAF blends as long as the fuel meets Jet A specs. In contrast, if someone wanted to use an unleaded automotive gasoline in an aircraft piston engine, they need an STC (Supplemental Type Certificate) because it's a different spec fuel (this has been done for many smaller aircraft to use automotive gasoline). Similarly, using a fuel outside of spec in any certified engine typically violates warranty or regulations unless explicit approval is given.

Regulatory bodies are actively supporting SAF: ICAO has incorporated SAF into its policies for reducing aviation emissions (CORSIA framework for accounting emissions reductions from SAF). FAA and EASA fund research and test programs – for instance, FAA's CLEEN program and ASCENT Center have projects on alternative fuels, and EASA has participated in tests of unleaded avgas and SAF sustainability assessments. The close collaboration between standards organizations (ASTM), industry, and regulators aims to ensure that, as SAF use expands, it does so safely. In ground transport, regulations tend to be fuel-neutral as long as emission standards are met, so introducing renewable fuels is more about meeting fuel specs and sometimes incentives (e.g. renewable fuel standards, CO_2 fleet averaging credits for automakers, etc.) [21].

Standards like ASTM D7566 (for SAF jet fuel) and EN15940 (for renewable diesel) provide frameworks to certify and use these fuels in piston engines where applicable. The certification process ensures that engines using SAF perform equivalently to those using conventional fuels. Ongoing regulatory efforts (FAA EAGLE, CORSIA, EU mandates) are creating an environment that encourages the adoption of SAF and even demands it in some cases (e.g. EU will require increasing SAF use in aviation over time. For widespread use in piston engines, especially in aviation, updated standards for a high-octane renewable avgas may be needed in the future [24].

3. Performance in piston engines

3.1. CI and SI combustion

The feasibility of using SAF in piston engines depends on the combustion characteristics of the fuel relative to conventional fuels (gasoline, diesel, or avgas). Key considerations include ignition quality (cetane or octane rating), energy content, and how the fuel behaves across operating conditions e.g. cold start, altitude, resistance to aging processes etc.

Compression-Ignition (Diesel Cycle) piston engines – whether in aircraft or ground vehicles – are generally more compatible with SAF because SAF blends are formulated to mimic kerosene/diesel fuel. SAF like HEFA-SPK consists almost entirely of normal- and iso-paraffins, giving it a very high cetane number (typically 70 – cetane for neat HEFA, versus ~45–55 for fossil diesel) [12, 20]. This high cetane means SAF ignites readily in compression ignition, often leading to smoother combustion and potentially a shorter ignition delay. Studies in diesel engines have shown that pure HVO (a fuel equivalent to HEFA) can actually slightly increase or maintain engine power output relative to conventional diesel. For example, one experimental study found that a tractor engine running on 100% HVO delivered about the same or slightly higher peak torque and power than on fossil diesel [34]. Another engine test reported HVO yielding a small (~5%) decrease in power in a specific case, but that engine also saw significant emissions reductions (e.g. NO_x down ~12%, CO down ~14%) when using HVO [34]. Generally, because HVO/HEFA fuels have slightly lower density (≈ 6–7% lower than diesel) but similar energy per mass, an engine's volumetric fuel flow might need to increase by a few percent to deliver equal power. Modern fuel injection systems can often accommodate this automatically via longer injection duration if operating on a volumetric basis. In terms of operability, paraffinic SAF fuels have excellent low-temperature performance (high cetane and low freeze point), which is beneficial for high-altitude operation. In fact, a study on an aviation diesel (heavy-fuel) piston engine found that at

5,500 m altitude, the power loss was marginally less with SAF than with normal diesel – power drop of ~22.1% on SAF vs 23.4% on diesel (relative to sea level performance) [39]. This suggests SAF may have slightly better high-altitude combustion characteristics, possibly due to its very low aromatics improving fuel evaporation and mixing at low air densities. Overall, SAF and RP-3 fuels show comparable combustion trends to conventional diesel, with minor deviations in peak pressure and pressure rise timing that become more evident at lower engine loads. This suggests good compatibility of SAF for compression ignition engines across a range of operating conditions, as shown in Fig. 5.

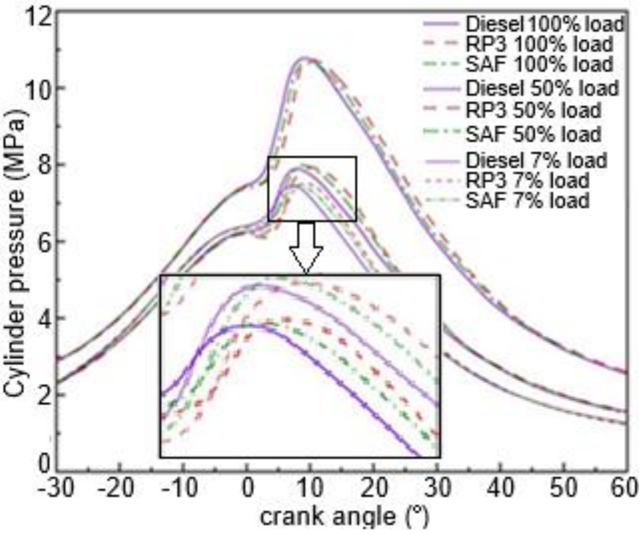

Fig. 5. In-cylinder pressure profiles for diesel, RP-3, and SAF fuels at varying engine loads [39]

For Spark-Ignition Engines (Otto Cycle) that require gasoline or avgas (typically small aircraft and most automobiles), the use of SAF presents a different challenge. Neat SAF as produced today is mostly a kerosene-type fuel with high cetane but low octane – not suitable for spark-ignition, which needs high octane to avoid knock. Aviation gasoline (100LL) has an octane rating over 100 (MON), whereas kerosene's octane rating would be far below that (roughly 20–30 octane if measured as gasoline). Therefore, direct use of SAF (as kerosene) in a gasoline engine is not feasible without engine modifications (e.g. to a compression-ignition conversion or spark-assisted diesel cycle). However, there are efforts to create high-octane sustainable fuels. One approach is to produce synthetic gasoline or bio-avgas via processes like Fischer–Tropsch (which can output gasoline-range hydrocarbons) or other bio-refineries. These fuels are not yet commonly called "SAF" but rather "renewable gasoline." For example, there are demonstration fuels such as isopentane or iso-octane made from bio-feedstocks that could serve in high-compression engines. Another approach for aviation is to modify piston aircraft engines to use existing SAF (jet fuel): this is already done in the form of diesel aircraft engines (e.g. Austro Engine AE300, Continental CD-155), which are certified to run on Jet A fuel. Those engines could likely run on SAF-blend Jet A just as turbine engines do, since from the engine's perspective, the fuel meets the same ASTM D1655 spec. Indeed, any piston engine certified for Jet A can use blended SAF without issues [37]. For legacy spark-ignition aircraft engines that rely on leaded avgas for octane, the transition to a sustainable fuel is more complex. Unleaded avgas alternatives (UL91, UL94) are petroleum-derived and only meet lower-octane requirements, suitable for ~70% of the fleet but not the highest-performance engines [14]. A truly sustainable high-octane avgas would require new fuel formulations (e.g. bio-derived aromatics or high-octane components). This is an area of active research, but no "bio-100LL" has been certified yet. In concept, alcohols like ethanol or isobutanol provide high octane and are renewable, but their other properties (low energy density, high vapor pressure, or freezing point) make them problematic for aircraft use. Thus, in spark engines, SAF use today mostly means using ethanol blends in cars (up to E10/E85, though ethanol is not a drop-in fuel) or using renewable gasoline components as they become available. Another angle is using methane or biogas in piston engines – not "SAF" per se, but sustainable fuel. However, this falls outside the drop-in hydrocarbon focus of SAF and has its own infrastructure needs.

In summary, SAF in piston engines is most straightforward for diesel/jet-fueled engines, where the combustion characteristics of paraffinic SAF (high cetane, clean combustion) are largely beneficial. For spark-ignition applications, significant fuel re-formulation (to increase octane or create new high-octane synthetic components) is required, or alternately, engine technology must shift (e.g. towards compression ignition engines that can use kerosene-type fuels).

3.2. Material compatibility and engine durability

Any alternative fuel must be compatible with the materials (metals, elastomers, plastics) used in fuel systems to avoid leaks, corrosion, or degradation. A critical difference between today's SAF and conventional fuels is the lack of aromatic hydrocarbons in SAF. Conventional gasoline, diesel, and kerosene contain aromatic compounds, which tend to swell certain rubber seals and O-rings (Fig. 6). These seals were often selected assuming the presence of aromatics. Aromatics in fuel are needed to maintain seal swell; without aromatics, some elastomers shrink and harden, leading to fuel leaks or component failures [19]. This is a well-documented issue in aviation: when synthetic paraffinic fuels (FT, HEFA, etc.) were introduced, it was found that O-rings and gaskets in older aircraft could shrink due to the fuel's low aromatic content. For this reason, ASTM D7566 initially limited SAF blending to 50% max – ensuring the final blend still has ~8% or more aromatics (since typical Jet A has ~16–18% aromatics). It was a conservative measure to guarantee seal compatibility. Modern aircraft and engine manufacturers are now addressing this by testing seals in low-aromatic fuel and, where necessary, using fuel-resistant elastomers. Some newer engines and airframes already use materials (like fluoropolymers, fluorosilicone, etc.) that do not depend on aromatics for swelling. Going forward, to enable 100% SAF use, either the fuel will need to include synthetic aromatics or the sealing materials must be qualified to tolerate all-paraffinic fuels. There are research programs looking at bio-derived aromatics (for example, from lignin or other sources) to add to SAF so that it truly becomes a drop-in replacement even at 100% [7].

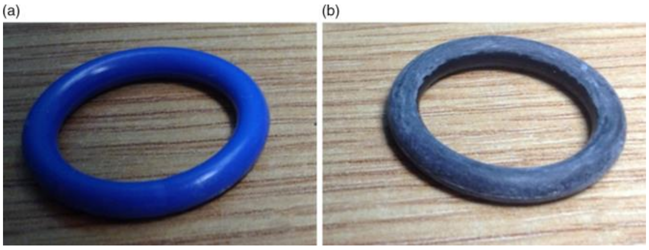

Fig. 6. Swelling and shrinkage behavior of elastomeric O-rings depending on fuel aromatic content: (a) O-ring exposed to conventional fuel containing aromatics (swollen), (b) O-ring exposed to SAF with low aromatic content (shrunken and hardened) [2]

Apart from seal swell, other material issues include lubricity and corrosivity. Ultra-low-sulfur, aromatic-free fuels like neat SAF have lower lubricity – the fuel's ability to lubricate fuel pumps and injectors. In conventional diesel, trace sulfur and aromatics provide natural lubricity; in Jet A, additives are not commonly used for lubricity, so the fuel itself must suffice. It has been noted that no dedicated lubricity additives are currently allowed in jet fuel, so the blend limit of 50% SAF also helps ensure the mix has adequate lubricity [32]. In practice, neat HEFA or FT fuels have to be treated or blended because running 100% could cause excessive wear in fuel pumps due to poor lubricity. For on-road diesel usage, this is mitigated by standards like EN 15940 (paraffinic diesel fuel), which requires a lubricity spec – HVO diesel is added to meet wear scar requirements. Similarly, any future 100% SAF for aviation may require an approved lubricity additive or a small fraction of synthetic aromatic content to protect pumps.

Metal corrosion is generally less of an issue with SAF than with biodiesel or alcohol fuels. SAF is hydrocarbon-based and contains no oxygenates, so it doesn't tend to absorb water or form acidic byproducts that corrode metals. In fact, HEFA and FT fuels are very clean (no sulfur, no olefins), which can reduce corrosive tendencies and deposit formation. Turbine engine tests on SAF have not revealed significant corrosion issues; we expect the same for piston engines – if anything, SAF may burn cleaner and leave fewer deposits that could cause hot corrosion or spark plug fouling. For example, unleaded fuel eliminates lead deposits on spark plugs and valves in aircraft engines, which should reduce maintenance needs (one motivation for unleaded avgas).

Engine wear can be affected by fuel via lubricating properties, deposit formation, and combustion temperature/pressure changes. With SAF, a positive finding is that combustion is generally cleaner, leading to fewer carbon deposits and particulate matter that can contaminate oil or cause abrasion. A study of heavy-fuel (jet-fueled) aircraft piston engines running on 100% HEFA showed dramatically lower particulate output, which implies less soot getting into the oil and less soot loading on cylinder walls [38]. Lower soot and a lack of sulfur also mean the engine oil will remain cleaner and less acidic over time, potentially extending oil life and reducing wear on rings and bearings. On the other hand, if lubricity is not managed, certain high-pressure fuel system components could wear faster with neat SAF. To address this, manufacturers like Bosch, Continental, etc., are testing pumps with SAF. So far, industry reports indicate that a 50% blend of SAF poses no problems – for instance, no hardware changes or accelerated wear have been observed when operating diesel engines or turbines on approved SAF blends. Cummins Inc. has approved its diesel generator engines to run on 100% HVO (renewable diesel) with no modifications, maintaining warranty, after validating performance and durability in testing. This suggests that, at least for compression-ignition designs, the base engine durability is not compromised by the fuel, provided it meets the spec for lubricity and such. In spark-ignition engines, using a fuel that meets the required octane will be critical to prevent knock damage. (For example, using a lower-octane fuel than required can cause pinging and eventually piston damage – a risk if someone tried to fuel a high-performance avgas engine with a kerosene-type SAF improperly.

In summary, material compatibility is a central concern for SAF use in any engine. The primary issue is the absence of aromatics in the current SAF, which impacts seal swelling and lubricity. Solutions under development include new additive packages and updated material standards. Engine durability on SAF appears promising, especially given the cleaner-burning nature of these fuels, but it requires careful attention to ensure fuel systems are appropriately conditioned for low-aromatic content.

3.3. Emission characteristics and environmental impact on the engine

One of the motivations for SAF (and related renewable fuels) is the potential to reduce harmful emissions. There are two facets to consider: regulated engine emissions (CO, HC, NOx, particulates) and life-cycle greenhouse gas emissions. We also consider how those emissions relate to engine health (deposits, wear). Figure 7 below shows the chosen pollutant emissions of HF-APE, RP3 (aviation kerosene surrogate fuel, Jet-A1 fuel substitute on the Chinese market), and Diesel fuel under specific load conditions and typed fuels are shown.

Empirical studies consistently show that paraffinic SAF fuels burn cleaner in terms of particulate matter and carbon monoxide/unburnt hydrocarbon emissions. The absence of aromatics (which tend to produce soot) and the high cetane of SAF lead to more complete combustion. For instance, tests on a heavy-fuel aircraft piston engine running 100% HEFA SAF found marked reductions in CO (Fig. 7a) and unburned HC emissions compared to RP3 jet fuel. Particulate emissions were significantly lower as well – the study reported a ~43% reduction in non-volatile particulate number and ~65% reduction in particulate mass compared to diesel fuel at the same operating condition [38].

These are substantial improvements, indicating a much cleaner exhaust. Similarly, in diesel truck engines, pure HVO has been shown to cut soot (black carbon) emissions by over 60%, with hydrocarbon and CO emissions roughly 40% lower than with petroleum diesel [26]. A comprehensive study by McCaffery et al. (2022) on an off-road engine

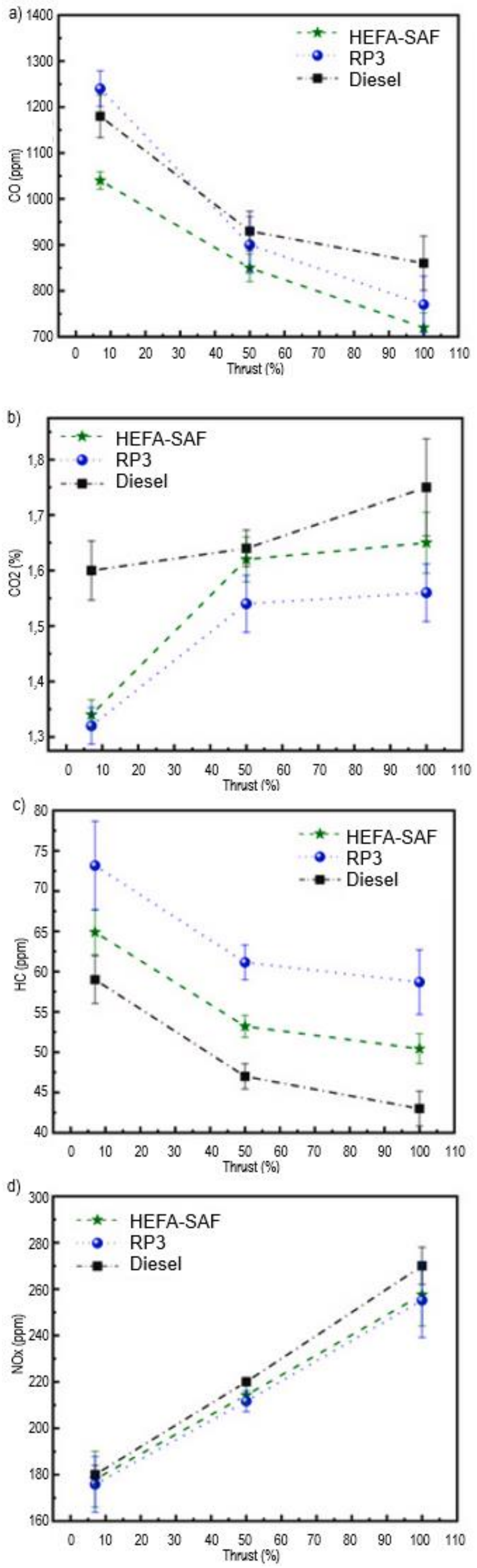

Fig. 7. Emission characteristics of different aviation fuels (HEFA-SAF, RP-3, and Diesel) at various engine thrust levels: (a) carbon monoxide, (b) carbon dioxide, (c) hydrocarbons, and (d) nitrogen oxides [38]

noted statistically significant reductions in NO_x as well (contrary to some earlier concerns that biodiesel can raise NO_x): in their tests, switching to 100% HVO decreased NO_x emissions, whereas blending biodiesel increased NO_x (Fig. 7d). They also observed fewer polycyclic aromatic hydrocarbons (PAHs) in the exhaust and lower toxicity of the particulate matter with HVO. These trends are very positive from an air quality standpoint – less smoke, less CO, and potentially lower NO_x [27].

For spark-ignition engines, if a high-octane sustainable fuel were used, emissions would likely also improve compared to gasoline, because renewable components could be formulated to avoid benzene and other aromatic toxins present in gasoline. One example: ethanol, a bio-fuel, when used in high blends (E85) drastically lowers tailpipe PM and reduces CO (owing to oxygenated fuel and high octane allowing optimized combustion), though it can raise evaporative HC emissions. A fully synthetic high-octane fuel might resemble iso-octane or other clean components, which would burn very cleanly. However, data in this area are sparse until such fuels are tested.

It's worth noting that modern automotive engines have aftertreatment (catalytic converters, particulate filters) that mitigate emissions regardless of fuel. Still, lower engine-out emissions with SAF mean the aftertreatment has less work to do and can be more effective (for example, less soot means diesel particulate filters regenerate less frequently and have longer life).

Tailpipe CO_2 emissions from SAF are similar to fossil fuels on a per-energy basis (because burning a hydrocarbon always produces CO_2). The real climate benefit of SAF comes from the renewable sourcing: the CO_2 released was previously absorbed by the biomass or was waste carbon, so the net life-cycle CO_2 is lower (Fig. 7b). Depending on feedstock and process, SAF can achieve anywhere from ~60% to 85% reduction in net GHG emissions [31]. Some pathways, like ATJ ethanol to jet, can claim up to 94% reduction in ideal cases [14]. These figures assume sustainable practices (e.g. used cooking oil feedstock has very high savings; a crop-based oil might have lower savings if land-use change is accounted). Using SAF in piston engines would confer the same life-cycle CO_2 benefits. For example, a diesel truck fleet running on HVO from waste oils can cut CO_2 emissions by ~80% compared to petro-diesel – this is already being realized in parts of Europe [34]. The environmental benefit for aviation piston engines (most of which currently use fossil avgas or Jet A) would be similarly significant in terms of carbon footprint.

Cleaner combustion with SAF generally means less soot and acidic byproducts, which is beneficial for engine longevity. Lower sulfur in fuel yields virtually zero SO_x emissions, preventing sulfuric acid formation in oil and exhaust. Also, fewer particulate emissions translate to less soot accumulation in oil, which can slow the degradation of oil and reduce engine wear due to abrasive particles. Some studies correlate the use of neat HVO with reduced engine deposits in combustion chambers and fuel injectors (because HVO has no heavy components or ash). That said, one must ensure that the fuel's lubricity is sufficient – if not, fuel pump wear could offset some benefits. In practice, adding a lubricity improver or blending with a few percent of conventional fuel is enough to protect components.

In summary, SAF and related renewable fuels offer a clear emissions advantage: significantly lower local pollutants (PM, CO, HC, and, depending on conditions, NO_x reduction or at least no increase) and a large net reduction in CO_2 emissions when considering the full fuel production cycle. Additionally, by eliminating lead in avgas and sulfur in diesel, they remove two major toxic emissions (lead aerosols and SO_2) that affect health and the environment. For engine health, the cleaner burn of SAF can mean fewer deposits and potentially longer engine life, provided material compatibility issues are managed.

4. Economic and environmental considerations

4.1. Cost and availability

A major barrier to SAF adoption in any sector today is cost. SAF is currently significantly more expensive to produce than fossil fuels – roughly 2–5 times the price of Jet A on a per-gallon basis, depending on feedstock and region. This is due to the smaller scale of production, the cost of feedstocks, and processing costs. As of the mid-2020s, global SAF production is only a tiny fraction of total jet fuel use (on the order of < 1% of aviation fuel). Similar renewable diesel production is also limited relative to global diesel demand, though it's growing with many new plants under construction. There are policy measures (subsidies, tax credits, carbon pricing) that aim to bridge the price gap. For example, the United States' SAF Grand Challenge not only sets volume targets but also seeks to reduce the cost to \$3 per gallon by 2030 through R&D and scaling. In road transport, some countries have mandates or incentives for renewable fuel blending (e.g. California's Low Carbon Fuel Standard credits have made renewable diesel economically attractive in that market).

For piston-engine aviation (general aviation aircraft), the market is much smaller and fragmented compared to airlines, so expecting a dedicated SAF for avgas might be economically challenging. The unleaded avgas solutions being rolled out are mostly drop-in from existing refineries. If a fully renewable avgas were developed, it would likely cost even more per liter than SAF for jets due to more complex processing (creating high-octane components efficiently is hard). Thus, in the near term, it is more practical that piston aviation decarbonizes via fleet changes (e.g. more Jet-A diesel engines that can use SAF, or electrification for short-range aircraft) rather than via a unique SAF for spark-ignition engines.

For automotive and marine, renewable fuels can piggyback on the supply being made for aviation. Indeed, refiners often produce a mix of products; for instance, a HEFA plant might output some renewable diesel and some SAF. If policies drive aviation SAF use, that could increase supply and eventually lower costs for all sectors. Conversely, if a lot of renewable diesel is pulled into trucking and shipping, it might compete with SAF for feedstock. There is a feedstock limitation: fats, oils, and greases are in finite supply, so to scale to large volumes, cellulosic and waste feedstocks via FT or ATJ must come online, which is technologically more complex.

From the consumer perspective, unless subsidized, fuel users are cost-sensitive. Airlines can perhaps pass on a small ticket surcharge for using SAF (and justify it by sustainability commitments). Private pilots or trucking companies might be less willing to pay a premium for green fuel unless required or incentivized. Thus, a combination of mandates (like blending requirements) and incentives (credits, lower taxes for SAF) is considered necessary to drive initial adoption.

Comparison of market prices for conventional Jet A-1 and various sustainable aviation fuel production pathways, including FT, AtJ, and E-jet, is shown in Fig. 8. While Jet A-1 maintains relatively stable and lower prices, alternative fuels—particularly electrofuels—show higher and more variable cost trends, reflecting technological maturity, feedstock availability, and scale-up challenges.

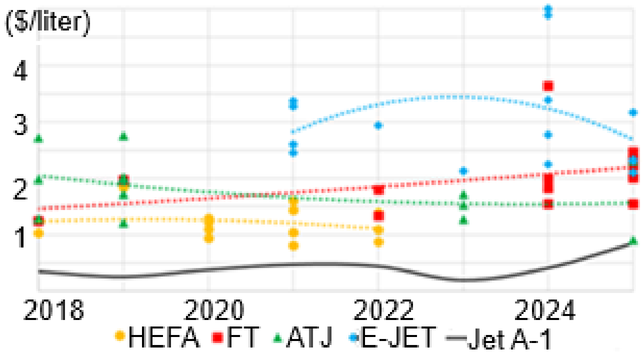

Fig. 8. Historical jet fuel prices (2018–2025) for conventional and alternative aviation fuels [23]

4.2. Environmental and sustainability aspects

The core reason for SAF is to reduce net carbon emissions and mitigate climate impact, but there are other environmental factors: resource use, land use, and air quality. If SAF is made from waste materials, it has a strong sustainability argument (avoiding landfill, utilizing residues). If made from purpose-grown crops, it raises questions about land use change, food vs fuel, etc. Regulatory criteria (like those in CORSIA or EU RED II) attempt to ensure sustainability by excluding high-deforestation risk feedstocks and encouraging advanced (non-food) feedstocks. In an optimistic scenario, SAF could provide up to 65% of the aviation sector's needed CO_2 reduction by 2050 according to industry roadmaps [36] – but only if production is scaled up massively and sustainably. For other sectors, renewable fuels are seen as a bridge or complement to electrification. For example, cars may mostly go electric, but heavy trucks, ships, and planes – sectors hard to electrify – might rely on biofuels/SAF to cut carbon. Using SAF in existing piston engines offers a way to decarbonize the existing fleet. Every piston aircraft or diesel truck that can run on a drop-in biofuel means we reduce emissions without waiting for fleet turnover or expensive modifications. This is a big environmental win in the near to medium term, as new technologies (like electric aircraft or hydrogen fuel cells) will take time to mature and replace legacy engines.

However, one must also consider non-CO_2 emissions and effects. In jet aviation, SAF's reduction in soot may also reduce contrail formation and its climate impact, an often-cited co-benefit. In piston aviation, contrails are not an issue, but local air quality around airports (particularly piston aircraft emit lead and unburned hydrocarbons) would improve with cleaner fuels. Using unleaded, low-sulfur, low-aromatic fuels in ground vehicles improves urban air quality by cutting pollutants and air toxics (important until the vehicle fleet is fully zero-emission). Another consideration is that SAF often has slightly different density/energy content, which can affect range. Neat paraffinic SAF is a bit less dense (e.g. HEFA jet fuel might have ~3–4% lower energy per liter than standard Jet A due to no aromatics). In aircraft, that could translate to a small range reduction if tanks are volume-limited – though if burn is more efficient, the difference is minor. In practice, at blend levels of 50% or less, the effect is negligible. For HVO in diesel cars, drivers might observe a few percent higher volumetric fuel consumption, but again, very small differences in real use.

To weigh the economic and environmental aspects: on the pro side, SAF enables the use of existing engines and infrastructure while achieving large GHG reductions and cleaner emissions – essentially a drop-in decarbonization solution. It can be implemented incrementally (blending) without waiting for new technology. On the con side, current SAF supply is limited and expensive; relying on bio-based fuels alone may face feedstock constraints, and without careful sustainability governance, some pathways could have negative externalities (e.g. inducing palm oil expansion, etc.). Thus, SAF is part of a broader strategy – especially vital for aviation and long-haul transport – but not a silver bullet to replace all fossil fuel usage unless coupled with massive investment and sustainable feedstock sourcing.

5. Current studies and test campaigns

5.1. Aviation piston engine

Research and demonstration projects are actively exploring SAF use in various piston engine contexts.

Diamond Aircraft Industries announced in 2023 a dedicated SAF test program for their Austro Engine line of jet-fuel piston engines (turbocharged compression-ignition engines used in aircraft like the DA62) [13]. They installed a specialized engine test bench to run the engines on various SAF blends and measure real-time cylinder pressure and emissions (CO, NO_x, HC, CO_2). The aim is to validate and eventually approve 100% SAF (or high blends) for use in those aircraft. As of early 2023, Diamond noted they were awaiting sufficient quantities of certified SAF to conduct extensive tests, since the availability of the seven ASTM-approved SAF types was limited. In the meantime, they experimented with "regenerative fuels certified for road application" – likely HVO diesel – as an analogue. This indicates that engine manufacturers are proactively working toward SAF compatibility. We can expect results from such programs to demonstrate whether any adjustments are needed for fuel systems, and to quantify performance differences. Early indications (from informal reports and the heavy-fuel engine studies cited earlier) suggest the engines will run well on SAF, with improvements in emissions.

5.2. Heavy-fuel engine research

A team at Beihang University (China) has published studies on a heavy-fuel aviation piston engine (a compression-ignition aero-engine) running on 100% HEFA SAF. They examined both performance and emissions. One paper reported that using SAF slightly improved high-altitude engine performance (as mentioned, marginally less power loss at altitude) and met all operability requirements [38, 39]. Another paper from the same group focused on emissions and found drastically lower particulate output and reduced CO/HC with neat SAF [39]. These are among the first peer-reviewed results confirming that a piston aircraft engine can run on neat SAF and actually benefit emissions-wise. Such data is crucial for regulators considering allowing 100% SAF in general aviation in the future.

5.3. Unleaded Avgas development

In the realm of spark-ignition aviation, current test campaigns are mostly around unleaded (petroleum-based) fuels. The FAA's Piston Aviation Fuels Initiative (PAFI) had tested candidate unleaded avgas formulations over the last decade, though none met all criteria to fully replace 100LL at that time [28]. Now GAMI 's G100UL fuel has an FAA approval via STC, and another contender, Swift Fuel's UL102, is in development. These are not SAF in the strict sense, but they solve the lead problem and could serve as a bridge – if their components could be synthesized from sustainable sources in the future, that would effectively create a SAF for piston GA. One could envision, for example, synthetic isoparaffins and aromatics combined to meet a 100 octane spec. Research is needed in this area; so far, no large-scale projects are publicly known, likely because the priority has been on turbine SAF.

5.4. Automotive engine trials

On the ground, there have been numerous trials of HVO and other renewable fuels in cars, trucks, and buses. For instance, cities in Scandinavia have operated bus fleets on 100% HVO diesel for years, with success in reducing pollution and no reported engine issues. Volvo Trucks and Scania officially support HVO in their engines, and field data show performance is on par with diesel. A recent demonstration by Porsche and partners has been the production of synthetic gasoline (from CO_2 and renewable electricity) – this "e-fuel" was tested in Porsche sports cars and even in motorsport to prove that a renewable gasoline could meet demanding engine requirements. This e-fuel (made via FT synthesis to produce a gasoline-range product) essentially functioned identically to premium gasoline in high-performance engines. Such demonstrations underline that, given the right fuel composition, piston engines don't "care" about the carbon origin of the fuel. The challenges are mainly economic and scaling ones.

5.5. Marine trials

The marine sector is also testing SAF-equivalent fuels (renewable diesel/HVO) in ship engines. The UK's National Oceanography Centre, for example, conducted trials in 2024 using 100% HVO in their research ships RRS *James Cook* and *Discovery*, which normally run on marine gas oil [30]. They found HVO to be a viable drop-in with no modifications, and it was attractive for its stability and performance in cold climates (Arctic) as well as warm regions. The trials noted that HVO's cost and limited availability were the main hurdles, not technical performance. Other marine trials include harbor tugs in Singapore and Brazil running on HVO blends, and the British Antarctic Survey testing HVO in the polar research vessel *Sir David Attenborough* to reduce its carbon footprint [10, 18]. These pilot programs are important to build confidence that renewable fuels can meet the heavy-duty requirements of marine engines over long durations.

5.6. Military and multi-fuel engine tests

The military has been interested in "single battlefield fuel" capability – using a common fuel (typically JP-8, a kerosene) in all equipment, including piston engines. This has indirectly fostered research into how different fuels perform in diesel engines. Some NATO trials have used FT synthetic fuels in armored vehicle engines, etc. The results generally found that engines run fine on these fuels, with maybe minor adjustments. Now, militaries are also exploring SAF as part of energy resilience and emissions goals. In 2018, the U.S. Navy tested ships and aircraft on biofuels (the "Great Green Fleet" demonstration), using a 50/50 blend of HEFA in naval diesel engines and jet turbines. This showed that even warship engines (some of which are essentially marine diesel engines) could use SAF blends seamlessly [10, 18, 41].

6. Conclusions and future outlook

Based on the technical evidence reviewed, SAF can be used in piston engines. For compression-ignition (diesel-cycle) piston engines, SAF in the form of synthetic paraffinic fuels (HEFA, FT, etc.) is essentially a drop-in replacement for conventional diesel or jet fuel. These fuels can power diesel engines in aircraft, vehicles, and ships with equal or better performance, providing cleaner combustion and dramatic emissions benefits (lower soot, CO, HC, and zero sulfur). Test programs by engine manufacturers (Diamond/Austro, Cummins, Volvo, etc.) have demonstrated operation on neat SAF or HVO with no modifications needed, confirming compatibility when the fuel meets appropriate standards. Thus, the primary hurdles for diesel engines are not technical but rather fuel availability, certification, and cost. As SAF production grows and standards evolve to allow 100% use, diesel engines are ready to leverage the full potential of SAF. For spark-ignition engines, the situation is more complex. Current SAF molecules do not meet the high-octane requirements, so direct use in existing gasoline engines is not feasible. However, this is spurring research into high-octane renewable fuels. In the near term, unleaded avgas initiatives will remove lead from aviation gasoline – a big environmental win – but remain fossil-derived. The long-term vision could involve synthesizing gasoline-like fuels from sustainable sources, essentially creating a "SAF for pistons" that is high-octane. This will likely lag behind the diesel side in timeline. In the interim, a practical approach for aviation piston fleet is the growing use of CI engines (many new small aircraft models offer Jet-A piston options), which can directly use SAF. Automobiles will likely see increasing blends of bio-components (ethanol, renewable gasoline fractions) as part of climate policies until electrification predominates.

Pros of SAF in piston engines:

1. Greenhouse gas reduction – SAF offers life-cycle CO_2 reductions of 50–80%+, helping decarbonize legacy fleets.
2. Air quality improvement – lower particulate matter, NOx, CO, and absolutely no lead or sulfur emissions. This has positive health impacts, especially in urban areas and around airports.
3. Drop-in convenience – in many cases, the existing distribution infrastructure and engines can be used, avoiding the need for costly new engine technologies or fuel systems. For sectors like aviation and marine, where electrification is extremely challenging, SAF provides one of the few viable paths to significant emissions cuts.
4. Energy security and flexibility – SAF can be made from diverse feedstocks available domestically in many countries, reducing reliance on petroleum and enhancing fuel supply resilience.

Cons and challenges of SAF in piston engines:

1. High cost and limited supply – currently, SAF is scarce and expensive, which limits adoption. Policy support is crucial to scale up production and drive down costs.
2. Feedstock sustainability – ensuring that feedstock sourcing (e.g. bio-oils, waste, CO_2) truly yields environmental benefits without adverse side effects (deforestation, food competition) is a constant concern. Strong sustainability criteria and perhaps next-generation feedstocks (algae, municipal waste, etc.) are needed.
3. Compatibility issues – while largely manageable, issues like seal swell and lubricity require careful qualification. Older equipment might need retrofits (e.g. swapping out a rubber seal for a fluoropolymer) if running high SAF content.
4. Regulatory and certification hurdles – the certification of new fuels, especially for aircraft, is a lengthy and rigorous process. A collaborative industry effort is needed to test and approve fuels in all the different engine models and to update standards accordingly
5. Competing solutions – in the long run, other technologies (electric, hydrogen) will also come into play, potentially limiting the window for SAF in some applications. For example, by the time SAF is cheap and abundant enough for cars, many cars might be electric. Nonetheless, for heavy-duty and aviation, SAF looks indispensable for the foreseeable future.

In conclusion, SAF has strong potential to be used in internal combustion piston engines and to make them more sustainable. In the diesel domain, the transition is already happening [41]: fleets and even aircraft engines are slowly adopting SAF blends. In the gasoline domain, more innovation is needed, but not impossible – it represents the next frontier for sustainable fuels. Achieving broad use of SAF in piston engines will require continued research, targeted investment, and supportive policy frameworks. When used appropriately, SAF can extend the useful life of existing engine technology into a low-carbon future, buying time for new technologies to mature and ensuring that even legacy engines become part of the solution to climate change rather than just part of the problem. The journey to scale up SAF is underway, and its successful integration into piston engines across sectors will be a critical component of global decarbonization efforts.

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Nomenclature

ASTM	American Society for Testing and Materials
ATJ	alcohol-to-jet synthetic paraffinic kerosene
AVGAS	aviation gasoline
CI	compression ignition
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
FT	Fischer-Tropsch
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IRENA	International Renewable Energy Agency
LCA	life cycle assessment
PtL	power-to-liquid
SAF	sustainable aviation fuel
SI	spark ignition
SIP	synthesized iso-paraffins
TEL	tetraethyl lead
UCO	used cooking oil

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