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Qualification of sustainable aviation fuels: system constraints and opportunities for scale

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Sustainable aviation fuels (SAF) are widely recognised as a key component of aviation decarbonisation strategies. However, the introduction of new fuels into a safety-critical aviation system requires robust evaluation to ensure compatibility with existing aircraft, engines and fuel infrastructure. This review examines the qualification of synthetic aviation turbine fuels within established qualification and certification frameworks, with a focus on how the ASTM D4054 evaluation process operates in practice and how it interacts with broader factors influencing SAF deployment. The paper analyses how differences in fuel composition, including bulk properties, trace species and performance characteristics, are translated into proportionate evidence requirements through a structured, risk-based approach. It highlights that qualification is not a prescriptive sequence of tests, but a distributed evidence-generation and governance process involving fuel developers, testing organisations, original equipment manufacturers, standards bodies and other stakeholders. As the diversity and maturity of synthetic blend components increases, the performance of the qualification system is shaped not only by intrinsic technical uncertainty, but also by structural factors including testing infrastructure, representative fuel availability, data quality, OEM review capacity and stakeholder coordination. The review distinguishes clearly between fuel qualification and deployment. For several established pathways, qualification has not generally been the primary constraint on SAF uptake; deployment remains strongly influenced by feedstock availability, production scale, economics, infrastructure and policy certainty. However, the complexity, timescales and cost of evaluation can still influence pathway accessibility, particularly for more novel fuels, highlighting the need to improve qualification efficiency without compromising technical integrity or safety assurance. As policy ambition increases and more chemically diverse candidate fuels seek approval, qualification may become a more material constraint on the pace, predictability and diversity of future SAF deployment. Drawing on developments in pre-screening, distributed testing, Clearing House coordination, qualification-readiness assessment, data standardisation and proportionate evaluation approaches, the review shows that the qualification system is evolving to improve efficiency and scalability while maintaining the requirements of safety, operability and long-term system integrity. Overall, the paper positions fuel qualification as an enabling component of the SAF ecosystem whose future scalability will depend on earlier uncertainty reduction, improved data generation, coordinated testing infrastructure and continued expert review.

KEYWORDS
ASTM D4054, ASTM D7566, aviation decarbonisation, aviation fuel standardisation, fuel evaluation and approval, fuel qualification, sustainable aviation fuel (SAF), synthetic aviation turbine fuels

1 Introduction

The decarbonisation of aviation represents one of the most significant challenges in the transition to a low-carbon global energy system. Unlike other transport sectors, aviation is constrained by high energy density requirements, long asset lifetimes and stringent safety standards, limiting the range of viable technological alternatives to conventional fossil-derived fuels for the vast majority of commercial and military applications. Among the available options, sustainable aviation fuels (SAFs) have emerged as a primary pathway for reducing lifecycle greenhouse gas emissions while maintaining compatibility with existing aircraft and infrastructure (International Civil Aviation Organization, 2022; International Energy Agency, 2023; International Air Transport Association, 2024).

Considerable progress has been made in the development of SAF production technologies, supported by increasing policy ambition, industrial investment and growing demand from airlines seeking to meet decarbonisation targets (International Energy Agency, 2023; International Air Transport Association, 2024). Multiple production pathways have now been approved for use in commercial aviation, and a broader pipeline of emerging technologies continues to expand. However, despite this progress, large-scale deployment remains limited, with production volumes falling significantly short of projected demand under net-zero scenarios (International Energy Agency, 2023). This policy momentum is increasingly formalised through legally binding deployment targets, including the United Kingdom's Sustainable Aviation Fuel Mandate and the European Union's ReFuelEU Aviation Regulation, which establish escalating SAF supply obligations over the coming decades (UK Department for Transport, 2023; European Union, 2023).

It is important to distinguish fuel qualification from broader deployment constraints. While qualification defines the pathway through which new fuels are approved for use in aviation, large-scale deployment is often more strongly influenced by factors such as feedstock availability, production economics, infrastructure development, project finance and policy certainty. The availability of approved pathways such as hydroprocessed esters and fatty acids and Fischer–Tropsch fuels, which remain supply constrained despite established qualification routes, illustrates this distinction. Qualification is therefore a necessary condition for deployment, but it is not sufficient on its own to deliver production scale, market uptake or emissions reduction.

To date, fuel qualification has not generally been the primary constraint on SAF deployment for the technologies that dominate near-term supply. Several established production routes already have recognised approval pathways, and current deployment shortfalls are more directly associated with limited production capacity, feedstock constraints, production cost, infrastructure and investment conditions. However, this does not mean that qualification is without practical constraint. The complexity, timescales and cost associated with fuel evaluation can influence pathway accessibility, particularly for novel fuels or developers with limited access to representative fuel volumes, specialist testing and OEM engagement. The industry is therefore seeking to improve qualification efficiency, coordination and predictability, while maintaining the technical integrity and safety assurance of the process. This balance may become increasingly important as SAF mandates increase, production technologies mature and a more diverse pipeline of candidate fuels seeks approval. This prospective constraint does not imply that qualification requirements should be compromised. Aviation fuel approval is necessarily conservative because fuel forms part of the certified aircraft and engine operating envelope. Rather, it highlights the need to examine whether the existing qualification system has the capacity, data infrastructure and decision-making tools required for a larger and more chemically diverse pipeline of candidate fuels. The central question is therefore not whether robust qualification remains necessary, but how the qualification process can continue to provide safety assurance while improving throughput, transparency and predictability as SAF deployment pressure increases.

The existing literature has extensively examined the challenges associated with SAF and low-carbon fuel deployment, including feedstock availability, lifecycle emissions, production economics, infrastructure requirements and policy frameworks (Morganti et al., 2024; Wandelt et al., 2025). Recent meta-analyses highlight a consistent set of barriers, including cost, scalability, infrastructure and regulatory uncertainty, reflecting the multi-dimensional nature of the SAF transition. In parallel, technical studies have explored the compositional and performance characteristics of synthetic fuels, including blending limits and the implications of transitioning toward fully synthetic fuels (Kramer et al., 2022). Collectively, these studies show that SAF deployment is not solely a technological challenge, but a system-level transition involving the interaction of supply chains, infrastructure, regulatory frameworks, fuel standards and market mechanisms.

Comparatively less attention has been given to the qualification process itself as a system-level function within this transition. Existing studies have described the technical structure, safety rationale and operational basis of aviation fuel evaluation processes, particularly in relation to ASTM D4054 and the incorporation of new synthetic blending components within ASTM D7566 (Rumizen, 2021). However, the structural characteristics of these frameworks have received less analytical attention as potential influences on future deployment timelines, scalability and pathway accessibility under conditions of rapid technological expansion. In particular, the interaction between fuel chemistry, evidence generation, testing infrastructure, original equipment manufacturer review capacity, data standardisation and consensus-based specification governance remains underdeveloped in the literature.

Fuel qualification represents a critical interface between innovation and operational deployment. Aviation fuel is not a conventional commodity, but an integral component of certified aircraft and engine systems, defined within specifications that act as operational limitations. As such, any change in fuel composition must be demonstrated not to adversely affect system performance, operability or safety across a globally distributed fleet. The qualification process is therefore not simply an administrative step prior to deployment, but a structured risk-management process through which the compatibility of new fuels with existing aircraft, engines and fuel systems is established.

This review contributes a system-level analysis of sustainable aviation fuel qualification within the ASTM D4054/D7566 framework. Its central argument is that qualification has

historically functioned as an essential enabling mechanism for aviation fuel safety and compatibility, but may become an increasingly important system constraint as SAF demand, pathway diversity and policy ambition increase. The review therefore examines qualification not simply as a technical checklist, but as an evidence-generation and governance process shaped by fuel chemistry, fit-for-purpose testing, OEM review capacity, testing infrastructure, data standardisation and consensus-based specification development. In doing so, it identifies improvement opportunities that could increase the efficiency and predictability of qualification while preserving the safety assurance on which aviation fuel approval depends.

By framing fuel qualification as part of a wider aviation decarbonisation system, rather than as an isolated technical procedure, this review advances understanding of how evaluation frameworks interact with broader deployment objectives. This perspective is particularly important as the number and diversity of candidate SAF pathways increases, placing greater pressure on established testing, review and governance processes. Understanding these interactions is essential to ensuring that qualification practices can continue to provide robust safety assurance while supporting the scale and diversity of sustainable aviation fuel pathways required for the transition to low-carbon aviation.

The review first outlines the technical and certification framework within which potential SATFs are assessed, including the relationship between fuel chemistry, fit-for-purpose evaluation and specification limits. It then analyses the structural characteristics of the qualification process, identifying key constraints related to testing escalation, infrastructure availability, stakeholder coordination, data fragmentation and review capacity. Finally, it examines ongoing developments aimed at improving efficiency and scalability, including coordinated testing networks, pre-screening methodologies, enhanced data management practices and approaches to improving qualification readiness before formal ASTM evaluation.

2 Technical and certification framework for sustainable aviation fuels

2.1 Aviation fuel within the certification framework

Commercial aviation operates within one of the most tightly regulated technical environments of any transport sector. Aircraft and engines are certified against detailed airworthiness requirements that define performance, operability, durability and safety across a wide range of operating conditions (FAA, 2023; European Union Aviation Safety Agency, 2022). Within this framework, aviation turbine fuel is not treated as a generic commodity, but as an integral component of a certified aircraft and engine system.

Fuel specifications are embedded within aircraft documentation as operational limitations. Compliance with defined standards such as ASTM D1655 or Defence Standard 91-091 is therefore required to maintain continued airworthiness (ASTM International, 2025a; Defence Standard 91-091, 2025; FAA, 2023; European Union Aviation Safety Agency, 2022). As a result, any change in fuel composition must be demonstrated not to adversely affect system performance, operability or safety across the global fleet.

Sustainable aviation fuels are often described in terms of feedstock origin, production route and lifecycle greenhouse gas performance. However, within the aviation certification and qualification framework, candidate fuels are assessed primarily on their chemical composition, trace species and performance characteristics relative to established aviation turbine fuel requirements. For this reason, the term synthetic aviation turbine fuel (SATF) is used in this review when referring to alternative fuels evaluated within existing specifications, independent of their sustainability attributes. Where appropriate, these materials are introduced as synthetic blend components (SBCs), which are currently blended with conventional fuel to produce a final aviation turbine fuel meeting specification requirements.

A defining feature of this framework is the distribution of responsibility across stakeholders. Fuel producers develop and supply candidate materials, but aircraft and engine original equipment manufacturers (OEMs) retain responsibility for the safety, performance and continued airworthiness of certified systems. This responsibility is exercised within certification frameworks governed by authorities such as the Federal Aviation Administration and the European Union Aviation Safety Agency, under which fuel specifications are linked directly to certified configurations (FAA, 2023; European Union Aviation Safety Agency, 2022). Consequently, proposed changes to fuel composition must be assessed against their potential impact on system behaviour across current and legacy fleets. This responsibility cannot be delegated to standards bodies, Clearing Houses, testing organisations or wider industry groups. These organisations can support evidence generation, coordination, technical review and consensus-building, but they do not assume responsibility for the continued airworthiness, safety or operability of certified aircraft and engine systems. OEM involvement in fuel qualification therefore reflects a non-transferable safety obligation.

This allocation of responsibility has important implications for how new fuels are evaluated. OEMs must maintain confidence not only in current production systems, but also in aircraft and engines developed over several decades of operational experience, while considering durability and compatibility over future service lives (Edwards, 2017; Maurice et al., 2001). The resulting evaluation process is necessarily evidence-based and cautious. Although this is sometimes interpreted as conservatism, it reflects the safety-critical function of aviation fuel and the long service life of aviation systems.

The concept of the “drop-in” fuel has emerged as a direct response to this certification structure. SATFs are required to be compatible with existing aircraft, engines and fuel infrastructure without modification, avoiding the need for recertification of the global fleet (ASTM International, 2025b; International Air Transport Association, 2024). In practice, this is achieved through the use of synthetic blend components, which are blended with conventional jet fuel within defined limits to produce a final fuel that meets established specifications and is technically equivalent to conventional fuel in all relevant respects. This equivalence extends beyond aircraft performance to include production, distribution, storage and handling across the aviation

fuel supply chain (Staples et al., 2018; International Energy Agency, 2023).

In addition to synthetic blend components defined under ASTM D7566, sustainable aviation fuels may also be introduced through co-processing routes, in which biogenic or waste-derived feedstocks are processed alongside conventional petroleum streams within existing refinery infrastructure. In these cases, the resulting fuel is not treated as a distinct blending component, but forms part of the overall refinery output and must meet the applicable base fuel specification (International Civil Aviation Organization, 2022; International Energy Agency, 2023). Co-processing therefore provides a route to SATF production within established systems, but remains subject to the same requirement to demonstrate that the resulting fuel does not introduce adverse impacts on performance, operability or system compatibility.

The dominant international mechanism for incorporating new synthetic blending components is the annex-based structure within ASTM D7566. Under this framework, SBCs derived from specific production pathways are evaluated and approved with defined compositional and blending limits (ASTM International, 2025b; Staples et al., 2018). Once blended within these limits, the resulting fuel must meet the base specification, ensuring technical equivalence to established specifications and fit for purpose properties.

The evaluation process that underpins this framework is guided by ASTM D4054. At a high level, D4054 provides guidance rather than a prescriptive test programme. It is applied through structured technical review by expert stakeholders, including OEMs, to identify potential risks associated with new production techniques and fuel compositions and to define the testing required to demonstrate that those risks have been appropriately mitigated (ASTM International, 2025c). The process is inherently risk-based, with the scope and depth of evaluation determined by the level of uncertainty, the nature of the candidate fuel and its deviation from established aviation turbine fuel experience.

The aviation fuel certification and evaluation framework is therefore both enabling and protective. It provides a globally recognised route for the introduction of new fuels while ensuring that safety, operability and long-term system integrity are not compromised. At the same time, because qualification depends on evidence generation, specialist testing, OEM review and consensus-based specification development, it also introduces structural constraints on the rate and predictability with which new fuels can be approved. These constraints are justified by the safety-critical nature of aviation fuel, but they become increasingly important to understand as SAF policy ambition, pathway diversity and deployment pressure increase.

2.2 Established vs. novel pathways

Synthetic aviation turbine fuels are produced through a range of conversion pathways, each generating hydrocarbon mixtures with distinct compositional and performance characteristics. Within the qualification framework, these materials are introduced as synthetic blend components and are assessed on the basis of their production route, bulk composition, trace composition and performance characteristics relative to established aviation turbine fuel requirements (ASTM International, 2025c; Colket et al., 2017).

A key distinction is between fuels produced through pathways and process configurations already defined within ASTM D7566 annexes, and those that introduce greater deviation from the established production, compositional and performance envelope (ASTM International, 2025b; ASTM International, 2025c). For established annexes, developer activity is focused on demonstrating alignment with the approved pathway definition, relevant production controls, known compositional families and specification limits. In these cases, the task is usually to demonstrate conformity with an existing qualification basis rather than to establish a fundamentally new approval route. In contrast, new pathways, altered process configurations, alternative intermediates or fuel compositions that introduce greater technical novelty increase uncertainty in system behaviour and may require more extensive formal evaluation.

The qualification approach is therefore not driven solely by final fuel composition or by production pathway in isolation. It is driven by the degree of confidence that the candidate fuel, its production process and its resulting compositional and performance characteristics remain within an established qualification envelope. For fuels produced under an existing ASTM D7566 annex, producers must demonstrate not only that the fuel meets the relevant annex and finished fuel specification requirements, but also that the feedstock, process configuration, catalyst system, operating conditions and impurity control strategy are consistent with the technical basis on which the annex was approved (ASTM International, 2025b). Formal alignment with an annex therefore does not remove technical uncertainty entirely. Differences in feedstock, process severity, catalyst selection, intermediate composition or contaminant profile may generate fuels that meet specification limits but differ from the prototype fuels and supporting datasets on which the annex was originally based. In such cases, additional due diligence testing beyond minimum specification requirements is appropriate, including expanded fit-for-purpose testing to confirm that the fuel remains within the expected range of aviation turbine fuel behaviour.

However, established pathways are not technically static. Feedstock variation, catalyst selection, process severity, intermediate composition and impurity management can influence hydrocarbon distribution, isomerisation, trace species and final fuel properties. For HEFA, differences in lipid source and hydrotreatment conditions may affect carbon number distribution, isomerisation level and trace composition. For Fischer–Tropsch fuels, interest in alternative syngas sources, including CO_2-rich or waste-derived intermediates, may influence process operation and the resulting product slate. These variations do not necessarily alter the underlying pathway, but they can test the boundaries of the historical qualification envelope and require careful interpretation against the datasets that supported the original annex approval.

Alcohol-to-jet pathways illustrate a less tightly bounded production and compositional space. These routes convert alcohol intermediates, such as ethanol or isobutanol, into hydrocarbons through dehydration, oligomerisation and hydrogenation (Geleynse et al., 2018; International Civil Aviation Organization, 2022). Product composition can vary depending on alcohol feedstock, oligomerisation chemistry, catalyst system and upgrading conditions, influencing properties such as density,

volatility and thermal stability (Colket et al., 2017). Emerging variants, including methanol-to-jet, extend this space further by introducing alternative intermediates and process configurations. Where resulting fuels remain chemically comparable to previously evaluated materials, behaviour can be interpreted with greater confidence. Greater deviation, however, may require additional compositional, property and fit-for-purpose testing to demonstrate that expected performance and operability are maintained.

Power-to-liquid is often described as an emerging SAF pathway and is frequently referred to in policy and industry contexts as electro-SAF or eSAF. However, from a qualification perspective, PtL is more accurately understood as a feedstock and process integration route rather than a distinct fuel pathway. PtL systems use captured carbon dioxide and low-carbon hydrogen to generate synthetic intermediates that are subsequently converted into aviation fuel through downstream routes such as Fischer–Tropsch synthesis or methanol-intermediated processes (International Energy Agency, 2023; International Civil Aviation Organization, 2022). The qualification question is therefore not whether a fuel is "PtL" or "eSAF", but whether the production route and resulting synthetic blend component align with an established pathway, process basis and compositional-performance envelope. PtL-derived Fischer–Tropsch fuels may align with existing FT synthetic paraffinic kerosene experience. Methanol-to-jet-derived materials are being considered within the alcohol-to-jet qualification framework, with MTJ-SPK addressed through revision of ASTM D7566 Annex A5 rather than as a wholly separate PtL or eSAF pathway. This illustrates the broader point that qualification is governed by the approved conversion route, process controls and resulting fuel composition, rather than by the policy, feedstock or sustainability label applied to the production system.

A wider group of waste-derived and thermochemical pathways introduces greater potential qualification uncertainty. These include routes based on pyrolysis, hydrothermal liquefaction of wet wastes, plastic-to-jet processes, tyre-derived oils, lignocellulosic intermediates and mixed municipal, agricultural or industrial waste streams. These routes are important because they could expand the future SAF feedstock base beyond the lipid, alcohol and syngas-derived routes that dominate current approved pathways. However, with the exception of routes in which waste-derived carbon is converted through an already approved pathway such as gasification to Fischer–Tropsch synthesis, these technologies do not yet have the same established ASTM D7566 approval basis as HEFA, FT-SPK or ATJ-SPK. In particular, pyrolysis-derived oils, plastic-derived oils, tyre-derived oils and wet-waste hydrothermal liquefaction biocrudes are not currently represented as general approved synthetic blend component pathways within ASTM D7566.

The qualification challenge arises because these processes can generate chemically complex intermediates whose composition is strongly influenced by feedstock variability, process severity, catalyst selection, hydrotreating effectiveness and contaminant control. Potential issues include variation in cycloparaffinic and aromatic content, residual oxygenates, nitrogen-containing species, metals, halogens, sulphur species and other trace contaminants associated with waste-derived feedstocks, plastic additives or tyre-derived materials. These compositional and process-derived features may influence thermal stability, lubricity, deposit formation, emissions, corrosion and materials compatibility. Importantly, these concerns are not confined to aircraft and engine fuel systems; trace species and contaminant-derived products may also affect fuel injectors, combustor hardware and downstream hot-section components through deposit formation, corrosion or altered combustion behaviour. Such risks may therefore require expanded analytical characterisation and risk-based testing to demonstrate that associated hazards have been appropriately understood and mitigated (Colket et al., 2017; International Energy Agency, 2023; ASTM International, 2025c).

Across these pathway families, qualification scope is determined by the interaction between production process, molecular composition and operational performance. Conventional aviation turbine fuel is defined through a combination of bulk property limits and selected compositional controls, including total aromatics and naphthalene content, rather than through explicit specification of all hydrocarbon species (Edwards, 2017; Maurice et al., 2001). Candidate fuels that are produced through recognised process routes and remain chemically comparable to established aviation turbine fuel families benefit from a broader operational and analytical experience base, supporting more predictable evaluation. Materials that significantly alter process conditions, hydrocarbon class distribution, impurity profiles or key compositional balances increase uncertainty in system behaviour and may require additional analytical characterisation, materials compatibility assessment or higher-tier testing.

This distinction is increasingly relevant as the candidate SATF pipeline diversifies. Conventional aviation turbine fuel contains a broad mixture of normal paraffins, iso-paraffins, cycloparaffins and aromatics, whereas many established synthetic paraffinic kerosenes are dominated by paraffinic structures and are assessed against an experience base built around those compositions. Fuels with higher cycloparaffinic content or other atypical hydrocarbon distributions may therefore sit outside the narrower SPK experience base, even where they meet finished-fuel bulk specification limits. Differences in molecular structure can influence density, elastomer compatibility, thermal behaviour and other performance characteristics that are not always fully captured by standard specification parameters (Colket et al., 2017; ASTM International, 2025c). The relationship between production pathway, process control, molecular composition and operational performance therefore determines not only fuel characteristics, but also the level of evidence required to support progression through qualification.

This pathway landscape helps explain why qualification has not historically been the primary constraint for established SATF technologies, but may become more significant as policy-driven demand and pathway diversity increase. Where candidate fuels are produced through recognised process routes and align closely with existing annexes, historical datasets and established compositional envelopes, qualification activity can be relatively predictable. Where fuels rely on novel feedstocks, altered process configurations, different catalyst systems, alternative intermediates or less familiar molecular distributions, uncertainty increases and the evaluation process may require more extensive data generation, specialist testing and OEM review. This creates a strategic tension for future SAF deployment: the feedstocks and conversion routes

that may be needed to expand supply beyond currently constrained pathways are also those most likely to increase qualification uncertainty and evidence requirements. The future scalability of SAF deployment therefore depends not only on production capacity and economics, but also on the ability of the qualification system to assess a broader range of production routes and chemically diverse candidate fuels efficiently while maintaining safety assurance.

2.3 Key properties governing operability and specification limits

Within the aviation certification framework, fuel properties are not defined solely as compositional descriptors. They function as operational risk controls that ensure safe, reliable and predictable performance of aircraft and engine systems (ASTM International, 2025a; FAA, 2023; European Union Aviation Safety Agency, 2022). Specification limits are therefore not arbitrary thresholds, but boundaries within which fuels are expected to behave consistently with established operational experience and certified system assumptions (ASTM International, 2025a; Edwards, 2017).

Fuel properties can be considered across three interrelated domains: bulk composition, trace composition and performance behaviour. Bulk properties, including density, viscosity, volatility and freezing point, reflect the overall hydrocarbon distribution and govern fundamental aspects of fuel handling, atomisation, combustion and low-temperature operation. These parameters are critical to ensuring consistent engine performance and fuel system operation under both normal and extreme conditions (Colket et al., 2017; ASTM International, 2025a).

Trace composition, including sulphur, nitrogen and oxygen containing species, metals and other contaminants, can have a disproportionate impact on system behaviour. Even at low concentrations, such species may influence thermal stability, deposit formation, corrosion, emissions and materials compatibility. Control of trace composition is therefore particularly important for fuels derived from waste streams, novel intermediates or process configurations where such species may be present in elevated, variable or less well-characterised forms (Colket et al., 2017; International Energy Agency, 2023; ASTM International, 2025a). The identity of these species may be as important as their concentration, since different heteroatomic compounds or contaminants can interact with each other in difficult to predict ways even at trace levels.

Performance related properties represent the function of both bulk and trace composition under operational conditions. These include characteristics such as thermal stability, lubricity, seal compatibility and combustion behaviour, which are directly linked to system durability and reliability. Thermal stability governs the tendency of a fuel to form deposits under high-temperature conditions within engines and aircraft systems. Elevated fuel temperatures arise because fuel is routed through equipment located in thermally demanding engine environments and is also used as part of the aircraft and engine thermal management system, including heat exchange with other systems. Lubricity is critical to the performance and service life of pumps and fuel control components. Aromatic content also influences elastomer swelling behaviour and therefore seal integrity within fuel systems (Edwards, 2017; ASTM International, 2025a).

Collectively, these properties define a multidimensional envelope within which fuels must operate to ensure compatibility with legacy aircraft, engines and fuel infrastructure. This envelope reflects a combination of empirical experience, materials limitations and system design constraints accumulated over decades of operation (Edwards, 2017; Maurice et al., 2001). Importantly, not all aspects of fuel behaviour are explicitly captured by specification limits alone. Specifications act as practical proxies for a broader set of performance expectations derived from historical data, engineering judgement and operational experience (ASTM International, 2025a; Colket et al., 2017).

From a qualification perspective, deviations from this established property envelope represent potential sources of risk. Where a synthetic aviation turbine fuel aligns closely with established property ranges, production experience and compositional characteristics, behaviour can be inferred with greater confidence from existing datasets. Conversely, where deviations occur, particularly in areas not fully bounded by specification parameters, additional investigation may be required to understand the implications for system performance, operability and durability (ASTM International, 2025c).

This logic is reflected in ASTM D4054, which provides a framework for identifying and mitigating risks associated with new fuel compositions and production routes. Rather than prescribing a fixed test programme, D4054 enables a staged evaluation in which the scope and depth of testing are determined by the degree of uncertainty associated with a candidate material. Fuel properties therefore provide the technical basis for this assessment, linking observed differences in production route, composition and measured performance to potential impacts on certified aircraft and engine systems (ASTM International, 2025c).

In this context, fuel properties act as the critical interface between fuel chemistry, production process and certified system behaviour. They define the boundaries within which fuels can be introduced without compromising safety or operability, while also identifying where additional evidence is required. As SAF pathways diversify, this interface becomes increasingly important because novel process routes, impurity profiles or molecular distributions may produce fuels that satisfy headline specification limits but still require further evidence to confirm equivalence with established aviation turbine fuel behaviour. Fuel properties therefore play a central role in determining how new fuels progress through qualification and, ultimately, into operational use (ASTM International, 2025a; ASTM International, 2025c).

2.4 Evaluation and specification frameworks

Detailed descriptions of the ASTM D4054 process and its relationship with ASTM D7566 have been provided elsewhere in the literature and supporting industry guidance (Rumizen, 2021; Heyne et al., 2021; Commercial Aviation Alternative Fuels Initiative, 2026). This section therefore provides only the necessary context for the system-level analysis developed in the following sections, focusing on how fuel property evaluation, pathway-specific specification development, OEM review and consensus-based standardisation interact within the current qualification framework.

International aviation turbine fuel specifications, including ASTM D1655 and Defence Standard 91-091, define the property and compositional requirements necessary to ensure safe and reliable operation across the global aviation fleet. Within this framework, ASTM D7566 provides the principal mechanism through which new synthetic blend components are incorporated via pathway-specific annexes, while ASTM D4054 provides the technical evaluation process used to support these decisions (ASTM International, 2025a; ASTM International, 2025b; Defence Standard 91-091, 2025).

ASTM D4054 is not itself a fuel specification. Rather, it provides guidance on the data generation, fit-for-purpose evaluation and risk-based assessment required to determine whether a candidate fuel or fuel component is suitable for use within existing aviation systems. The outcomes of this evaluation inform the ASTM consensus process, through which new synthetic blending component pathways may be incorporated into ASTM D7566 via ballot and approval cycles. Similar evaluation principles may also support cases involving co-processing, where modifications to conventional aviation turbine fuel specifications, including ASTM D1655 and Defence Standard 91-091, may be required. In this way, D4054 functions as the technical foundation upon which consensus decisions are based, linking detailed evaluation of fuel properties, process characteristics and system behaviour to formal acceptance within globally recognised aviation fuel standards (ASTM International, 2025c).

The purpose of D4054 is therefore broader than demonstrating that a candidate fuel can meet existing specification properties. It also supports the development of an appropriate specification and control framework capable of ensuring consistent fuel behaviour in commercial service. This includes assessing whether existing analytical methods and specification parameters, many of which were originally developed around conventional petroleum-derived fuels, remain suitable for characterising and controlling novel synthetic fuel compositions. Where new compositional features, atypical property relationships or trace species are introduced, additional analytical approaches, modified methodologies or new specification controls may be required to ensure that fuel behaviour can be reliably measured, reproduced and managed throughout the supply chain.

At a practical level, D4054 is commonly described in terms of four tiers of increasing scope, fuel volume and system relevance. Tier 1 focuses on specification properties, requiring the candidate synthetic blend component, candidate fuel or relevant blends to be assessed using standardised test methods applied to conventional aviation turbine fuels. While synthetic blend components themselves may not be required to comply directly with finished fuel specifications such as ASTM D1655 or Defence Standard 91-091, equivalent property measurements are used to establish how the material compares with accepted aviation fuel behaviour and specification expectations.

Tier 2 expands the evaluation to fit-for-purpose properties. These are characteristics not necessarily controlled directly within fuel specifications, but which are inherent to petroleum-derived jet fuel and important to aircraft, engine and fuel system performance. Examples include viscosity and density behaviour across temperature, surface tension, thermal conductivity, dielectric constant, conductivity response, water solubility, additive response, storage stability, filtration behaviour and preliminary materials compatibility. Together, Tier 1 and Tier 2 provide the initial technical evidence base used by OEMs and the ASTM task group to determine whether a candidate fuel is suitable for progression to higher-tier testing or whether specific areas of uncertainty require further investigation (ASTM International, 2025c).

Where uncertainties or potential deviations are identified during these earlier stages, higher-tier testing is used to investigate specific compatibility or operability concerns in greater detail. Tier 3 may include targeted component, rig or materials testing, particularly where fuel-system compatibility, seal behaviour, combustion characteristics or other system interactions require further evidence. For fuels introducing more substantial compositional or process-derived differences, or where questions remain unresolved following earlier evaluation, Tier 4 testing may be required. This can include more extensive component, rig, engine or aircraft testing to demonstrate acceptable performance, operability and durability under representative operating conditions prior to broader commercial deployment (ASTM International, 2025c; Colket et al., 2017).

These tiers provide a useful organising framework for understanding qualification, but they should not be interpreted as the central focus of this review. Consistent with the property-based approach described in Section 2.3, the scope and depth of testing are determined by the degree of uncertainty associated with a given material, its production route and its departure from established aviation turbine fuel experience. The evaluation process is also iterative. Higher-tier testing is often used to confirm, under increasingly realistic operating conditions, whether behaviour predicted from compositional data, specification testing and laboratory-scale fit-for-purpose assessment is valid at component, rig, engine or aircraft-system level. Data generated at each stage are subject to technical review and may lead to refinement of test programmes, additional analysis or targeted investigation of specific behaviours. Progression is therefore determined not by completion of predefined steps alone, but by the extent to which available evidence demonstrates that identified risks have been appropriately understood and mitigated.

It is important to distinguish fuel qualification from regulatory certification. Qualification establishes that a fuel or fuel component is suitable for use within existing certified aircraft and engine systems, subject to defined specification and blending requirements. Certification remains the responsibility of airworthiness authorities and applies to aircraft and engine designs rather than to fuel specifications themselves. The qualification process therefore operates as a critical interface between fuel innovation and certified aviation systems. It is not an isolated analytical exercise, but a coordinated technical and governance process involving fuel producers, testing organisations, OEMs and expert stakeholders within standards committees (Staples et al., 2018; International Civil Aviation Organization, 2022; International Energy Agency, 2023).

Overall, the evaluation and standardisation framework is both structured and adaptive. For the purposes of this review, its significance lies not in the procedural detail of D4054 itself, but in the way the process translates production and compositional differences into evidence requirements, technical review,

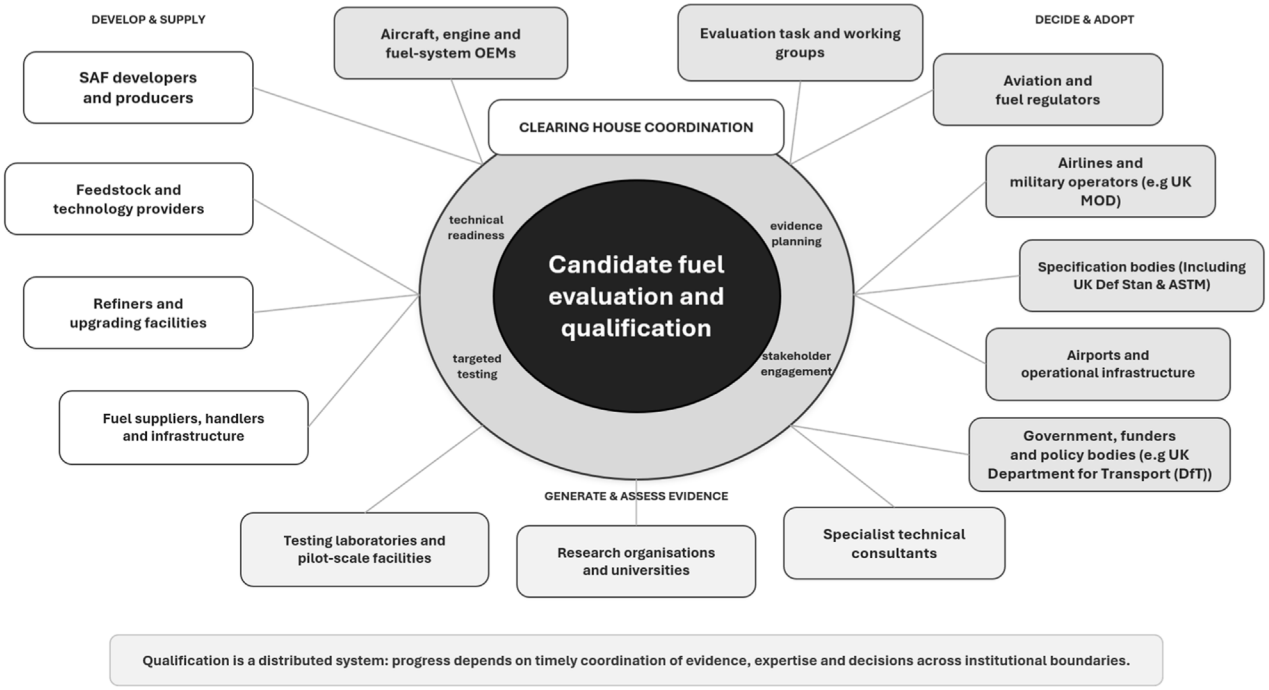


FIGURE 1
SAF qualification stakeholder ecosystem. Candidate fuels progress through a distributed system involving development and supply actors, evidence-generation and assessment organisations, and decision-making and adoption stakeholders. Clearing House coordination supports technical readiness, evidence planning, targeted testing and stakeholder engagement across these institutional boundaries. The figure illustrates that qualification throughput depends not only on fuel properties, but also on timely coordination of evidence, expertise and decisions across the wider SAF ecosystem.

specification development and consensus decisions. This combination has enabled the introduction of multiple synthetic fuel pathways while maintaining safety, operability and long-term system integrity. However, as pathway diversity increases, the practical operation of this framework becomes increasingly shaped by the availability of specialist testing infrastructure, the quality and comparability of data, OEM review capacity and the coordination required to reach consensus. These features are essential to robust safety assurance, but they also define the throughput and predictability of the qualification system.

3 Qualification and evaluation practices: constraints, coordination and evolution

Building on the technical and regulatory foundations outlined in Section 2, this section examines the structural characteristics of the qualification system that influence the rate, cost, predictability and overall throughput of sustainable aviation fuel approval. A central feature of this system is that qualification is distributed across multiple institutional actors rather than being controlled by a single organisation or test sequence. Candidate fuels progress through coordinated evidence generation, technical review and specification decision-making involving fuel developers, feedstock and technology providers, testing laboratories, pilot-scale facilities, research organisations, OEMs, standards bodies, regulators, fuel suppliers, operators and policy bodies. Within this distributed system, ASTM and Defence Standard governance structures provide essential organising frameworks for coordinating technical evidence, resolving expert review and translating qualification outcomes into recognised fuel specification requirements. Figure 1 illustrates this stakeholder ecosystem and the role of Clearing House coordination in aligning technical readiness, evidence planning, targeted testing and stakeholder engagement across these boundaries.

3.1 Qualification practice constraints on evaluation throughput

As the number and diversity of candidate sustainable aviation fuel pathways increases, qualification throughput is increasingly influenced not only by the technical characteristics of individual fuels, but also by the structure and capacity of the evaluation system itself. In practice, progression through qualification depends on the interaction of technical uncertainty, analytical testing requirements, infrastructure availability, representative fuel production, stakeholder coordination, OEM review and consensus-based governance processes. These factors influence the rate, cost and predictability of fuel evaluation within the current framework (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

A useful way to understand this interaction is to consider the annex-based structure through which synthetic blend components are incorporated into ASTM D7566. Each annex reflects a specific combination of feedstock, production route, compositional controls and blending limits. This structure has enabled the progressive introduction of multiple synthetic aviation turbine fuel pathways while maintaining traceability and control within a safety-critical system. However, the existence of multiple approved annexes should not be interpreted as evidence that qualification follows a uniform or easily comparable timeline. Historic approval durations are difficult to compare because public information does not consistently define when a candidate fuel entered formal D4054 evaluation, how much pre-submission development had already occurred, whether evaluation was paused for additional data generation, how long OEM review took, or how ballot comments and technical objections were resolved.

For this reason, the more useful question for candidate fuel producers is not how long previous pathways took to qualify, but which factors most strongly influence qualification readiness and progression. These include the degree of alignment or divergence with an existing annex, the maturity and consistency of the production process, the availability of representative fuel samples, the quality and comparability of early-stage data, the level of uncertainty associated with composition and trace species, and the extent to which OEM and ASTM expectations are understood before formal evaluation begins. Table 1 therefore summarises the approved pathway landscape and associated qualification implications, rather than presenting a simplified timeline.

The annex-based architecture of ASTM D7566 therefore reflects a pragmatic and historically effective approach to incorporating new synthetic blend components into aviation fuel specifications. Developed as a necessary means of defining acceptable fuels within a safety-critical system, each annex specifies a combination of feedstock, processing route, compositional constraints and blending limits, providing traceability and assurance for properties not fully captured by routine specification testing (ASTM International, 2025b). However, this pathway-specific structure also means that fuels falling outside existing definitions may require a new annex or revision to an existing annex, even where the resultant composition is broadly comparable to established fuel chemistries. Consequently, progression can be influenced not only by demonstrated fuel performance, but also by alignment with existing pathway definitions and the ability to define an appropriate specification control framework (Staples et al., 2018; International Air Transport Association, 2024).

One major constraint on evaluation throughput is the level of technical uncertainty associated with the candidate fuel. Fuels that align closely with established production routes, compositional envelopes and historical datasets can generally be evaluated with greater confidence. Conversely, fuels based on novel feedstocks, altered process configurations, less familiar molecular distributions or uncertain impurity profiles require more extensive evidence to demonstrate that system behaviour remains acceptable. This is particularly relevant for emerging waste-derived and thermochemical routes, including plastic-to-jet pathways, pyrolysis-derived oils, tyre-derived intermediates and hydrothermal liquefaction of wet wastes such as sewage sludge, food waste or other municipal organic streams. Although waste-derived carbon can in some cases enter existing approved routes, for example, through gasification followed by Fischer–Tropsch synthesis, direct upgrading of pyrolysis oils, plastic-derived oils, tyre-derived oils or wet-waste HTL biocrudes does not yet have the same established ASTM D7566 approval basis as mature HEFA, FT-SPK or ATJ-SPK pathways. These routes can introduce chemically complex intermediates containing variable levels of heteroatoms, metals, halogens, residual oxygenates, nitrogen-containing species, sulphur species, additives or other contaminants. Such features may influence thermal stability, deposit formation, corrosion, emissions, lubricity and materials compatibility, and are not always fully resolved by standard specification testing alone.

This constraint is reinforced by the step changes in testing requirements inherent in the ASTM D4054 evaluation process, where progression to higher tiers requires substantially greater fuel volumes, time and resource commitment. This escalation reflects a structured and risk-based approach, in which the scope and intensity of testing increase in proportion to the level of uncertainty associated with a candidate fuel. Early-stage analytical characterisation and property testing can be conducted with relatively small fuel volumes and modest resource requirements, enabling rapid iteration and initial risk identification. These early-stage activities are often undertaken in a pre-screening context, providing a low-cost, low-volume and iterative environment for process optimisation and risk reduction prior to entry into formal D4054 evaluation. As development progresses, additional evidence is generated to address remaining uncertainties, with higher tiers of assessment, including materials compatibility, rig testing and full engine evaluation, providing increasingly system-representative validation (Colket et al., 2017; International Civil Aviation Organization, 2022).

While this progression is necessary to ensure that risks are appropriately identified and mitigated, it is associated with step changes in fuel volume requirements, testing duration and financial commitment. In practice, progression to higher tiers is often dependent not only on technical readiness, but on the availability of sufficient volumes of representative fuel and the ability to demonstrate process maturity at increasing scale. This can introduce discontinuities in development timelines, particularly where a candidate fuel has promising early-stage properties but the production process is not yet capable of generating the volumes or batch consistency required for later-stage evaluation (International Energy Agency, 2023).

This relationship highlights an important interaction between qualification and industrial scale-up. Analytical capability, specialist testing infrastructure and higher-tier evaluation capacity do not develop independently of commercial reality. They are more likely to expand where there is credible market demand, sufficient sample volume, repeatable fuel production and a pipeline of technically mature candidates capable of justifying investment in specialised equipment and expertise. At the same time, novel pathways may require access to those capabilities before they have reached full commercial scale. The qualification system therefore both depends on industrial scaling and can influence which pathways are able to progress toward it.

Original equipment manufacturer involvement represents a further critical factor influencing evaluation throughput. Aircraft

TABLE 1 Approved SATF routes, co-processing provisions and proportionate evaluation mechanisms relevant to qualification.

ASTM route	Pathway	Feedstock/ process basis	Maximum blend limit	Qualification maturity	Qualification implication
ASTM D7566 annex A1	Fischer–tropsch synthetic paraffinic kerosene (FT-SPK)	Syngas-derived hydrocarbons produced via fischer–Tropsch synthesis and upgrading	50%	Established	Mature synthetic paraffinic route with the earliest approval basis, supported by industrial-scale fischer–Tropsch production experience and the syngas-mediated nature of the process, which helps decouple final fuel composition from feedstock variability. Future evaluation questions are more likely to concern syngas composition, process variation or product conformity than a wholly new fuel family
ASTM D7566 annex A2	Hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK)	Lipid-derived feedstocks converted through hydrotreatment, deoxygenation, hydrocracking and isomerisation	50%	Established/commercially dominant	Well-established route with significant operational and qualification experience. Current deployment constraints are generally more strongly associated with feedstock availability, production scale, cost and project development than pathway approval
ASTM D7566 annex A3	Synthesised iso-paraffins (SIP)	Biologically derived farnesane/iso-paraffinic hydrocarbons	10%	Approved but bounded	Illustrates controlled approval of a narrower compositional pathway at a lower blend limit, reflecting the relationship between compositional envelope, supporting evidence and permissible introduction level
ASTM D7566 annex A4	Fischer–Tropsch synthetic kerosene with aromatics (FT-SKA)	Fischer–Tropsch-derived synthetic kerosene containing aromatic hydrocarbons	50%	Established but less widely deployed	Demonstrates that synthetic fuels containing aromatics can be approved where composition and performance are adequately controlled, but also highlights the importance of defining aromatic species and associated material compatibility behaviour
ASTM D7566 annex A5	Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)	Alcohol intermediates converted through dehydration, oligomerisation, hydrogenation and fractionation	50%	Increasingly mature	Demonstrates expansion from lipid and FT routes into alcohol-derived intermediates. Qualification implications depend on alcohol feedstock, conversion chemistry, process control and resulting hydrocarbon distribution. The annex also includes the provision for methanol-to-jet.
ASTM D7566 annex A6	Catalytic hydrothermolysis jet fuel (CHJ)	Defined lipid-type feedstocks converted using catalytic hydrothermolysis and upgrading	50%	Approved for defined feedstock/process basis	Important distinction from broader wet-waste hydrothermal liquefaction biocrudes, which are not represented by the same general approved D7566 pathway

(*Continued*)

TABLE 1 Continued

ASTM route	Pathway	Feedstock/ process basis	Maximum blend limit	Qualification maturity	Qualification implication
ASTM D7566 annex A7	Hydrocarbon-hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HC-HEFA-SPK)	Hydrocarbon-based esters and fatty acids converted through hydroprocessing	10%	Approved but bounded	Example of a lower-blend-limit route where approval is constrained by a narrower process and compositional basis
ASTM D7566 annex A8	Alcohol-to-jet synthetic kerosene with aromatics (ATJ-SKA)	Alcohol-derived synthetic kerosene containing aromatic hydrocarbons	50%	Emerging approved pathway	Extends the alcohol-to-jet family beyond purely paraffinic products and illustrates the continuing diversification of approved synthetic blend component chemistry
ASTM D1655/ Defence standard 91-091 co-processing routes	Co-processed aviation turbine fuel	Biogenic or waste-derived feedstocks processed with conventional petroleum refinery streams	Defined by specification and co-processing limits	Established but specification-dependent	Provides a refinery-integrated route rather than a separate D7566 synthetic blend component annex. Qualification implications centre on feedstock control, trace species, refinery process control and finished fuel compliance
ASTM D4054 annex A4 fast track	Reduced-scope evaluation route	Candidate fuels meeting defined compositional and performance criteria close to conventional jet fuel behaviour	10%	Proportionate evaluation route, not a D7566 fuel pathway	Provides a mechanism to reduce evaluation burden where technical uncertainty is low and compositional similarity is strong. It does not remove technical review and is not applicable to fuels requiring broader evaluation because of novel chemistry, process route or unresolved system risks

Pathway descriptions and blend limits are summarised from ASTM D7566, ICAO, SAF conversion process summaries and supporting qualification guidance (ASTM, international, 2025b; International Civil Aviation Organization, 2022; Rumizen, 2021; Commercial Aviation Alternative Fuels Initiative, 2026).

and engine systems are certified to operate on approved fuel and additive specifications, which constitute operational limitations embedded within engine and aircraft certification documentation, including type certificates, operating limitations and associated maintenance and operating manuals. The introduction of new synthetic blend components or novel fuel compositions therefore requires structured engineering evaluation to determine whether the proposed fuel remains effectively drop-in and does not introduce unacceptable risk to certified systems. This assessment forms part of broader management of change processes associated with continued airworthiness obligations under FAA and EASA regulatory frameworks (FAA, 2014; European Union Aviation Safety Agency, 2013; European Union Aviation Safety Agency, 2025).

In practice, OEM internal review processes operate in coordination with the ASTM D4054 evaluation framework and involve formal risk identification, assessment and mitigation activities. These may include consideration of combustor operability, emissions behaviour, materials compatibility, thermal management, fuel system interactions, long-term durability, overall operability and performance. These assessments must often consider broad product portfolios encompassing multiple generations of aircraft and engine technologies operating across globally distributed fleets and extended service lifetimes. OEM review therefore generally comprises two related functions. First, OEMs evaluate the proposed specification change and supporting technical evidence to determine whether the fuel can be incorporated within the approved fuel framework. Second, they assess compatibility with aircraft and engine hardware to support continued airworthiness and operational use.

Through this process, OEMs act as primary technical gatekeepers within the qualification system, providing feedback and guidance to fuel developers and specification bodies, particularly where novel compositions, atypical property relationships or trace species introduce elevated uncertainty or engineering concern. However, OEM review and bespoke test facility capacity are inherently limited and must be prioritised across multiple concurrent internal and external programmes. As the number and diversity of candidate fuels increases, these pressures become more apparent, with progression timelines influenced by reviewer availability, competing priorities and the complexity associated with evaluating fuels across a globally distributed fleet operating over extended service lifetimes.

In parallel, the consensus-based governance structure of aviation fuel standardisation introduces additional temporal constraints. The ASTM standards system requires that technical objections raised during ballot processes are formally addressed and resolved prior to approval (ASTM International, 2015). While this ensures technical robustness and stakeholder confidence, it also introduces procedural

timelines that operate alongside the technical evaluation process. Where objections necessitate additional data generation, clarification or revision of specification language, iterative testing and re-submission cycles can extend timelines beyond those associated with technical validation alone (Staples et al., 2018).

A lack of clarity regarding evidentiary expectations and testing strategies further reduces system efficiency, particularly for new entrants. Developers without prior experience of the qualification process may not fully understand what data are required, how they should be generated or how they will be assessed. This can lead to suboptimal sequencing of testing activities and an increased likelihood of rework, as additional data are requested at later stages of evaluation (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023). For candidate fuel producers, the practical implication is that the most effective route to reducing qualification time is not to rely on historical approval timelines, but to reduce uncertainty before formal evaluation. This includes generating representative material, demonstrating process consistency, selecting appropriate analytical methods, aligning early datasets with D4054 expectations and engaging with relevant technical stakeholders before committing to higher-volume testing.

Ambiguity in technical decision-making can arise at multiple stages of the D4054 process. At Tier 1 and Tier 2, ambiguity may result from limited historical baseline data for a particular molecular family, uncertainty over whether conventional specification tests adequately capture atypical property relationships, differences between laboratories or methods, or the difficulty of interpreting trace species where concentration alone does not define risk. For example, two candidate fuels may meet headline specification properties but differ in hydrocarbon class distribution, impurity profile or response in fit-for-purpose tests. In these cases, additional data may be required to determine whether the observed differences are operationally meaningful.

At Tier 3 and Tier 4, ambiguity becomes more system-specific. The question is no longer only whether a fuel meets a property target, but whether observed behaviour in materials, components, rigs or engines is sufficiently representative, repeatable and applicable across the wider fleet. This is where OEM judgement, historical experience and system-level interpretation become particularly important. Uncertainty may arise from limited availability of representative fuel volume, uncertainty over batch-to-batch reproducibility, the relevance of a specific component or rig test to broader fleet behaviour, or the difficulty of extrapolating from targeted tests to long-term durability and operability across multiple aircraft and engine types.

The fragmentation of data across qualification programmes represents an additional structural constraint. Extensive datasets are generated through analytical testing, materials compatibility assessment and system-level evaluation, yet these data are not always systematically aggregated or standardised across the industry. While coordinated programmes can demonstrate the benefits of pre-competitive data generation, such approaches operate within a context of commercial sensitivity. Collaboration can reduce duplication and cost, but may also involve sharing proprietary information, meaning that incentives for data sharing are not always aligned with wider system-level benefits. As a result, data are often generated within programme-specific or producer-specific boundaries, limiting opportunities for cumulative learning across pathways (Colket et al., 2017; International Energy Agency, 2023).

This reflects a limitation in the treatment of data as a wider qualification resource. Fragmentation, inconsistent structuring and limited accessibility reduce the potential for reuse across related evaluations. However, data standardisation should not be understood as a substitute for industrial maturity. Improved reporting, comparable methods and structured datasets can reduce ambiguity and rework, but they cannot remove the need for representative fuel production, process control and sufficient sample volume. The most effective improvements are therefore those that connect better data practices with the practical realities of scale-up.

Finally, the evolution of fuel specifications is sometimes constrained by the availability of validated and reproducible measurement methods. New compositional features or fuel properties may be scientifically understood, but cannot be incorporated into specifications until robust analytical methods are standardised. This introduces a measurability constraint, linking the pace of specification development to the availability of validated analytical capability (ASTM International, 2025c). This constraint is particularly relevant for novel fuels where advanced analytical methods may be needed to characterise species or property relationships not adequately captured by routine specification tests.

Taken together, these factors demonstrate that qualification throughput is governed by interacting structural constraints, including technical uncertainty, testing escalation, representative fuel availability, infrastructure capacity, OEM review, governance processes, data fragmentation and measurement capability. As the system scales, these constraints define overall system performance. Approval timelines are therefore influenced not only by the intrinsic properties of candidate fuels, but by the maturity of the production process, the quality of early evidence generation, the availability of specialist testing and the ability of stakeholders to translate data into specification decisions. For candidate pathways, the most practical route to accelerating qualification is therefore to reduce uncertainty systematically: produce representative and reproducible fuel, understand the relevant annex or approval route, generate qualification-grade data early, identify potential fit-for-purpose risks before higher-tier testing, and engage with OEM, ASTM and Clearing House stakeholders before major resource commitments are made.

3.2 Coordination and evolving testing infrastructure

The structural characteristics identified in Section 3.1 have driven the development of more coordinated approaches to testing infrastructure and system organisation within the synthetic aviation turbine fuel qualification ecosystem. As the volume and diversity of candidate synthetic blend components expands, efficient progression through qualification depends not only on robust evaluation frameworks, but also on the effective organisation, accessibility and utilisation of testing capability (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023). Coordination is therefore not peripheral

to qualification; it is one of the mechanisms through which uncertainty, rework and inefficient use of finite evaluation capacity can be reduced.

A useful way to conceptualise this coordination function is as a qualification readiness funnel. Candidate fuel producers enter the evaluation ecosystem at different levels of technical maturity, process definition and fuel readiness. Some may have only small quantities of early-stage material generated from an evolving laboratory process, while others may have pilot-scale production capability and a more stable product slate. The role of coordinated support is to help producers move from early concept and exploratory testing toward qualification-ready fuel, qualification-grade data and structured engagement with OEMs and standards bodies. This does not imply that all candidate fuels follow a linear or identical pathway. Rather, it illustrates that efficient qualification depends on preparing producers, improving the reliability of data and facilitating effective technical review before resource-intensive evaluation stages are reached. This coordination function is represented conceptually as a qualification readiness funnel in Figure 2.

A key development in this context has been the establishment of Sustainable Aviation Fuel Clearing Houses. These functions provide a structured interface between fuel developers, testing laboratories, original equipment manufacturers and ASTM task groups, improving coordination across stakeholders and reducing inefficiencies associated with fragmented access to infrastructure and limited visibility of evidentiary expectations (International Civil Aviation Organization, 2022; European Union Aviation Safety Agency, 2024). Clearing Houses support developers in understanding evidentiary requirements, designing appropriate testing strategies and generating data aligned with ASTM D4054 evaluation expectations. This includes guidance on compositional analysis, fit-for-purpose property testing, sampling strategy design, process-readiness assessment and sequencing of test programmes, as well as structured engagement with OEMs, relevant ASTM working groups and standards bodies.

This coordination role is particularly important because not all fuel data are equally useful for qualification. Early analytical results may be valuable for process development, but they do not necessarily constitute evaluation-ready evidence. Qualification-grade data require representative material, appropriate sampling, validated or well-understood methods, clear reporting, traceability to the production process and sufficient confidence that the material tested reflects the fuel that would be produced at larger scale. The readiness funnel therefore helps distinguish between early R&D data, which support technical learning and process optimisation, and evaluation-ready data, which can support formal risk assessment, OEM review and specification development.

Within the United Kingdom and other regions, Clearing House models have facilitated the development of coordinated and networked testing capability, bringing together commercial laboratories, research institutions and pilot-scale facilities. This enables broader access to early-stage analytical and property testing for candidate synthetic blend components, improves flexibility in test execution and reduces barriers to entry for developers. Coordination between Clearing Houses also supports greater consistency in sampling protocols, data reporting and initial screening methodologies, contributing to improved comparability between datasets (International Energy Agency, 2023; IATA, 2024). These functions provide a structured mechanism for aligning data generation with qualification requirements within the current framework.

Pre-screening plays an increasingly important organisational role within this broader qualification ecosystem. In practice, pre-screening helps align early-stage data generation with ASTM D4054 expectations, improves sequencing of test programmes and reduces the likelihood of inefficient or misaligned progression into formal evaluation. Within coordinated Clearing House structures, pre-screening enables more effective interaction between developers, laboratories and OEM stakeholders, improving overall system efficiency and reducing unnecessary demand on higher-tier evaluation resources (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023). It is especially valuable for candidates based on novel feedstocks or processes, where early identification of compositional risks, trace contaminants, unstable intermediates or atypical property relationships can guide process modification before larger and more costly fuel batches are produced.

The value of this approach is most apparent when considering the staged nature of fuel development. At early stages, producers may be able to generate only millilitre- or litre-scale quantities of material while feedstock handling, catalyst selection, hydrotreating severity, fractionation and process control are still being optimised. At this point, small-volume compositional analysis and targeted fit-for-purpose testing can support rapid iteration. As the process matures, the focus shifts toward demonstrating that the fuel can be produced reproducibly, in representative quantities and with sufficient consistency to justify more extensive evaluation. This transition from exploratory samples to representative evaluation material is critical. Entering formal qualification too early can increase the likelihood of rework, additional data requests or delays if the tested material does not reflect a stable production process.

In parallel with broader refinement of ASTM D4054 and associated evaluation practices, more proportionate assessment approaches have been introduced to better align testing requirements with the level of uncertainty associated with candidate fuels. One example is D4054 Annex A4 Fast Track, which provides a structured mechanism for enabling more targeted evaluation where a candidate synthetic blend component demonstrates strong alignment with established compositional and performance envelopes. Under this provision, such materials may progress through a reduced evaluation scope while remaining subject to formal technical review and bounded introduction, including limited maximum blending levels. Fast Track therefore demonstrates that efficiency gains are possible where uncertainty is low, but also that such approaches depend on the candidate fuel being sufficiently similar to established SBC and/or final fuel blend behaviour.

A further area of development is the increasing alignment and standardisation of testing practices across distributed laboratory networks. As testing capability expands, ensuring consistency in analytical methods, reporting practices and data interpretation becomes increasingly important. Ongoing inter-laboratory validation and standardisation efforts are therefore critical to ensuring that data generated across different facilities are comparable and suitable for use in qualification, particularly

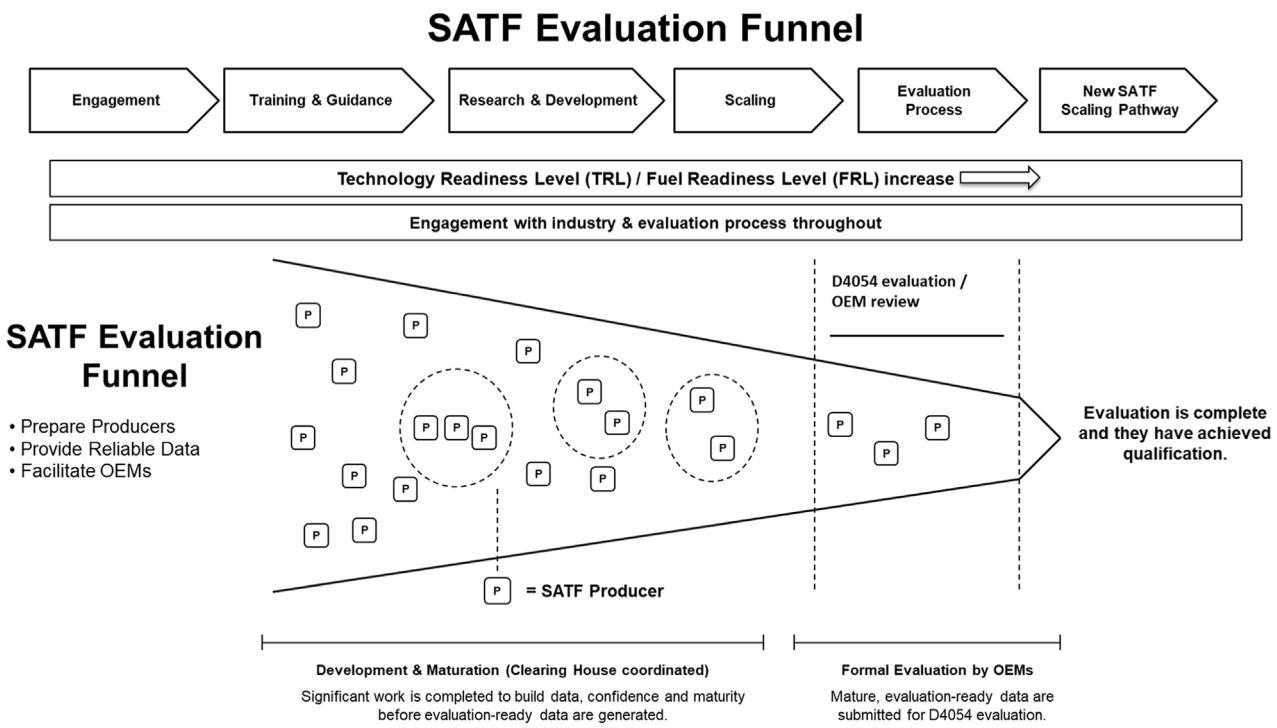


FIGURE 2
Conceptual representation of a SATF qualification readiness funnel. Candidate fuel producers enter the evaluation ecosystem at different levels of technology and fuel readiness. Coordinated support through engagement, technical guidance, research and development, process optimisation, scaling, data generation and OEM facilitation helps reduce uncertainty before formal evaluation. The funnel illustrates that qualification throughput is influenced not only by the intrinsic properties of candidate fuels, but also by producer readiness, process maturity, representative fuel availability, data quality and the effectiveness of coordination between developers, laboratories, OEMs and standards bodies.

where multiple laboratories contribute to a single evaluation programme (International Energy Agency, 2023). This directly addresses a key source of technical ambiguity: whether observed differences in fuel behaviour reflect genuine fuel characteristics, differences in method execution, laboratory-to-laboratory variability or limitations in the underlying analytical approach.

In this context, a distinction remains between general testing capability and evaluation-grade capability. Many laboratories can perform routine specification testing, but qualification increasingly relies on confidence in the application of more bespoke or technically challenging fit-for-purpose methods where methodological sensitivity, operational experience and interpretation are critical. These can include specialised compositional analyses, trace contaminant determination, thermal stability assessments, materials compatibility screening and other methods where procedures may still be evolving, highly operator dependent or not yet fully standardised across laboratories. Consequently, data supporting these aspects of evaluation are typically generated by a more limited subset of laboratories with established experience in qualification-related testing. Early efforts to standardise test methods, reporting practices and inter-laboratory validation are therefore playing an important role in broadening confidence across an increasing number of contributing laboratories (Colket et al., 2017; ASTM International, 2025c).

However, standardisation and documentation should not be understood as substitutes for industrial maturity. Improved reporting templates, shared data structures and harmonised methods can reduce ambiguity and rework, but they cannot remove the need for representative fuel production, process control and sufficient sample volumes. Advanced analytical capability and specialist test infrastructure are also more likely to develop where there is credible commercial demand, sufficient candidate throughput and a pipeline of technically mature fuels requiring those capabilities. The development of qualification infrastructure is therefore linked to industrial scaling: market demand and representative sample availability help justify investment in specialist machinery, expertise and test capacity, while access to these capabilities supports the progression of novel fuels toward approval.

This relationship becomes more pronounced as testing progresses to higher tiers of evaluation. Early-stage analytical and property testing can be distributed across a broad network of laboratories, whereas higher-tier assessment increasingly depends on specialised capability, including materials compatibility testing, rig testing, component evaluation and engine-based assessment. Such facilities are inherently limited and, in many cases, represent high-capital assets primarily designed and operated for hardware development and certification rather than dedicated fuel testing. As a result, while access to early-stage testing has expanded, higher-tier evaluation remains dependent on a smaller number of specialised facilities and expert reviewers (International Civil Aviation Organization, 2022; International Energy Agency, 2023).

The readiness funnel concept helps manage this constraint by reducing unnecessary progression into high-volume and high-cost

testing before a candidate fuel is technically ready. For Tier 1 and Tier 2 activity, coordination can improve the quality of compositional, specification and fit-for-purpose datasets, reduce method ambiguity and identify whether the candidate fuel is likely to align with an existing annex or require a new approval route. For Tier 3 and Tier 4 activity, coordination can support better planning of representative fuel production, test sequencing, facility access and OEM review. In this way, the funnel is not simply an administrative model; it is a mechanism for improving system efficiency by ensuring that higher-tier resources are reserved for fuels with sufficient technical maturity, representative sample availability and a credible pathway to evaluation.

The role of data within the qualification ecosystem is also evolving. Evaluation programmes generate extensive datasets across compositional analysis, property testing and system-level assessment. Increasing coordination through Clearing Houses and the use of more standardised reporting approaches are supporting improved consistency in how data are generated and presented. However, broader reuse of data across programmes remains limited in practice, with datasets often retained within programme-specific boundaries because of intellectual property, commercial sensitivity and the need to protect producer-specific process information (Colket et al., 2017; International Energy Agency, 2023). This limits opportunities for cumulative learning, particularly across related pathway families where previous data could help inform proportionate evaluation of new candidates.

Collectively, these developments demonstrate increasing alignment between fuel developers, testing organisations, OEMs and ASTM task groups. They improve the sequencing of testing activities, the consistency of qualification-relevant data generation and the readiness of candidate fuels before formal evaluation. While these mechanisms do not fundamentally alter the underlying structure of the qualification framework, they improve its practical operation by reducing avoidable uncertainty and supporting more efficient use of finite evaluation capacity. As pathway diversity and evaluation demand continue to increase, the ability to coordinate producers through the readiness journey from concept, to representative fuel, to reliable data and structured OEM engagement will become increasingly important to the scalability of the qualification system.

3.3 Opportunities to enhance qualification efficiency and scalability

The developments described in Sections 3.1 and 3.2 indicate that the qualification framework for synthetic aviation turbine fuels is already evolving in response to increasing pathway diversity, growing evaluation demand and accumulated operational experience. The central opportunity is not to reduce the technical rigour of qualification, but to improve the efficiency with which uncertainty is identified, reduced and translated into proportionate evidence requirements. In this context, qualification efficiency depends on earlier readiness assessment, better data quality, clearer use of existing knowledge, more coordinated infrastructure and improved alignment between fuel developers, laboratories, OEMs and standards bodies (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

One of the most important opportunities is the further formalisation of pre-screening and structured early-stage guidance. Pre-screening provides a mechanism for aligning candidate fuels with ASTM D4054 expectations before formal evaluation begins, helping developers understand whether their material is likely to align with an existing annex, require a modification to an established pathway or need a more extensive new approval route. This is particularly valuable for early-stage developers, who may be producing only millilitre- or litre-scale quantities of material while feedstock handling, catalyst selection, hydrotreating severity, fractionation and process control are still being optimised. In this context, small-volume compositional analysis and targeted fit-for-purpose testing can support rapid process iteration and reduce the risk of generating larger fuel batches before the process is technically mature (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023; ASTM International, 2025c). The role of pre-screening as a decision-support step before formal qualification is illustrated in Figure 3.

The value of pre-screening is therefore not simply that it provides earlier test data. Its wider function is to improve qualification readiness by identifying potential risks before high-volume and high-cost evaluation stages are reached. This includes identifying trace contaminants, unstable intermediates, atypical hydrocarbon distributions, problematic property relationships or uncertainty in process reproducibility. Where such issues are identified early, developers can modify feedstock selection, process conditions, upgrading strategy or fractionation approach before evaluation-ready material is produced. This improves the likelihood that fuel entering formal D4054 evaluation is representative, reproducible and accompanied by evidence that is relevant to OEM and ASTM review. Pre-screening can also help developers define an appropriate qualification strategy by indicating whether the most credible route is alignment with an existing annex, modification of an existing annex, use of a proportionate evaluation mechanism such as Fast Track, or progression through a full D4054 evaluation. This allows technical, economic and production trade-offs, including cost, risk, product slate, yield, fuel volume and development time, to be considered before major resource commitments are made.

A related opportunity is the development of clearer readiness criteria for candidate fuels. At present, developers may not always know when a fuel concept is sufficiently mature for formal evaluation or what evidence is needed to support progression. More explicit readiness criteria could help distinguish between early R&D material, process-development samples and evaluation-ready fuel. Such criteria could include evidence of process definition, batch reproducibility, representative sampling, preliminary compositional characterisation, trace species control, fit-for-purpose property screening and a clear understanding of the intended approval route. This would not replace expert judgement, but it would improve transparency and reduce avoidable rework by giving developers a clearer basis for planning qualification activity.

Clearing Houses are well placed to support this function because they sit at the interface between developers, laboratories of varying capability, OEMs, specification bodies and other industry stakeholders. A practical opportunity is therefore to strengthen the role of Clearing Houses as qualification-readiness coordinators. This includes translating ASTM D4054 expectations

into practical guidance, helping developers design appropriate test programmes, supporting sampling strategies, advising on process maturity and coordinating structured technical engagement before formal review. In this role, Clearing Houses can help ensure that the right evidence is generated at the right stage, using appropriate methods and representative material (International Civil Aviation Organization, 2022; European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

Standardised reporting and data presentation represent a second major opportunity. Qualification programmes generate extensive datasets across compositional analysis, specification testing, fit-for-purpose properties and system-level assessment. However, these data are not always produced and presented in a consistent, industry-defined format that allows analysis, interpretation and cross-programme comparison to be carried out easily. More consistent research report templates, method-specific reporting expectations and structured data packages would improve the ability of OEMs, ASTM task groups and technical reviewers to assess evidence efficiently and compare results across related fuels. This is particularly important for Tier 1 and Tier 2 evaluation, where ambiguity can arise from differences in analytical method execution, reporting format, laboratory practice or the interpretation of trace species and atypical property relationships (Colket et al., 2017; ASTM International, 2025c). Over time, improved data consistency could support more evidence-informed and proportionate evaluation, reducing unnecessary duplication while maintaining appropriate technical safeguards and confidence in fuel behaviour.

Improved data standardisation should not be understood simply as a documentation exercise. To be useful for qualification, data must be traceable to representative material, linked to a defined production process and generated using methods that are appropriate for the question being addressed. A structured data package should therefore connect feedstock, process configuration, sample history, compositional analysis, specification properties, fit-for-purpose behaviour, method precision and uncertainty interpretation. This would help reviewers understand not only what the measured values are, but also what they mean in terms of real-world fuel performance, system compatibility and the candidate fuel's proposed approval route.

Inter-laboratory standardisation and method validation are closely linked to this opportunity. As distributed testing networks expand, confidence in data comparability becomes increasingly important. Routine specification tests may be widely available, but some qualification-relevant methods require specialist expertise, careful interpretation and consistent execution. These include advanced compositional analysis, trace contaminant determination, thermal stability assessment, materials compatibility screening and other bespoke or developing methods. Broader inter-laboratory validation, shared reference materials and greater transparency in method application would reduce uncertainty over whether observed differences reflect genuine fuel behaviour or laboratory-to-laboratory variability (Colket et al., 2017; ASTM International, 2025c; International Energy Agency, 2023).

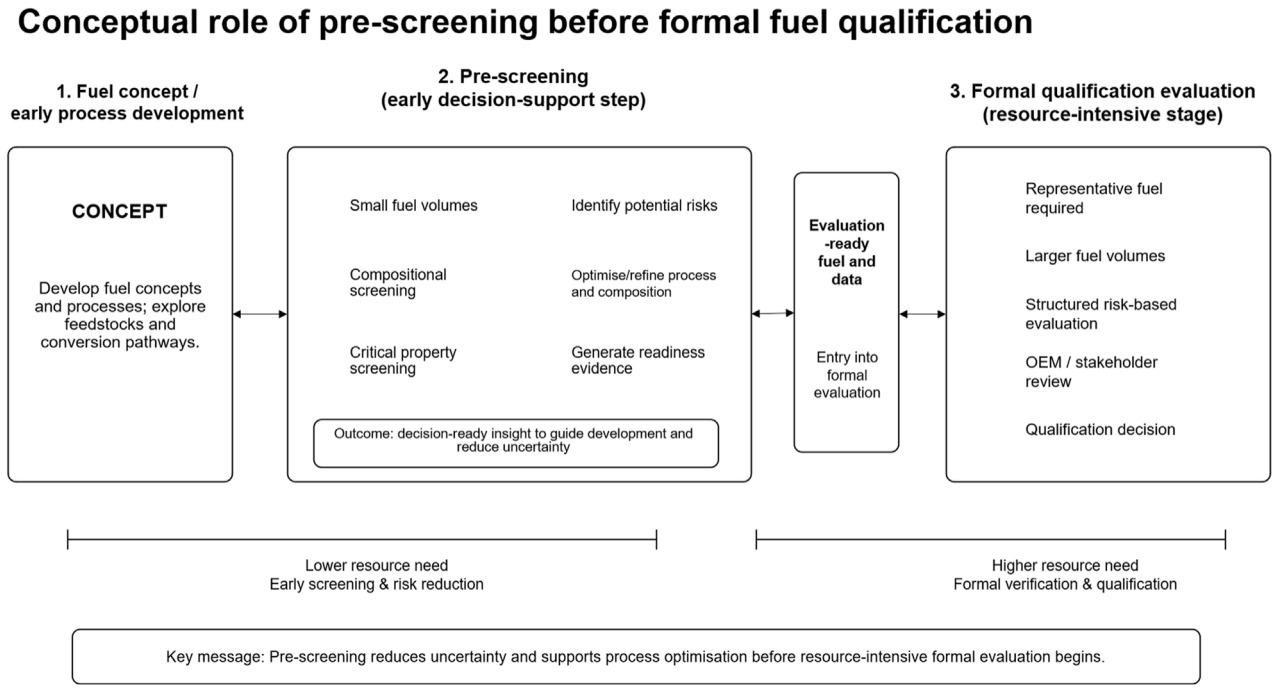


FIGURE 3
Conceptual role of pre-screening before formal fuel qualification. Pre-screening provides a low-volume decision-support stage for compositional screening, critical property testing, early risk identification and process optimisation before representative fuel is generated for formal qualification evaluation. It is not a substitute for formal risk-based evaluation, but a readiness step that helps reduce uncertainty and improve use of higher-volume testing, OEM review and stakeholder evaluation resources. The process should also be understood as iterative: evidence generated at any stage may identify the need for further analysis, process optimisation or additional fuel production, requiring a return to an earlier development or testing stage before progression can continue.

A third opportunity is the more systematic use of existing knowledge through proportionate evaluation and compositional equivalence. ASTM D4054 is already risk-based, and approaches such as D4054 Annex A4 Fast Track demonstrate that reduced evaluation scope can be appropriate where a candidate fuel is compositionally and behaviourally close to established aviation fuel experience. Further development of this principle could improve scalability by enabling existing datasets to inform the evaluation of new candidates where similarity is technically justified. This is particularly relevant as increasing numbers of candidate fuels may occupy related regions of compositional space, such as synthetic paraffinic kerosenes or fuels with controlled cycloparaffinic and aromatic content (ASTM International, 2025c; Staples et al., 2018; International Civil Aviation Organization, 2022).

However, equivalence-based approaches must be applied carefully. Similarity in headline specification properties does not necessarily mean equivalence in system behaviour. Fuels with similar density, freezing point or distillation characteristics may differ in hydrocarbon class distribution, trace species, thermal stability, elastomer interaction or combustion behaviour. Any broader use of equivalence must therefore be supported by clear compositional boundaries, validated analytical methods, relevant reference datasets and defined limits on where existing evidence can and cannot be extrapolated. The opportunity is not to assume equivalence, but to define it more rigorously so that unnecessary testing can be reduced where uncertainty is demonstrably low.

This has particular relevance for emerging pathway families that are chemically related to existing approvals but differ in feedstock, intermediate or process configuration. Where candidate fuels remain within well-understood compositional and performance envelopes, proportionate evaluation may reduce duplication and improve throughput. Where fuels introduce novel molecular structures, uncertain impurity profiles or less familiar process-derived risks, more extensive testing remains necessary. The future efficiency of qualification will therefore depend on the ability to distinguish clearly between novelty that is operationally insignificant and novelty that may affect safety, operability or durability.

A fourth area of opportunity is the continued development of specialist analytical and testing infrastructure. Advanced analytical methods, including high-resolution and multidimensional chromatographic approaches, are becoming increasingly important for differentiating candidate synthetic blend components that may appear similar under routine specification testing. These methods can improve understanding of hydrocarbon class distribution, trace composition and composition-to-performance relationships. However, the value of increasingly detailed compositional data lies not only in describing the fuel more precisely, but in using that information to interpret and predict real-world fuel behaviour with greater confidence. Improved analytical capability should therefore support better assessment of thermal stability, materials compatibility, combustion behaviour, deposit formation and other system-relevant risks. This requires specialised instrumentation, skilled operators, validated methods and consistent interpretation. Increasing the availability and standardisation of such capability would improve the evidence base for qualification and reduce reliance on a small number of expert facilities (Colket et al., 2017; ASTM International, 2025c).

At higher tiers of evaluation, the key opportunity is to improve coordination of scarce specialist resources and manage the high cost of testing. Materials compatibility testing, component testing, rig testing and engine-based assessment require specialised facilities that are expensive, limited and often primarily configured for hardware development rather than fuel evaluation. As candidate fuel numbers increase, access to these resources may become a more significant constraint. More coordinated national and international testing networks could improve visibility of available capability, support better sequencing of test programmes and reduce delays caused by fragmented access to facilities. This would be particularly valuable where multiple candidate fuels require similar forms of higher-tier assessment (International Civil Aviation Organization, 2022; International Energy Agency, 2023).

Pipeline coordination and prioritisation represent a further opportunity. As more developers seek to enter the qualification system, it will become increasingly important to understand which candidates are technically ready, which require further process development and which are unlikely to progress without substantial redesign. Improved pipeline visibility across Clearing Houses, laboratories, OEMs and standards bodies could support more effective allocation of finite evaluation capacity. This does not imply that qualification decisions should be based on commercial preference rather than technical merit. Rather, it recognises that evaluation resources are limited and should be directed toward candidates with sufficient technical maturity, representative fuel availability and a credible route to approval and deployment (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023; International Air Transport Association, 2024).

These opportunities must remain aligned with the practical realities of industrial scale-up. Improved pre-screening, better data structures and proportionate evaluation can reduce uncertainty and rework, but they cannot remove the need for representative fuel production, process control and sufficient sample volume. A candidate fuel cannot be fully evaluated on the basis of early exploratory material if the production process remains unstable or if the material tested does not represent the fuel that would be produced at larger scale. Qualification efficiency therefore depends on the interaction between technical evaluation and industrial maturity. The system can help developers reach qualification readiness more efficiently, but it cannot substitute for process reproducibility or scalable production capability (International Energy Agency, 2023; International Civil Aviation Organization, 2022).

Looking further ahead, advances in analytical capability, accumulated qualification datasets and improved understanding of composition-to-performance relationships may support a gradual shift toward more evidence-informed and equivalence-based evaluation. A key opportunity is the development of tools and datasets that allow behaviour observed in compositional analysis and small- or laboratory-scale testing to be interpreted with greater confidence as a predictor of larger-scale system performance. Where technically justified, this could reduce unnecessary reliance on high-volume validation testing while preserving, rather than weakening, the risk-based assurance required for aviation fuel approval. Such a shift is likely to be incremental rather than disruptive. The empirical foundation of aviation fuel qualification, the role of OEM judgement and the safety-critical nature of fuel use mean that new approaches must build on existing frameworks rather than replace them. The most

credible pathway to improved scalability is therefore a combination of earlier uncertainty reduction, better data quality, more coordinated infrastructure, proportionate use of existing evidence and continued expert review.

Taken together, these opportunities show that the qualification system can improve its operational efficiency without compromising its underlying safety function. As pathway diversity increases, the most important improvements are those that help candidate fuels reach formal evaluation in a more mature, better characterised and more representative state. This would reduce avoidable rework, improve predictability, support more efficient use of OEM and testing capacity, and enable the qualification framework to manage a larger and more chemically diverse pipeline of synthetic aviation turbine fuels while preserving the high level of assurance required for aviation.

4 Discussion

The analysis presented in this review demonstrates that the qualification of synthetic aviation turbine fuels is best understood as a distributed evidence-generation and governance process rather than as a linear technical checklist. Candidate fuels progress through a system in which fuel chemistry, production process maturity, analytical evidence, fit-for-purpose testing, OEM review, standards development and stakeholder coordination interact. This system has enabled the safe introduction of multiple synthetic blend component pathways, but its future performance will become increasingly important as policy ambition, pathway diversity and evaluation demand increase (ASTM International, 2025b; ASTM International, 2025c; International Civil Aviation Organization, 2022).

This framing addresses an important gap in the existing literature. Much of the literature on sustainable aviation fuel deployment focuses on feedstock availability, lifecycle emissions, production economics, infrastructure, policy frameworks and market uptake (International Energy Agency, 2023; International Air Transport Association, 2024; Morganti et al., 2024; Wandelt et al., 2025). These factors remain central to SAF deployment. However, less attention has been given to qualification itself as a system-level function that shapes the transition from fuel innovation to operational use. The contribution of this review is therefore to show how the qualification framework translates chemical and process novelty into evidence requirements, technical review, specification development and consensus decisions. In doing so, it highlights that qualification can be both an enabling mechanism and a potential future constraint, depending on the maturity, volume and diversity of candidate fuels entering the system.

A key implication is that qualification has not generally been the primary constraint for the SAF pathways that dominate near-term supply. Established routes such as hydroprocessed esters and fatty acids and Fischer–Tropsch-derived fuels already have approved pathways, yet deployment remains constrained by feedstock availability, production scale, project economics, infrastructure and policy certainty (ASTM International, 2025b; International Civil Aviation Organization, 2022; International Energy Agency, 2023; International Air Transport Association, 2024). This distinction is important because approval within ASTM D7566 and incorporation into finished fuel specifications such as ASTM D1655 or Defence Standard 91-091 establishes that a fuel is suitable for use within existing aviation systems, but does not itself ensure widespread production or commercial adoption (ASTM International, 2025a; ASTM International, 2025b; Defence Standard 91-091, 2025). Qualification is therefore a necessary condition for deployment, but it is not sufficient to deliver market scale.

However, this balance may change as SAF mandates increase and the candidate pathway landscape diversifies. Future SAF supply is likely to require a broader range of feedstocks, intermediates and conversion technologies, including routes that do not fit neatly within existing ASTM D7566 annexes or that introduce less familiar compositional features (International Energy Agency, 2023; International Civil Aviation Organization, 2022; Morganti et al., 2024). Under these conditions, qualification may become a more material determinant of the pace, predictability and diversity of deployment. The issue is not that qualification requirements should be weakened, but that the system must be capable of managing a larger and more chemically diverse pipeline while preserving the level of safety assurance required in aviation.

The most important constraints on future qualification throughput can be grouped into five interacting categories.

- Technical uncertainty, which increases where fuels deviate from established production routes, compositional envelopes or historical datasets.
- Representative fuel availability and process maturity, because higher-tier evaluation requires material that reflects a stable and reproducible production process rather than an early exploratory sample.
- Specialist testing infrastructure, which remains finite, particularly for advanced compositional analysis, materials compatibility, rig testing, component evaluation and engine-based assessment.
- OEM review capacity, because OEMs must assess candidate fuels in relation to certified aircraft and engine systems across diverse and long-lived fleets.
- Data fragmentation, method variability and limited standardisation, which can reduce the efficiency with which evidence is interpreted and reused across related evaluations (Colket et al., 2017; ASTM International, 2025c; European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

These constraints do not operate independently. A technically novel fuel may require advanced analytical methods, larger volumes of representative material and higher-tier testing, while also placing greater demands on OEM review and ASTM consensus processes. If the production process is not sufficiently mature, promising early-stage data may not translate into evaluation-ready evidence. Similarly, unclear reporting or incomplete traceability between feedstock, process history, sample handling and test results can increase ambiguity during technical review. Qualification throughput is therefore determined by the interaction between fuel novelty, production maturity, data quality, infrastructure access and decision-making capacity rather than by fuel properties alone (Colket et al., 2017; European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

The stakeholder ecosystem and qualification readiness funnel described in this review help explain why coordination is so

important. Qualification depends on timely interaction between developers, laboratories, research organisations, OEMs, standards bodies, regulators, operators and policy or funding bodies. No single actor controls the whole process, and each stakeholder group operates with different responsibilities, incentives and capacity limitations. Clearing House coordination is therefore significant because it provides a practical mechanism for aligning technical readiness, evidence planning, targeted testing and stakeholder engagement and coordination across institutional boundaries (International Civil Aviation Organization, 2022; European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

This coordination function is particularly important because fuel development should be treated as a readiness journey rather than as a single entry point into D4054 evaluation. Candidate fuels may enter the ecosystem at very different levels of maturity, from small quantities of exploratory laboratory material to pilot-scale products with more stable composition and process definition. Efficient qualification depends on moving candidate fuels from early concept, through process development and pre-screening, toward representative fuel production and qualification-grade data. This helps ensure that formal evaluation is undertaken when the fuel and supporting evidence are sufficiently mature to justify the resource commitment required (European Union Aviation Safety Agency, 2024; ASTM International, 2025c).

Pre-screening is a key mechanism within this readiness journey. Its value is not simply that it generates earlier data, but that it provides decision-ready insight before high-volume and high-cost evaluation stages are reached. Small-volume compositional analysis and critical property screening can help identify potential risks, guide process optimisation and determine whether a candidate fuel is likely to align with an existing annex, require an annex modification or need a more extensive approval route. In this sense, pre-screening improves system efficiency by reducing uncertainty before formal evaluation, rather than by reducing the technical rigour of qualification itself (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023; ASTM International, 2025c).

The distinction between early R&D data and evaluation-ready data is therefore central. Early analytical results may be useful for process development, but formal qualification requires data generated from representative material using appropriate methods, clear reporting and traceability to a defined production process. This distinction is especially important for novel pathways, where early samples may not reflect the fuel that would later be produced at larger scale. A candidate fuel that enters formal evaluation too early may generate rework, additional data requests or delays if the tested material does not reflect a stable process or if key risks have not been adequately characterised (International Energy Agency, 2023; ASTM International, 2025c).

Data standardisation is another important opportunity, but it should not be understood narrowly as improved formatting. The main value of standardisation lies in improving the interpretation, comparability and traceability of evidence. For Tier 1 and Tier 2 evaluation, ambiguity may arise from method variability, limited baseline data for a molecular family, uncertainty over whether conventional specification tests capture atypical property relationships, or difficulty interpreting trace species where concentration alone does not define risk. At higher tiers, ambiguity becomes more system-specific, involving questions of representativeness, repeatability, fleet applicability, durability and continued airworthiness. Standardised reporting, method-specific expectations and structured data packages can support review, but they cannot replace representative testing, expert assessment or OEM judgement (Colket et al., 2017; ASTM International, 2025c; FAA, 2023; European Union Aviation Safety Agency, 2022; European Union Aviation Safety Agency, 2025).

Proportionate evaluation approaches, including Fast Track provisions within ASTM D4054, demonstrate that the qualification system can adapt where uncertainty is demonstrably low based on clear guidelines and an ever expanding experience database. These approaches are important because they show how existing knowledge and reference data can support more efficient evaluation where a candidate fuel is compositionally and behaviourally close to established aviation fuel experience. However, proportionate evaluation depends on a robust technical basis. Similarity in headline specification properties does not necessarily establish equivalence in system behaviour. Fuels with comparable density, freezing point or distillation characteristics may still differ in hydrocarbon class distribution, trace species, thermal stability, elastomer interaction or combustion behaviour. Equivalence-based approaches therefore require clear compositional boundaries, validated analytical methods and defined limits on where existing data can reasonably be extrapolated (ASTM International, 2025c; Rumizen, 2021; Commercial Aviation Alternative Fuels Initiative, 2026).

The role of industrial scale-up must also be considered. Improved pre-screening, data structures, testing networks and equivalence frameworks can reduce uncertainty and improve evaluation efficiency, but they cannot remove the need for representative fuel production and process reproducibility. This is a critical distinction for policy and funding bodies. Investment in qualification infrastructure is valuable, but it must be aligned with realistic development pathways in which producers can generate sufficient volumes of stable, representative fuel. Conversely, fuel developers may require access to analytical and pilot-scale support before reaching full commercial maturity. Qualification and scale-up therefore interact: industrial maturity supports evaluation, while coordinated evaluation support can help developers reach maturity more efficiently (International Energy Agency, 2023; International Civil Aviation Organization, 2022; International Air Transport Association, 2024).

For fuel developers, the practical implication is that the most effective route to reducing qualification time is to reduce uncertainty before formal evaluation. This means understanding the likely approval route, generating representative material, demonstrating process consistency, identifying compositional risks early, using appropriate analytical methods and engaging with Clearing House, OEM, ASTM and Defence Standard stakeholders before committing to large-volume test programmes. For Clearing Houses, the implication is that their most valuable function is not simply to provide access to testing, but to improve qualification readiness through guidance, sequencing, data quality, readiness assessment and stakeholder coordination (European Union Aviation Safety Agency, 2024; International Energy Agency, 2023).

For OEMs and standards bodies, the challenge is to maintain robust safety assurance while enabling proportionate evaluation

where the technical basis supports it. This requires continued development of reference datasets, validated methods, inter-laboratory comparison, and clearer approaches to compositional equivalence and fuel family assessment. For policymakers and funders, the implication is that qualification capacity should be considered part of the wider SAF deployment ecosystem. Support for production scale-up, analytical capability, pilot-scale facilities, data infrastructure and coordinated evaluation networks will be required if a more diverse candidate fuel pipeline is to progress efficiently (Colket et al., 2017; ASTM International, 2025c; International Energy Agency, 2023; Morganti et al., 2024).

Overall, the analysis suggests that the future scalability of SATFs qualification will depend less on changing the fundamental principles of D4054 than on improving the operational performance of the system around it. The framework is already risk-based and adaptive. The opportunity is to make it more predictable, better coordinated and more evidence-informed as demand increases. This includes earlier uncertainty reduction, clearer readiness criteria, more consistent data generation, improved testing infrastructure, more effective use of existing knowledge and continued expert review. Such developments would allow qualification to preserve aviation's very high level of safety while better supporting the scale and diversity of sustainable aviation fuel pathways required for long-term decarbonisation (ASTM International, 2025c; International Civil Aviation Organization, 2022; International Energy Agency, 2023).

5 Conclusion

The qualification of synthetic aviation turbine fuels is a structured, risk-based process that enables new fuel components to be introduced into existing certified aircraft and engine systems while maintaining safety, operability and long-term system integrity. This review has shown that qualification is not simply a fixed sequence of tests or an administrative step before deployment. Rather, it is a distributed evidence-generation and governance process through which differences in feedstock, production route, composition, trace species and performance behaviour are translated into proportionate technical evidence, OEM review and specification decisions.

A central conclusion is that qualification has not generally been the primary constraint on deployment for the SAF pathways that dominate current and near-term supply. Established routes such as hydroprocessed esters and fatty acids and Fischer–Tropsch-derived fuels already have recognised approval pathways, yet deployment remains limited by feedstock availability, production scale, project economics, infrastructure and policy certainty. Qualification is therefore a necessary condition for deployment, but it is not sufficient to deliver market scale or emissions reduction on its own.

However, this balance is likely to change as SAF mandates increase, production technologies mature and a more diverse pipeline of candidate fuels seeks approval. Future supply growth may require greater use of novel feedstocks, waste-derived intermediates, alternative process configurations and fuel compositions that do not fit neatly within existing approval envelopes. Under these conditions, qualification may become a more material constraint on the pace, predictability and diversity of SAF deployment. The challenge is not to compromise the technical requirements for qualification, risk identification and mitigation, but to ensure that the system can manage a larger and more chemically diverse candidate pipeline while preserving the level of assurance required in aviation.

The analysis identifies several interacting factors that will shape future qualification throughput: technical uncertainty, representative fuel availability, production process maturity, specialist testing infrastructure, OEM review capacity, data quality, method standardisation and consensus-based specification governance. These factors are justified by the safety-critical role of aviation fuel, but they also define the practical capacity and predictability of the qualification system. As the candidate fuel pipeline expands, system performance will increasingly depend on how effectively these constraints are managed across the wider stakeholder ecosystem.

The review also shows that the qualification system is already evolving. Clearing House coordination, pre-screening, distributed testing networks, standardised reporting, inter-laboratory comparison and proportionate evaluation approaches are improving the practical operation of the framework without changing its underlying safety principles. In particular, pre-screening and qualification-readiness assessment can help candidate fuels progress from early concept and process development toward representative fuel production and evaluation-ready data. This reduces uncertainty before formal evaluation, improves the use of finite OEM and testing resources, and lowers the risk of avoidable rework.

Improved data utilisation and compositional understanding are also central to future scalability. More structured datasets, clearer reporting expectations, validated analytical methods and better understanding of composition-to-performance relationships can support more evidence-informed and proportionate evaluation. However, these approaches must remain bounded by technical evidence. Similarity in headline specification properties does not necessarily establish equivalence in system behaviour, and novel fuels may still require expanded analysis, materials compatibility assessment or higher-tier testing where uncertainty remains.

Overall, the long-term scalability of SATF qualification is likely to depend less on replacing the existing ASTM D4054/D7566 framework than on improving the operational performance of the system around it. The most credible pathway to greater efficiency is earlier uncertainty reduction, stronger qualification-readiness support, better data quality, coordinated access to testing infrastructure, clearer use of existing knowledge and continued expert review. The future challenge is therefore not to make qualification less rigorous, but to make the qualification ecosystem more ready, better coordinated and more evidence-informed before candidate fuels reach the most resource-intensive stages of formal evaluation.

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