Real-Time Fuel Quality Measurement and Automated Compliance Monitoring for Aviation Refuelling Systems in Saudi Arabia

Abstract

The approach to quality control in the area of aviation refuelling is shifting from that of periodic sampling to one that makes use of a continuous method relying on a large amount of data, but the operational difficulties extend well beyond the simple installation of one sensor. In order to ensure safety, a system has to measure the pertinent characteristics of Jet A-1 with response times that are practical, be able to tell the difference between actual contamination and variations in the process, link the measurements to the approved specifications, and at the same time keep a record of the decisions for audit purposes. This review looks at the evidence published between 2020 and 2025 regarding real-time and near-real-time measurement of aviation fuel, the detection of contamination, sensor integration, and automated process management, and then applies those findings to refuelling systems at airports in Saudi Arabia. In order to carry out the review, a structured integrative approach was adopted, combining peer-reviewed studies with the current ASTM and Joint Inspection Group requirements and the official Saudi aviation strategy documents. The evidence shows that no single technique is at present capable of replacing all the laboratory tests. On the contrary, a layered system is technically more reliable: it makes use of optical or dielectric sensing for water, light-scattering or extinction methods for particles, inline conductivity and process instrumentation, and spectroscopic fingerprints for rapid multi-property screening. Edge validation, programmable logic, integration with SCADA or aircraft fuelling management systems, rule-based checks to guarantee compliance, and the controlled handling of exceptions cause these measurements to function as a means of operational assurance. The review suggests a model for implementation in Saudi Arabia in which sensing occurs at the point of receipt, during storage transfers, after filtration or at the hydrant delivery point, and also at the point when the fuel is released into the aircraft, while still retaining laboratory confirmation for cases that are certification-critical or unclear. This approach assists to achieve the aims of Vision 2030 and the Saudi Aviation Strategy by improving scalability, traceability, punctuality, asset protection, and toughness as passenger, cargo, and airport traffic increase. The key research priorities are field validation under the climatic conditions of Saudi Arabia, the establishment of standard uncertainty budgets, the development of sensor networks that are secure against cyber

attacks, the creation of reference datasets for sustainable aviation fuel blends, and the establishment of regulatory pathways that define when continuous measurements can be used to supplement or replace manual quality inspections.

1. Introduction

Before it can be taken on by an aircraft, Jet A-1 fuel has to go through a number of handling stages; these stages are its discharge at the refinery, its transfer at the terminal, its movement by road or by pipeline, its acceptance at the airport, its storage in bulk, filtration, distribution through hydrants, the use of a refueller or dispenser, and finally the transaction during which the aircraft is filled. At each stage of transfer, there is a possibility of a particular type of quality problem. Water may enter because of condensation, tank breathing, or poor drainage; particulate matter can appear because of corrosion, disturbances to the infrastructure, defective seals, or maintenance work; cross-product contamination could alter the fuel's volatility, thermal stability, conductivity, or water separation properties; and changes in temperature can influence the measured physical properties. Hence, modern fuel assurance has to consider both the chemistry of the fuel and the condition of the delivery system. Recent reviews have highlighted that water, solids, microbial material, and chemical contaminants are capable of reducing the performance of aviation fuel and causing safety, reliability, and maintenance issues (Pruski and Sprynskyy, 2024). Reviews of the relationship between composition and properties also show that apparently small changes in composition can have an effect on a number of bulk properties at the same time, making it difficult to make simple pass-fail decisions based on a single proxy measurement (Vozka and Kilaz, 2020; Romanczyk, 2024).

Even though a large amount of traditional quality control is carried out on a sporadic basis, it is still necessary. Visual inspection, manual sampling, laboratory titration, membrane filtration, distillation, and thermal-stability testing do provide reliable evidence when performed in accordance with controlled procedures, but they only yield a reading at one particular point in time rather than giving a complete picture of the continuously flowing fuel. The visual methods for detecting free water and particulate contamination are specified in ASTM D4176-21, while ASTM D6304-20, D2276-22, D4052-22 and D3241-23 include the laboratory or line sampling measurements for water, particulate matter, density and thermal oxidation stability. Although these methods act as authoritative reference standards, the times at which sampling and analysis take place can lead to gaps between tests. For facilities that manage high volumes, the primary engineering concern is therefore not whether laboratory testing should be given up, but rather how continuous sensing can detect abnormal conditions earlier, trigger the appropriate responses, and direct confirmatory testing to the correct location and time.

Saudi Arabia is in fact a particularly relevant example in this context. The Saudi Aviation Strategy states that by 2030 connectivity should be extended to more than 250 destinations together with a significant increase in both passenger and cargo capacity (GACA, 2023). The official performance report for 2024 indicated that the number of passengers had gone above 128 million and that air cargo had experienced strong growth, showing that scaling is already underway and is not still a goal for the future (NIDLP, 2024; GACA, 2025). As airport traffic, fuel transactions and the level of logistics activity are all rising, manual quality checks could become a bottleneck to capacity unless they are supported by reliable digital monitoring. Real-time fuel-quality assurance can therefore contribute to achieving the various aims of Saudi Vision 2030 concerning the modernisation of infrastructure, operational excellence, digital transformation and the development of a globally competitive logistics sector (Saudi Vision 2030, 2024).

2. Aim and objectives

The aim of this review is to set up a framework for the real-time evaluation of fuel quality and to enable automatic monitoring of compliance in aviation refuelling systems in Saudi Arabia. It does not intend to claim that laboratory certification should be abolished in all situations. Instead, it explores how continuous and rapid measurements can be introduced into the refuelling process, looks at the way in which their uncertainty should be treated in relation to the approved requirements, and studies the role that digital control can play in converting sensor readings into safe and traceable operational decisions.

The project has four aims. The first of these is to identify the key quality risks and decision points connected with Jet A-1 fuel from the moment it arrives at the airport until it is passed on to the aircraft. The second aim is to compare the measurement technologies employed between

2020 and 2025, considering the amount measured, the response speed, selectivity, the difficulty of calibration, environmental sturdiness and the degree of readiness for integration. The third objective consists in setting up an automated compliance system which links the field sensors to validation either at the edge or via a PLC, connects to SCADA and the aircraft fuelling management systems, includes the specification rules, interlocks and auditable exception handling. The fourth objective is to work out the implementation priorities specific to Saudi Arabia in the areas of climate, airport throughput, cybersecurity, labor force abilities, the transition to sustainable aviation fuel and the scaling linked to Vision 2030. Together, these objectives move the focus away from 'which sensor is the best' to 'which combination of measurement, validation and governance leads to defensible decisions about the release of fuel'.

3. Review methodology

A structured integrative review was selected because the subject area includes a wide variety of evidence, such as that from analytical chemistry, optical and microwave sensing, process automation, aviation-fuel standards, airport operating practices, and national strategy. A traditional meta-analysis is not appropriate since the different studies do not have a common intervention, outcome measure, or experimental design. Nevertheless, the review was carried out in accordance with the definite guidelines provided by PRISMA 2020, by explicitly stating the eligibility criteria, allowing the process of tracing the sources to be carried out, and by keeping the synthesis of the evidence separate from its interpretation (Page et al., 2021). The evidence window was restricted to the period 2020–2025 so that the technical discussion could focus on recent advances in sensing, digitalisation and regulatory practice. The earlier sensor paper was used only as a structural and graphical model for scientific presentation and was not cited as part of the evidence in the review.

The search involved using the terms 'jet fuel' or 'Jet A-1' together with water, particulate matter, contamination, spectroscopy, NIR, MIR, Raman, fluorescence, microwave radiation, dielectric properties, conductivity, sensor technology, instantaneous analysis, in-line monitoring, dynamic monitoring, PLCs, SCADA systems, airport fueling, and compliance. Peer-reviewed studies were only included if they were directly about aviation fuel or, in the case of those relating to water sensing, had examined a hydrocarbon matrix closely related to that one and had offered a reasonable route for in-line implementation. Standards and operating documents were included if they specified the relevant measurements, acceptance procedures, or process controls. Where official documents from Saudi Arabia dealt with the country's aviation capacity, logistics, or digital transformation background, they were taken into account. Sources were excluded if they were outside the date range, did not contain a sufficient technical description, dealt with types of fuel other than those in question without providing transferable sensing principles, or made claims that could not be linked to a measurable quality-control function.

The material was divided into five categories: contamination hazard; the variable being measured; the sensing principle and analytical performance; operational incorporation; and the compliance role. Technology readiness was evaluated qualitatively, rather than by assigning it a fictitious numerical score. A technique was termed 'reference' when it meets an established standard method, called 'deployable' if both the literature and industry practice indicate that it can be used in the field or online, classified as 'screening' if it is capable of rapidly detecting abnormal fuel even though it still requires confirmatory analysis, and regarded as 'emerging' in the case where promising performance has not yet been demonstrated under representative airport conditions. It must be pointed out that a high level of accuracy achieved in the laboratory does not necessarily imply that the technique can be reliably applied in a fueling environment which is always moving, vibrating, temperature-variable and safety-critical.

The technologies were subsequently allocated to the Saudi refuelling chain and to a control strategy. In order for each proposed automated action to be regarded as valid, it was necessary that the input measurement had a known validity status; that the decision should be based on an approved specification or site rule rather than just on an opaque prediction; and that the system had to be capable of failing safely should there be uncertainty, sensor drift, a loss of communication, or the expiry of the calibration. Figure 1 provides a summary of this review process. While this method is suitable for inclusion in a review paper it is not suitable for presenting experimental measurements which had not in fact been carried out.

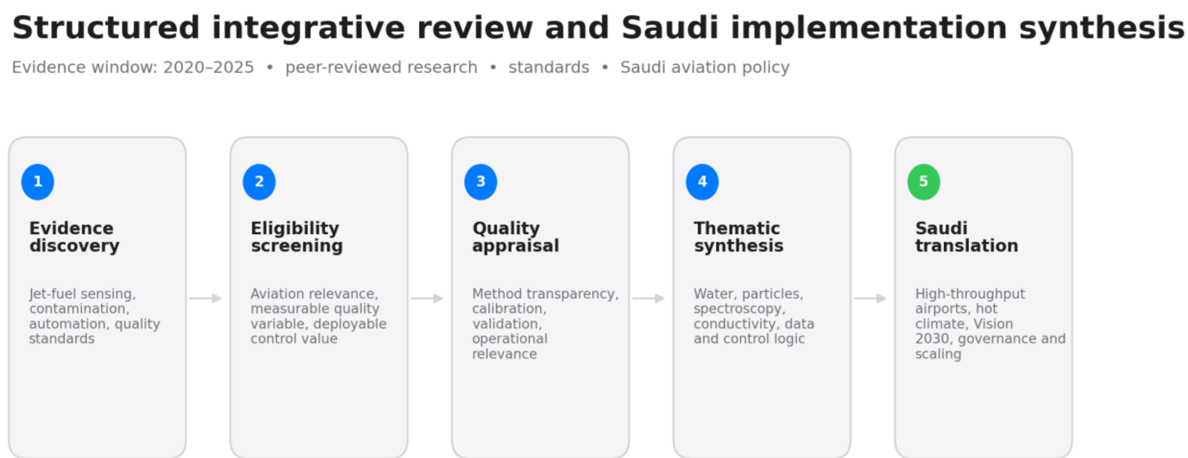

Figure 1. Structured integrative review workflow

4. Fuel-quality risks and measurement requirements

Water is the best choice for uninterrupted monitoring since it can change between its dissolved, entrained and free phases as a result of variations in temperature and in the way it is handled. A field instrument has therefore to be able to distinguish between a genuine increase in the amount of water and changes caused by temperature in terms of solubility, optical response or dielectric properties. In their 2022 study regarding dynamic monitoring, Brailko et al. proposed the continuous estimation of water content by measuring the changes in hydraulic resistance through porous water-separating elements and then using a PLC to process the pressure signals. In a later study they applied automated methods to the problem of losses in storage tanks and water contamination (Brailko et al., 2023). These methods are attractive since they link the measurement directly to the process conditions, but a refuelling assurance design should still provide an independent reference pathway. Coulometric Karl Fischer titration in accordance with ASTM D6304-20 is useful for verification, calibration studies and in the case of disputes because it provides a quantitatively recognised determination of water rather than just a process proxy.

Water can be detected directly or in an essentially direct manner through optical absorption, variations in the refractive index, photothermal effects, microwave dielectric reaction, or other interactions in which water differs markedly from the hydrocarbon matrix. Ricchiuti et al. (2022)

were able to achieve highly sensitive photothermal detection of trace quantities of water in organic solvents, therefore demonstrating the analytical potential of mid-infrared absorption on the condition that background effects are considered. Loconsole et al. (2021) discovered that a substrate-integrated microwave structure shows a response to low concentrations of water in diesel as a result of changes in electromagnetic transmission. Although diesel is not Jet A-1, the study is relevant to sensor design since it proves that compact dielectric interrogation can be carried out in a mixture of hydrocarbon and water. When thinking about using such a sensor at an airport, the main research questions are intrinsic safety, temperature compensation, cross-sensitivity to fuel composition, fouling, pressure rating, and flow disturbance together with correlation to the accepted aviation-fuel water metric.

Particles require their own physical pathway because static bottle or membrane samples might not manage to capture the temporary bursts that take place after the valve has been moved, whether because of maintenance, a disturbance to the hydrant, or as a result of filter degradation. To tackle this limitation, He et al. (2023) carried out a dynamic optical measurement of particle swarms in jet fuel, using the principles of Mie scattering and extinction across a range of typical flow conditions. The general conclusion is that a continuous particle sensor is capable of detecting temporal features which a periodic sample cannot. It is still necessary, however, for automated compliance systems not to treat each optical excursion as a clear sign of a solid-particle violation since bubbles, water droplets and fouling of the optical window can also cause light to be scattered. False alarms can be reduced by combining data from water detection, differential pressure measurements, flow steadiness assessments and signal shape diagnostics. ASTM D2276-22 is a suitable reference for assessing particulate contamination by means of line sampling and may therefore be used to validate a new in-line particle monitor and to confirm disputed events.

Electrical conductivity is very well suited to direct automation since the ASTM D2624-22 standard not only specifies methods for measuring conductivity both in the laboratory and in the field but also recognizes the use of in-line meters. It is important because the way charge is dissipated when the fuel is being handled depends on the electrical properties of the fuel and this can be changed by the use of additives. A strong compliance system should measure the conductivity together with the temperature, the history of additive usage and the batch number and then apply the appropriate approved limits for that type of fuel and for that location, at the same time preventing an automatic release if the calibration or compensation status is invalid. Density is just as useful as a rapid means of identifying the fuel and of detecting contamination. A reference value for density can be obtained using the ASTM D4052-22 method, while in-line density and temperature transmitters can provide continuous trend data. Even though a sudden change in density does not amount to a final determination of compliance, it can indicate mixing, the receipt of the wrong product or an abnormal transfer before a complete laboratory analysis can be carried out.

The issue of chemical contamination is the most difficult to deal with in the case of a sensor that is designed for a particular purpose, as a variety of unwanted substances have hydrocarbon properties similar to those of aviation fuel. It has been shown by researchers at Saudi Aramco that even a small amount of diesel contamination can have an effect on the properties required by the Jet A-1 specification, and that the use of simulated-distillation GC-FID is effective in detecting this kind of contamination (Naqvi et al., 2024). This reinforces two design principles. First, automated systems should consider both batch and transfer data because the risk of cross-product contamination rises at places where different products use the same infrastructure. Second, rapid spectroscopy should be seen as a fingerprint or anomaly detector and not be treated as a general substitute for reference chromatography and the specification tests; whenever an abnormal spectral pattern is detected, the fuel should be isolated and further confirmatory analysis carried out before it is permitted to reach the aircraft.

5. Real-time and rapid sensing technologies

Because the fundamental molecular vibrations provide a higher level of discrimination than the overtone-based bands in the near-infrared region, the use of mid-infrared and combined MIR/NIR techniques can improve chemical specificity. In a study carried out by Câmara et al. (2022), multivariate curve resolution and partial least-squares methods were applied to combined MIR and NIR spectra with the aim of identifying and quantifying contaminants in jet fuel. Boddapati et al. (2023) used extended-wavelength FTIR spectra in conjunction with statistical modelling to predict combustion-relevant properties of jet fuels and the various constituent species. These studies support the concept of spectral soft sensors, which are analytical models which transform a measured spectrum into estimates of properties or anomaly scores. In a compliance architecture, soft sensors are most useful when used for continuous surveillance and triage; if a prediction is nearing a specification boundary or goes outside the validated model domain, the system should call upon a reference method rather than making an irreversible release decision solely on the basis of the model.

Fluorescence and Raman techniques provide complementary results. Cámara et al. (2024) demonstrated that fluorescence excited-emission, when used in conjunction with PARAFAC and MCR-ALS, is suitable for the identification and quantification of kerosene-solvent contamination in Jet A-1, explicitly stating that the method is appropriate for on-line screening. Ambre et al. (2024) developed a chemometric method based on Raman spectroscopy for predicting the obtained cetane number and proposed a miniaturized flow-cell approach for live fuel sensing. These techniques have potential because they can be made compact and do not require the use of reagents, but they are sensitive to the condition of the optical window, the fluorescence background, laser stability and changes in the composition of sustainable or synthetic fuels. Consequently, self-check channels, automatic reference spectra, window-fouling diagnostics and maintenance alarms should therefore be included as standard quality features in future airport instruments rather than being regarded as afterthoughts.

Property modelling can be used just as effectively to complement physical sensing. In order to predict the properties of jet fuel and at the same time take uncertainty into account, Hall et al. (2022) applied a probabilistic mean quantitative structure-property relationship method. Because it takes uncertainty into consideration, this approach is very suitable for automated compliance. A digital system should not convert each model estimate into a simple green or red decision; rather, it needs to compare the confidence interval, the calibration status and the trend direction with the appropriate decision threshold. In case uncertainty overlaps a limit, the safe course of action is to say 'hold and verify', not to force a classification. Probabilistic logic also helps in prioritising the laboratory's workload since batches that are stable and far from the limits can be left to be monitored routinely, while those having uncertainty or showing a drift should be subject to immediate confirmatory testing.

Table 1 summarizes the most relevant measurement channels. The evidence shows that it is preferable to use a multimodal sensor pod rather than a single general-purpose instrument. A practical pod could include measurements of water content, optical particle monitoring, conductivity, density and temperature, differential pressure and flow, as well as a spectral channel at some of the high-risk checkpoints. This arrangement provides both direct variables and contextual variables. Context is important because different operational responses are required when there is a conductivity deviation during additive dosing, a particle surge after a hydrant has been restarted, and a spectral abnormality during product changeover, even if each of these situations causes a numerical alarm. The integrated system therefore needs event semantics, not just data acquisition.

Table 1. Real-time and near-real-time measurement technologies relevant to Jet A-1 quality assurance.

Measurand	**Candidate technology**	**2020–2025 evidence**	**Operational strengths**	**Key limitations**	**Recommended compliance role**
Water: dissolved / entrained / free	Optical, photothermal, dielectric or process-proxy sensing	Ricchiuti et al. (2022); Loconsole et al. (2021); Brailko et al. (2022)	Continuous trend, early ingress detection, can support automatic hold	Temperature and composition cross-sensitivity; fouling; correlation to reference metric	Continuous surveillance; confirm with ASTM D6304 when required
Particles / solids	Light scattering and extinction	He et al. (2023)	Captures transient contamination in flowing fuel	Bubbles/water can confound; optical-window condition; size dependence	Post-filter and into-plane event monitoring; validate with ASTM D2276

Electrical conductivity	In-line conductivity meter	ASTM D2624-22	Mature field measurement; fast deterministic input	Temperature/additive history and calibration status must be considered	Direct compliance/trend input where approved
Density / temperature	Vibrating or in-line density + temperature	ASTM D4052-22	Rapid identity and mixing indicator; useful compensation variable	Not a complete contamination diagnosis	Receipt verification, batch tracking, sensor compensation
Chemical fingerprint / multiple properties	NIR, MIR/FTIR, fluorescence, Raman + chemometrics	Câmara et al. (2022, 2024); Li et al. (2024); Ambre et al. (2024)	Rapid multiproperty screening and anomaly detection	Calibration-domain dependence; instrument transfer; SAF composition shifts	Screening, model-based alerts, targeted confirmatory testing
Filter/process condition	Differential pressure, flow, valve state, water-separator response	Brailko et al. (2022, 2023)	Connects product signal to equipment state and recovery actions	Indirect proxy; needs independent product-quality evidence	Sensor fusion, filter health, recirculation and maintenance logic

6. Automated compliance monitoring architecture

Compliance monitoring using automation starts with guaranteeing the integrity of the measurements. Each sensor channel must have a quality flag which includes information on calibration validity, the result of self-tests, the plausibility of the signal, time synchronization, communication condition, and the maintenance status. The logic at the edge level should discard impossible combinations and identify frozen values, drift, or disagreements between redundant channels. For instance, a water signal rising sharply without any corresponding change in optical turbidity, electrical response, or process state could be a sign of sensor fouling rather than real contamination. On the other hand, simultaneous changes in water level, particulate scattering, and filter differential pressure during transfer warrant a more severe response. The PLC or the edge computer therefore needs to carry out deterministic validation before the measurements are passed on to the compliance engine.

The compliance engine is a controlled rules service and not a general artificial-intelligence classifier. It is given validated measurements together with the batch's identity, the type of fuel, the location, the current version of the standard, the site's operating limits and the process state. The specification framework for aviation turbine fuels is provided by ASTM D1655-24b, while the various methods explain how each property is determined. The Joint Inspection Group's operating standards include the procedural controls applied at airport depots, at hydrants and during in-plane operations (JIG, 2021a; JIG, 2021b). The digital rule base must maintain this hierarchy. A value can be within the sensor's operating range and yet still be inappropriate for release if the required reference test is missing, the batch is not authorised, or a procedural hold is in place. Compliance is therefore automated by combining product evidence with workflow evidence.

It is better to have four possible outcome states than to use a simple pass-fail indication. A 'release' decision is made when the required evidence is valid and the values stay well within the approved limits. The 'hold and sample' option is used when uncertainty increases, a trend is approaching a boundary, or a soft sensor has left its calibration range. 'Recirculate or condition' is applicable when the facility has an approved recovery method, for example settling, filtration or water removal, and the process can be monitored until it becomes stable. 'Isolate or lockout' applies in the case of confirmed non-conformance, a risk of wrong product, disagreement by critical sensors, or failure of safety requirements. Human approval is still necessary for certain actions, but automation can stop a transaction from continuing once a hard interlock has been violated.

The information layer must link the PLC to the SCADA system, the aircraft fuelling management system, the laboratory information function, and the quality historian. Whenever a transfer takes place, it should create a traceable digital record which includes the source and destination, the batch number, the timestamps, the measured values, the calibration identifiers, any alarms, the operator's acknowledgements, the samples, the laboratory results and the final disposition. Brailko et al. (2022) stressed the need for integrating continuous water monitoring with airport systems and the usefulness of logging for making operational decisions. This same idea can be applied to multiparameter quality assurance. Having a signed event trail enables incident investigations, discussions with suppliers, filter-performance analysis, predictive maintenance and continuous improvement without the need to rely on reconstructed paper records.

Cybersecurity and functional safety should be designed in a combined manner. Since a connected fuel-quality sensor can act as a control input, it is necessary to include authentication, access control by role, network segmentation, secure configuration, version control and recovery procedures as part of the measures taken to secure correct measurements. The remote dashboards must not offer an uncontrolled means of bypassing a local interlock. Similarly, if the network connection is lost it should not quietly change an invalid state into a state that allows fuel to be pumped. Figure 2 shows a fail-safe architecture in which the measurements taken at the field level are verified locally, the compliance logic is made explicit, the higher-level applications provide the appropriate context and reporting, and the automated actions are kept within the approved procedures.

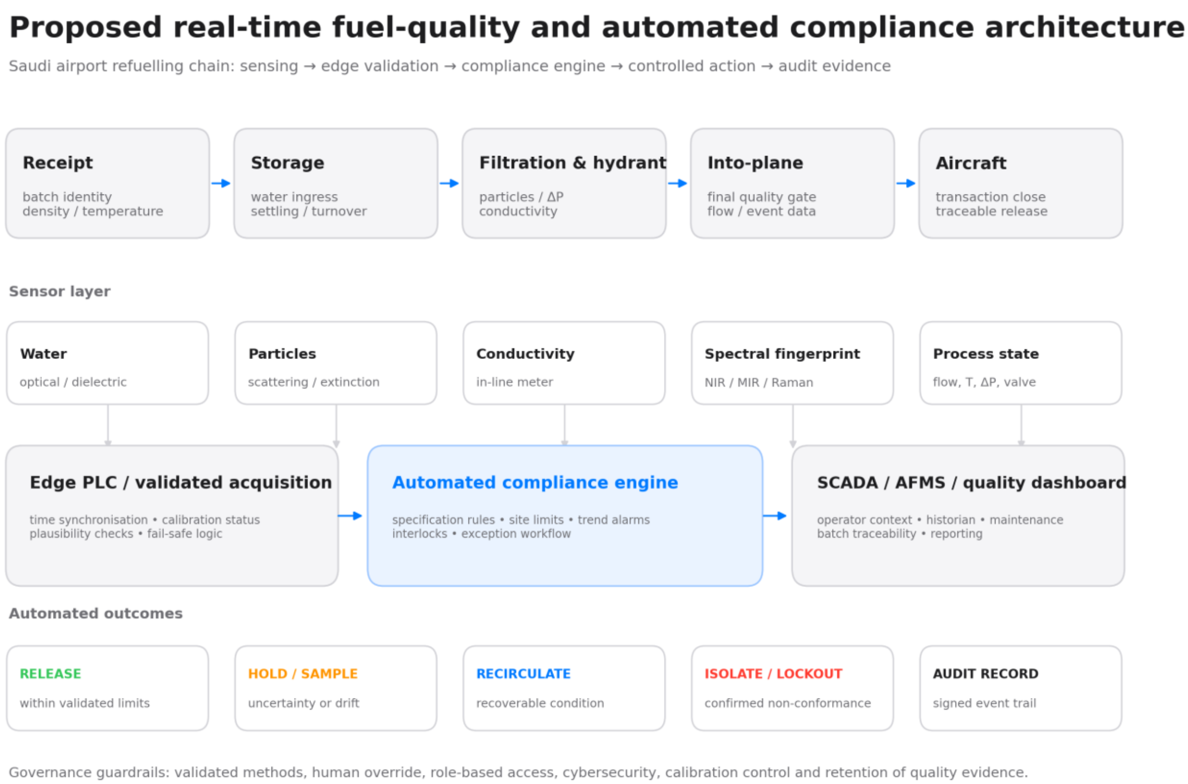

Figure 2. Proposed architecture for real-time measurement

Table 2. Illustrative automated compliance logic by refuelling-chain checkpoint. Exact acceptance values must follow the current approved specification, method and site procedure.

Checkpoint	**Continuous evidence**	**Decision logic**	**Automated response**	**Audit evidence**	**Saudi implementation value**
Airport receipt	Batch ID, density/T, conductivity, spectral fingerprint, water/particles	Compare with authorized batch and validated baseline; detect abnormal trend or wrong product	Hold receipt; route sample; isolate source if confirmed	Transfer record, sensor validity, sample/lab link	Prevents contamination propagation into airport inventory
Bulk/service storage	Water trend, T, tank movement, particle events	Trend water risk through settling/turnover; flag unexpected excursions	Hold transfer; settle/recirculate; inspect drain and tank condition	Tank event history and corrective-action record	Thermal cycling and dust require local sensor validation
Post-filtration / hydrant	Particles, water, conductivity, ΔP, flow	Correlate quality outputs with filter and hydraulic state	Stop/recirculate; change filter; sample downstream	Filter DP and alarm chronology	High throughput favours continuous early warning

Into-plane release	Final water/particle screen, conductivity where used, flow and transaction data	Require valid measurements, authorized batch and no unresolved hold	Prevent/stop transaction; sample and escalate	Aircraft transactio n-quality record	Supports traceability and punctuality without removing human oversight
Exception / degraded mode	Calibration status, communication s, redundant channels	Invalid or uncertain data cannot default to release	Safe hold or approved manual procedure	Reason code, override authority, time-stamped evidence	Cybersecurity and functional safety are measurement requirements

7. Saudi Arabia and Vision 2030 implementation context

The conditions existing at Saudi airports have an effect on both the engineering design and the business case; since high ambient temperatures, intense daily thermal cycling, dust contamination, the need for long outdoor pipe runs and fast turnaround operations can affect optics, electronics, seals, density compensation and the behaviour of water, field validation must be carried out during both summer and winter operations, as well as throughout day-and-night cycles, under low and high flow conditions, when hydrants are restarted, during tank turnover and at the time of maintenance. The aim is not simply to show that a sensor functions with a laboratory sample, but to measure the false-alarm rate, the risk of undetected detections, drift, the required cleaning interval and the level of uncertainty within the real environmental conditions. It is these parameters that decide whether or not automation reduces the workload or instead generates a new stream of alarms.

The larger the scale of aviation in Saudi Arabia, the more important it is to carry out early detection. According to the Saudi Aviation Strategy, by 2030 there will be over 250 destinations and major developments at airports and for cargo (GACA, 2023). NIDLP stated that in 2024 passenger numbers reached over 128 million and air cargo exceeded one million tonnes, while GACA also reported that during that same period there had been continued growth in the number of flights, connectivity and cargo (NIDLP, 2024; GACA, 2025). This growth results in a greater number of fuel transfers, more quality records, additional filter cycles and more opportunities for abnormal events. As long as the technology has been validated and the alarm logic is well controlled, continuous surveillance enables quality assurance to increase in proportion to the amount of data rather than in a manner that is directly tied to manual sampling.

The link with Vision 2030 is operational, not promotional. As highlighted in the Vision 2030 Annual Report 2024, national transformation, logistics capability, infrastructure performance and digital modernisation are the key areas in focus (Saudi Vision 2030, 2024). Real-time fuel-quality systems support these themes by enhancing asset utilisation, preventing excess fuel holds, improving auditability and enabling data-driven maintenance; they can also aid in guaranteeing punctuality. A contamination incident found on the aircraft has operational consequences; whereas if the same contamination is detected at the time of receipt or during storage transfer, it can be isolated before it spreads throughout the airport's distribution system.

It is better to carry out a national implementation in stages than to carry out a single large procurement. In the first phase, a reference dataset should be set up by installing non-controlling sensors alongside the existing approved tests at one or more of the high-throughput airports. In the second phase, the alarm thresholds should be verified, and advisory decision support should be introduced. In the third phase, reversible actions such as alerts, requests for sampling, recommendations for recirculation and holds on transactions should be automated. Hard interlocks should only then be connected to selected continuously measured variables after there has been sufficient evidence. This step-by-step approach secures safety while at the same time providing the performance data that is required by operators, regulators and fuel suppliers. It also results in the creation of a Saudi dataset which can be used to support future analytics without having to apply unvalidated machine-learning models to safety-critical control.

The inclusion of sustainable aviation fuel makes it necessary to have this roadmap. Even if the final fuel still conforms to the specified standards, alternative blending ingredients can alter the spectral fingerprints, density, aromatic content and other characteristics. Calibration models based solely on conventional petroleum-derived Jet A-1 might therefore fail to recognise legitimate fuels of the future as normal. Spectral libraries and soft sensors should be versioned according to the fuel production pathway and be updated using representative certified blends. Techniques such as NIR, FTIR, Raman and probabilistic property modelling could be highly useful exactly since they contain information on composition, but the governance of their calibration must keep up with changes in the fuel mix (Li et al., 2024; Boddapati et al., 2023; Hall et al., 2022).

8. Discussion

The literature does support continuous fuel-quality monitoring, but it does not back up the idea that a single sensor can certify Jet A-1 against all the requirements. The most viable approach in the near term is a layered one. Direct and well-established measurements, such as conductivity and the key process variables, can be used with deterministic rules. Water and particle sensors can offer high-frequency monitoring of contamination provided that they have been verified using reference methods. The spectroscopic channels can detect drift in multiple properties and chemical anomalies. Laboratory methods still serve as the final means of assessment for parameters which cannot be measured continuously, for certification events, and in all cases where uncertainty comes within a specification boundary. This hybrid approach upholds regulatory defensibility while guaranteeing the time coverage associated with uninterrupted monitoring.

Another point is that measurement uncertainty has to be regarded as an operational variable. Most academic sensor studies merely give information on sensitivity, prediction error or correlation, whereas airport operations require repeatability over a period of months, robustness with respect to temperature and flow, calibration traceability, ease of maintenance and knowledge of the possible failure modes. A sensor which picks up very small changes but suffers drift following window fouling may in fact be less useful than a sensor that is only slightly less sensitive but has reliable self-diagnostics. Procurement specifications should therefore include requirements for uncertainty budgets under real-field conditions, calibration-transfer procedures, response-time characterisation, contamination challenge tests, cybersecurity documentation and a defined safe state. Thus, technology assessment is shifted from impressive laboratory graphs to reliable quality assurance.

Another point relates to data architecture. Real-time compliance is not obtained by putting sensors on a dashboard; it is only when measurements are linked to information about a batch, a transfer and a decision that their value appears. Time synchronisation enables operators to tell the difference between an upstream contamination event and a fault in a downstream sensor. When the system is integrated with the filter differential pressure and the valve status, it becomes possible to determine whether a particle spike is due to a disturbance in the equipment. By associating laboratory results with the same event, the alert thresholds can be continuously recalibrated. This kind of contextual dataset can later be used to support predictive maintenance or anomaly detection, but deterministic traceability must be set up before advanced analytics are introduced.

There are also risks relating to governance. If a green icon masks out-of-date calibration, an expired model or missing laboratory evidence, it can give a false sense of confidence. The design of the human-machine interface should therefore make both validity and uncertainty clear. Operators should be able to see why a transaction has been held, which rule has been triggered, what evidence is absent and what authorised recovery action is available. Similarly, change management is important: when there is a revised ASTM or JIG requirement, it should result in a controlled rule update, a testing record and a defined effective date. The digital system should make compliance changes more traceable rather than hiding them within the software.

The review indicates that, for Saudi Arabia, the most appropriate first step is not the full automation of fuel release but rather the early detection of abnormal events within a rapidly growing aviation network. Monitoring upon receipt can guard against the airport storage tanks receiving the wrong or contaminated product; storage monitoring can detect water ingress and settling; sensing after filtration can show when the filter is breached or when particles are released; and monitoring inside the aircraft can provide a final record of the event. When these various checks are connected together, the system creates a continuous account of the quality of each fuel shipment. This account supports safety, operating efficiency and the possibility of scalable assurance as the targets of the Vision 2030 aviation programme are pursued.

9. Research gaps and future agenda

The following five research priorities arise. The first is that sensor trials must make use of representative Saudi Jet A-1 fuel and certified sustainable-fuel mixtures under local temperature, dust and humidity conditions. The second is that studies should include operational metrics, for example, the probability of detection, the frequency of false alarms, the time to detection, the drift rate, the cleaning interval and the recovery following calibration, not just the laboratory regression statistics. Third, multimodal fusion should be assessed by means of realistic confounders such as water droplets as opposed to solids, bubbles rather than particles, temperature changes rather than composition changes, and additive dosing instead of contamination. Fourth, common data models are required so that the sensors, PLCs, SCADA systems, AFMS and laboratory records all have access to the same batch identifiers, timestamps, units, quality flags and calibration metadata. Fifth, regulators and operators should establish the criteria for evidence when continuous measurements are to be used as either supplementary or substitutive compliance evidence.

Analytical research in the future should be directed towards transferability. Although spectrographic and machine-learning models can achieve a high degree of accuracy on carefully selected datasets, they fail when the instruments, airports, or fuel routes change. It is therefore more valuable to carry out external validation at various locations than to make gradual improvements on a single training dataset. Instead, probabilistic models, methods for detecting novelty, and conservative escalation rules should be chosen over simple point predictions. A national validation programme could keep the reference materials, use challenge datasets and organise inter-laboratory comparisons, thus allowing suppliers to show that new sensors perform consistently before they are linked to operational interlocks.

Above all, cybersecurity research should be regarded as a component of metrology. When a sensor reading is capable of stopping or allowing an aircraft fuelling operation, then the integrity of the measurement chain becomes a safety requirement. Pilots in the future should check secure time synchronisation, signed calibration records, authenticated firmware, the ability to maintain local control when the network is lost and the forensic preservation of alarms. This is especially important given that airport systems are becoming progressively interconnected and that quality data are being shared among suppliers, operators and regulators. The goal is to establish a digital chain of custody whereby both the fuel and the evidence relating to the fuel remain trustworthy.

10. Conclusion

The approach outlined contributes to Vision 2030 by enabling fuel-quality assurance to become more scalable, traceable and based on data as the aviation network grows. Yet its success will rely on rigorous testing rather than on enthusiasm for new technology. Continuous measurements must be compared with established methods, uncertainty should lead to escalation rather than requiring a forced pass-or-fail decision, and cybersecurity must be incorporated into the measurement assurance case. A step-by-step Saudi programme, which starts with parallel monitoring, moves on to issuing advisory alerts and then initiates carefully limited automated actions, will provide the necessary evidence for safe implementation. The ultimate aim is not automation for its own sake, but rather earlier detection, fewer propagation events, stronger compliance evidence and consistently safe aircraft refuelling on a national scale.

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