

Jet Fuel Contamination: Forms, Impact, Control, and Prevention

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Abstract: This paper describes commonly used processes to produce aviation fuel and alternative routes with potential production yields for sustainable aviation fuels (SAF) like HEFA and ATJ. It also presents the possible sources (crude oil, refinery processes), causes (filter clogging, engine failure), and forms of contamination in both conventional and alternatively produced aviation fuels. Special attention is focused on the threats of fuel contamination with solid particles/trace elements, water, microorganisms, and fatty acid methyl esters (FAME). This review also presents the standard and novel advanced methods (ICP-MS, MALDI, ViPA) for identifying contaminations in aviation fuel. It also identifies possible ways to control and eliminate the risk of contamination, such as the following coherent JIG system to ensure the quality of aviation fuel. Another approach that is very interesting and worth considering for future development is the idea of predictive maintenance and machine learning in monitoring and detecting contamination.

Keywords: jet fuel contamination; sustainable aviation fuels; solid particulates; trace elements; water; microorganism; FAME



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1. Introduction

The global aviation industry is expected to expand continuously in the coming years due to the movement of people all over the world using air transport [1]. Great air traffic expansion requires much aviation fuel, meaning that shrinking petroleum reserves will become a challenge. The International Civil Aviation Organization (ICAO) also targets the reduction in global CO₂ emissions by 50% (up to 2050) in comparison to emissions in 2005 within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program [2]. Moreover, in 2021, an even more ambitious plan for the aviation industry was created, according to which it will be possible to achieve net-zero carbon emissions by 2050 [2–4]. In this case, carbon reduction would be mostly achieved by Sustainable Aviation Fuel (SAF) production [2,3]. The main components with a higher potential of deployment in SAF technologies, such as Hydroprocessed Esters and Fatty Acids (HEFA) or alcohol to jet (ATJ), are produced from fats, oils, sugars, alcohols, or synthesis gas [5,6]. It is clear that synthetic blend components (SBC) should be compatible (meeting the technical specifications) with conventional jet fuel in order to replace it [4,6]. The technical certification of SBC as an alternative jet fuel (AJF) is regulated by ASTM D7566—“Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons” [7]. This is the first specification that SAF needs to meet. After that, it can be blended with conventional fuel up to the allowable certified percentage volume limit outlined in D7566. After the blending process, the prepared fuel mixture is certified under ASTM D7566 or ASTM D1655 [3,4,7,8]. The conventional fuel is determined by the Ministry of Defence namely Defence Standard DEF STAN 91-091 [9] or ASTM Standard Specification D1655. The above specifications were set in the Aviation Fuel-Quality Requirements for Jointly Operated

Systems (AFQRJOS) by a number of fuel suppliers in order to facilitate complex jet fuel supply arrangements.

In both approaches, quality is paramount in aviation fuels due to their critical application, regardless of the type of jet fuel production (conventional or AJF). It is crucial to protect an aircraft's safety, operability, functioning, and robustness [10]. A coherent system for conventional and novel technologies embraces successive types of inspections to ensure quality protection. The Joint Inspection Group (JIG), as the world-leading organization for the development of aviation fuel supply standards, stands as a permanent guard, upholding jet fuel quality control and working procedures for handling, covering the entire supply chain for aviation fuels, including production areas (refinery), fuel depots, and airports. JIG standards are adhered to by over 100 global member organizations located in over 100 countries operating with the mission to enhance aviation safety. Major standards and procedures are seen in EI 1530 for conventional aviation fuel and supplement in EI 1533 for SAF [11,12]. However, some contaminants could appear in aviation fuel, namely organic and inorganic contaminants, water, microbes, and FAME contaminants, which have a negative impact on the aircraft fuel systems, engine durability, and fuel metering system accuracy, as well as the performance and safety of jet fuel [13,14]. Unfortunately, fuel contamination is still a risk in aviation.

The most common contaminants in jet fuel are solid particles, which are derived from airborne dust, degradation products of fuel system lines (rust and scale, filter and catalyst fines), or the wear of other products. The occurrence of solid particles in jet fuels may adversely affect engines, block the engine fuel supply system, and erode critical parts in the engine and fuel control systems [12]. Water is the next meaningful contaminant, which is very dangerous for aircraft safety and could lead to aircraft catastrophe. Water can be introduced into the fuel in various ways (including humidity) from the fuel system, involving the tanks, pipelines, or cleaning operations, and it may exist in three forms: dissolved water, suspended water, and free water. In terms of the form of water, it could be observed through different methods of detection. e.g., Karl Fisher (KF-ASTM D6304/IP 438) titration for total water content or polymer optical fibres (POF) for dissolved water. The presence of water in aviation fuel at some temperature levels leads to the formation of ice crystals, finally blocking the fuel system and damaging the engine during the flight. Moreover, water causes the corrosion of metal surfaces and the forming of free particles of metal oxides, resulting in premature wear and the failure of fuel pumps [13,15]. Additionally, the water presence in fuel promotes the growth of microorganisms following the dangerous contamination of the aviation fuel. Microbial growth (bacteria and fungi) in aircraft fuel is a reliable indication that the water has not been properly stripped from the fuel because these microorganisms cannot grow without water. Water/moisture, oxygen, nutrients (e.g., alkanes, additives), temperature, and pH are all factors affecting the appearance, growth rate, and spread of microorganisms in fuel. Eliminating water is the primary method of limiting microbial growth [16]. Microbiological contamination of fuels causes the formation of gelatinous, slimy biofilms, which results in fuel-filter plugging, the failure of fuel-control devices, and corrosion of the metal and rubber surfaces of the fuel system components [17,18]. An assessment of microbial contaminations in the fuel system could be performed by standard and advanced methods, such as colony-forming units (CFU), Adenosine Tri-Phosphate (ATP), and Immunoassay-based Antibody tests [16,18]. Matrix-assisted laser desorption/ionization-time-of-flight mass spectrometry (MALDI-TOF MS) has been successfully involved in the classification and identification of petroleum microorganisms [19].

There have been discussions regarding the potential contamination of aviation fuel by Fatty Acid Methyl Ester (FAME) [6,20,21]. The presence of FAME is accepted in biodiesel, but not in aviation fuels. The contamination of jet fuels by FAME may arise due to the use of multi-product pipelines in the distribution systems. FAME is a compound that has excessive surface activity and adheres to the walls of pipes and tanks during the transport of diesel fuel. FAME from B7 biodiesel, which may be left in distribution manifolds, tanks,

or pipelines, could potentially contaminate jet fuel transported through the same fuel system [21,22]. The presence of FAME in jet fuel can be very dangerous for the safety of flight. It may affect the thermal stability, viscosity, and density of jet fuel, leading to coke deposits in the fuel system, and it may also impact the freezing point, resulting in fuel gelling [20,21]. FAME content is limited in jet fuels up to 50 ppm [23], and the contamination of jet fuel by FAME is a growing concern for the aerospace industry. Gas chromatography-mass spectrometry (GC-MS) (IP 585) can be used to analyse FAME up to 5 mg/kg, with the Fourier Transform Infra-Red (SPE-FTIR) Spectroscopy method (IP 583) being utilised for FAME monitoring. In the case of preventing aviation fuel contaminants, a key role is played by appropriate quality-control methods, facilities, and equipment at each point of the fuel distribution system.

This paper reviews the production pathways and specifications of conventional and non-conventional jet fuels, as well as the characterization of some crucial properties that determine fuel quality. Considered are the current problems in aviation fuel quality and the specificity of contaminants in aviation fuels, as well as advanced, innovative methods of aviation fuel quality control and prevention methods for protecting aviation fuel from contamination.

2. Conventional and Modern Pathways for Jet Fuel Production

Aviation fuels could be produced from different processes, depending on the refinery mode [24]. One of the typical processes is distillation with Merox, where the A2-3 fraction from the distillation unit is converted in the Merox process into a kerosene fraction—ready to use in aircraft after doping additives. Merox is a catalytic demercaptanization process that changes mercaptans into disulfides through oxidation. Merox is used to remove impurities and neutralise acidity in the absence of sulfur-alkaline effluents and exhaust air [25]. Merox has low CAPEX and OPEX, and the process is quite simple and robust, with unique features and the optimum usage of chemicals [26]. Aviation fuel, which is produced by using the Merox process, has a natural sulfur molecule that stops peroxide growth. In this case, there is no requirement to add antioxidants (AOX) [26,27].

Another very commonly used process is hydrotreating, which removes olefins, sulfur, nitrogen, contaminants, and aromatics from the fractions of distillation units. What is more, it changes the organometallic level. The process occurs at high temperatures and ambient pressures, where lighter naphtha and lower fractions are converted through catalytic reforming to obtain aviation fuel according to the main specification [28]. In the hydrotreating process, most peroxides are removed from the fraction, such as sulfur, nitrogen, and oxygen, which is why it is necessary to add AOX [27,28]. The lack of AOX destabilizes the fuel, which goes into oxygen reactions, causing hydroperoxide structures. Hydroperoxides negatively affect seals, membranes, and materials produced from nitrile rubber or neoprene [27]. Both specifications, DEF STAN 91-091 and ASTM D1655, treat using AOX as an optional additive for Jet A1. However, for military purposes, and for long-term storage for more than 6 months, it is necessary to dose AOX. A similar situation with AOX dosing is the hydrocracking process, where hydrocarbons are cut and short hydrocarbons are saturated by hydrogen [29]. It consists of the hydrotreating and hydrocracking processes to reject impurities from the heavy vacuum gasoil [30]. Considering the catalyst function, it is possible to distinguish four processes [29]:

- Two-way catalyst, responsible for dehydrogenation molecules to achieve alkenes and also for hydrogenating olefinic complexes.
- Single-way catalyst, responsible for carbon–carbon bond cutting and hydrogenation of molecules.
- Monofunctional acidic catalysts for molecular hydrogen initiated on Brønsted acid sites, known as “catalytic cracking”.
- A lack of a catalyst for hydropyrolysis in a temperature range from 500 °C up to 600 °C with gaining pressures.

Hydrocracking with a two-way catalyst transfers heavy vacuum gasoil (VGO) into aviation fuel, gasoline, and diesel [29]. According to Ch. Peng [30], nickel-molybdenum and nickel-tungsten-based catalysts are widely used in hydro-processing. In particular, the NiMo/ γ -Al₂O₃ catalyst has demonstrated good hydrotreating (HDS and HDN) activity, while the NiW/Y-zeolite catalysts have a hydrocracking activity and targeted product selectivity. Figure 1 represents a flow diagram of a hydrocracking unit with a different return of tail oil, namely: a single stage once through the process (SSOTP), full-tail oil recycled to the hydrotreating reactor (FRTHT), full-tail oil recycled to the hydrocracking reactor (FRTHC), and partial-tail oil recycled to the hydrotreating reactor (PRTHT) [29].

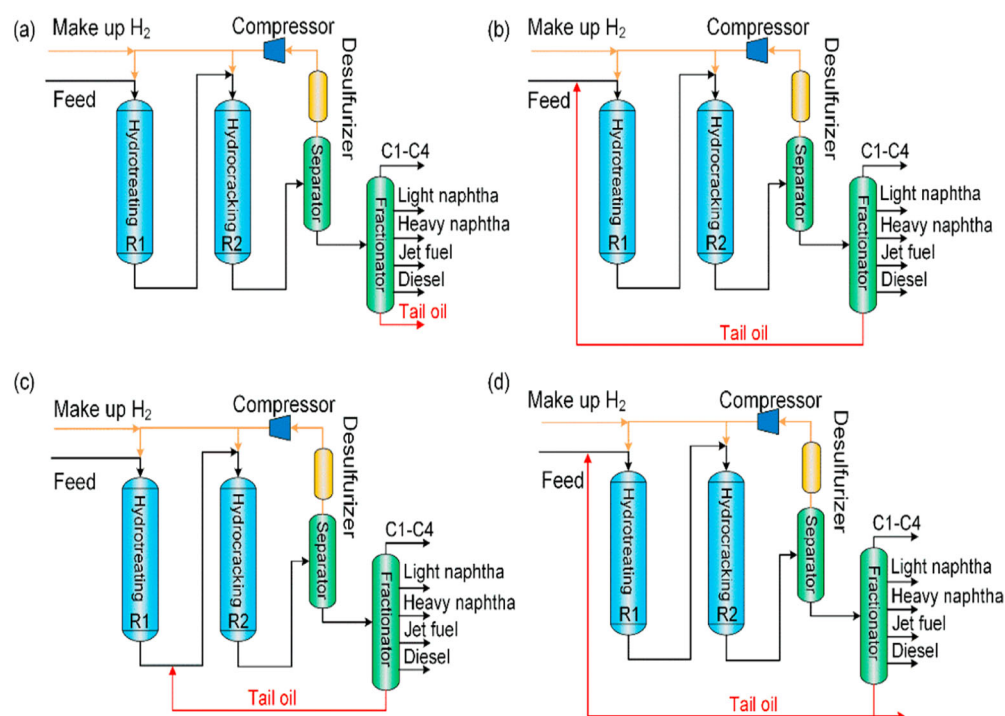


Figure 1. Hydrocracking process with different approaches of using tail oil: (a) SSOTP, (b) FRTHT, (c) FRTHC, and (d) PRTHC [30].

The main role of a hydrocracking process catalyst is to ensure the cracking and hydrogenation of heavy oils and vacuum residues. Hydrocracking with a metal catalyst ensures a product with a low boiling point or, depending on the objective, high-margin middle distillates. The hydrogenation phase (exothermic process) acts on olefins, aromatic hydrocarbons, and sulfur, as well as oxygen. The cracking process (endothermic) is concerned with the cleavage of C-C bonds. Thanks to the better selectivity of the catalyst, we can achieve better value-margin products. In order to obtain better performance from the catalyst, a few steps can be attempted, namely different modifications of the metal precursors (a metal such as molybdenum, nickel, or tungsten), which change the properties of the supports, like the structure and acidity, using new active centres like carbides and nitrides, or even using the catalyst boron, phosphorus, or fluorine [31].

Besides the production of aviation fuel from fossil sources, there is also a separate sustainable route where SBC is added to conventional jet fuel [24]. The list of components/technologies is defined in ASTM D7566. The increasing global demand for aviation fuel and the development of biocomponents are related to lowering greenhouse gas emissions and improving the technology in aircraft [32]. This leads to 80% lifecycle carbon savings compared to fossil jet fuel [24,32]. The main advantages of SBC are to reduce the emissions of soot and SO_x. What is more, it also affects the reduction in NO_x, CO, and UHC (Unburned HydroCarbons). It is worth mentioning that the main regulation drivers are involved with the Renewable Directive (RED III), ReFuelEU Aviation, ETS I Aviation, and

ICAO-CORSIA in order to introduce SAF. In general, SAF could reduce CO₂ emissions by up to 80%, depending on the level of SBC and the type of feedstock [33].

GHG could even show up to 80% reductions in the case of HEFA. These regulations are connected with increases in the share of renewable energy used in transport (RED-T). An additional aspect is the ability to spread the level of SAF in aviation fuel and the use of infrastructure for the SAF supply. In these approaches, the carriers must refuel 90% of the jet fuel available in union airports for their commercial flights. In the case of the ETS system, it is required from operators to achieve the emission allowances for all intra-EEA flights. For the broader picture of the aviation market, CORSIA wants to set annual limitations on the entire CO₂ emissions from international civil aviation by up to 85% to levels which were defined in 2019 [34].

Figure 2 presents two of the seven production technologies, namely HEFA and ATJ. It shows the main chemical processes for the production of synthetic base components ready for blending with conventional jet fuel. All these technologies comprise different types of biomasses to produce synthetic base components (SBC), which, when blended with conventional Jet-A1, provides SAF [23].

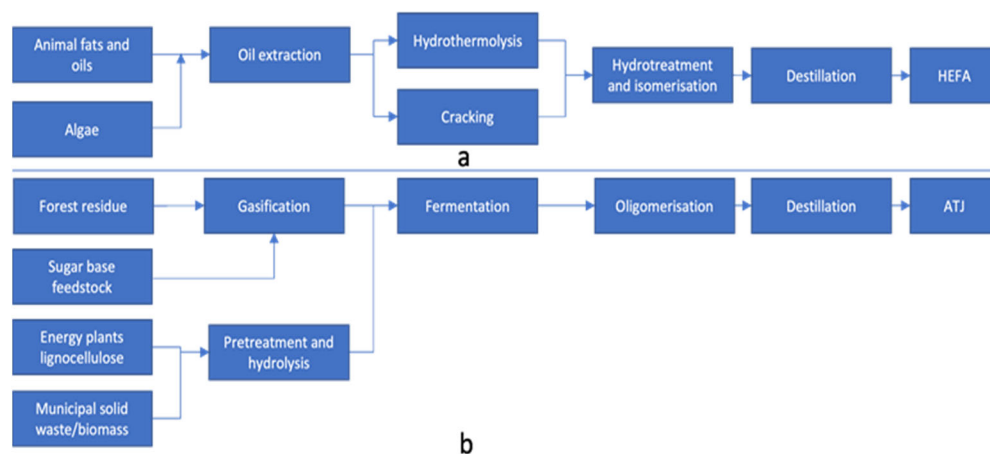


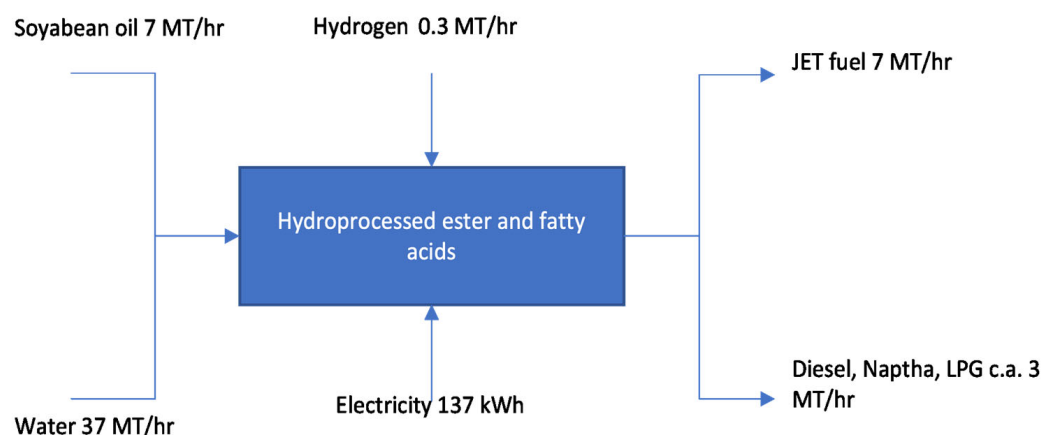
Figure 2. Selected SAF production processes with a potential raw material: (a) HEFA-production process and (b) ATJ-production process [24].

Table 1 presents the-production processes of SBC with potential feedstocks. The most popular process due to better yield and the cost-effective processes to produce SAF is HEFA. HEFA components could be blended with conventional fuel in a volume of 50% (v/v) according to ASTM D7566. The raw materials for HEFA include vegetable oil. From this group, we could choose canola, soybean, or jatropha. Another type of source we could select is grease, either brown or yellow. In terms of animal fat, we can find waste oils, like tallow or poultry fat [32,35]. Such triglycerides can be hydroprocessed to form basic synthetic components. The whole technology process consists of hydrogenation of the propane chain of the glycerol chain. In the next phase, fatty acids are put through decarbonylating and decarboxylating processes [35]. Further reactions include isomerization, which changes paraffinic hydrocarbon to iso-paraffinic in order to achieve a maximum crystallization point of -47°C [36]. At the final stage, we have distillation, which separates different streams to achieve propane, naphtha, jet, and diesel fractions [35,36].

Table 1. Alternative jet fuel production according to ASTM D7566 [23].

Pathway	Feedstock
Gasification + FT Synthesis	Waste
Fast Pyrolysis and Hydroprocessing (FPH)	Corn stover
Aqueous Phase Processing (APP)	Woody biomass
Hydroprocessed Esters, Fatty Acids (HEFA)	Soybean oil, tallow, yellow grease
Advanced Fermentation (AF)	Corn grain, sugarcane, herbaceous biomass
HydroThermal Liquefaction (HTL)	Woody biomass

Figure 3 shows the technology process of HEFA production, based on soyabean oil feedstock with the final products, namely jet fuel, diesel, naphtha, and LPG.

**Figure 3.** HEFA production technology based on soyabean oil with achieved products [35].

The HEFA process has a better fuel yield achieved from the feedstock at a level of 86–91%. Because feedstock has an extensive level of oxygen content, the process requires higher energy to be used. [35]. Another interesting technology in regard of easy access to ethanol is ATJ, which converts short-chain hydrocarbons into long-chain hydrocarbons. Thanks to this, we gain a component of Jet A1 of up to 50% (v/v) [37]. This technology uses catalytic phases, as well as the fermentation process [37]. The technology dehydrates all different oxygenates, namely ethanol, n-butanol, and iso-butanol, into olefins. In the next oligomerization phase, we obtain long hydrocarbons, which are comparable to aviation fuel [32,37]. The hydrogenation and deoxygenation olefins are modified into saturated hydrocarbons [35]. The final ATJ structure of aviation fuel, 8–16 carbon atoms, is achieved by the oligomerisation of dehydrated alcohol. This process must be conducted in a controlled way to produce the required aviation fuel specifications [37]. To achieve alcohol, a biochemical approach is often used, consisting of the yeast fermentation of sugars, saccharides from energy crops, and even microbes in some cases. The second option is to use thermochemical paths to alter the biomass to the desired alcohols, but this process involves gasification and catalytic reactions [37]. The oligomerisation of iso/n-butene lead from C12 up to C16 hydrocarbons affects the final boiling point. Of course, this process needs to be run in the presence of a dedicated catalyst to meet all of the specifications of the final Jet A1. Following oligomerisation, isomerisation and distillation achieve the jet component. The oligomerisation of olefin hydrocarbons is essential from the perspective of the maximisation of yields [32,37]. ATJ has a specific distillation curve when it is produced from butanol as the raw material. For example, the flash point of C8 oligomers is close to the flash point of Jet A1, which is about 38 °C. Higher hydrocarbons, such as C12, are in the half range of the boiling distillation range, whereas C16 hydrocarbons are at the final boiling point [38]. Figure 4 shows the technological process for the conversion of lignocellulosic feedstocks into end products, namely diesel, jet fuel, and naphtha, with the flow of the media and materials [32,35]. The lignocellulose technologies have yields at a

range of 9–23% [37,38]. ATJ could cause some performance issues, according to OEMs, and it may be involved with the relocation of carbons [38].

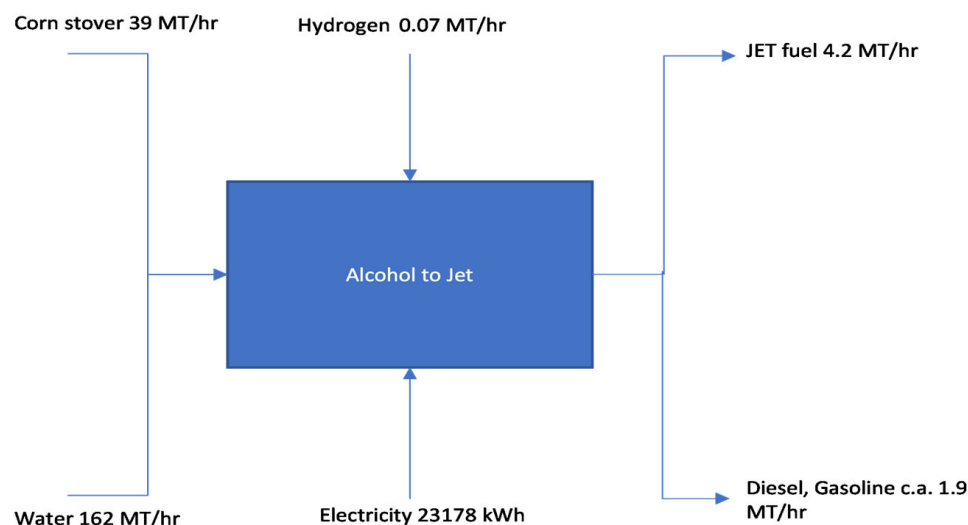


Figure 4. Product obtained using the alcohol-to-jet production technology based on corn stover [37].

ATJ and HEFA, as well as other components listed in ASTM D7566, are more exposed to the oxidation processes, which is why ASTM and DEF Stan specifications are adjusted. Hydroprocessed synthesized base components shall be doped with antioxidation additives directly after production [38].

Table 2 lists some of the main additives approved for use in the various aviation fuels.

Table 2. Additive types in aviation fuels [17].

Additive Type	JetA-1	JetA-1	JP4	JP-5	JP-8
Antioxidant	Allowed	Allowed	Required	Required	Required
Metal Deactivator	Allowed	Allowed	Agreement	Agreement	Agreement
Electrical Conductivity/ Static Dissipater	Allowed	Required	Required	Agreement	Required
Corrosion Inhibitor/ Lubricity Improver	Agreement	Allowed	Required	Required	Required
Fuel System Icing Inhibitor	Agreement	Agreement	Required	Required	Required
Biocide	Agreement	Agreement	Not Allowed	Not Allowed	Not Allowed
Thermal Stability	Not Allowed	Not Allowed	Not Allowed	Not Allowed	Agreement

Generally, aviation fuels are divided into two groups: civil as Jet-A1 (known from a military perspective as F-35) and military aviation as F-34 [39]. Jet-A1 is a kerosene fuel for turbine engines that could be used for civil aviation and military purposes [39]. This type of fuel contains several types of additives: AOX and SDA (static dissipator additive). AOX is intended to protect aviation fuel from peroxidation and gum formation. The final dosage should not exceed 24 mg/L, according to ASTM D1655/DEF STAN 91-091. From a military perspective, AOX should be in the range of 17.2–24 mg/L to protect fuel in long storage. Adding AOX blocks peroxide growth, stabilizes the fuel, and ensures long-term storage, especially for military jet fuel. By creating a constant form of radicals, synthetic phenolic antioxidants prevent the initiation of peroxide reactions [27,38]. Antioxidants are optional for fossil jet fuel. However, for synthetic base components for the production of an SAF, it is necessary to add AOX—a full list of antioxidants is specified in DEF STAN 91-091 [12,40].

For SDA (static dissipator additive), the use of this additive is essential to dissipate electric charges from the Jet-A1 during the movement of fuel. The requirement for Jet A-1 is in the range of 50–600 pS/m, which helps to prevent the casual ignition of the fuel. The first dosage rate at the manufacturing plant is up to 3 mg/L. However, there could be a situation later (due to the low conductivity of the product) to use a second doping, but in total, the dosage rate should not exceed 5 mg/L [23,36].

The physico-chemical properties of SAF are very similar to the properties of conventional jet fuel. This type of fuel can be mixed with conventional jet fuel in distribution terminals. This does not require infrastructure changes or modified engines to reduce fuel consumption [4,23]. The SBCs listed in ASTM D7566 could have trace metals and contaminants, which are either not visible or present at a very low scale in comparison to components derived from crude oil in the refinery components. That is why in ASTM D7566, there is a separate specification for SBC in order to allow the producer to learn how to handle the product, as well as the specification for SAF. It mainly concerns the production process and feedstock (both typical as well as non-conventional). Another very important issue is the means of transportation, storage, and usage of non-dedicated transport, which should be well prepared for aviation fuel or SBC [40]. Typical trace contaminants are heteroatoms and metals (e.g., iron, zinc, copper, or cadmium) that could affect the thermal stability of aviation fuel at ppb levels [40]. Each SBC process has to be distinguishable. For example, the Fischer–Tropsch Synthetic Paraffinic Kerosene (FT-SPK) pathway assumes the removal of tar and particulate matter, as well as elements such as sulfur, chlorine, and nitrogen [4]. Every producer must evaluate the manufacturing process and feedstock to monitor trace elements and contaminants.

Conventional aviation fuel is produced according to several specifications, both for civil and military purposes. The civil aviation fuel specification is determined by “Ministry of Defence namely Standard DEF STAN 91-091/Issue 14 7 March 2022 for Turbine Fuel, Kerosene Type, Jet A-1, NATO Code F-35, Joint Service Designation and ASTM Standard Specification D1655 for Aviation Turbine Fuels “Jet A-1” (Latest issue)” [40]. Both specifications are combined in AFQRJOS, which were introduced by a number of fuel suppliers in order to facilitate the complex jet fuel supply arrangements. Novel methods of producing jet fuel components required a new specification: ASTM D7566 revision 15 July 2021—Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, which covers the detailed specifications for synthetic components and their percentage level in conventional jets, Jet A1 especially [23]. This revision covers seven technologies [23]:

- Annex A1: Fischer–Tropsch hydroprocess synthesized paraffinic kerosene (SPK)—maximum volume in conventional Jet A1 is 50%.
- Annex A2: Synthesized paraffinic kerosene produced from hydroprocessed esters and fatty acids—maximum volume in conventional Jet A1 is 50%.
- Annex A3: Synthesized iso-paraffins (SIP) produced from hydroprocessed fermented sugars—maximum volume in conventional Jet A1 is 50%.
- Annex A4: Fischer–Tropsch Synthesized Paraffinic Kerosene plus Aromatics (SPK/A)—maximum volume in conventional Jet A1 is 50%.
- Annex A5: Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)—maximum volume in conventional Jet A1 is 50%.
- Annex A6: Catalytic hydrothermolysis jet (CHJ)—maximum volume in conventional Jet A1 is 50%.
- Annex A7: Synthesized paraffinic kerosene from hydroprocessed hydrocarbons, esters, and fatty acids (HC-HEFA SPK)—maximum volume in conventional Jet A1 is 10%.

Each specification has characterized the properties of fossil aviation fuel and synthesized hydrocarbons with the requirements and information about using specific additives to improve or protect the properties [37]. ASTM D1655 and DEF STAN 91-091 have fuel and production requirement specifications [37,38]. The components listed in ASTM D7566 have to pass stringent regulations according to ASTM D4054 Standard Practice for Qualification

and Approval of New Aviation Turbine Fuels and Fuel Additives [37]. A component fulfilling ASTM D7566 should be on-spec while blending with conventional Jet A1, namely ASTM D1655 [38]. Each component aligned with the additives, which are on the list in ASTM D7566, and each has to be assessed during the stringent and cost worthy process described in ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives [23,38]. ASTM D4054 for the synthetic base component covers a separate test approval that includes the evaluation of specification characteristics, evaluation of performance characteristics, component/rig/APU testing, engine testing, flight testing, the documentation in an ASTM research report, the approval of the research report by OEMs and the ASTM fuel panel, and the approval of the ASTM vote to include the fuel in a specification [23,38]. AFQRJOS describes 64 research methods and requirements, together with ASTM and IP.

A global approach to eliminating greenhouse gas emissions opens new pathways for researchers to find new routes to fuel aircraft engines. FlyZero has approved a programme for hydrogen-fuelled aircraft, which will be conducted by the UK Government's Aerospace Technology Institute (ATI) [41].

Another innovative perspective is ammonia (NH_3) and hydrogen (H_2), which are zero-carbon fuels and reduce greenhouse gas emissions. A mixture of NH_3 and H_2 is being investigated where hydrogen is used as a combustion initiator to enhance the combustion of ammonia. The main focus is to differentiate between the low-laminar flame propagation of ammonia and the high-laminar propagation of hydrogen [42]. Ammonia is mixed with hydrogen to improve combustion performance and reduce CO_2 [43].

3. Characterization of the Main Types of Contamination in Aviation Fuels

In this section, we will review the most common contaminants in jet fuel, such as particulates, trace elements, water, microorganisms, and FAME.

Standard and innovative methods in contamination monitoring

In DEF STAN 91-091 and ATM D1655, there are several methods to assess the contamination of jet fuel, which will be called standard methods in this chapter, but there are also innovative methods. A stringent specification fulfils the proper functioning of an aircraft engine, including operability in the fuel system/logistic chain. In the case of standard methods used to assess the contamination of aviation fuel during production, we could underline such methods as appearance, Saybolt colour, flash point, distillation at 15 °C, corrosion on copper, existent gum, conductivity at a specific temperature, micro-separometer, thermal stability, FAME content for cross-contamination, and particulate contamination [12].

Visual inspection (ASTM 4176) in aviation fuel is a very important parameter in assessing fuel contamination in the entire logistics chain. This method is a fail/pass procedure that helps to check for potential particulates in middle distillate fuels with a distillation end point of 400 °C [44]. More details are described in DEF STAN 91-091, Issue 14 Annex F.1. According to DEF STAN 91-091, Issue 14, tank-side sampling could be assessed by visual appearance, which means clear, bright, and visually free from solid matter and undissolved water [44]. Colour (ASTM D156)—the Saybolt Chromometer Method is valid at the point of manufacture and described as “Saybolt Colour units” [45].

The visual appearance may be declared when the aviation sample colour does not allow the Saybolt scale. In this case, all unusual colours of the base fuel should be noted in the Certificate of Quality (CoQ) as the colour change could be an effect of fuel contamination [9]. In some situations, the production unit colour could change due to changes in the catalyst, level of aromatic content or crude oil characteristics, and the refining process. More details are described in DEF STAN 91-091, Issue 15, Annex F.4.

Another property is corrosion on copper (ASTM D130), where in a 2 h bath at a temperature of 100 °C, the corrosiveness is assessed on the copper material. It is known that crude oil has a sulfur content, which is removed in different installations, such as the hydrotreating unit or Merox process. However, in this case, the most important are

the different chemical compounds of sulfur, which affect corrosion and the corroding of numerous metals, as well as affecting the conductivity properties. Sulfur could be in the form of mercaptans, sulfides, disulfides, or thiophenes. The free (elemental) form of sulfur affects the corrosivity of metals, especially copper [46]. Mercaptan sulfur leads to the corrosion of cadmium, as a metal or plating, and causes a negative effect on synthetic rubbers [47].

Electrical Conductivity (ASTM D2624)—High electrical conductivity releases electrostatic charges from the fuel to prevent autoignition. It is possible to add a static dissipater additive to protect aviation fuel. Jet A1 should have electrical conductivity ranging from 50–600 pS/m. Raw hydrocarbons are non-polar, and their blends are not conductors of electricity. However, in practice, they always enclose trace amounts of constituents, which cause the growth of conductivity [47]. It is known that electrical conductivity dissipates charges as the fuel passes through the logistics chain, so the best way is to add SDA downstream of the chain. If the product does not have conductivity, this information should be noted in the Certificate of Quality (CoQ). Sometimes electrical conductivity drops below 50 pS/m (it could decrease up to 25 pS/m). This information should also be declared on the CoQ—in this case, the product can be released, but with annotation: “Product released below 50 pS/m due to conductivity loss as per Annex F of DEF STAN 91-091” [40]. EI 1530 defines some possible methods of affecting conductivity (it does not specify whether the conductivity will decrease or increase): impurities, additives/other chemicals in the water phase, microbes, icing, surfactants, poor quality of caustic, or inactive clay filters in the Merox process [12]. Electrical conductivity correlates with the temperature of the fuel. A high-fuel temperature could mean a change in conductivity. A similar situation occurs with the viscosity of the fuel, where highly viscous fuel may cause high changes in electrical conductivity. Some additives, like lubricity-improver additives for military purposes, show more loss in electrical conductivity. The main reason to add SDA is to increase electrical conductivity to dissipate charges and prevent ignition of the fuel. On the other hand, higher levels of electrical conductivity, above 600 pS/m, could lead to errors in fuel-level gauges [47].

The following method is thermal stability (JFTOT) (ASTM D3241), which is used to characterize the propensity of aviation fuel to deposit breakdown products within the fuel system. The fuel is pumped above a heated pipe at around 260 °C, with the flow of aviation fuel from 3 mL/min for over 150 min. The decrease in pressure on the filter is also defined. Interferometric tube rating (ITR) and ellipometric tube rating (ETR) are treated as referee methods, where the thickness of the deposit should not exceed 85 nm. Degradations in the pipe are comparable to the reference scale, and the referee number is stated as decomposition in SI units [48].

The most important parameter is particulate contamination (ASTM D5452), involving jet fuel sample filtration through a membrane filter (tested) and control membrane. After that, the mass difference is assessed between the weight of the membrane [49]. ASTM D5452 covers gravimetric determination by filtration of the particulate contaminant in a sample of aviation turbine fuel delivered to a laboratory. The values stated in SI units are to be regarded as the standard. The mass-change difference identifies the contaminant level per unit volume. Gravimetric filtration has a limit set at a maximum of 1.0 mg/L [49]. However, assessing particle counts could result in misleading false/positive values, where low levels of free water are present in aviation fuel, meaning it is essential to utilize a chemical treatment to remove water. Joel Schmitgal [50] ran an investigation in respect of the area of contamination. He noticed a particle count limit of 19/17/14/13 for the 4 µm (c)/6 µm (c)/14 µm (c)/30 µm (c) size channels in MIL-STD-3004 for aviation turbine fuel, and that MIL-DTL-83133 has been shown to be in agreement 92% of the time.

In the case of novel methods, we could underline Scanning Electron Microscopy (SEM), which provides images and the insights into the nature of the particles at the level of nm. The initial area of utilization was the nuclear sector to research radioactive and harmful materials [51]. A Scanning Electron Microscope provides crucial information about the

structure and external morphology of the analysed constituents. An SEM is combined with backscattered electrons (BSE) and, thanks to its high sensitivity, it provides better-quality pictures of the analysed material. The energy of beam electrons is from 1 keV to 30 keV, which provides detailed information about structure and could penetrate material up to 100 nm for SE and 500 nm for BSE. SEM and transmission electron microscopy (TEM) could be used together to prevent an improper evaluation of the material structure [52]. SEM analysis could be combined with the energy-dispersive X-ray analysis (EDX) to assess the filter's performance and reduction of trace elements. EDX helps to characterize separate parts of the filter by about 1 mm² with a concentration of trace elements. In this case, Caprita F. et al. used SEM images from a 500 µm scale bar FEI QUANTA 200 scanning electron microscope [53].

Both scanning transmission electron microscopy methods can be utilized to assess ash structure in the soot particles from marine and aviation engines [54]. However, the most widely used analytical technique for the assessment of trace metal is Inductively Coupled Plasma Mass Spectrometry (ICP-MS), which, together with Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), utilizes aqueous samples. However, the high organic load and viscosity of crude oil may cause the deposition of carbon on and choke the nebulizer and plasma tube of the ICP-OES, and the nebulizer, plasma tube, and sampler cone and skimmer cone of the ICP-MS, leading to the plasma being unstable, or even destroyed. That is why there is a need for a product like crude oil to utilise a pretreatment or mineralization by strong acid digestion or wet or dry combustion and direct emulsion/micro-emulsion to achieve high precision and high-accuracy results. Both ICP-MS and ICP-OES can analyse multiple elements (over 70) simultaneously, but these techniques are more expensive than atomic absorption spectrometry (AAS) and flame atomic absorption spectrometry (FAAS). ICP-OES ranges from a few to tens of ppm for special analysts where ICP-MS could reach a very low level of detection (as low as 0.02 pg/g, commonly around 1 pg/g) for almost all elements. It can perform isotope-related analysis as it separates different kinds of ions by the mass-to-charge ratio (m/z). The new triple quadrupole ICP-MS (QQQ-ICP-MS), or even multi quadrupole ICP-MS, overcome the boundaries of the single quadrupole ICP-MS (Q-ICP-MS), such as polyatomic interferences, isobaric interferences, and non-mono-charged interferences [1]. The ICP MS with multi quadrupoles (four quadrupoles) could be used to determine trace metals < 1 ppt in hot plasma with good stability of the results and repeatability [55].

Spanu D et al. ran quantitative assessments of trace elements, namely V, Cr, Mn, Fe, Ni, Cu, Zn, Mo, Ag, Cd, Ba, and Pb, in gasoline and jet fuel by ICP MS. They showed the trend of development of liquid–liquid microextraction technics. They also showed that controlling the extraction level is very important for the extractant volume. It was considered that quantitative extraction of trace elements could be performed in aqua regia extractants at 50 °C for 1 h with an enrichment factor equal to 20 (stringent environments) and was confirmed in the sulfate-ashing method ASTM D5708 [56].

The next method of assessing contamination is dynamic light scattering (DLS), a fast and financially cost-effective method [52]. The hydrodynamic radius is characterized as a potential crystallite, which spreads with a similar speed as the particles. The size of the particles can be measured with an additional cap, namely X-ray diffraction (XRD) [52].

DLS is used to determine the average size calculation of particles but is not appropriate for poly-disperse systems [52]. Moreover, it could be utilized to characterize the average droplet size of nanoemulsions, e.g., in jet fuel [57]. Kazerooni et al. stated that DLS could be used to determine the different levels of additive (iron cerium oxide) in diesel fuel at approximately 30 nm. They also proved that this technique could characterize the stability of microemulsion, which was tested over 6 months [58]. Together with DLS, we could use zeta potential, which can determine bacterial-compartment electric properties. It can also characterize the electric potential interface between the aqueous solution and the secondary phase, as well as measure the stability of colloids. The state of bacteria cells affects the zeta

potential, which correlates with surface charge, the viability, or even lack of life of bacterial cells, while differences in species or strains change the zeta potential [59].

3.1. Solid Particulates and Trace Element Contamination

Solid particles are small solid or semi-solid particles that are present in the fuel. These contaminations are derived from airborne dust, corrosion, or the wear of products. They may be divided as solid particles into three different groups: clusters, separate spherical metallic droplets, and debris [26]. Figure 5 shows cluster particles with sizes in the range of 4–4 μm (Figure 5d—cluster of droplets) to 20–40 μm (Figure 5a), with oblong or asymmetric shapes having an amorphous form. Crystalline (Figure 5b) and amorphous shapes mainly comprise W, Mo, O, and trace elements, such as Cu, Fe, and Zr. In Figure 5c, we can see a darker site, which represents about 53 at.%, and a brighter site, representing about 80 at.% of W and 5% of Mo [60].

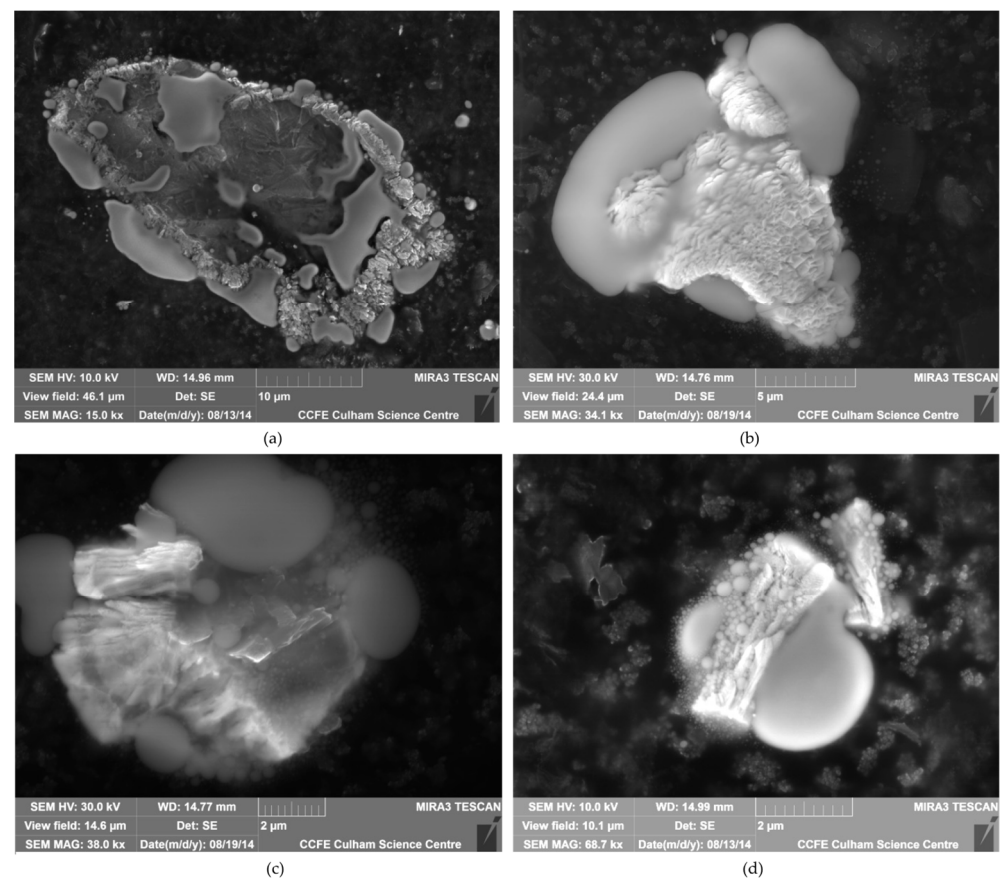


Figure 5. Cluster particles in SEM: (a) cluster particles, sizes: 20–40 μm , (b) crystalline particles, (c) amorphous particles, and (d) cluster particles, sizes: 4–4 μm [60].

The second group is separate spherical metallic droplets [26]. Under EDX analysis, these droplets show diameters below 5 μm when containing Ni and below 1 μm when containing W. Ni-based droplets, W-based particles with Mo, and the rarely noticed O tend to show visible edges. The last particle group is defined as debris, with cluster sizes of up to 500 μm and a debris shape in the form of a disc. The source of these particles is probably a reciprocating probe from a vessel with an average conformation of B0.45N0.55 (at.%) [60]. Figure 6 shows boron nitride and carbon fibre, the source of which is probably CFC tiles and Inconel components.

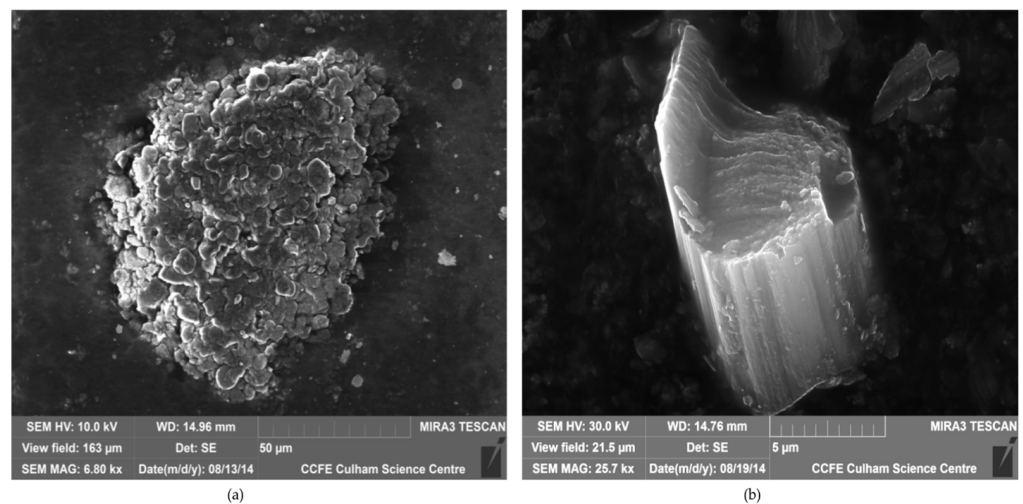


Figure 6. SEM analysis of particles that are classified as debris: (a) boron nitride and (b) carbon fibre [60].

Figure 7 shows different size and shapes of microfiltered particles of aviation fuel in the distribution system performed by SEM. The sample was taken from a FAUDI microfilter and situated in a main pipeline-filter vessel [61].

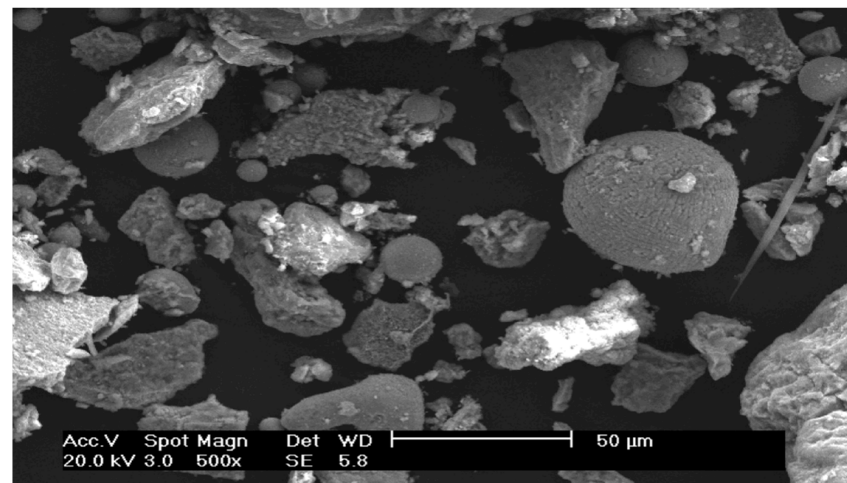


Figure 7. SEM analysis of particulates from jet fuel taken after the filtration system [61].

The Sources and Specifications of Solid Particulate Contamination

The main source of contamination is derived from rust, as well as dust, pollen, rubber, fibres, and microbial life. Solid particles could come from fuel production and processing methods, or the fuel-handling system. Deposits may be created due to the oxidation reaction of sulfur compounds, such as methyl phenyl sulphide or dibenzyl disulphide. Sometimes the particles comprise perfluorinated chemical (PFC) materials, which are found in the coatings and machines used in jets for conditioning, protecting C fibres, Cr, Ni from Inconel, Mo, and W. [60].

Another possible source of contamination is filter monitors, namely superabsorbent polymer (SAP), which are the elements of filters activated by salt water. SAP becomes saturated and puffed when small gel material enters the fuel. It is a very dangerous situation, which can lead to engine damage [62]. Metals may exist in fuels in the form of acid salts, organic complexes, or soluble forms, which have a different origin.

When analysing trace elements in aviation fuel from a different publication, we could observe that there are huge differences in the level of sulfur, sodium, zinc, and silicon,

which could be involved with a type of crude oil, as well as a type of process used for producing aviation fuel, such as distillation, hydrocracking, or hydrodesulfurization. Other elements presented in Table 3, and their concentrations in aviation fuel, could be involved with the distribution infrastructure or potential problems with corrosion, like iron, chrome, copper, and aluminium. Nevertheless, there are several other factors that could affect the final concentrations of elements, such as used additives, storage, deactivation of the catalyst, etc.

Table 3. Elemental concentrations in jet fuel samples in mg/kg by different methods [56,63–65].

Element	Concentration (ppm by wt.)							
S	46.40	440.00	110.00	49.00	360.00	334.00	122.0000	-
Si	11.60	7.71	12.00	22.50	-	-	ND	-
Na	19.50	14.50	ND	ND	<6.00	<7.00	ND	-
K	6.80	5.72	6.61	0.50	<7.00	<7.00	ND	-
Ca	7.52	1.15	0.50	14.40	<4.00	<4.00	0.5500	-
Mg	13.40	ND	ND	ND	<85.00	<130.00	ND	-
P	ND	ND	3.03	16.70	-	-	ND	-
Cl	0.50	0.50	4.35	0.50	<10.00	<15.00	ND	-
Al	ND	ND	5.98	0.50	6.00	3.00	ND	-
V	1.26	ND	ND	2.24	0.02	0.03	ND	0.0001
Ni	4.98	2.08	10.40	1.67	-	-	ND	0.0027
Fe	1.17	0.84	1.38	4.26	<3.00	<3.00	0.2100	0.3290
Cu	1.34	0.90	2.30	1.09	<0.20	<0.10	0.0500	0.0230
Zn	4.25	6.06	19.70	10.20	<3.00	<0.30	ND	0.0240
Pb	0.51	0.68	0.68	6.08	-	-	0.0110	ND
Cr	0.10	0.70	0.48	0.10	<0.05	<0.05	0.0300	0.0005
Analytic *	PIXE	PIXE	PIXE	PIXE	NAA	NAA	ICP-MS	ICP-MS
Reference	[63]	[63]	[63]	[63]	[64]	[64]	[65]	[56]

* Particle-induced X-ray emission (PIXE), neutron activation analysis (NAA), Inductively Coupled Plasma Mass Spectroscopy (ICP-MS), ND—Not Detected, “-” —Not Measured.

However, is not easy to assess and detect particular trace elements. Choosing an exact and certified method is very challenging when assessing trace elements. It is crucial to determine appropriate extractants, conditions, reference materials, and procedures for the analysed sample in order to release them from complexes, e.g., extracting from insoluble sulfates and attaining quantitative levels of trace elements [56]. Table 3 presents the concentration of elements in Jet A1 samples in mg/kg, which have been tested by different analytics, namely PIXE, NAA, and ICP-MS.

Saith et al. performed an analysis of elements of aviation fuel samples by vacuum PIXE at the Nishina Memorial Cyclotron Center (NMCC) [63]. The Jet A1 samples were attacked with 2.9 MeV protons, and the X-ray spectra then were examined using the SAPIX program. However, it is important to consider the errors in the analytical results, which are associated with spectrum fitting, detection efficiency, and the values of x-ray transmittance through the absorber. The error may be different for specific elements, and, for example, for Fe, Cu, and Zn, we may have a 10% relative error. For Al, V, and Cr, this error could be 10–20%, while for the elements Si, K, and Pb, it could be 20–40% [63]. Fordyce et al. analysed jet fuel using neutron activation analysis (NAA) [30]. This analysis has good sensitivity to specific elements, and the variation could be up to 20% for all elements except sulfur, where the variation could be up to 50%. Deviations for aviation fuel elements may be a function of the storage and distribution infrastructure [64]. The PIXE method may have different detection limits for certain elements, e.g., for P below 10 ppm by w/w , and Fe below 0.5 ppm by w/w [63]. Shumway et al. tested elements of aviation fuel using ICP-MS and Flame Atomic Absorption Spectrometry (FAAS) [31]. In order to assess the concentration of particular elements of aviation fuel, a sample digestion method is needed. In this case, Ultrex II nitric acid was used and the sample was heated for 12 h. At the end of a vigorous refluxing stage, the sample volume was reduced twice and the digested fuel samples were treated with a water reagent, placed in acid, and washed for the final analysis.

In the case of Cr, Cu, and Fe elements, graphite furnace atomic absorption spectrometry (GFAAS) was used [65].

Except for the presence and source of contaminants, there are other very important characteristics of solid particles, namely size and hardness [50]. Table 4 shows the commonly occurring particles and their strength characteristics.

Table 4. Hardness and size of particles [50].

Common Name	Formula	Mohs Hardness	Density, g/cm ³	Particle Size Distributions, %	18 Field Samples Median
Silica	SiO ₂	7	2.65	69–77	36.6
Aluminium oxide	Al ₂ O ₃	9	3.95	8–14	15.85
Hematite (iron (III) oxide)	Fe ₂ O ₃	5–6	5.3	4–7	3.4
Magnetite	Fe ₂ O ₃	5.5–6.5	5.15	-	-
Calcium oxide	CaO	3.5	3.34	2.5–5.5	7.45
Potassium chloride	KCl	2	1.98	2–5	-

It is worth emphasizing that most trace element metals appear in asphaltenes in crude oil, especially carbon, hydrogen, sulfur, oxygen, and, to a lesser level, nitrogen elements. Trace element metals appear at around the 0.01–0.1% level, but they could also appear at an ultra-trace level, below 0.01%. This can help distinguish vanadium, nickel, calcium, potassium, iron, copper, zinc, boron, arsenic, selenium, silicon, and phosphorus [1]. Trace metals, as mentioned above, are derived from crude oils; more precisely, from metal loporphyrins, which are formed during the early diagenesis and catagenesis of the source rocks and can be detected by means of spectroscopic/chromatographic methods. In the case of porphyrins, they are derived from the chlorophylls of algae and phytoplankton, or from the chlorophylls of plants that come from the Earth. Yang W, Gao Y, Casey J et. al. noticed in their work that porphyrins and non-porphyrins of Ni (II) and VO (II) are typical metals within crude oils [34]. Table 5 presents the trace elements of seven crude oils samples taken from the Trinidad region.

Crude oil is made up of different types and structures of the hydrocarbons that were formed by plants and animals that existed millions of years ago. Trinidad offshore is rich in crude oils with five selected subbasins, which can be differentiated by the structure and trace elements content due to structural movements in different periods. Table 5 shows a significant difference in the abundances of trace elements, a difference of several orders of magnitude.

SBCs such as HEFA are produced from used cooking oil (UCO—consisting of fatty acids and mono-triglycerides), waste animal fats, oil refining, and other non-glyceride feedstocks. These feedstocks can contain many impurities, such as various metals (phosphorus, iron, etc.), water, polymers, chlorides, and nitrogen, which can affect the functionality of the catalyst. That is why, before refining these feedstocks, it is necessary to use pre-treatment processes (such as steam injection, heating, filtration, deactivation, vacuum evaporation, and sedimentation) to improve the quality of the feedstock [66–68].

The most typical method for analysing trace elements is ICP-MS, but there are other methods such as atomic absorption spectrometry (AAS), ICP-OES, etc. The primary advantages of the ICP MS technique involve the detection limits, which is typically from 0.02 pg/g, or around 1 pg/g, and could assess up to almost 70 trace elements. However, there are still elements that are not covered by the ICP MS methods, and the upper limit is below 4% [1].

Table 5. Trace elements (ng/g) of seven crude oils samples from Trinidad offshore made by ICP MS with SRC microwave [1].

Elements	T1	T2	T3	T4	T5	T6	T7
Sr	11	39	50	218,685	40	16	53
Y	7.6	6.6	2.1	320	5.5	7.2	1.8
Zr	43	33	26	762	21	32	14
Nb	0.5	0.4	0.1	22	0.2	0.2	ND
Mo	346	722	321	805	722	326	289
Ag	0.01	ND	ND	174	ND	ND	ND
Cd	1.3	24	197	46	25	1.3	175
Sn	31	36	33	210	34	42	99
Sb	2.5	1.9	2.6	442	1.5	1.0	1.5
Cs	ND	ND	ND	114	ND	0.003	ND
Ba	80	419	446	14,648	35	42	397
La	0.6	0.5	0.3	508	0.4	0.7	0.2
Ce	1.4	1.4	0.5	1105	1.0	1.6	0.4
Pr	0.2	0.1	0.03	134	0.1	0.2	0.03
Nd	1.1	0.9	0.3	498	0.8	1.1	0.3
Sm	0.5	0.4	0.1	108	0.3	0.5	0.1
Eu	0.2	0.1	0.01	31	0.1	0.1	0.01
Gd	0.8	0.7	0.2	94	0.6	0.8	0.2
Tb	0.2	0.1	0.01	14	0.1	0.1	0.01
Dy	1.4	1.0	0.3	77	1.0	1.4	0.3
Ho	0.3	0.2	0.03	14	0.2	0.2	0.03
Er	0.8	0.6	0.2	38	0.6	0.8	0.1
Tm	0.1	0.1	ND	5.2	0.05	0.1	ND
Yb	0.7	0.5	0.1	33	0.6	0.5	0.1
Lu	0.1	0.05	ND	4.5	0.04	0.04	ND
Hf	0.6	0.6	0.5	33	0.3	0.4	0.2
Ta	0.01	0.002	ND	0.1	0.1	0.1	0.3
W	2.3	0.6	ND	90	ND	ND	ND
Tl	0.2	0.1	ND	8.2	ND	ND	ND
Pb	26	51	140	180,128	49	29	120
Th	0.4	0.4	0.3	262	0.3	0.4	0.2
U	0.4	0.2	0.2	106	0.05	0.3	0.1
V	63,860	67,954	56,789	6849	75,843	67,036	55,078
Ni	55,332	51,533	50,398	15,499	57,544	58,582	50,158
S	15,155,778	18,912,171	13,110,159	4,015,333	20,692,112	15,833,724	12,575,015
V + Ni	119,191	119,488	107,187	22,348	133,387	125,618	105,236
Ni/V	0.87	0.76	0.89	2.26	0.76	0.87	0.91

The Influence of Solid Particulate Contamination on Fuel Quality

Contamination of jet fuel by solid particles or trace metals could be very dangerous in terms of the safety of aircraft. One of the problems is the presence of solid particles, which could lead to wear of the fuel system and the injectors due to erosion by the hard particles. Another aspect that correlated with the size and quantity of the particles is filter plugging by reducing filter life and, hence, inadequate fuel dosage into the engine. The size of the particles at the ultrafine particulate level could block the fuel system flow (e.g., filter water separator (FWS), filter monitor (FM), and other fuel filters of aircraft) and movement of on-spec fuel [50]. What is more, micron-size particles could cause faster settlement and agglomeration of particles, with poorer stability of the fuel affecting the operation of the fuel system. What is more, Ferrão I, Mendes M, et. al. observed in their work that adding nano-size particles to the fuel could lead to higher burning rates and reduced lifetimes [51]. The presence of particles affects the quality of the aviation fuel, which will be characterized later. It was noticed in their work that aluminium particles affect the appearance of jet fuel, changing it from transparent to dark and opaque, accordingly influencing radiation absorption [51]. Moreover, when fuel is contaminated by particles or ion metal, it could affect the conductivity of the jet fuel.

It is important to bear in mind that even a ppb level of around 100 ppb for copper, 150 ppb for iron, and 200 ppb for zinc could degrade the breakpoint of thermal stability to 260 °C [64]. The contamination of fuel could be very hazardous and cause stiction in the

Fuel Metering Units of the engine, leading to total seizure and a final lack of thrust control during aircraft approach [62].

3.2. Microbiological Contamination

Microbial contamination is very dangerous for fuel quality and aircraft safety. It mostly involves the presence of water and bad housekeeping practices related to the fuel tanks [17]. Jet fuel consists of different hydrocarbons, which are a source of microbial contamination growth [69]. What is more, microorganism growth is generally detectable at the fuel and water–fuel interface, as well as in the infrastructure surfaces. Bacteria start to produce scinnogens, which are surfactants and lipopolysaccharides, which may have an effect on the efficiency of the filter water separator [70].

The primary factors contributing to microbial contamination

Jet A1 is sterile when it leaves the refinery. However, carbon fuel and the presence of oxygen and free water in the logistics chain create a suitable environment for microbial contamination to proliferate. Microbes could be introduced to the fuel from the soil and air, or enter the fuel via the air, contaminated wash water, or dirty pipelines [16]. Microorganisms need free water along with organic and inorganic nutrients. Additionally, they require the presence or lack of oxygen, as well as an appropriate temperature and pH for the growth of the contamination [71]. All of these factors will be described here.

One of the main factors that is needed for growing microorganisms is water. The vegetative cell mass of microorganisms is made up of 75–90% water [72]. Free water comes from rainfall when storage tanks are equipped with a floating roof without a dome, faulty seals and vents, poor tank cleaning, and fuel systems. Water also condenses on the sides and bottom of the tank when the temperature changes. Water from microbes such as *Hormoconis resinae* could be treated as a residue from the degradation of hydrocarbons in cellular metabolism. On the other hand, there is also water dissolved in jet fuel. The solubility of water depends on the length of the hydrocarbon chain, the aromatic hydrocarbon molecule, and the temperature. Short-chain paraffins dissolve more water than longer ones. What is more, aromatic hydrocarbons dissolve five times more water than straight-chain hydrocarbons. C4 and below are very water-insoluble or hydrophobic [73]. Water-soluble salts are a good factor for microbial growth. Microbes need water to grow because nutrients diffuse into the cell in a water solution or emulsion. Microbes build cell structures from specific nutrients that they absorb. Therefore, they need carbon, hydrogen, sulfur, nitrogen, and phosphorus in appropriate proportions to proliferate [74].

Another factor is the organic nutrients, like hydrocarbons or additives, which are the source of carbon for multiple species of microorganisms. Microbes metabolise paraffinic hydrocarbons, cyclic hydrocarbons, and aromatic hydrocarbons for the production of energy. Hydrocarbons are degraded the most from paraffinic to aromatic hydrocarbons. The branched hydrocarbons are slower to degrade than straight ones [72]. The biodegradability of hydrocarbons decreases with aromatic content and higher distillation temperatures [75]. It was also noticed that surfactants also contribute to microbe growth [76]. Shkilniuk et.al stated in their paper that “oxygenation starts the utilization of one oxygen atom from its molecular form in the terminal methyl groups of hydrocarbons [52]. Bonds with weak breaking energy (C–C, C–H) are replaced by bonds with intense breaking energy (C–B, H–O)”. Table 6 shows the classification of the biological damage of hydrocarbons caused by microorganisms. It was also noticed that the first group, namely n-alkanes and iso-alkanes, is the most sensitive to degradation by microorganisms. There is also the fifth group, which consists of penta-aromatic, asphaltenes, and resins. This group is more resistant to microbial degradation, which is about 0–30% [77].

Table 6. Classification of the biological damage to hydrocarbons caused by microbes [72].

Group	Group Name	Degree of Biodestruction (%)	Hydrocarbons
I	Highly sensitive	80–100	n-Alkanes, isoalkanes
II	Sensitive	60–80	Cyclones with 6, 1, 5, 2 pins, S-aromatics, monoaromatics,
III	Moderately sensitive	45–60	Three aromatics
IV	Resistant	30–45	Tetra-aromatics, triteipenes, naphthenic-aromatic compounds
V	Highly resistant	0–30	Penta-aromatic, asphaltene, resins

An additional factor is oxygen, which is used by aerobic microorganisms for proliferation. Oxygen is used for respiration and biosynthesis, and jet fuel could have more than 300 ppm of dissolved oxygen. Some types of micro-organisms, such as sulphate-reducing bacteria (SRB), can grow in the absence of oxygen. Oxygen depletion occurs at the bottom of the water, where aerobic microorganisms breathe [78]. The biodegradation of hydrocarbons arises intracellularly by specific oxidative enzymes of the oxygenase class.

Inorganic nutrients are another factor for microbial growth, which covers iron oxide [76], nitrogen, sulfur, phosphorus, magnesium, calcium, iron, and potassium. Other trace elements, such as cobalt, copper, manganese, molybdenum, selenium, and zinc, together with sodium chloride, tungsten, and nickel, could be also needed for the growth of some microbes. Most of these inorganic metals are available in the sediment, water, and dust [78].

In the case of temperature, each microbe species has its minimum, desired, and maximum temperature for existence and growth. Above the maximum temperature, some microorganisms die or retard their growth. However, the average suitable temperature is approximately 25–30 °C [17]. Microorganisms could be divided into three categories: psychrophiles—microorganisms with environmental growth at temperatures up to 10 °C; mesophiles—microorganisms with environmental growth at ambient temperatures: 25–40 °C; and thermophiles—microorganisms that exhibit environmental growth actively at temperatures above 50 °C [72].

pH level is another factor for the proliferation of microbes, where a neutral pH is optimal for bacteria, 4–6 pH for fungi, and 7.5 pH for sulfate-reducing bacteria. Tank water bottoms have a range of 6–9 pH [17].

In order to mitigate the risk of microbial growth, it is essential to use appropriate coating materials for tanks, railcars, aircraft-construction materials, treating methods, and fuel production and processing methods. It is also essential to maintain good housekeeping of fuel handling systems [76].

Microbial contamination control in fuel systems. Standard and new advanced methods

The assessment of microbial contamination in fuel systems could be performed using standard and advanced methods. There are several methods, such as CFU, microscopy, and ATP (adenosine triphosphate) molecular techniques, that can be used to assess the microorganisms in the fuel and fuel–water interfaces [79].

Standard methods of detecting microorganisms include isolation of the microorganism. The most common method is culture technics, which includes sterile dishes with a slide and appropriate agar medium with a nutrient. This is used to identify bacteria, yeasts, and fungi. However, it does not allow us to determine all the organisms available in a group. Other than some constraints, culture-based methods are still the most broadly used due to the price advantages [16].

One of the simplest methods is CFU per ml. When multiple cycles of microbial cells are replicated, microbial colonies are formed at set temperatures and times. Each CFU represents a single viable microbial cell that has replicated. After reproduction, visible spots can be observed by the lab technician. A colony is not only an important issue

but also the colour and morphology. Using this method is possible to investigate fuel or water on an agar plate, which is then incubated. After reproduction, the colonies can be counted. However, only a fragmented percentage of the microorganism will grow, which is the reason for the development of molecular biology, a subject of the next part of this review [73].

In the laboratory, most techniques used for the cultivation of microorganisms involve a complex nutrient substrate like nutrient agar, luria agar, or tryptic soy agar. On the other hand, these substrates prevent oligotrophic bacteria from proliferating due to nutrient shaking.

It is important to mention the Petri dishes used in cultivation methods, which help the use of autoinducers and homoserine lactone in the substrate medium to increase the growth of some bacteria. Another high-throughput method for accelerating the growth of previously uncultured microorganisms is the encapsulation of individual cells in gel microdroplets, followed by growth under a continuous flow of a nutrient-depleted medium. The cultivation of terrestrial recalcitrant microorganisms evolved throughout the use of a polycarbonate membrane as a solid support and a soil slurry as a source of carbon and a natural element essential for the culture of microcolonies. All these microorganisms that can be cultured may be used as a model system for the phenotypic and genotypic [80].

Another advanced method involves DNA/RNA equipment, which helps to culture microbes in vitro. Molecular methods allow us to assess an uncultured microorganism at 99% by scanning their DNA sequences. Here, we could use 16S rDNA gene analysis to characterize the microbial populations in jet fuel. The development in ribosomal DNA (rDNA) allows us to classify a broad spectrum of microorganisms without standard culture-based methods. The 16S rDNA gene analysis covers both molecular technology and phylogenetic concepts. To use this method, a typical gene needs to be selected to be amplified and sequenced. The analysed gene has to be present in every cell, grow at a constant rate, and have adequate different regions in order to observe the differences. Furthermore, the selected gene should be naturally replicating in situ rather than moving between organisms. The main objective is to identify the properties and composition of the microbial community present in a specific environment, such as jet fuel [73].

Metagenomic analysis is another method for selecting a microorganism from samples. Many estimators and software programs have been used in metagenomics for the statistical analysis of genomes. Nowadays, many of the programs could use the 16S rDNA sequencing method to characterize the microorganism community [73].

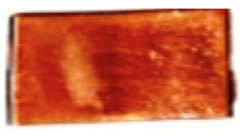
Polymerase chain reaction (PCR) represents molecular biology and is a DNA analysis method that allows for the amplification of a selected area or gene of interest. DNA molecules provide the long-term storage of genetic information. DNA consists of a structure known as chromosomes, where the chromosomes are made of various segments of genetic information known as genes. DNA is made up of two long polymers of simple units called nucleotides, with a backbone of sugars and phosphate groups that are linked together by ester bonds. DNA polymerase is used to amplify a piece of DNA by in vitro reproduction [17,81].

There are many methods used to assess the contamination of microorganisms, such as aerobic cultivation, denaturing gradient gel electrophoresis (DGGE), and restriction fragment-length methods pyrosequencing. These methods provide only the qualitative structure of the microbiome. Quantitative polymerase chain reaction (qPCR) is considered a detailed method for the quantification of microorganisms, both cultivable and non-cultivable [82]. In addition, the sequencing of ribosomal markers, such as the 16S rRNA gene (16S), is considered a detailed method for analysing bacteria, as well as rDNA internal transcribed spacers (ITS), or the 18S rRNA gene for fungi [82]. Using the NL1f/LS2r primers for targeting the 28S rDNA gene, the total amount of fungal DNA can be quantified by qPCR [82]. Martin-Sanchez et. al. noticed in their work that, in many fuel samples, various species of *Bacillus*, *Lactobacillus*, and *Lysinibacillus* were detected. Here, *Bacillus* was only analysed in JP-8 [82].

Another method is Adenosine Tri-Phosphate (ATP Bioluminescence—ASTM D7463 or ASTM D7687), which is involved in quantifying the amount of ATP and correlates with the level of microbial contamination. The ATP substance is present in all living and biological organisms, which emit light when adding an enzyme reagent. The test can detect the metabolic activity of bacteria, yeast, and moulds, as well as SRBs and other anaerobe microbes. The results are presented in Relative Light Units (RLU)/lt. However, it cannot differentiate between different species [16].

Other than typical microorganism detection, we can also use indirect methods such as the corrosivity of aviation fuel on a copper plate and acidity. When the corrosivity of Jet A1 is increasing, there is a noticeable colour change of the plate, which informs us about contamination by the microorganism. Table 7 shows the effect of microbe contamination, ranging from bright yellow, which means no microbiological contamination, up to dark orange. Dark spots and colour changes indicate the presence of bacteria and fungi that metabolize ammonia, hydrogen sulfide, and organic acids [69].

Table 7. List of samples for research and test purposes [69].

Samples			
Clean fuel for jet engines TC-1	Clean fuel for jet engines Jet A-1	Fuel for jet engines TC-1 with microbiological pollution	Fuel for jet engines Jet A-1 with microbiological pollution
			

There is also a method that has its roots in PCR. This method is known as high-throughput sequencing (HTS), and it is an innovative microbiological detection technique. It is a precise qualitative and quantitative method for assessing microorganisms, but it cannot be divided between live and dead microbes. It is known that propidium monoazide (PMA) enters membrane-damaged cells and DNA. It inhibits the strengthening of DNA during PCR, making it possible to detect dead and living microbes. For this reason, this method, together with culture-base techniques, is a good way to determine microorganisms in aviation jets [81].

Another interesting technique is Matrix-Assisted Laser Desorption/Ionization, which is usually connected with the time-of-flight analyser mass spectrometry (MALDI-TOF MS), a fast and precise technique used to determine microbial identification in different sectors from FEMG, agriculture, refinery, and clinical research [83]. It is used as an ionization mass spectrometry method within which pseudo-molecular ions are created [19,52].

There are several possibilities to prepare samples for identifications in MALDI, including the reduction chem panel method on stable surface tryptone soya agar (TSA) and the cultivation method when culturing on universal TSA. Isolates can be chosen by their differences in morphology. It is a very robust approach, thanks to the two-dimensional imaging of the metabolite separation by cultivated bacteria and fungi [52]. The whole process of analysis covers “(1) microbe cultivation on a thin agar, (2) transfer of the excised culture-containing agar slice onto the MALDI target plate, (3) solid matrix application, (4) dehydration of the sample, and (5) data acquisition and interpretation” [84]. The most important phase is preparing the sample to run the analysis. The crystal size and consistency of the coating in the solid matrix are critical and can have an impact on the final result [84]. MALDI-TOF MS is a quick method, providing results in a few minutes. It helps to determine the “RNA and DNA of bacteria, proteins, bacterial proteomics, virulence markers, and detection of bacteria at genus, species, and strain level” [85]. Studies running on crude samples show that MALDI-TOF MS can be used for “bacterial proteins (e.g., bacterial toxins), bacterial DNA, or RNA, as well as bacterial metabolites” [85].

Profiling the microbial contamination in aviation fuel

In microbial contamination, it is crucial to know what kind of microorganism and which form we encounter in aviation fuel, as well as what kind of genes comprise a microorganism, the frequency of presence, and which one is forming a biofilm [17]. In aviation fuel and aviation fuel systems, we can identify bacteria, yeasts, and filamentous fungi, which could be aerobes or anaerobes such as sulphate-reducing bacteria (SRB) [16]. It is essential to learn how the microorganisms present in a fuel system differ from each other by their structure. Bacteria are single-cell microbes that lack a membrane-bound nucleus. Where fungi have a well-defined nucleus, the nucleus is an organelle that encloses most of the cell's genes physically. Fungi are classified into two groups: filamentous moulds and single-cell yeasts. Bacteria and fungi are completely viable, so the treatment will be different [70].

Table 8 was used for the 16S rDNA sequence for aviation fuel, where classification by the RDP Classifier covers main phylum members: *Acidobacteria*, *Actinobacteria*, *Bacteroidetes*, *Chloroflexi*, *Cyanobacteria*, *Deinococcus-Thermus*, *Firmicutes*, *Gemmatimonadetes*, *Nitrospira*, *Plantomycetes*, *Proteobacteria*, TM7, and *Verrucomicrobia* [17].

Table 8. Phylum distribution of aviation fuel sequences [17].

Phylum	JP-8 (n * = 828)	Jet A (n * = 311)	Biodiesel (n * = 61)	Total (n * = 1200)
<i>Acidobacteria</i>	15	0	0	15
<i>Actinobacteria</i>	85	63	4	152
<i>Bacteroidetes</i>	5	0	0	5
<i>Chloroflexi</i>	7	0	0	7
<i>Cyanobacteria</i>	56	0	0	56
<i>Deinococcus-Thermus</i>	2	0	0	2
<i>Firmicutes</i>	83	99	2	184
<i>Gemmatimonadetes</i>	2	0	0	2
<i>Nitrospira</i>	49	0	0	49
<i>Plantomycetes</i>	2	0	0	2
<i>Proteobacteria</i>	459	149	55	663
TM7	1	0	0	1
<i>Verrucomicrobia</i>	2	0	0	2
Unclassified Bacteria	57	0	0	57
Unclassified Root	3	0	0	3

* n—number of phyla detected.

Three sequences form an unclassified root category. An unclassified root refers to sequences for which the RDP classifies could not be identified as bacterial 16S genes. The percentage of the phylum distribution of aviation fuel sequences includes proteobacteria, which embraces the broadened spectrum of phylum and consists of 47.9% Proteobacteria, 31.8% Firmicutes, and 20.3% Actinobacteria [17].

Proteobacteria, *Firmicutes*, and *Actinobacteria* were represented in Jet A and biodiesel and were the only phyla signified. The detailed phyla microorganisms for aviation fuel are defined in Table 9 [17].

Table 9. Phylogenetic classification of aviation fuel sequences [17].

Phylogenetic Classification	JP-8 (n = 828)	Jet A (n = 311)	Biodiesel (n = 61)	Total (n = 1200)
Acidobacteria				
<i>Gpl</i>	1	0	0	1
<i>Gpl 6</i>	4	0	0	4
<i>Gpl 7</i>	10	0	0	10
Actinobacteria				
<i>Actinomyces</i>	0	1	0	1
<i>Agromyces</i>	1	0	1	2
<i>Arthrobacter</i>	2	12	0	14
<i>Corynebacterium</i>	2	0	0	2
<i>Curtobacterium</i>	3	0	0	3
<i>Kytococcus</i>	1	0	0	1
<i>Microbacterium</i>	6	15	0	21
<i>Mycobacterium</i>	0	7	0	7
<i>Propionibacterium</i>	17	6	1	24
<i>Quadrispliaera</i>	1	0	0	1
<i>Rhodococctis</i>	40	21	1	62
<i>Rothia</i>	1	1	0	2
Unclassified Actinomycetales	6	0	0	6
Unclassified Corynebacterineae	1	0	1	2
Unclassified Microbacteriaceae	2	0	0	2
Unclassified Nocardiaceae	1	0	0	1
Unclassified Rubrobacterineae	1	0	0	1
Bacteroidetes				
<i>Cloacibacterium</i>	1	0	0	1
<i>Hymenobacter</i>	2	0	0	2
Unclassified <i>Sphingobacteriales</i>	2	0	0	2
Chloroflexi				
<i>Caldilinea</i>	1	0	0	1
Unclassified Anaerolineae	5	0	0	5
Unclassified Chloroflexi	1	0	0	1
Cyanobacteria				
<i>Streptophyta</i>	46	0	0	46
Unclassified Cyanobacteria	10	0	0	10
Deinococcus-Thennus				
<i>Deinococcus</i>	1	0	0	1
<i>Truepera</i>	1	0	0	1
Finnicutes				
<i>Anaerotruncus</i>	3	2	0	5

Table 9. Cont.

Phylogenetic Classification	JP-8 (n = 828)	Jet A (n = 311)	Biodiesel (n = 61)	Total (n = 1200)
<i>Bacillus a</i>	0	11	0	11
<i>Bacillus d</i>	31	19	0	50
<i>Bacillus f</i>	0	1	0	1
<i>Bacillus h</i>	8	0	0	8
<i>Clostridium</i>	0	3	0	3
<i>Staphylococcus</i>	2	43	0	45
<i>Streptococcus</i>	1	3	1	5
Unclassified Bacillaceae 2	2	0	0	2
Unclassified Bacillales	1	0	0	1
Unclassified Bacilli	0	0	1	1
Unclassified Bacillus	0	12	0	12
Unclassified Clostridiales	1	0	0	1
Unclassified Riuninococcaceae	34	5	0	39
Gemmatinonadetes				
<i>Gemmatimonas</i>	2	0	0	2
Nitrospira				
<i>Nitrospira</i>	49	0	0	49
Planctomycetes				
<i>Pirellula</i>	2	0	0	2
Proteobacteria				
Alphaproteobacteria				
<i>Bosea</i>	11	0	0	11
<i>Bradyrhizobium</i>	2	1	0	3
<i>Brewindimonas</i>	23	0	6	29
<i>Caulobacter</i>	0	0	1	1
<i>Hyphomicrobium</i>	0	1	0	1
<i>Methylobacterium</i>	46	87	0	133
<i>Phenylobacterium</i>	0	0	1	1
<i>Rhodocista</i>	1	0	0	1
<i>Sphingobium</i>	3	0	1	4
<i>Sphingopyxis</i>	7	0	0	7
Unclassified Alphaproteobacteria	3	5	0	8
Unclassified Bradyrhizobiaceae	1	0	0	1
Unclassified Caulobacteraceae	3	0	1	4
Unclassified Methylobacteriaceae	1	0	0	1
Unclassified Phyllobacteriaceae	1	1	0	2
Unclassified Rhizobiaceae	0	1	0	1
Unclassified Rhizobiales	6	3	0	9
Unclassified Rhodospirillaceae	1	0	0	1
Unclassified Sphingonionadaceae	3	1	1	5

Table 9. Cont.

Phylogenetic Classification	JP-8 (n = 828)	Jet A (n = 311)	Biodiesel (n = 61)	Total (n = 1200)
Betaproteobacteria				
<i>Acidovorax</i>	0	1	0	1
<i>Alcaligenes</i>	1	0	0	1
<i>Aquabacterium</i>	2	0	0	2
<i>Burkholderia</i>	24	15	2	41
<i>Comamonas</i>	6	0	1	7
<i>Cupriavidus</i>	1	0	0	1
<i>Delftia</i>	29	0	1	30
<i>Herbaspirillum</i>	3	0	0	3
<i>Janthinobacterium</i>	11	0	1	12
<i>Pandoraea</i>	0	5	0	5
<i>Pelomonas</i>	1	0	0	1
<i>Ralstonia</i>	0	0	1	1
Unclassified Alcaligenaceae	70	0	29	99
Unclassified Burkholderiaceae	11	0	0	11
Unclassified Burkholderiales	1	0	0	1
Unclassified Comamonadaceae	1	12	2	15
Unclassified Incertae sedis 5	17	0	3	20
Unclassified Oxalobacteriaceae	1	0	0	1
Unclassified Rhodocyclaceae	5	1	0	6
<i>Variovorax</i>	0	1	0	1
Gammaproteobacteria				
<i>Acinetobacter</i>	6	0	0	6
<i>Alkanindiges</i>	2	0	0	2
<i>Citrobacter</i>	1	0	0	1
<i>Dyella</i>	1	0	0	1
<i>Flavimonas</i>	2	0	0	2
<i>Pseudomonas</i>	91	10	1	102
<i>Shigella</i>	0	1	0	1
<i>Stenotrophomonas</i>	6	0	1	7
Unclassified Enterobacteriaceae	9	0	0	9
Unclassified Gammaproteobacteria	5	0	2	7
Unclassified Pseudomonadaceae	5	0	0	5
<i>Yersinia</i>	24	2	0	26
Deltaproteobacteria				
Unclassified Deltaproteobacteria	2	0	0	2
Epsilonproteobacteria				
Unclassified Helicobacteraceae	1	0	0	1
<i>Wolinella</i>	0	1	0	1
Unclassified Proteobacteria	8	0	0	8

Table 9. Cont.

Phylogenetic Classification	JP-8 (n = 828)	Jet A (n = 311)	Biodiesel (n = 61)	Total (n = 1200)
TM7				
TM7 genera <i>Incertae sedis</i>	1	0	0	1
Vemicomicrobia				
Subdivision 3 genera <i>Incertae sedis</i>	1	0	0	1
Xiphinematobacteriaceae genera <i>Incertae sedis</i>	1	0	0	1
Unclassified Bacteria	57	0	0	57
Unclassified Root	3	0	0	3

Phylogenetic analysis recognized 68 microbial genera with a confidence level of approximately 80% with 42 genera (61.8%) identified in jet fuel. In the case of biofilm, these were identified: *Plantomycetes*, *Actinobacteria*, *Sphingomonas*, *Rhizobiales*, *Enterobacteriaceae*, *Staphylococcus*, *Clostridium*, *Mycobacterium*, *Bacillus*, *Deinococcus*, *Streptococcus*, *Burkholderia*, and *Pseudomonas* [17].

Other classifications of microorganisms selected in studies from 1958 up to 2005 for aviation fuel were made by Rauch [71], and it is presented in Table 10.

GC-FAME and DNA sequencing results present genera, such as *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Dietzia*, *Kocuria*, *Leucobacter*, *Micrococcus*, *Pantoea*, *Sphingomonas*, *Staphylococcus*, fungal genera, *Aureobasidium*, and *Discophaerina*. The most isolated microorganism, *Bacillus licheniformis*, was identified from 7 of the 11 bases. The GC-FAME results were similar but not identical [71]. Microbial contamination is changing in regard to the transformation of aviation fuel composition, additive types, and biocides [86].

D. Hu et al. indicated in their publication that there are more isolated bacteria than fungi, and the diversity of detected bacteria is rather low [87]. However, this phenomenon does correlate with other research [71]. *Actinobacteria* is a principal microorganism in jet fuel that is coherent with other reports [71,88]. Some bacteria (phylum firmicutes) are gram-positive and produce endospores, enabling their survival in harsh environments. Furthermore, belonging to the same taxon, Proteobacteria were the most commonly identified bacteria [86].

In regard to fungi identified in an aviation fuel system and isolated in one phylum, *Ascomycota*, it consisted of: *Alternaria*, *Cladosporium*, *Penicillium*, and *Talaromyces*. Hu et al., in their study, noticed that the most regularly identified fungal genus was *Penicillium* sp. (including *Penicillium oxalicum* sscl-5, *Penicillium oxalicum* SX8, and *Penicillium corylophilum* Su-VII-3). This microorganism is very dangerous as it could cause a high risk of corrosion and a possible risk for health problems. Apart from *Penicillium* sp., there were also detected *Cladosporium* sp. (including *Cladosporium oxysporum* 2-00002-2 and *Cladosporium perangustum* Bt150L) [87].

Hydrocarbons could be degraded by more than 150 species. They are defined by quantity, viable form, distribution, and their interaction with the environment and effect on it. Shkilniuk et al. present in their work on a different group of microorganisms that has an effect on the degradation of hydrocarbons [72]: Bacteria—*Achromobacter*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Bacterium*, *Brevibacterium*, *Citrobacter*, *Clostridium*, *Corynebacterium*, *Desulfovibrio*, *Enterobacter*, *Escherichia*, *Flavobacterium*, *Methanobacterium*, *Micrococcus*, *Micromonospora*, *Mycobacterium*, *Nicrococcus*, *Pseudomonas*, *Sarcina*, *Serratina*, *Spirillum*, *Vibrio*, and *Thiobacillus*; Fungi—*Alternaria*, *Aspergillus niger*, *Aspergillus fumigatus*, *Hormoconis resinae*, *Monacus floridanus*, *Phialophora* sp., *Cephalosporium*, and *Penicillium*; Yeast—*Candida*, *Debaryomyces*, *Endomycopsis*, *Hansenula*, *Rhodotorula*, *Saccharomyces*, *Torula*, *Torulopsis*, *Trichoderma*, and *Trichosporon*.

Table 10. Microbial contaminants identified from different aviation fuels (JP-4, Jet A, Jet A-1, JP-8) from 1958 to 2005 [71].

Microbial Contaminants	JP-4 1958–1966	Jet A 1988–1997	Jet A-1 1998–1999	JP-8 2002	JP-8 2006
Bacteria <i>Acinetobacter</i> (<i>calcoaceticus</i> , <i>cerificans</i>)	-	Yes	Yes	-	-
<i>Arthrobacter</i>	-		Yes	-	Yes
<i>Aerobacter aerogenes</i>	Yes	Yes	Yes	-	
<i>Aeromonas</i> sp.	-	Yes	Yes	-	
<i>Alcaligenes</i>	-	Yes	Yes	-	Yes
<i>Breyibacterium ammoniagenes</i>	Yes		Yes	-	
<i>Desulfofytibrio</i> sp. (SRB) <i>Dietzia</i> sp.	Yes	Yes	Yes	-	Yes
<i>Escherichia</i> sp. <i>Enterohacter</i>	Yes		Yes	-	-
<i>Flayobacterium</i> (<i>arborescens</i> , <i>diffusum</i>) <i>Kocuria rhizophilia</i>	Yes	Yes	Yes	-	Yes
<i>Leucobacter komagatae</i>	-			-	Yes
<i>Micrococcus</i> sp.	Yes	Yes	Yes	-	Yes
<i>Pantoea ananatis</i>	-	-		-	Yes
<i>Streptomyces</i> sp. <i>Staphylococcus</i> sp.	-	-	Yes	-	Yes
<i>Sphingomonas Serratia</i>	-	-	Yes	-	Yes
<i>Bacillus</i> sp. (<i>acidocaldarius</i> + others)	Yes	Yes	Yes	Yes	Yes
<i>Pseudomonas</i> sp. (<i>aeruginosa</i> + others)	Yes	Yes	Yes		
Fungi <i>Acremonium</i> sp. (<i>strictum</i>)	-	Yes	Yes	-	-
<i>Aspergillus</i> sp. (<i>niger</i> , <i>fumigatus</i> + others)	Yes	Yes	Yes	-	-
<i>Aureobasidium pullulans</i>	Yes		Yes	-	Yes
<i>Candida</i> sp. (<i>famata</i> , <i>lipolytica</i> + others) <i>Discophaerina fagi</i> <i>Exophiala jeanselmei</i>	-	Yes	Yes	Yes	Yes
<i>Fusarium</i> sp. (<i>moniliforme</i> + others)	-	Yes	Yes	-	-
<i>Hormoconis</i> (<i>Cladosporium</i>) <i>resinae</i>	Yes	Yes	Yes	Yes	-
<i>Hebninthosporium</i> sp.	Yes	-	Yes	-	-
<i>Paecilomyces</i> (<i>yariotii</i> + others)	Yes	Yes	Yes	-	-
<i>Penicillium</i> sp. (<i>corylophilum</i> + others)	Yes	Yes	Yes	-	-
<i>Phialophora</i> sp.	-	Yes	Yes	-	-
<i>Rhinoclaadiella</i> sp.	-	-	Yes	-	-
<i>Rhodotorula</i> sp.	-	Yes	Yes	-	-
<i>Trichosporium</i> sp.	-	-	Yes	-	-
<i>Tothersrichoderma</i> sp. (<i>yiride</i> + others)	-	Yes	Yes	-	-

It was found that different studies identified larger number of mycelial fungi in aviation fuel and the jet fuel system. Figure 8 shows *Hormoconis resinae* as a “kerosene” fungus that lives in subtropical and tropical soils in ambient environments. They were identified in Australia, Brazil, the USA, Great Britain, Denmark, India, Syria, Nigeria, Japan, and New Zealand. *Hormoconis resinae* fungus could be also called *Hormodendrum resinae*, *Cladosporium resinae*, or *Amorphotheca resinae* [72].

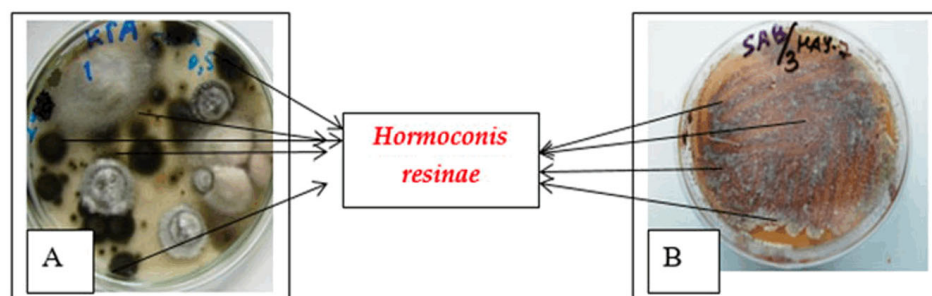


Figure 8. *Hormoconis resiniae* fungus in aviation fuel: (A) fungus in aviation fuel TC-1, (B) fungus in diesel fuel [72].

Hu et al., using the HTS method in aviation storage tanks, observed the following bacteria: Proteobacteria and Actinobacteria, as the most frequent bacteria identified in jet fuel [81]. They also identified *Cyanobacteria*, *Firmicutes*, *Bacteroidetes*, and *Planctomycetes*. What is more, *Ralstonia* bacteria are very resistant to different biocide concentrations and an extensive range of temperatures. From the corrosion point of view, *Bacillus* and *Pseudomonas* have a notable influence on it. In regard to the fungal contaminant that Hu et al. identified (*Ascomycota* and *Euryarchaeota*), they are the most frequently noticed. Other detected fungi were *Amorphotheca* and a species of *Alternaria* [81].

The most common bacteria identified in aviation fuel using the culture-base method is *Bacillus*, *Micrococcus*, *Pseudomonas*, *Arthrobacter*, *Amorphotheca resiniae*, *Aspergillus*, *Penicillium*, and *Candida*. However, these typical microbes live together with other microorganisms and can be detected using molecular techniques [87]. Nearly 200 species of microorganisms were identified, including 30 families that could degrade hydrocarbons mainly as a source of carbon and energy. Table 11 presents the most typical microorganisms, divided into fungi, bacteria, and yeast types that cause fuel contamination.

Table 11. Typical microorganisms that cause fuel contamination [87].

Microorganism	Microbial Species
Fungi	<i>Acremonium</i> sp., <i>Alternaria alternata</i> , <i>Aspergillus</i> sp., <i>Aspergillus clavatus</i> , <i>Aspergillus flavus</i> , <i>Aspergillus fumigatus</i> , <i>Aspergillus niger</i> , <i>Cladosporium</i> sp., <i>Cladosporium cladosporioides</i> , <i>Fusarium</i> sp., <i>Fusarium moniliforme</i> , <i>Fusarium oxysporum</i> , <i>Hormoconis resiniae</i> , <i>Monascus floricola</i> , <i>Paecilomyces variotii</i> , <i>Penicillium</i> sp., <i>Penicillium cyclopium</i> , <i>Rhizoglyphus</i> sp., <i>Trichoderma viride</i> , <i>Trichosporon</i> sp.
Bacteria	<i>Acetobacter</i> , <i>Alcaligenes</i> , <i>Bacillus</i> sp., <i>Clostridium</i> , <i>Sporogenes</i> , <i>Flavobacterium difusum</i> , <i>Micrococcus</i> sp., <i>Pseudomonas</i> sp., <i>Pseudomonas aeruginosa</i> , <i>Serratia marcescens</i>
Yeasts	<i>Candida</i> sp., <i>Candida famata</i> , <i>Candida guilliermondii</i> , <i>Candida lipolytica</i> , <i>Rhodotorula</i> sp.

Fungi are the most dangerous group of microorganisms, whereas *Cladosporium resiniae* (modern name *Hormoconis resiniae* or *Amorphotheca resiniae*) is the worst one because it causes filter and pipeline clogging, as well as corrosion of metal surfaces. It is classified in the *Monascus floricola* group [69]. What is more, fungi dominate the microorganism position leading to biological disaster. Figure 9 shows the appearance of typical microorganism species, which degrade the hydrocarbons and are the most common.

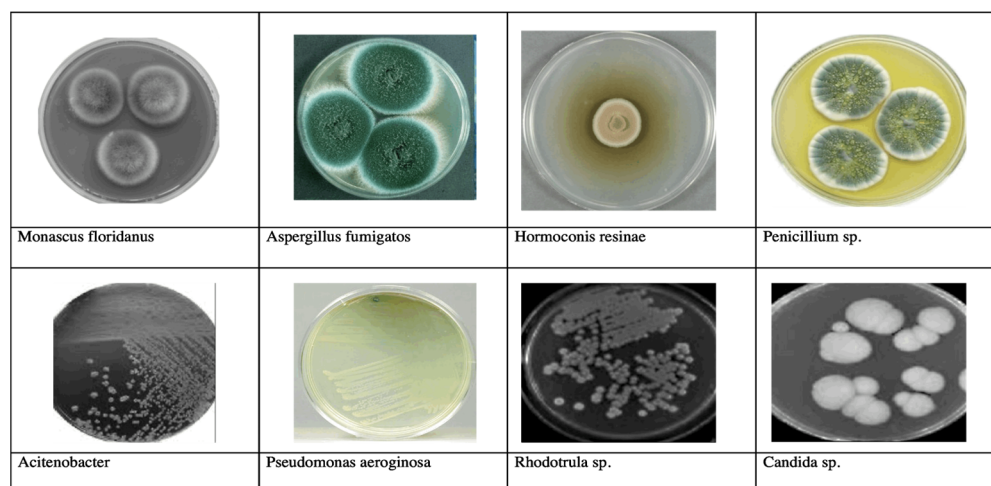


Figure 9. Typical species of microorganisms that degrade hydrocarbons [69].

There are some strains that biodegrade cyclic alkanes such as *Cordonia*, *Xanthobacter*, and others. Strains that are capable of biodegradation of cyclic alkanes include bacteria of the genera *Cordonia*. *Hormoconis resiniae* proliferate in fuel at a temperature of 50 °C where the growth is set in jet fuel at 28 °C, while the strains of *Aspergillus fumigatus* last in aviation kerosene up to 80 °C [72].

Impact of microbiological contamination on fuel quality

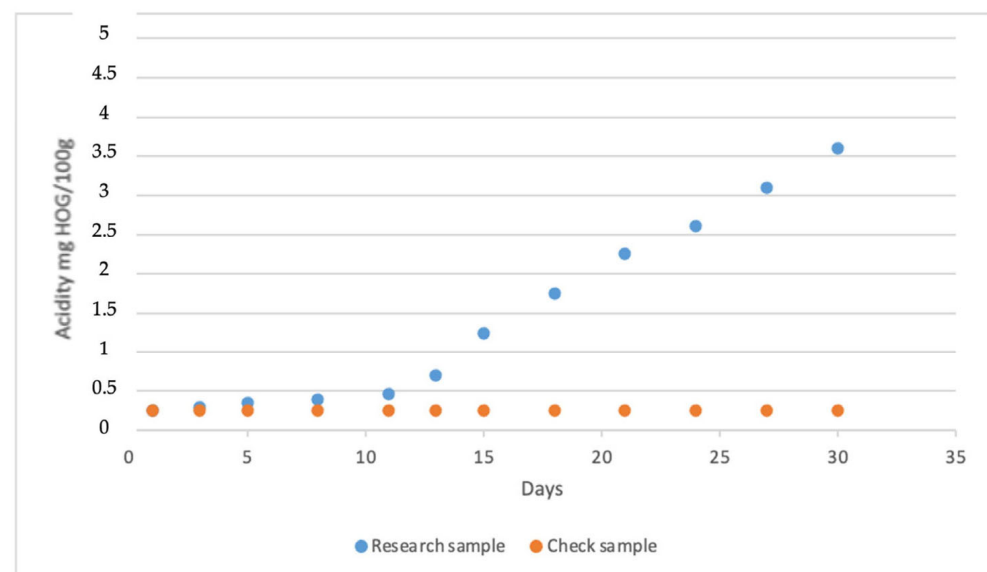
Aviation fuel has to be clear, bright, and without any debris detectable by the human eye [77]. Microbiological contamination has a crucial impact on jet fuel quality and could lead to an emergency landing and disaster. The main causes are slime and biofilms, with the next steps being the clogging of fuel filters and damage to equipment, such as filter water separators [73]. The next point is corrosion of the fuel, namely microbiologically influenced corrosion (MIC) on metal contacts, which is detectable on copper plates or steel rods. Corrosivity of the fuel leads to corrosion of the fuel tank, damage to the pipelines, and internal coating of the tanks, which lead to increased maintenance costs. Corrosion is an electrochemical process in which water comes into contact with different parts of the tank. The result is a difference in charge, like anodes and cathodes. Fuel contaminated with microbes has a higher water and sulfur content [17,89]. The presence of microbial contamination affects the chemical stability of the aviation fuel and can affect its quality in long-term storage. Further changes also include the density of the aviation fuel by decreasing the number of alkanes, as well as the flash point, distillation properties, and combustion parameters. Alkanes have lower flash points and higher combustion heat [17]. Table 12 shows the influence of microbial contamination on jet fuel properties and potential changes in specific parameters.

The increased acidity of jet fuel caused by microbiological contamination is related to the higher content of organic acids in jet fuel. Higher acidity is the effect of the formation of shorter-chain fatty acids and derivatives [79]. A higher number of organic acids increases the lubricity of the fuel, but on the other hand, it increases its corrosivity, which causes wear to engine parts. Figure 10 shows an increasing level of acidity when fuel is contaminated with microorganisms. It is noticeable that after 8 days, the acid number starts to grow.

What is more, a higher level of resin could lead to deposits in the combustion chambers, as well as injectors and engine crankcase [72]. In the case of additives, microbes affect the performance of additives. Microbes also increase the pH level and refractive index. Aviation fuel also has a specific odour and is cloudy [69].

Table 12. Influence of microbiologic on the properties of aviation fuel [72].

Name Quality Indicator	TC-1		RT		Jet A-1	
	Before Bio Cont.	After Bio Cont.	Before Bio Cont.	After Bio Cont.	Before Bio Cont.	After Bio Cont.
Acidity, mg KOH on 100 sm ³	0.2	6.8	0.2	6.5	0.1	6.6
The concentration of actual resins, mg/100 sm ³	2.5	8.7	1.8	7.6	3.8	9.8
Testing on copper plate	1	2a	1	2a	1	3a
Temperature of crystallization, °C	−61	−58	−59	−50	−51	−44
Density 20 °C, kg/m ³	793	791	781	781	779	777
Cinematic viscosity, 20 °C, mm ² /s	1.35	1.4	1.38	1.41	1.36	1.42
Lower combustion heat, kJ/kg	43.1	43.0	43.3	42.8	42.9	42.4
Flash point, °C	34	30	39	33	41	35
Thermal oxidation stability precipitation rate, mg/100 sm ³	9	15	4	12	3	10

**Figure 10.** Increasing level of acidity for contaminated aviation fuel by microorganisms [69].

Factors that can be controlled to reduce microbiological contamination risk

Regular monitoring of fuel quality and microbe presence is essential to prevent microbial contamination. It is crucial to monitor the water at the bottom of the tank, the stagnating point of lines, and the periodic removal of this water [17]. Good maintenance of the production and terminal tanks, as well as aircraft tanks, inhibit microorganism proliferation [81]. Another very important aspect of jet fuel quality is the settling time in the tank to remove particles and water. This process prevents the accumulation of water and the growth of microorganisms [77]. The regular inspection of coalescer filters provides us with information about the effectiveness of filtration. When emulsified or entrained water is not filtered, the coalescer has lost its effectiveness [76]. Continuous observation of aviation fuel provides us with information about microbiological sludge or slimes. What is

more, the presence of iron oxides, surfactants, water-soluble salts, and water tells us about microbiological life [76].

F. Passman presented microbiological risk criteria, which determined a low risk at 64 cm rainfall, medium risk when rainfall is between 64 and 190 cm, and high risk when rainfall is over 190 cm [72]. The risk level also combines the number of days when rainfall occurs. A low range of microbiological risk happens in less than 100 days per year, the medium is between 100 and 200 days per year, and the high range is for more than 200 days per year [72]. In Poland, there is a low risk of microbial contamination when there is average rainfall in a year.

The most dangerous points of microbial contamination in the logistic fuel system are the bottoms of the tanks, the walls of the tanks, and the recesses of the pipeline [69,90]. The described system of monitoring microbiological contamination controls microbiological contamination, and jet fuel before refuelling into the plane tank (see Figure 11). It helps to quickly observe microbiological contamination of the fuel. In the airport, if contaminated fuel is detected twice, it should be returned to the supplier [75].

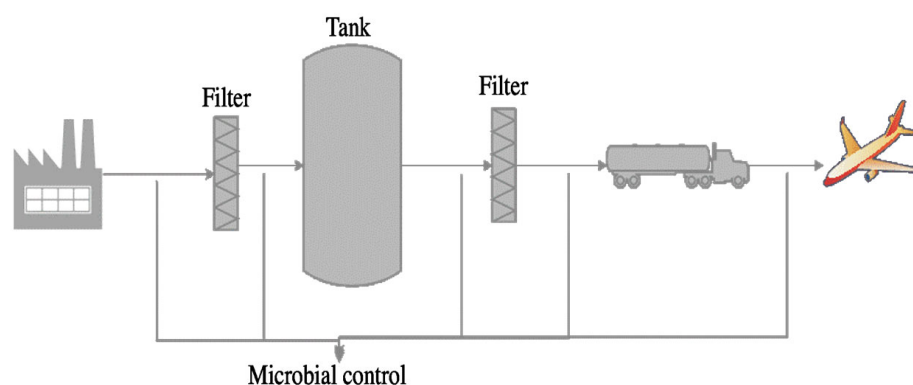


Figure 11. Fuel system scheme of microbiological control (FP—filter point, CAR—centralized aircraft refuelling) [72].

To prevent the spread of microorganisms throughout the system, it is essential to control the number of microbial colonies and microbial species in jet fuel and fuel systems. [75]. Using ultraviolet and electromagnetic radiation also prevents microbiological proliferation as ultraviolet lamps kill microbes and protect them from ignition. Typically, UV lamps are installed in the bottom of the fuel tank or along the fuel line. In the case of electromagnetic radiation, it destroys microorganisms at some specific radio frequencies.

Shkilniuk et al. stated that one of the contamination controls could also be centrifuged with agglomeration filtration, flotation, ion exchange resins, electrohydraulic separation, and ultrasonic control [72].

Tanks with furan resin coating are a good prevention method to reduce microorganism growth. There are a few aspects to control the risk of microbiological contamination, including engineering, monitoring, maintenance, and treatment [70]. These four aspects are crucial to control the risk of microorganisms. When we look at the engineering part, it is important to have a service entry for inspection and for large tanks to allow sediments to be drained. A conical bottom helps to drain water, sludge, and sediments. Stainless steel has an internal epoxy coating to assure integrity. In addition, drains from the lowest point of the pipework system help to prevent water accumulation [70]. Monitoring, as was previously stated, provides information about microbiological contamination above an acceptable level and protects from unforeseen microbial contamination. When necessary, preventive actions are essential, and when sampling the fuel, a water interface is essential to assess microbial life. Sampling and analysis of microbial life should be done as soon as possible to prevent the proliferation of the microorganism. Maintenance also protects from microbe contamination thanks to reducing water gathering and inspections for corrosion [70].

3.3. Water Contamination

Water contamination in jet fuel could be very dangerous for flight safety. One of the reasons is that blends of water and aviation fuel at some level could lead to the formation of ice crystals, which can block fuel systems and damage the engine during the flight [15]. What is more, water could cause corrosion of iron surfaces and the formation of free particles of iron oxides, which then causes the failure of nozzles and premature wear of fuel pumps. Water also influences the power of the engines and could lead to a flameout of the engine, which is very dangerous for the safety of the passengers. Water in fuel at 80 ppm may be invisible in ambient conditions, while a small amount of water and a lower fuel temperature could cause the fuel pipes to freeze [47]. When jet fuel is produced, it is almost dry. Water in fuel enters the fuel system when it is in tanks (moisture, venting valves, unsealed floating roofs), rail tanks, ships, pipelines, and road tankers. What is more, water can also appear during cleaning operations and while flying over rain clouds. Large volumes of water or ice could enter the fuel tanks through the fuel vent ports [15].

Water in aviation fuel can be noticed in three forms. One of these is dissolved water in aviation fuel, which is not visible to the naked eye and burnt during flight [15]. Dissolved water exists where water molecules are assigned to hydrocarbon molecules. The level of dissolved water is associated with the humidity, temperature, and chemical structure of jet fuel. It is characterized by ppm levels and, when the fuel is cooled down, the dissolved water appears as suspended water or free water. At a temperature of 21 °C, the dissolved water may be in the range of 40–90 ppm (*v/v*). Mechanical processes such as sedimentation, filtration, and separation methods cannot remove dissolved water from aviation fuel [91].

The second form is suspended water (also called entrained water) in jet fuel, which is visible as a hazy and cloudy appearance during fuel emulsion. This form of water could be separated during settlements of jet fuel in the tanks or coalescing in the filter water separators [15]. Suspended water could cause ice crystals at the temperature between −1 °C and −3 °C. At the level of −9 °C and −11 °C, it starts to stick to the surrounding infrastructure. Below −18 °C, it starts to stick to surfaces and become large forms of crystals [75]. Huge droplets from water emulsion are not stable, and the free water becomes settled. The influence of equal sign static charges with water droplets causes stable emulsion, which stops coalescence [15]. Suspended water could also occur in metastable solutions, which are supersaturated and supercooled solutions. Supercooled droplets are in a crystalline domain of stability below the freezing-point temperature [15].

The third form is free water, which is heavier than aviation fuel. It separates as another layer at the bottom of the tank. When free water is cooled down below the freezing point of water, it becomes ice [75].

Hygroscopicity of jet fuel

The hygroscopicity of aviation fuel is involved with the ability to absorb moisture from the air. It is involved with the atmospheric conditions (humidity and temperature) where the jet fuel is being used. It is essential to know the difference between hygroscopicity and solubility. Solubility is involved with the level of water, which could be dissolved in fuel in order to make solutions. It is associated with the hydrocarbon base and the hygroscopic phenomena of aviation fuel to absorb water to its surface where water molecules combine with the hydrocarbon base [15]. When there is no equilibrium between the relative humidity of the space above jet fuel and aviation fuel, when the relative humidity is lower than jet fuel, it attracts moisture from the air. Humidity climates could cause water absorbing to jet fuel. High-altitude temperatures during the day influence the absorbing ability of water in the tanks, so drainage is essential. The higher the temperature, the higher the solubility of water in the aviation fuel where the water molecules dissociate with the aviation fuel (reversible hygroscopicity). Figure 12 shows the correlation between the solubility of water in aviation fuel and temperature.

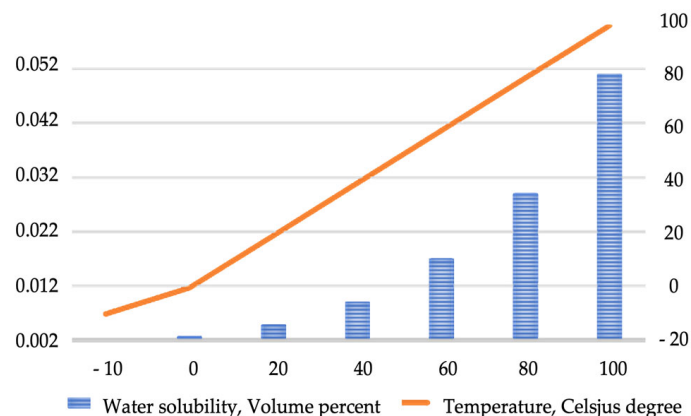


Figure 12. Water solubility in correlation to temperature for aviation fuel [15].

At 14 °C, water is dissolved in jet fuel such that no cloudiness or haziness is visible when assessing jet fuel quality. In Figure 13, we can see the fog phenomenon. When the temperature decreases below 14 °C, water is extracted from the aviation fuel and haziness is visible from the bottom up to the top (Figure 13a). Haziness is first visible after 13 min at the bottom (Figure 13b), then 30 min in the middle of the tank (Figure 13c), and 58 min for full haziness (Figure 13d).

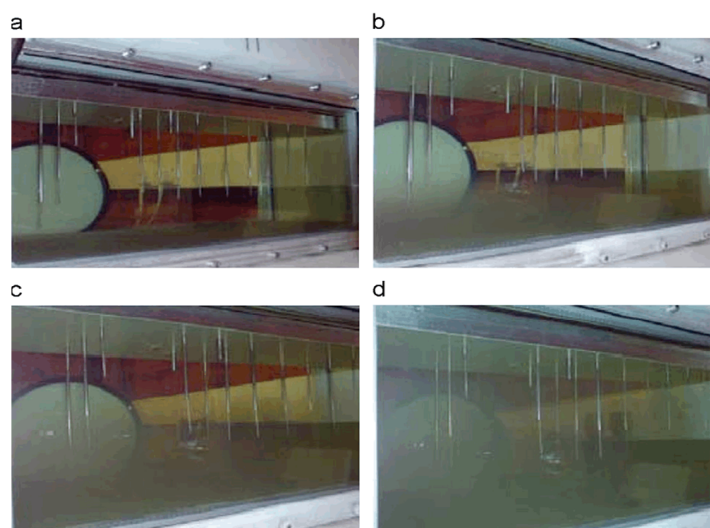


Figure 13. Water fog phenomena in time after cooling aviation fuel: (a) $t = 0$ min, (b) $t = 14$ min, (c) $t = 30$ min, (d) $t = 58$ min [15].

The hygroscopicity of jet fuel is characterized by the water solubility of the hydrocarbon constituents. Water is not soluble in hydrocarbons and has a very strong stable dipole because of the huge difference in electro-negativity. What is more, there are strong adjacent interactions between the atoms of water molecules, leading to hydrogen bonding networks. The enthalpy of water is similar to the enthalpy of hydrogen bonding, which means that in order to make water soluble in aviation fuel, it is essential to break the same amount of hydrogen bonds. The solubility of water in aromatic hydrocarbons does not increase linearly but remains four times higher than in alkanes or cycloalkanes for the same hydrocarbon content [15,92]. Higher water solubility in aromatic hydrocarbons leads to higher hygroscopicity. However, the hygroscopicity of SBCs are not well known [15]. The Coordinate Research Council reported that when the temperature of aviation fuel decreases by 10 °C, it causes the extraction of 15–25 ppm (v/v) of water from the dissolved water/fuel solution. It is not a huge amount of water, but together with the suspended water and free water, it could lead to ice formation. Nevertheless, it is very important to deliver dry fuel to

aircraft and undertake research in new components to better understand water behaviour in jet fuel [15].

Development of detection methods

In the case of the form of the water, it could be evaluated by different methods of detection. Dissolved water in aviation fuel could be of a specific amount, and when crossing the saturation point, it can be extracted as entrained water or free water. Water conductivity could cause the risk of ignition damage and support the growth of microorganisms. It is essential to keep the amount of water as low as possible and monitor its level. Fuel contains saturated water, which could be at a level between 40 and 80 ppm dissolved water at 21 °C. This solubility differs regarding temperature. Free water in aviation fuel could be measured by different kinds of laboratory equipment [93]. The American Society for Testing and Materials (ASTM) standardized test for undissolved water uses UV-illuminated pad fluorescence. However, these tests, compared to a photocell comparator, provide more accurate results than chemical tests [93]. Total water content could be assessed by laboratory methods such as coulometric Karl Fisher (KF-ASTM D6304/IP 438) titration, and this method of evaluating the free water content is difficult to compare with UV-illuminated pad fluorescence [93]. These two methods are very useful in the aviation industry when evaluating water content [9,12].

Optical methods can also be used for the detection of dissolved water. POF sensors have many positive advantages, such as high elongation limits, high fracture toughness, high flexibility in bending, and large negative thermal-optical factors. If the POF of some materials has an affinity to water, e.g., polymethyl methacrylate (PMMA). It causes swelling of the fibre and growth in the refractive index, both of which influence increases in the Bragg wavelength of a PMMA-based optical fibre Bragg grating (POFBG). A POFBG is very good at assessing a very small amount of water. Finding the equilibrium of fuel–water and fuel–air atmospheres takes a matter of minutes. Right now, POFBG has a limited range of temperatures, and there is a need to gain equilibrium. Water content could be measured through detection in aviation fuel by using a PMMA-based optical fibre grating [93].

In the case of ISO numbers for detecting the size of solid particles (4, 6, 14, and 30 µm), it was proven that there is a higher linear effect of the amount of water over the ISO numbers than solid effects. Water influences the results of the number of solid particles. The ISO numbers could be used to determine the level of water using a linear regression model [94]. Another interesting method is the Visual Process Analyzer (ViPA), which involves image capturing and the size analysis of particles. This method allows for the technician to assess the water and particle size distribution [61].

Free water could be determined by two other methods. ASTM D3240 is involved with the response between water and a fluorescencic pad, which absorbs water where the colour changes regarding concentrations between 0 and 48 ppm. However, the precision at higher water concentrations is low. The second method is the Shell Water Detector, used to assess dispersed free water in aviation fuel. The changing colour is an indicator of the presence of free water. The disadvantage of this method is that it has lower precision than ASTM D3240 [93].

The system to control, monitor, and prevent water content in the jet fuel

Monitoring the water contamination is essential to keeping the fuel system clean and free from microbial life and corrosion problems, as well as to keep the aircraft safe. Aviation fuel must be clear and free of water at every point in the logistics chain, from production to the wing of the aircraft. Water in fuel can freeze at −1 °C, meaning that it could clog, break scavenge jet pumps. The human factor is the most important in taking care of monitoring before fuel with water can be transferred to an aircraft [15]. What is more, fuel has to be clean without the surfactants that destabilize the coalescing and separation filter system. Another very good practice is to keep jet fuel for a certain period of time for settling. Thanks to this, any water and debris separate out and can be drained. A similar situation occurs with aircraft where the fuel must stand for settling any free water at the bottom, which can then be drained. In some aircraft, the scavenging jet pumps pick up free water, mix it with

the aviation fuel, and feed it to the engine. Military and business aircraft use Fuel System Icing Inhibitor (FSII) additives to prevent water from turning to ice. Civil aviation also uses fuel heaters to protect against icing [15,36].

At every supply chain point, such as the production unit, logistic terminals, and the aircraft terminal, there are special water-separator filters to extract water from the fuel. In some situations, ultrasonic technology is used to terminate microbes in the fuel. In large transport airplanes, water-scavenging systems are used, with systematic drainage of fuel tanks for water. However, the scavenge jet pumps only operate if the fuel booster pump is working, that is when the aircraft is at the airport plate during a night stop. In the Boeing 777, there is an ultrasonic water detector installed in each fuel tank to inform about any water in the fuel tank. If the signal is shorted, then it means that there is water in the fuel tank. The Fuel Quantity Indication System (FQIS) assesses the fuel amount in the tanks [75].

Nevertheless, aircraft tanks have a fuel tank-venting system in order to keep atmospheric pressure, and contaminants like ice, water, sand, and debris can enter to fuel there. Another protective system is ultrasonic technology, which heats the aviation fuel, kills microorganisms, and maintains fuel quality. When the fuel is heated up to the appropriate temperature, the ultrasonic system is switched off. What is more, ultrasound can remove deposits from almost any place where other cleaning techniques cannot. It is one of the most effective systems available to ensure the safety of an aircraft [75].

3.4. Jet Fuel Contamination from Other Fuels and FAME Contamination

Jet fuel is also exposed to surfactant contamination from production units using different fuels and components due to the common pipeline system or railcar transport when positive segregation is not done. The contamination of FAME could happen with biodiesel or aviation fuel, for example, due to not releasing the railcar from FAME or diesel. A very useful method in this case is ASTM D7797-18, which describes the Flow Analysis by Fourier Transform Infrared Spectroscopy. The maximum level is 50 mg/kg. Another method for assessing jet fuel contamination by other distillates is existent gum (ASTM D381), which characterizes the existent gum content of Jet A1, including the procedure covering air or steam as a vaporizing stream. This method is commonly used in aviation and for automotive gasoline, as well as other distillates. Higher amounts of gum reflect fuel contamination by greater boiling oils or particulate matter. It is involved mainly with aspects of improper handling operations in the distribution chain [6,95].

A helpful method in detecting contamination is IP 170, which determines the manual and automated closed cup flash point of combustible liquids in a range between $-30.0\text{ }^{\circ}\text{C}$ and $75.0\text{ }^{\circ}\text{C}$. However, precision only occurs in the range from $-8.5\text{ }^{\circ}\text{C}$ to $75.0\text{ }^{\circ}\text{C}$. The flash point is a very important parameter to determine whether Jet A1 fuel is contaminated by gasoline or other hydrocarbons. This property is used to determine the flammability hazard of combustible fuels. In this case, the required flash point for Jet A1, which is set at a minimum of $38\text{ }^{\circ}\text{C}$, could increase diesel contamination or reduce gasoline contagion [23,96].

Another parameter to determine the potential contamination is distillation at $15\text{ }^{\circ}\text{C}$ using ASTM D86 for Jet A1, which is atmospheric distillation for determining the boiling range. However, the most important points are set at 10% of distillates up to $205\text{ }^{\circ}\text{C}$ and the final boiling point, which is a maximum of $300\text{ }^{\circ}\text{C}$. It is crucial as it involves safety, performance, and the volatility of jet fuel. Accordingly, the flash-point distillation can tell us about contamination by, for example, heavier hydrocarbons as the final boiling point of distillation will be higher than for Jet A1, which is a maximum of $300\text{ }^{\circ}\text{C}$ [23].

The next standard test method is ASTM D3948 for assessing the water separation of aviation fuel, known as a micro-separometer (MSEP). The minimum requirement for this parameter is set without an SDA additive at 85 units and at 70 units with an additive. This method was created for assessing the presence of surfactants from the refinery or surface-active elements that collect in the fuel system. As mentioned before, some additives could affect the final rating of MSEP and the capability of the filter separator to select free

water from aviation fuel—in this case, the rating is lower. When we obtain results higher than 100 units, it is involved with the reduction of light transmittance by the substance that is present in the fuel [23].

Visual appearance could also be very helpful in assessing jet fuel contamination, especially for light diesel, which is coloured by red dye [23].

To mitigate the risk of jet fuel contamination by other fuels and additives, good housekeeping procedures are followed, especially positive segregation of jet fuel, which means separate means of transport. Another important case is the quality monitoring of the above-mentioned methods and statistical analysis to be used as quickly as possible to prevent contamination.

FAME contamination

FAME is a jet fuel contaminant that may be involved with cross-contamination in undedicated transport systems, such as pipelines or rail tanks with fuel containing FAME like diesel B7. ASTM D1655 and Defence Standard 91-091 set requirements in this field, limiting FAME content up to 50 mg/kg. In critical situations at the airport terminal, it is possible to cross above the limit, up to 100 mg/kg. However, it should be confirmed and authorised by the aircraft operator. In dedicated systems for jet fuel, there is no need to run testing of FAME [22].

Contamination of aviation fuel could come from biodiesel, especially from a non-dedicated means of transport. ASTM D7566 sets the requirements for FAME level at a maximum limit of 5 mg/kg. If there is no dedicated means of transport for aviation fuel, or there is no knowledge about possible interactions between diesel with FAME in refinery-to-refinery transfers, then some monitoring should be done for refinery import tanks, marine Terminal Receipt Tanks, multi-product Terminal Receipt Tanks, multi-product Terminal Receipt Tanks, Airport Tanks, and Non-Dedicated Supplies in systems containing FAME. It is recommended for shipping operators who are transporting jet fuel in vessels to monitor three cargoes ahead. Before transporting aviation fuel, there should not be any fuel with FAME. In case this rule cannot be used, then testing of FAME content should be conducted, with recertification of aviation fuel with all properties [22].

The influence of FAME contamination on fuel quality

FAME in conventional jet fuel could be very dangerous for the safety of the flight. It could affect many properties, including cold properties. FAME could affect the freezing temperature in conventional jet fuel, which is very important when changing flight altitude. Another very important property is thermal stability, where the presence of FAME could be involved with the appearance of hydroperoxides, solved and unsolved gums, and, finally, with the forming of a deposit on an element of the engine or even creating particles. It is involved with oxidation reaction and some reactions connected with nitrogen, sulfur, organic acids, and olefins. What is more, FAME (36–39 MJ/kg) affects the energy content of conventional fuel (42 MJ/kg), so the final fuel energy is lower in some specific volumes. Further important properties relate to viscosity, which is very important for low temperatures, especially at -20°C , and densities [20].

Adding FAME to conventional aviation fuel decreases the strength of rubber seals. This is unlike conventional jet fuels, which cause rubber to shrink, which is why they affect the growth of hardness. FAME works as a plasticizer, which increases the movement of macromolecules and the space between them. Finally, they cause a lower strength for rubber sealant [97]. Figure 14 shows how increasing the level of FAME in aviation fuel results in lower hardness, poorer ductility, and lower tensile strength.

Increasing the level of FAME also causes the swelling and agitation of the rubber sealant. Figure 15 shows how sealant behaves under long-term contact with FAME/conventional jet blends.

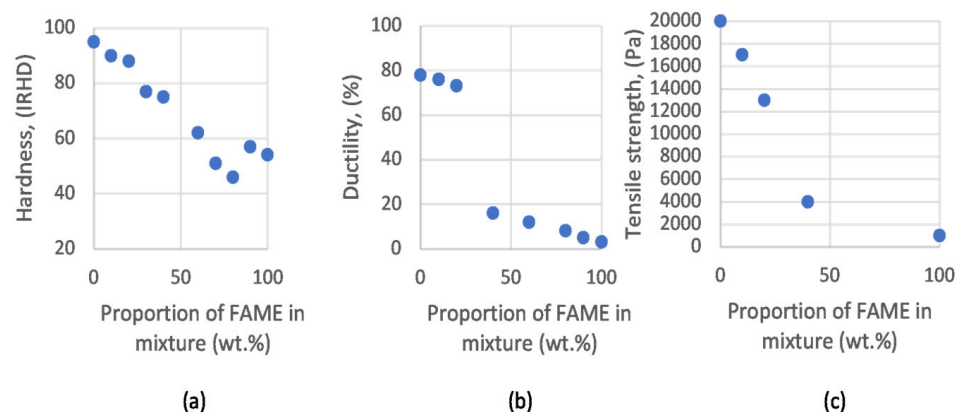


Figure 14. Effect of higher content of FAME in aviation fuel on hardness (a), ductility (b), and tensile strength of rubber sealant (c) [97].



Figure 15. Effect of higher contents of FAME in aviation fuel on volume of rubber in long-term storage [97].

Development of FAME detection methods

In the case of FAME monitoring, one very detailed and expensive method is gas chromatography-mass spectrometry (GC-MS) (IP 585), which is used to analyse FAME up to 5 mg/kg. This is why many fuel producers use this method to control FAME in the logistics chains [22]. This method is very good at detecting FAME species (C16:0–C18:3), but it cannot control short-chain carbons in the range from C8 up to C14. One example is coconut oil, where detection is not possible due to the co-elution of these species with aviation blends.

When the limit of FAME content was extended up to 50 mg/kg, new methods arose, namely the IP 583/ASTM D7797 Solid Phase Extraction and Fourier Transform Infra-Red (SPE-FTIR) spectroscopy methods, which are cheaper and faster than IP 585. The FTIR spectroscopic ASTM D7797 method could also provide false positive results of FAME content due to the presence in the sample of non-FAME carboxylic acid esters (plasticizers from elastomers). It is involved with close levels of adipates ($1742\text{--}1748\text{ cm}^{-1}$) and sebacates (1742 cm^{-1}) to that of FAME (1748 cm^{-1}). Aviation fuel, which has contact with elastomers, could lead to false positive results when assessing FAME by the FTIR spectroscopic ASTM D7797 method [98].

Another very promising method is two-dimensional gas chromatography (GC $\times$ GC), which allows for the analysis of the trace level of FAME and FAME components. In between gas and liquid chromatography is supercritical fluid chromatography (SFC). This method has a better diffusion coefficient and lower viscosity and surface tension than liquid solvents. This method is promising in terms of good mass transfer. A method that helps to determine monoacylglycerols, diacylglycerols, and triacylglycerols, as well as free glycerol itself, in fuel is ultrahigh-performance supercritical fluid chromatography-mass spectrometry (UHPLC-MS). It is a very sensitive method, with the limit of detection (LOD)

and limit of quantification (LOQ) required for RME [99]. Figure 16 presents the differences in FAME analysis by different methods: GC-MS, UHPLC-MS, and UHPLC-MS.

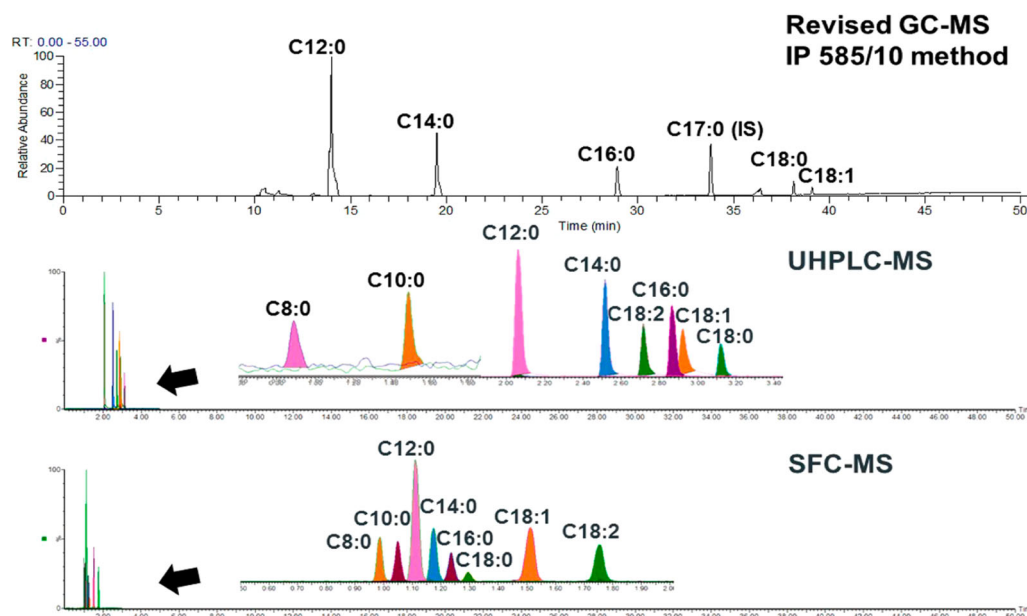


Figure 16. Comparison of the FAME analysis by different methods: GC-MS, UHPLC-MS, and UHPLC-MS [99].

The figure shows GC-MS and UHPLC-MS chromatograms, as well as UHPLC-MS for the FAME blends. The UHPLC-MS method is robust and suitable for analysing FAME in aviation fuel, especially for lower chain-length methyl esters related to the GC-MS method for the inclusion of CME in jet fuel [99].

The system to control (monitoring) and prevent FAME contamination

The most secure system for contamination of aviation fuel by FAME is using dedicated systems, namely separate means of transport only for jet fuel, an approach known as positive segregation. Another way to control and secure aviation fuel from contamination is monitoring the FAME content at a level of less than 5 mg/kg in the whole logistic chain from the manufacturing point. In logistics systems where FAME could come into contact with aviation fuel, it is essential to use a Management of Change procedure in order to mitigate the risk of FAME contamination and keep it within a specified level. When there is a risk of crossing the limit of 5 mg/kg, testing for FAME and reporting must begin. It is crucial to pay attention to systems where the procedure has not changed, and FAME contamination could be at a higher level for transported aviation fuel [22].

In sea transport, it is very important to remember vessel cleaning, especially when using a multiproduct before aviation fuel transporting and to continue testing. In this case, ship owners/operators are responsible for preparing the vessel and checking it before loading aviation fuel. One good practice is to track the history of the three previous shipments and utilise control, cleaning, and testing for FAME content. When some conflicting recommendations appear, then the more robust approach shall exist: cleaning, control, and testing [22].

According to DEF STAN 91-091 and ASTM D1655, when aviation fuel is transported in multi-product systems that contain FAME, then the procedural control will not secure FAME content below 5 mg/kg in aviation fuel. In such systems, the logistic operator is responsible for testing for FAME content and performing recertification analysis and follow the limits according to the quality specification. On the other hand, in multiproduct systems where there is no FAME, operators do not have to run FAME testing, but they do have to run recertification. In dedicated systems, it is not required to run FAME testing. In

dedicated logistics systems that are transitional, testing and recording FAME content must occur [22].

4. Conclusions

The development of the aviation sector will become increasingly important in the coming years, especially considering the environmental aspects. The ecological problem is related to the very large amount of greenhouse gas emissions when aviation fuels produced from conventional fossil components are used in the aviation industry. Conventional forms of aviation production, such as distillation, hydrodesulfurisation, and hydrocracking, are being replaced by the need to reduce greenhouse gas emissions. The production of SAF from variable renewable feedstocks presents a promising solution to address this challenge, with feedstocks being a critical driver. SAFs are new, alternative paths to conventional jet fuels, which are presented and characterized in ASTM D7566, including the most favourable HEFA and ATJ. In the future, there will also be new components, namely renewable fuels of non-biological origin (RFNBO) or even hydrogen, but this is for the 2030–2050 period.

Except all these different ways of producing aviation fuel, good housekeeping practices have to be used to prevent potential contamination. As has been mentioned in this review, aviation fuel must meet very rigorous quality requirements. For conventional fuel, it was determined by the British Ministry of Defence Standard DEF STAN 91-091 and ASTM Standard Specification D1655. For the novel fuel known as SAF, there is a new regulation, ASTM D7566-21, which specifies seven approved technologies/components with specifications and percentage volumes limited in conventional fuel now. JIG compiled the required fuel quality control and working procedures for handling, including areas for production, fuel depots, and airports.

Solid particles, microorganisms, and water remain the main types of contamination for both conventional and SAF. Solid particles may be derived from airborne dust, corrosion, wear of products, and trace metal from crude oils. Solid particles could erode fuel systems and equipment, as well as plugging or reducing filter life, leading to aircraft catastrophe. However, there are now standard and innovative methods in contamination monitoring, such as particulate contamination (ASTM D5452), as well as novel methods like ICP MS, SEM, or TEM. Another very dangerous contamination is microbiological life, which is mostly detectable at the fuel and water interface, as well as infrastructure surfaces. Microbial development requires free water, organic and inorganic nutrients, the presence or absence of oxygen, and appropriate temperature and pH levels. It is essential to control microbiological life in aviation fuel, and this could be achieved by standard and new advanced methods (CFU, ATP, MALDI TOF-MS). Microbial contamination influences fuel quality, mainly acidity, concentration of resins, corrosivity on copper plate, density, kinematic viscosity, lower combustion heat, flash point, and thermal stability. To reduce the microbiological contamination risk, it is crucial to control water at the bottom of the tank, the stagnating point of the lines, keep the settling time of aviation fuel in tanks, and maintaining the periodic removal of this water. Water is a form of contamination that can be very dangerous for flight safety, as water at some level could lead to the formation of ice crystals, finally blocking the fuel system and damaging the engine during the flight. There are new methods, such as the Visual Process Analyzer (ViPA), which are involved with image capture, the size analysis of particles, and water detection. The contamination of jet fuels by FAME that may arrive in biodiesel often remains due to the use of multi-product pipelines or railcars, which could be also very dangerous for the safety of flight as it affects the thermal stability, viscosity, and density of jet fuel, leading to coke deposits in the fuel system, and it may also impact the freezing point, resulting in fuel gelling.

Monitoring and preventive actions are essential to maintain the quality of aviation fuel as one of the most important aspects of aircraft safety. Refineries have to use a coherent system for conventional and novel technologies that embraces successive types of inspections to ensure quality protection. JIG compiled the fuel-quality control, and working procedures for the handling, production, fuel depot, and airports in two main standards:

EI 1530 (for conventional fuel) and EI 1533 (for semi-synthetic jet fuel and SBCs). What is more, it is essential to introduce new methods and run both continuous monitoring and prevention actions to maintain the high quality of the products. Future approaches could be predictive maintenance together with advanced statistical analysis in order to detect problems before failures occur.

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Abbreviations

ATP	Adenosine Tri-Phosphate
AF	Advanced Fermentation
ATJ	Alcohol To Jet
ATJ-SPK	Alcohol To Jet Synthetic Paraffinic Kerosene
AJF	Alternative Jet Fuels
ASTM	American Society for Testing and Materials
AOX	Antioxidants
APP	Aqueous Phase Processing
AAS	Atomic Absorption Spectrometry
AFQRJOS	Aviation Fuel Quality Requirements for Jointly Operated Systems
BSE	BackScattered Electrons
CHJ	Catalytic Hydrothermolysis Jet
CoQ	Certificate of Quality
CFU	Colony Forming Units
DGGE	Denaturing Gradient Gel Electrophoresis
ETR	Elliptometric Tube Rating
ETS	Emissions Trading System
EDX	Energy-Dispersive X-ray
FPH	Fast Pyrolysis and Hydroprocessing
FAME	Fatty Acid Methyl Ester
FM	Filter Monitor
FWS	Filter Water Separator
SPK/A	Fischer-Tropsch Synthesized Paraffinic Kerosene plus Aromatics
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
FAAS	Flame Atomic Absorption Spectrometry
FQIS	Fuel Quantity Indication System
FRTHC	Full Recycled Tail oil to HydroCracking reactor
FRTHT	Full Recycled Tail oil to HydroTreating reactor
GC-MS	Gas Chromatography—Mass Spectrometry
GFAAS	Graphite Furnace Atomic Absorption Spectrometry
HTS	High-Throughput Sequencing
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	HydroThermal Liquefaction
ICP-MS	Inductively Coupled Plasma—Mass Spectrometry

ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
ITR	Interferometric Tube Rating
ITS	Internal Transcribed Spacers
ICAO	International Civil Aviation Organization
JIG	Joint Inspection Group
LOD	Limit Of Detection
LOQ	Limit Of Quantification
MALDI-TOF MS	Matrix-Assisted Laser Desorption/Ionization Time-Of-Flight Mass Spectrometry
MIC	Microbiologically Influenced Corrosion
NAA	Neutron Activation Analysis
NMCC	Nishina Memorial Cyclotron Center
PRHT	Partial tail oil Recycled To HydroTreating reactor
PFC	Perfluorinated Chemicals
POFBG	PMMA based Optical Fiber Bragg Grating
PMMA	PolyMethyl MethAcrylate
POF	Polymer Optical Fibre
PCR	Polymerase Chain Reaction
PMA	Propidium MonoAzide
qPCR	quantitative Polymerase Chain Reaction
RLU	Relative Light Units
RED III	Renewable Energy Directive
RED-T	Renewable Energy Directive used in Transport
RFNBO	Renewable Fuels of Non-Biological Origin
SEM	Scanning Electron Microscopy
SSOTP	Single Stage Once Through Process
SPE-FTIR	Solid Polymer Electrolyte Fourier Transform Infra-Red
SDA	Static Dissipator Additive
SRB	Sulphate Reducing Bacteria
SAF	Sustainable Aviation Fuel
SIP	Synthesized Iso-Paraffins
HC-HEFA SPK	Synthesized paraffinic kerosene from hydroprocessed hydrocarbons, esters and fatty acids
SBC	Synthetic Blend Component
TEM	Transmission Electron Microscopy
QQQ-ICP-MS	Triple Quadrupole ICP-MS
TSA	Tryptone Soya Agar
GC × GC	Two-dimensional gas chromatography
UHC	Unburned HydroCarbons
UHPSFC-MS	UltraHigh-Performance Supercritical Fluid Chromatography—Mass Spectrometry
UHC	Unburned HydroCarbons
UCO	Used Cooking Oil
VGO	Vacuum Gas Oil
ViPA	Visual Process Analyzer
XRD	X-ray diffraction

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