CABIN AIR QUALITY ON NON-SMOKING COMMERCIAL FLIGHTS: A REVIEW OF PUBLISHED DATA ON AIRBORNE POLLUTANTS

Ruiqing Chen[1], Lei Fang[2], Junjie Liu[1], Britta Herbig[3], Victor Norrefeldt[4], Florian Mayer[4], Richard Fox[5] and Pawel Wargocki[2]*

[1] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, China
[2] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark
[3] LMU University Hospital Munich, Institute and Clinic for Occupational, Social and Environmental Medicine, Germany
[4] Fraunhofer Institute for Building Physics IBP, Holzkirchen Branch, Germany
[5] Aircraft Environment Solutions Inc., USA

* Corresponding author: email paw@byg.dtu.dk

Abstract

We reviewed 47 documents published 1967-2019 that reported measurements of volatile organic compounds (VOCs) on commercial aircraft. We compared the measurements with the air quality standards and guidelines for aircraft cabins and in some cases buildings. Average levels of VOCs for which limits exist were lower than the permissible levels except for benzene with average concentration at 5.9±5.5 μg/m^3. Toluene, benzene, ethylbenzene, formaldehyde, acetaldehyde, limonene, nonanal, hexanal, decanal, octanal, acetic acid, acetone, ethanol, butanal, acrolein, isoprene and menthol were the most frequently appearing compounds. The concentrations of SVOCs (Semi-Volatile Organic Compounds) and other contaminants did not exceed standards and guidelines in buildings except for the average NO_2 concentration at 12 ppb. Although the focus was on VOCs, we also retrieved the data on other parameters characterizing cabin environment. Ozone concentration averaged 38±30 ppb below the upper limit recommended for aircraft. The outdoor air supply rate ranged from 1.7 to 39.5 L/s per person and averaged 6.0±0.8 L/s/p (median 5.8 L/s/p), higher than the minimum level recommended for commercial aircraft. Carbon dioxide concentration averaged 1,315±232 ppm, lower than what is permitted in aircraft and close to what is permitted in buildings. Measured temperatures averaged 23.5±0.8°C and were generally within the ranges recommended for avoiding thermal discomfort. Relative humidity averaged 16%±5%, lower than what is recommended in buildings.

Key words: Commercial aircraft; Cabin air quality; In-flight measurement; Contaminants; Thermal environment.

Practical Implications

The present work provides an empirical benchmark for contaminants at the concentrations typically measured on commercial aircraft on which no tobacco smoking occurs. The information can be used to study the risk of adverse health effects and discomfort for passengers during commercial flights. The data can serve as a reference in policy documents that set the permissible levels of airborne pollutants in aircraft cabins. Aircraft manufacturers may find the present data useful in developing new tools and solutions for monitoring and mitigating elevated levels of pollutants in aircraft cabins.

Abbreviations

ACH: Air Change rate per Hour

ACGIH: American Conference of Governmental Industrial Hygienists

AHSD: Air Health Science Division office

ANSI: American National Standards Institute

AP: Aviation Regulations

ASD-STAN: Aerospace and Defence Industries Association of Europe-Standardization

ASHRAE: American Society of Heating Refrigerating and Air-Conditioning Engineers

ASTM: American Society of Testing Materials

CAA: Civil Aviation Authority

CCAC: Civil Aviation Administration of China

CEN: Comité Européen de Normalisation

CFU: Colony Forming Unit

CO: Carbon monoxide

CO_2: Carbon Dioxide

CSS: Consolidated Safety Services

DEHP: Diphenyl-2-ethylhexyl phosphate

EASA: European Aviation Safety Agency

ECS: Environmental Control System

EN: European Norm

EPA: Environmental Protection Agency

EU: European Union

FAA: Federal Aviation Administration

FH: Flight hours

FID: Flame Ionisation Detector

IAC: Russia's Interstate Aviation Committee

IAGVs: Indoor Air Guideline Values

JAA: Joint Airworthiness Authorities

LOD: Level of Detection

6-MHO: 6-methyl-5-hepten-2-one

NIOSH: National Institute for Occupational Safety and Health

NOAEL: No observed adverse effect level

NR: Not reported

O_3: Ozone

ODT: Odour detection threshold

OEHHA: Office of Environmental Health Hazard Assessment

PELs: Permissible Exposure Levels

PID: Photo-Ionisation Detector

PM: Particulate Matter

PMV: Predicted Mean Vote

PPD: Predicted Percentage Dissatisfied

RELs: Recommended Exposure Levels

RH: Relative humidity

RSP: Respirable Suspended Particulates

SD: Standard Deviation

SI: Supplementary Information

SOA: Secondary organic aerosols

ST: Short Term Exposure Levels

SVOCs: Semi-volatile organic compounds

TBP: Triisobytyl phosphate

TCAC: Technical cabin air contamination

TCE: Trichloroethylene

TCEP: Tris (chloroethyl) phosphate

TCPP: Tris (chloro-isopropyl) phosphate

TCPs: Tricresyl phosphates

TDCPP: Tris (1,3-dichloro-isopropyl) phosphate

TEHP: Tris (ethyl-hexyl) phosphate

TiBP: Tributyl phosphate

T-m-CP: Tri-m-cresyl phosphate

T-mmp-CP: Tri-mmp-cresyl phosphate

T-mpp-CP: Tri-mpp-cresyl phosphate

TMPP: Trimethyllolpropane phosphate

TnBP: Tri-n-butyl phosphate

TOCP: Triorthocresyl phosphate

T-p-CP: Tri-p-cresyl phosphate

TPP: Triphenyl phosphate

TBEP: Tris (butoxy-ethyl) phosphate

TXP: Trixylyl phosphate

TVOC: Total concentration of VOCs

TWA: Time Weighted Average

US: United States

VOCs: Volatile organic compounds

WHO: World Health Organization

1. Introduction

Commercial airlines carried more than 4.5 billion passengers in 2018[1] and before the COVID-19 pandemic occurred this number was expected to grow[2]. Around 96 billion gallons of fuel were consumed by commercial airlines worldwide in 2019[3]. Two to five percent of fuel is used to maintain pressurization and ventilation of the air in aircraft cabins[4]. Ventilation reduces the risk of adverse health effects and improves the comfort and well-being of passengers on commercial aircraft as well as the working conditions for crew members. Consequently, maintaining adequate air quality through proper ventilation and filtration of aircraft cabins is important not only from the passenger and crew members point of view but also for the airline because economically significant fuel savings can be achieved if the systems for maintaining cabin environmental quality are operated and controlled according to the actual pollution loads while not exceeding the permissible levels of the parameters defining the quality of air in the aircraft cabin. The ventilation of aircraft cabins is particularly energy demanding because the air is taken from the jet engines (so-called bleed air) or compressed by electrically driven compressors and must be conditioned before it can be used for ventilation. Aircraft cabin ventilation is composed typically of 60-80% outdoor air (bleed air) and 20-40% recirculated air (extracted from the cabin)[5,6]. The B787 does not use bleed air but an electric air compressor to provide outdoor air to the aircraft cabin; cabin air in the B787 contains approximately 50% fresh air and 50% recirculated air. The National Research Council (US) Committee suggested some models of aircraft should use different amounts of recirculation or even no recirculation[7] but the European Aviation Safety Agency (EASA) states that each passenger and crew compartment must be ventilated and each crew compartment must have enough outdoor air (not less than 0.28 m^3/min) to enable crewmembers to perform their duties without undue discomfort or fatigue[8]. The Environmental Control System (ECS) that provides conditioned air to the cabin crew and passengers is the most energy demanding sub-system of an aircraft, being responsible for up to 5% of the total fuel consumption of the engines[9]. The traditional ECS requires a minimum of 0.4 pounds per minute per person outside air to maintain pressurization and avionics cooling[10], and the air supplied may exceed the regulatory requirement of 0.55 pounds per minute per person of outside air in order to account for flow measurement error in the bleed air supply system to the ECS[8]. The new optimized ECS has potential for reducing fuel consumption by reducing the ventilation rate required to achieve permissible levels of air quality. It is estimated that it could potentially save nearly 0.8% to 2% of the fuel in comparison with traditional ECS if the outdoor air supply rate could be reduced[9,11]. This amounts to fuel savings of between 235,000 litres (62,000 gallons) and 587,500 litres (155,000 gallons)/year/airplane.

Ventilation is used to control the levels of pollutants generated inside the cabin as well as to remove some heat[12]. Ventilation removes or dilutes the pollutants generated by the occupants, their activities, the materials in the cabin and any other activities that are taking place in the cabin such as the preparation and serving of meals. Ventilation can also be the carrier of engine generated emissions as well as of contaminants present outdoors (e.g., ozone). Because commercial aircraft traffic has increased, cabin air quality and its relation to cabin ventilation has become a topic of considerable interest in recent years[13]. Many studies examined the effects of cabin air quality on passengers[14-18] and flight attendants[19-21]. The types and levels of air pollutants typically measured on commercial flights must be well defined and information on how they affect comfort and well-being and the risk for adverse health effects on passengers, flight attendants and pilots must be documented for proper risk assessment and for the accurate operation of systems for controlling cabin air quality.

The present paper focuses on cabin air pollutants and extends the available information on the types of pollutants and the concentrations measured on commercial flights, which has been summarized in reviews published in the past[15,22-24]. We briefly summarize a few of them in the following.

Nagda et al.[22] published a detailed review in 2000 of studies reporting measurements of cabin air quality that had been carried out since the mid-1980s. They reported measurements in studies of up to about 100 flights. These included information on bioaerosols, carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM). Only a few of the studies measured formaldehyde, ozone (O_3), or volatile organic compounds (VOCs); semi-volatile organic compounds (SVOCs) were measured but were extremely low in concentration (below detection limits of 1 μg/m^3) and thus not reported as no conclusions could be drawn; naphthalene was the only SVOC barely above the minimum detection limits.

Space et al. [23] reviewed in 2000 the same studies as Nagda et al.[22] and agreed that in general the levels of pollutants measured in aircraft were low and comparable to the levels found in buildings. In particular, microbial levels in airplane cabins were found to be lower than those in a typical dwelling or office building. CO and respirable particulate levels were within comfort and health guidelines[25], maximum O_3 concentrations were lower than FAA[25] regulatory limits, and formaldehyde concentrations were lower than the maximum value recommended in ASHRAE 62 Standard[26]. The average reported concentrations of CO_2 were about 1,500 ppm and were thus higher than 1,000 ppm which is the upper level typically recommended in buildings for odour control, but they were not higher than is found in other means of transportation such as trains, buses, or subways. Concentrations of VOCs were measured with a variety of techniques, but the data were inadequate for developing well-founded recommendations and conclusions. It was considered possible that interactions between some pollutants and other parameters defining the quality of an aircraft cabin environment could cause discomfort for crew members or passengers.

Nagda and Rector[15] published a review in 2003 of six studies involving two to thirty flights; the concentrations of both VOCs and SVOCs were reported. The review concluded that contaminant levels in aircraft cabins during routine aircraft operations were about the same as those in residential and office buildings. However, two exceptions were noted. The measured levels of ethanol and acetone were higher in aircraft than in buildings and the levels of benzene, tetrachloroethylene and xylenes were lower. It was also noted in the data from two studies that under normal operating conditions the levels of SVOCs, including trimethylolpropane phosphate (TMPP) and triorthocresyl phosphate (TOCP) were typically below the limits of detection. The review suggested that any generalization of results from different measuring campaigns would require data from a larger sample of flights, covering different types of aircraft and operating conditions. Furthermore, it was suggested that measured VOCs and SVOCs, although also seen in other environments, might not include the full spectrum of pollutants and their reaction products that are present in aircraft[27]. The authors therefore called for a comprehensive assessment of the chemical species found in aircraft cabin air.

Lindgren[24] studied in 2003 the aircraft cabin environment and identified the personal and environmental risk factors associated with symptoms and perceptions of cabin air quality. He also investigated whether a ban on smoking and increased relative humidity of air on intercontinental flights could have a beneficial health effect. The review concluded that the relative humidity, reported to be 3% to 8% during intercontinental flights, was very low. Mould and bacteria ranged between 10 and 300 Colony Forming Units (CFU)/m^3. Tobacco smoking, which was still permitted at the time of this study, increased the number of respirable particles present in cabin air from 3 to 49 $\mu g/m^3$ and increased the amount of cotinine in urine. The exposure to tobacco smoke was highest in the aft part of the cabin, where the smoking section was located. Lindgren[22] concluded that tobacco smoke and the low relative humidity of cabin air in aircraft are important environmental factors and that atopy and work stress could be significant risk factors for symptoms and adverse environmental perceptions.

The present review was a part of the ComAir[28] and CognitAir projects that investigated how cabin ventilation and exposure to pollutants on commercial aircraft affect the cognitive performance, comfort, and well-being of passengers; some results obtained in these projects are reported elsewhere[28] and all will be reported later when the analyses are completed. It was additionally initiated by the increasing interest in developing methods that would simultaneously control cabin air quality to improve comfort and reduce health risks while also reducing the increased fuel consumption caused by over-ventilating the aircraft. The overall aim was to identify all VOC studies published to date that reported measurements of air quality on aircraft and to summarize the results to create a proper reference. Among the many initial questions, the present review was intended to provide answers to the following queries: (i) How many studies performed measurements on aircraft cabin environment and how many flights on different aircraft were included in these studies? (ii) Which types of environmental parameters and contaminants were measured? (iii) What were the most measured contaminants? and (iv) What levels of each contaminant were measured? A central question was whether the measured levels of contaminants complied with the current standards and recommendations regulating aircraft cabin air quality. For this purpose, we also reviewed standards, guidelines, and regulations governing air quality in aircraft cabins and other relevant regulations and guidelines and compared them with the reported levels.

2. Review methodology

We searched Google Scholar, Web of Science and Research Gate for articles and reports on measurements of air quality in commercial aircraft published before November 2019. The main key words included: aircraft cabin air quality, air pollutants, gaseous contaminants, VOCs, SVOCs, particles, microorganisms. We selected primarily archival articles that provided adequate information on measurements of pollutants and their concentrations, and the measuring methods used. Our focus was mainly measurements of VOCs, but we present also all other measurements that were reported together with the VOCs in the studies that we identified during our search.

More than 40,000 publications were found in the initial search. They were screened by reading through their titles and abstracts. Among them, forty-seven original documents were selected for the purpose of this review. We included papers reporting measurements on aircraft under normal commercial flight conditions. We did not include studies reporting measurements in the simulated mock-up of an aircraft[29,30], focusing on engine emissions[31], reporting unusual exposures during which crew members complained about cabin air quality[32] or aimed at developing air monitoring and its applications[33]. The selected documents reported measurements published as early as in 1967. The following measurements were reported in the selected studies in addition to VOCs: temperature, relative humidity (RH), ventilation, concentrations of CO_2, CO, NO_x, O_3 and SVOCs, particulate matter (PM) and microorganisms. We report the measurements on non-smoking aircraft and all data including aircraft where smoking occurred are presented in SI.

The data pertinent to the objectives of the present review were extracted from the selected documents and presented both in tabular form and graphically. To create a proper reference, we extracted the following information: names of the authors, publication year, flight duration (haul-type), study location, number of flights during which the measurements were made and aircraft type. We also extracted all available information on VOC measurements and performed quality assurance/quality control (QA/QC) analysis similar to the one performed by Nagda and Rector[15]; these data are presented in SI in Table S1, and in Table 9.

The average and median measured levels of the identified contaminants were calculated and presented together with the minimum and maximum levels in each study. The averages were weighted by the number of flights during which the measurements were made. Similar data treatment was used for other parameters that included temperature, RH, and ventilation. The measured values reported in the forty-seven papers included in the present review were compared with the permissible levels included in the standards and guidelines. For this purpose, we reviewed standards or recommendations that are pertinent to air quality in aircraft.

We additionally compared average levels of VOCs with their published odour detection thresholds (ODT) to determine probability of detection of the pollutants that were reported. To obtain ODT we used modelled thresholds by Abraham et al.[34]; these modelled thresholds correlate well with the experimental ODTs obtained by Nagata and Takeuchi[35].

3. Results and discussion

3.1 Overview of standards and guidelines related to air quality in aircraft cabins

Seven standards, guidelines, and regulations were collected and reviewed. They are listed in Table 1. Two of them are from the USA [36,37], three from Europe [10,38,39], one from Russia [40], and one from China [41].

Table 1 presents the specific upper limits for the air contaminants listed in these documents. These contaminants are: CO, CO_2, O_3, VOCs, SVOCs, PM, bacteria, and fungi. Ventilation requirements that affect cabin air quality are also listed.

Only two documents contain upper limits for specific VOCs. These are BS-EN4618[39] and AP-25[40]; they are listed in Table 2. We present the prescribed levels in BS-EN4618[39] but note that the standard has been withdrawn as a result of a decision of the European committee CEN/BT 31/2013. We kept this document for future reference as it is one of only two attempts to regulate the levels of VOCs on aircraft.

BS-EN4618[39] stipulates that the bacteria, virus and fungus limits should be those applied to the levels of micro-organisms in non-industrial indoor environments[42] and in the workplace as prescribed by one European guideline[43]; the limits for mixed populations of fungi and bacteria, not being a main focus of the present review, are presented in Supplementary Information (SI) in Table S12[42].

It is worth mentioning that ASHRAE Standard 161[36] listed in Table 1 also prescribes the quality of the thermal environment in the cabin. The temperatures should be in the range between 18.3°C-23.9°C both during in-flight and on-ground operations, and should not exceed 26.7°C during in-flight, and 26.7°C (with entertainment systems not operating) or 29.4°C (with entertainment systems in operation) on the ground. ASHRAE handbook[44] suggests that typical design temperatures for commercial aircraft should be between 24°C and 27°C for hot-day ground design conditions, 21°C for cold-day ground-operating conditions, and 24°C during cruise for both, and that the air distribution system should by design provide approximately 4.7 L/s/p of outdoor air. No other recommendations are provided. Aircraft design requirements do not follow building recommendations for RH levels for occupant comfort because the upper humidity limits are imposed by safety during flight to reduce any condensation that might result in corrosion of the fuselage and the risk of electrical short-circuiting[36]; RH in B787 is about 25% because of the use of composite materials[45].

Table 1 Requirements regarding air quality in aircraft, where TWA stands for Time-Weighted Average.

Parameter	FAR[37]	ASHRAE 161[36]	JAR[38]	CS[10]	BS-EN4618[39]	CCAR[41]	AP-25[40]
CO	50 ppm*	9 ppm TWA10min 50 ppm 1 min peak	50 ppm	50 ppm	50 ppm peak 25 ppm TWA1h 10 ppm TWA8h	50 ppm	50 ppm
O_3	100 ppb TWA 3h 250 ppb any time	100 ppb TWA 3h 250 ppb any time	100 ppb TWA 3h 250 ppb any time	100 ppb TWA 3h 250 ppb any time	100 ppb TWA 3h 250 ppb any time 60 ppb TWA 8h	100 ppb TWA 3h 250 ppb any time	100 ppb TWA 3h 250 ppb any time
CO_2	5000 ppm	-	30000 ppm	5000 ppm	20000 ppm 15min 5000 ppm peak 2,000 ppm	5000 ppm	5000 ppm
Ventilation rate	0.55 pounds/min per person (corresponding to 3.5 L/s per person)	3.5 L/s per person (min. outside) 7.1 L/s per person (min. total)	4.7 L/s per person (min. outside)	4.7 L/s per person (min. outside)	-	0.55 pounds/min per person (corresponding to 3.5 L/s per person)	-
VOCs	-	-	-	-	See Table 2	-	See Table 2
$PM_{2.5}$	-	-	-	-	100 μg/m^3 TWA 1h (health) 40 μg/m^3 continuous (health)	-	-
PM_{10}	-	-	-	-	150 μg/m^3 TWA 24h	-	-
Bacteria and fungi	-	-	-	-	See Table S12	-	-
SVOCs	-	-	-	-	-	-	Phosphate cresol mixture 0.5 mg/m^3 Dioctyl sebacate 5 mg/m^3

*The original language is 1 part in 20,000 parts of air.

Table 2 Limits for specific VOCs in BS-EN4618[39] and for AP-25[40], where TWA stands for Time-Weighted Average.

Country/Organization	VOC	Limit (mg/m^3)	Time average	Comments
BS-EN4618[39]	Benzene	3.2	TWA 8h	Safety
		12.8	15min exposure	Health
	Toluene	760	15min exposure	Safety
		190	TWA 8h	Health
		153	-	Comfort
	Formaldehyde	2.47	15min exposure	Safety
		0.93	TWA 8h	Safety
		< 0.1	30min exposure	Health
	Acetaldehyde	45	15min exposure	Safety
		1.8	TWA 24h	Health
	Acrolein	0.75	15min exposure	Safety
		0.25	TWA 8h	
		0.05	TWA 30min	Health
	Acetone	3630	15min exposure	Safety
		1210	TWA 8h	
		1782	15min exposure	Health
		1188	TWA 8h	
		240	-	Comfort
	Butanone	897.8	15min exposure	Safety
		1795.5	TWA 8h	
		897.8	15min exposure	Health
		598.5	TWA 8h	
	Dichloromethane	< 3	TWA 24h	Safety
		< 3	TWA 24h	Health
AP-25[40]	Gasoline vapor	300	-	Part of VOCs
	Mineral oil vapor and aerosols	5	-	Part of VOCs
	Synthetic lubricating oil vapor and aerosols	2	-	Part of VOCs
	Acrolein	0.2	-	VOC
	Phenol	0.3	-	VOC
	Formaldehyde	0.5	-	VOC
	Benzene	5	-	VOC

Notes:

- Safety Limits: limits for cabin environment parameters that if exceeded would prevent the safe operation of the aircraft.
- Health Limits: limits for cabin environment parameters that if exceeded would lead to temporary or permanent pathological effects on the occupants.
- Comfort Limits: limits for cabin environment parameters that if exceeded would prevent the achievement of an acceptable cabin environment.
- Regarding the safety and health limits, occupational exposure limits and regulatory limits are taken from cognizant authorities, where appropriate.
- Concerning an acceptable cabin environment, it is defined as one in which majority of the people exposed would not be expected to express dissatisfaction with the air quality contaminants and/or environmental criteria.

- Comfort limits where appropriate are taken from cognizant authorities that provide indoor environment standards and guidelines.

3.2 Overview of studies reporting measurements of air quality in aircraft

Table 3 provides a summary of the studies included in the present review. It shows that the measurements reported were performed on 2,251 flights and that the first study was published as early as 1967. About forty different aircraft types were examined including those used for regional or intercontinental flights. The length of flight determined different categories of flight duration from very short-haul, short-haul, medium-haul to long-haul flights the categories of flight duration used in the original studies were adopted as there were differences in the methods used to categorize flight duration between various studies. Accurate determination of flight duration was considered irrelevant for the purpose of the present review.

The U.S. ban on inflight smoking began with domestic flights of two hours or less in April 1988, and was extended to domestic flights of six hours or less in February 1990, followed by the extension to all domestic and international flights in 2000[46]. The ban in the EU was introduced in 1997[47]. We therefore considered all studies published after 2000 to have reported measurements on aircraft on which smoking did not occur unless the authors stated that smoking was still taking place. For the studies published before 2000 we specifically looked for information on whether the measurements were made on aircraft where smoking did not occur, see Table 3 for details.

Table 4 summarizes parameters characterizing cabin air quality measured in the studies included in the present review together with the number of flights on which the measurements were made. VOCs and SVOCs were reported in 27 and 12 studies respectively on 1080 and 540 flights. PM was measured in 17 studies on a total of 451 flights. The other contaminants measured were CO, NO, NO_2, NO_X, SO_2; they were measured respectively on 378, 5, 37, 41 and 5 flights. Bacteria, fungi, and moulds were measured on 195, 152 and 2 flights respectively. O_3 was measured in 21 studies on 1092 flights. Ventilation was measured on 364 flights in nine studies. CO_2 was measured in 20 studies covering 655 flights. Fourteen studies measured temperature on 371 flights. Seventeen studies measured RH on 407 flights. The details of measurements, measurement location and QA/QC analysis are shown in Table S1 in SI; the measurements were mainly made in the passenger area.

Table 3 Summary of studies included in the present review that reported measurements of air quality in aircraft cabins.

Study	Year	Flight type[a]				Study location	Number of flights	Aircraft type		
		Very short-haul flights	Short-haul flights	Medium-haul flights	Long-haul flights			Airbus	Boeing	Others
Brabets et al.[48]	1967	-	-	-	-	North America	285		-	
Bishof[49]	1973	-	-	-	-	Europe	14		√	√
Perkins et al.[50]	1979	-	-	-	-	North America	2		√	
Rogers[51]	1980		√ (NC)		√ (NC)	North America	157	√	√	√
Nagda et al.[52]	1992	-	-	-	-	North America	92	√	√	√
Dechow et al.[53]	1997			√ (NC)	√ (NC)	Europe	2	√		
ASHRAE[54]	1999[NS]			√ (NC)	√ (NC)	North America	8		√	
Lee et al.[55]	1999	√ (1h 25min)	-	-	√ (14h 15min)	Asia	16	√	√	
Haghighat et al.[56]	1999	-	-	-	-	North America	43	√	√	√
Fox[6]	2000[NS]			NC		North America	2			√
Dumyahn et al.[57]	2000[NS]			NC(1h-7.2h)		North America	49		√	
Ree et al.[58]	2000	-	-	-	-	Europe	40		√	
Wieslander et al.[59]	2000	-	-	-	-	Europe	2		√	
Nagda et al.[60]	2001	-	-	-	-	North America	10		√	
Lindgren and Norbäck[47]	2002[S]	-	-	-	-	Europe	26		√	
Waters et al.[61]	2002[S]		√ (< 2h)	√ (2-8 h)	√ (>8h)	North America	36		-	
Spicer et al.[62]	2004-RP-1262 Part 1				√ (3 h-3h 49 min)	North America	4		√	√

Spengler et al.[63]	2004	-	-	-	-	North America	106	√	√	√
Duc et al.[64]	2007	-	-	-	-	North America	4		-	
Bhangar et al.[65]	2008	-	-	-	-	North America	68	√	√	
Muir et al.[66]	2008	-	-	-	-	Europe	1			√
Mckernan et al.[67]	2008	-	-	-	-	North America	12		√	
Osman et al.[68]	2008		√ (NC)		√ (NC)	North America	16		√	
Solbu et al.[69]	2011	-	-	-	-	Europe	40			√
Crump et al.[70]	2011-Part 1	-	-	-	-	Europe	100	√	√	√
Crump et al.[71]	2011-Part 2	-	-	-	-	Europe	100	√	√	√
Spengler et al.[72]	2012		√ (<3h)	√ (3-6h)	√ (>6h)	North America	83	√	√	
Gładyszewska-Fiedoruk[73]	2012		√ (Lasted 3h)			Europe	1		-	
Giaconia et al. [74]	2013		√ (<1.5h)			Europe	14	√		
Weisel et al.[75]	2013	-	-	-	-	North America	52		√	
Ji and Zhao[76]	2014	-	-	-	-	Asia	5	√	√	
Guan et al.[77]	2014-Part 1	-	-	-	-	Asia	107	√	√	
Guan et al.[78]	2014-Part 2	-	-	-	-	Asia	51	√	√	

Li et al.[79]	2014		√ (1h 27min-3h 50min)			Asia	9		√	
Ree et al.[80]	2014	-	-	-	-	Europe	20		√	
Wang et al.[81]	2014	-	-	-	-	Asia	14		√	
Wang et al.[82]	2014	-	-	-	-	Asia	14		√	
Guan et al.[83]	2015	-	-	-	-	Asia	6		-	
Gao et al.[84]	2015	-	-	-	-	Asia	5		√	
Rosenberger et al.[85]	2016		√ (NC)		√ (NC)	Europe	108	√		
Schuchardt et al.[86]	2017		√ (NC)		√ (NC)	Europe	69	√	√	
Cao et al.[87]	2017		√ (NC)			Asia	64	√	√	
Cao et al.[88]	2018		√ (<2h)	√ (2–6h)		Asia	179	√	√	√
Rosenberger[14]	2018	-	-	-	-	Europe	17	√		
Schuchardt et al.[89]	2019	-	-	-	-	Europe	177	√	√	
Guan et al.[90]	2019	-	-	-	-	Asia	14	√	√	
Liu et al.[91]	2019	-	-	-	-	Asia	7	√	√	
Total	1967-2019	**1**	**11**	**5**	**10**		**2251**	**22**	**35**	**12**

Notes:

- NC: not clear.
- a: length of flight according to the information provided in the reviewed papers; it was not possible to provide the length of flights in minutes/hours.
- Studies reported after 2000 are on non-smoking flights unless indicated with S at the date; studies before 2000 were considered to be carried out on smoking flights unless indicated NS at the date.

Table 4 Number of flights on which air quality parameters were measured in the studies selected for the present review.

Study	Year	Parameters measured in aircraft cabin（Flight number）															
		Temperature	RH	Ventilation	CO_2	O_3	VOCs	SVOCs	Particulates	CO	NO	NO_2	NO_x	SO_2	Bacteria	Fungi	Molds
Brabets et al.[48]	1967					285											
Bishof[49]	1973					14											
Perkins et al.[50]	1979					2											
Rogers[51]	1980					157											
Nagda et al.[52]	1992	92	92	35	92	92			92	92					92	92	
Dechow et al.[53]	1997						2		2						2		
ASHRAE[54]	1999	8	8		8	8	8		8	8					8	8	
Lee et al.[55]	1999	16	16		16	16	5		8	8	5	5	5	5	3	3	
Haghighat et al.[56]	1999	43	43		43												
Fox[6]	2000	2	2		2		2	2		2							
Dumyahn et al.[57]	2000	49	49		49	27	49		49	49		27			49	49	
Ree et al.[58]	2000		18			31											
Wieslander et al.[59]	2000	2	2		2	2	2		2						2		2
Nagda et al.[60]	2001	10	10		10		10	10	10	10							
Lindgren and Norbäck[47]	2002	5	5	24	5	13	22		26			5					
Waters et al.[61]	2002	36	36		36	36	36		36	36			36				
Spicer et al.[62]	2004-RP-1262 Part 1	4	4	4	4	4	4	4	4	4							
Spengler et al.[63]	2004					106											
Duc et al.[64]	2007														4		
Bhangar et al.[65]	2008					68											
Muir et al.[66]	2008						1	1									
Mckernan et al.[67]	2008														12		
Osman et al.[68]	2008														16		
Solbu et al.[69]	2011						31	40									

Crump et al.[70]	2011-Part1						100	100	40								
Crump et al.[71]	2011-Part2						100	100									
Spengler et al.[72]	2012	83	83	83	83	83	83	63(21 available）	81	83							
Gładyszewska-Fiedoruk[73]	2012	1	1		1												
Giaconia et al.[74]	2013		14	14	14												
Weisel et al.[75]	2013					52	52										
Ji and Zhao[76]	2014					5	5		5								
Guan et al.[77]	2014						107										
Guan et al.[78]	2014-Part1						51										
Li et al.[79]	2014-Part2			5	5				9								
Ree et al.[80]	2014							20									
Wang et al.[81]	2014						14										
Wang et al.[82]	2014						14										
Guan et al.[83]	2015			6	6		6										
Gao et al.[84]	2015					5	5										
Rosenberger et al.[85]	2016						108										
Schuchardt et al.[86]	2017	20	20		69	69	69	69		69							
Cao et al.[87]	2017								64								
Cao et al.[88]	2018			179	179												
Rosenberger[14]	2018				17	17	17	17		17							
Schuchardt et al.[89]	2019						177	177									
Guan et al.[90]	2019			14	14				14								
Liu et al.[91]	2019		4						1						7		
Number of studies	1967-2019	**14**	**17**	**9**	**20**	**21**	**27**	**12**	**17**	**11**	**1**	**3**	**2**	**1**	**10**	**4**	**1**
Number of flights	1967-2019	**371**	**407**	**364**	**655**	**1092**	**1080**	**540**	**451**	**378**	**5**	**37**	**41**	**5**	**195**	**152**	**2**

3.3 Measured VOCs

Different methods were used to detect and analyse VOCs in studies included in the present review. We grouped the results according to the method used.

Two methods were used to monitor the total concentration of VOCs (TVOCs). These were the Flame Ionisation Detector (FID)[55] and the Photo-Ionisation Detector (PID)[70,71,83,86]. Average TVOC concentration measured using a real-time FID monitor was about 8 mg/m^3. Average TVOC concentration measured using a real-time PID method was 277 µg/m^3; the range was from 0 to 38 mg/m^3. FID is often reported as ppb methane and PID as ppb isobutylene equivalent; Schuchardt et al.[89] reported it as Toluene equivalent in µg/m^3. We were not able to determine the calibration details for these detectors, but they may explain the large differences in TVOC observed between the two methods.

Three sampling methods were used to measure VOCs: active sampling, passive sampling, and canister sampling. Active sampling was used in the majority of the studies included in the present review, resulting in 140 measured VOCs[53,54,61,70-72,75,76,78,81,82,84-86]. There is no detailed concentration data on the type of contaminants for other active sampling studies of VOCs[14,69,77,83,89]. Passive sampling was used in a few studies resulting in 48 measured VOCs[47,59,62,92], while canister sampling was used in five studies resulting in 96 measured VOCs[60,62,72]. As active sampling detected more compounds and was used in the greatest number of studies the results obtained in this way are presented below. All other measurements are tabulated in SI where a distinction is made between the compounds measured on all flights and on non-smoking flights only.

The concentrations of VOCs measured using active sampling were in the range from 0 to 3 mg/m^3 with the average concentration ranging between 0.1 and 100 μg/m^3. For non-smoking flights, Figure 1 shows the VOCs measured in 12 studies. Fifteen classes of VOCs were measured, with alcohols accounting for most of the compounds measured (57.8%) followed by aldehydes (6.4%), alkanes (4.8%), terpenes (4.5%), aromatics (3.5%) and ketones (3.4%); all other groups of VOCs each accounted for less than 3% of the compounds measured (Figure 1). Comparing concentrations of measured VOCs with the permissible levels set out by AP-25[40] and the now withdrawn BS-EN4618[39], it can be seen that even the maximum concentrations of the listed compounds measured in the aircraft cabins were lower than the prescribed limits (Table 5).

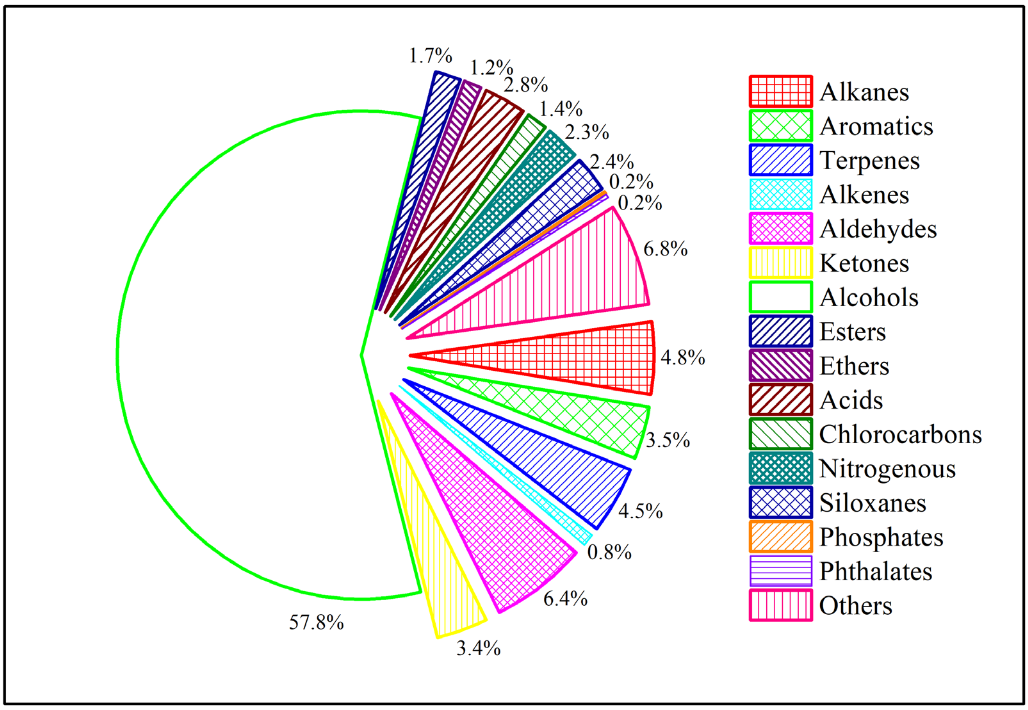

Figure 1 VOCs measured on non-smoking aircraft in 12 studies classified by chemical functional group[54,70-72,75,76,78,81,82,84-86].

Table 5 Concentrations of measured VOCs in non-smoking commercial flights compared with the permissible levels set out by BS-EN4618[39] (withdrawn) and AP-25 [40], where TWA stands for Time Weighted Average.

VOC	Chemical Abstract System (CAS) no.	Concentration($\mu g/m^3$)				Limit（mg/m^3）	Time average	Comments
		Avg.	SD	Min.	Max.			
Benzene	71-43-2	5.9	5.5	0.0	78	3.2[39] 12.8[39]	TWA 8h 15min exposure	Safety Health
Toluene	108-88-3	15	12	0.0	209	760[39] 190[39] 153[39]	15min exposure TWA 8h -	Safety Health Comfort
Formaldehyde	50-00-0	5.4	1.5	0.0	44	2.47[39] 0.93[39] < 0.1[39] 0.5[40]	15min exposure TWA 8h 30min exposure -	Safety Safety Health VOC
Acetaldehyde	75-07-0	6.4	1.2	0.3	90	45[39] 1.8[39]	15min exposure TWA 24h	Safety Health
Acrolein	107-02-8	< 0.8	1.0	0.0	53	0.75[39] 0.25[39] 0.05[39] 0.2[40]	15min exposure TWA 8h TWA 30min -	Safety Health VOC
Acetone	4468-52-4	14	5.6	<LOD	384	3630[39] 1210[39] 1782[39] 1188[39] 240[39]	15min exposure TWA 8h 15min exposure TWA 8h -	Safety Health Comfort
Butanone	78-93-3	2.4	0.8	0.0	32	897.8[39] 1795.5[39] 897.8[39] 598.5[39]	15min exposure TWA 8h 15min exposure TWA 8h	Safety Health
Phenol	108-95-2	1.2	0.1	0.1	5.0	0.3[40]	-	VOC

Note: in some cases, the admissible levels for 8-hour exposure are higher than admissible levels for 30 min exposure; the reason is that they refer to different outcomes, as indicated in the table above.

Table 6 shows a list of compounds that were measured in two or more studies, with the highest concentration, with the lowest ODTs. The compounds most frequently appearing on these lists were toluene, benzene, ethylbenzene, formaldehyde, acetaldehyde, limonene, nonanal, hexanal, decanal, octanal, butanal, acetic acid, acetone, ethanol, acrolein, isoprene, and menthol; aldehydes and acids were with the lowest ODTs (the SI provides more detail). Table 7 shows compounds that were frequently measured (measured in ≥ 2 studies) and compared with some examples of Indoor Air Guideline Values (IAGVs) for VOCs proposed by WHO, US and in various other countries.

Toluene, benzene and ethylbenzene are fuel-related and engine-related compounds[39], and toluene concentration was previously regulated[39]. The maximum measured concentrations of toluene (Table 7**)** were lower than the previously recommended maximum level of toluene (Table 2). Toluene was among the few pollutants that were most frequently found to be present on aircraft at high concentrations (Table 6 and Table S10 in SI); this reflects the sampling methods applied collecting mainly hydrocarbons and not oxygenates and other miscellaneous compounds. According to the Indoor Air Guideline Values (IAGVs) (Table 7), the average benzene concentration of 5.9±5.5μg/m^3 exceeded the 8-hour Recommended Exposure Levels (RELs) and the Chronic RELs[93]. Benzene is a genotoxic carcinogen in humans and no safe level of exposure can be recommended. The geometric mean of the range of the estimates of the excess lifetime risk of leukaemia at an air concentration of 1 μg/m^3 is 6×10^{-6}. The concentrations of airborne benzene associated with an excess lifetime risk of 1/10,000, 1/100,000 and 1/1,000,000 are 17, 1.7 and 0.17 μg/m^3, respectively. The average level of benzene measured on aircraft was around 5.9±5.5μg/m^3 which corresponds to excess lifetime risk of leukemia of 1/30,000[94]. Figure S1 in SI presents the relationship between measured toluene and benzene levels in 5 studies[66,76,78,81,86] that can be used to estimate benzene levels based on the toluene levels. It shows that the concentration of toluene is twice that of benzene.

Formaldehyde and acetaldehyde are likely to have been products of the O_3 chemistry that occurs in aircraft[95-97], and associated with lubricant and hydraulic oils and fuel[39]. They were being considered for regulation by BS-EN 4618[39] before it was withdrawn (Table 2 and Table 5).

Many sources can emit limonene, such as fragrances in aircraft cabins, fragrances in wet napkins, cleaning agents and deodorizers[97,98], as well as from soft drinks[99] and (earl grey) tea[100] and citrus fruits[99]. It is one of pollutants that was measured frequently and at high concentration (Table 6). It is also worth mentioning that limonene was frequently detected on cabin air filters at 4 mg/g carbon (6.0% of the total mass of all compounds) that had been used for 660 flight hours, and at 6 mg/g carbon (3.7% of the total mass of all compounds) on filters that had been used for 3,937 flight hours[101]. Limonene can undergo chemical transformations. Reactions with O_3 can produce secondary organic aerosols (SOAs)[102,103] and aldehydes[97,98], among others formaldehyde and acetaldehyde, and oxy and poly-oxygenated gaseous VOCs/SVOCs.

Nonanal, capronaldehyde/hexaldehyde/hexanal, decanal and octanal were detected frequently in aircraft cabins at high concentrations (Table 6). These pollutants are associated with the presence of humans but are the results of heterogeneous reactions between O_3 and human skin oils[75,84,104]. Skin oils are present on human skin but can also be present on clothing and on all surfaces that have been touched by human skin, such as seats, armrests, and headrests.

The products of the chemical reaction between squalene and O_3 is one of the sources of acetic acid in aircraft cabins[84], which is one of the pollutants that were measured frequently at high concentration (Table 6). Ethanol is associated with emissions from humans due to metabolic processes (or consumption of alcohol)[105], it is one of pollutants that was measured frequently and at the highest concentration (Table 6). Acetone is also a pollutant emitted by humans[105] that was one of the compounds measured most frequently and with the highest concentrations on aircraft (Table 6); acetone was being considered for regulation by BS-EN 4618[39] before it was withdrawn (Table 2).

Table 6 The list of compounds that were measured with the highest average concentration and those that were measured in more than two studies and had lowest ODT; the most common pollutants are in bold on each list.

Compounds with the highest average concentration	Measured in ≥2 studies	Compounds with the lowest ODT[34]
Ethanol	**Toluene**	Isovaleraldehyde
1-Propanol	**Limonene**	**Octanal**
Isoalkanes C14-C20	m&p-Xylene	**Capronaldehyde/ Hexaldehyde/ Hexanal**
1,2-Propanediol	**Benzene**	**n-Butyraldehyde/ Butanal**
Limonene	Benzaldehyde	Valeraldehyde
Acetonitrile	Undecane	**Decanal**
Hexane	o-Xylene	**Acetaldehyde**
Cyclopentasiloxane	**Ethylbenzene**	**Nonanal**
Toluene	Styrene	Propionaldehyde
Decanal	**Nonanal**	Hexanoic acid
Acetone	**Acrolein**	Octanoic acid
Acetic acid	**Formaldehyde**	**Acrolein**
Isopropyl alcohol	**Capronaldehyde/Hexaldehyde/Hexanal**	**Acetic acid**
Menthol	Tetrachloroethene/Tetrachloroethylene/Perchlorethylene	Butyl acetate
Nonanal	**Decanal**	Phenol
1-Hexanol,2-ethyl-	**Acetone**	Methacrolein
Tetrachloroethene/Tetrachloroethylene/Perchlorethylene	Dodecane	**Ethylbenzene**
6-methyl-5-hepten-2-one/6-MHO	6-methyl-5-hepten-2-one/6-MHO	Crotonaldehyde
N, N-dimethylformamide/Dimethylformamide	Trichloroethene	**Isoprene**
Isoprene	**Acetaldehyde**	**Menthol**
Ethyl acetate	**Isoprene**	
Acetaldehyde	Ethyl acetate	
Benzene	p-dichlorobenzene/1,4-dichlorobenzene	
Dioctyl ether	Hexane	
Formaldehyde	**Octanal**	
Capronaldehyde/Hexaldehyde/Hexanal	Nonane	
Benzoic acid	Heptane	
Perfluoro derivates	Decane	
1,3-Butanediol	**Acetic acid**	
	n-Butyraldehyde/Butanal	
	Butanone/2-butanone	
	2,2,4-Trimethylpentane dioldiisobutyrate	
	Isopropyl alcohol	
	Dichlormethane/methylene chloride	
	Methylcyclohexane	
	Heptanal	
	N, N-dimethylformamide/Dimethylformamide	
	2-ethyl-1-hexanol/2-Ethylhexanol	
	Menthol	
	Ethanol	

Tridecane
Pentane
3-Carene
a-Pinene
b-Pinene
Octane

Table 7 Examples of Indoor Air Guideline Values (IAGVs) for VOCs proposed by WHO, US and in various countries; the list of compounds that were frequently measured (measured in ≥ 2 studies), where TWA stands for Time-Weighted Average.

Compounds	Chemical Abstract System (CAS) no.	Concentration(μg/m³)					Odour Detection Threshold (ODT) [34]		US[93]	Japan[106]	China[107]	Canada[108]	WHO[94]	Germany[109]			Threshold limit value[110] (mg/m³)		NIOSH/OSHA[111]			
														Workplace guide value (mg/m³)	Indoor Guide Values (mg/m³)				PELs (NIOSH) (mg/m³)		PELs (OSHA) (mg/m³)	
		Avg.	SD	Min.	Medium	Max.	ppb	μg/m³	Inhalation REL (μg/m³)	Guide value (μg/m³)	Guide value（mg/m³）	Guide value (μg/m³)	Guide value (μg/m³)	TRGS 900	I	II	TWA	ST	TWA	ST	TWA	10 min peak
Toluene	108-88-3	15	12	2.5	12	123	79	299	37000(A) 300(C)	260 (>1 year)	0.2(1h)	2.3 mg/m³ (24h) 15 mg/m³ (8h)	-	190	0.3	3	75	-	375	560	750	1875
Limonene	138-86-3	24	31	1.4	12	276	9863	54921	-	-	-	-	-	-	1	10	-	-	-	-	-	-
m&p-Xylene	108-38-3 106-42-3	2.5	2.3	0.6	1.6	21	41 58	178 251	22000(A) 700(C)	870 (>1 year)	-	-	-	-	0.1	0.8	435	655	435	655	435	-
Benzene	71-43-2	5.9	5.5	0.1	0.6	57	2698	8613	27(A) 3(8)↑ 3(C)↑	-	-	keep indoor levels as low as possible	17[a] 1.7[b]↑ 0.17[c]↑	-	-	-	1.6	8.0	0.3	3.2	3.2	16
Benzaldehyde	100-52-7	＞2.5	2.0	0.0	2.0	14	-	-	-	-	-	-	-	-	0.02	0.2	-	-	-	-	-	-
Undecane	1120-21-4	2.9	1.6	0.0	2.2	13	871	5565	-	-	-	-	-	-	-	-	-		-	-	-	-
o-Xylene	95-47-6	2.5	2.8	0.3	1.0	14	380	1650	22000(A) 700(C)	870 (>1 year)	-	-	-	-	0.1	0.8	435	655	435	655	435	-
Ethylbenzene	100-41-4	2.3	2.9	0.2	0.7	23	6	26	2000(C)	3800 (>1 year)	-	-	-	88	0.2	2	-	-	435	545	435	-
Styrene	100-42-5	1.0	0.9	0.0	0.5	6.1	35	149	21000(A)	220 (>1 year)	-	-	-	86	0.03	0.3	86	172	215	425	425	-

									900(C)													
Nonanal	124-19-6	7.8	5.6	1.9	5.4	24	1	3	-	41 (>1 year)	-	-	-	-	-	-	-		-	-	-	-
Acrolein	107-02-8	<0.8	1.0	<LOD	0.4	3.2	4	8	2.5(A) 0.7(8) 0.35(C)	-	-	-	-	0.2	-	-	-	0.25	0.25	0.8	0.25	-
Formaldehyde	50-00-0	5.4	1.5	2.7	5.9	7.1	500	614	55(A) 9(8) 9(C)	100 (30min)	0.1	50 (8h) 123 (1h)	100 (30min) 360 (4h) 600 (NOAEL)	0.37	0.1	not derived	-	0.37	0.02	-	0.92	-
Capronaldehyde/Hexaldehyde/Hexanal	66-25-1	5.2	4.8	1.7	2.8	14	0	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tetrachloroethene/Tetrachloroethylene/Perchlorethylene	127-18-4	7.3	5.7	0.6	3.8	16	769	5213	-	-	-	-	-	-	0.1	1	-	-	Minimize workplace exposure concentrations	-	678	-
Decanal	112-31-2	14	5.0	2.7	15	36	0	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acetone	4468-52-4	14	5.6	0.5	16	49	832	1975	-	-	-	-	-	1200	-	-	1185	2375	590	-	2400	-
Dodecane	93685-81-5	3.1	1.8	0.0	1.9	13	110	765	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6-methyl-5-hepten-2-one/6-MHO	129085-68-3	7.0	3.5	0.2	8.5	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Trichloroethene	79-01-6	0.4	0.2	0.1	0.3	0.7	3899	20941	-	-	-	-	230[d] 23[e] 2.3[f]	-	-	-	-	-	-	-	537	-
Acetaldehyde	75-07-0	6.4	1.2	5.2	5.3	7.7	1	3	470(A)	48 (>1 year)	-	280 (24h)	-	91	0.1	1	-	45	-	-	360	-

									300(8) 140(C)			1420 (1h)										
Isoprene	78-79-5	6.8	4.9	0.8	9.0	14	49	135	-	-	-	-	-	8.4	-	-	-	-	-	-		
Ethyl acetate	141-78-6	6.5	4.4	3.9	4.9	16	245	884					-	730	0.6	6	1400	-	1400	-	1400	-
p-dichlorobenzene/1,4-dichlorobenzene	106-46-7	2.4	2.9	0.1	1.0	6.9	-	-	800(C)	240 (>1 year)	-	-	-	12	-	-	60	-	-	-	450	-
Hexane	110-54-3	20	31	0.0	0.5	68	1500	5283	700(C)				-	180	-	-	1800	3600	1800	-		
Octanal	124-13-0	4.2	1.8	1.3	2.9	10	0.2	0.9	-	-	-	-					-	-	-	-	-	-
Nonane	111-84-2	>1.4	0.7	0.0	1.8	2.0	2198	11522	-	-	-	-	-	-	-	-	1393	-	-	-		
Heptane	142-82-5	>0.7	0.3	0.0	0.9	0.9	670	2744	-	-	-	-	-	2100	-	-	1600	2000	2000	-		
Decane	124-18-5	1.1	0.6	0.0	1.0	1.7	619	3603	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acetic acid	64-19-7	11	2.7	1.1	12	16	5	13	-	-	-	-	-	-	-	-	25	37	25	37	25	-
n-Butyraldehyde/Butanal	123-72-8	1.0	0.2	0.8	0.9	1.3	0	1						64			-	-	-	-	-	-
Butanone/2-butanone	78-93-3	2.4	0.8	1.2	2.9	2.9	440	1296	-	-	-	-	-	600	-	-	-	-	590	885	590	-
2,2,4-Trimethylpentane dioldiisobutyrate	NO	1.1	0.3	0.2	1.0	1.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Isopropyl alcohol	67-63-0	10	3.4	3.5	13	13	501187	1231222					-	-	-	-	-	-	980	1225	980	-
Dichlormethane/methylene chloride	75-09-2	1.4	1.0	0.0	1.1	2.8	160000	555448	-	-	-	-	-	180	-	-			-	-	-	-
Methylcyclohexane	108-87-2	0.6	0.5	0.1	0.6	1.1	150	602	-	-	-	-	-	810	-	-	1600	-	1600	-	2000	-
Heptanal	111-71-7	3.2	1.3	0.7	2.3	4.6	30	140	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N, N-dimethylformamide/Dimethylformamide	68-12-2	<6.8	3.9	0.0	7.7	7.7	-	-	-	-	-	-	-	15	-	-	30 [skin]	-	30 [skin]		30 [skin]	

2-ethyl-1-hexanol/2-Ethylhexanol	104-76-7	4.7	1.0	2.9	4.0	5.9	74	395	-	-	-	-	-	0.1	-	-	-	-	-	-	-	-
Menthol	15356-70-4 491-02-1	9.6	3.6	1.0	12	12	22	140	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ethanol	64-17-5	386	899	81	82	3009	331	624	-	-	-	-	-	380	-	-	-	1900	1900	-	1900	-
Tridecane	629-50-5	1.5	0.4	0.0	1.7	1.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pentane	109-66-0	1.4	0.4	0.4	1.4	4.7	1400	4128	-	-	-	-	-	3000	-	-	1770	-	350	-	2950	-
3-Carene	13466-78-9	1.1	0.5	0.0	1.3	1.3	1671	9305	-	-	-	-	-	-	-	-	-	-	-	-	-	-
a-Pinene	80-56-8	1.1	0.3	0.0	1.2	1.2	18923	105374	-	-	-	-	-	-	-	-	-	-	-	-	-	-
b-Pinene	127-91-3	0.5	0.2	0.0	0.6	0.6	11749	65424	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Octane	111-65-9	>0.5	0.1	0.0	0.5	0.6	1698	7929	-	-	-	-	-	2400	-	-	2350	-	350	-	1410	-

Notes:

- concentration (average, SD, average minimum, average medium, average maximum).
- A = acute, 8 = 8-hour, C = chronic. Exposure averaging time for acute RELs is 1 hour. For 8-hour RELs, the exposure averaging time is 8 hours, which may be repeated. Chronic RELs are designed to address continuous exposures for up to a lifetime: the exposure metric used is the annual average exposure.
- a: an excess lifetime risk of 1/10000.
- b: an excess lifetime risk of 1/100000.
- c: an excess lifetime risk of 1/1000000.
- d: an excess lifetime cancer risk of 1/10000.
- e: an excess lifetime cancer risk of1/100000.
- f: an excess lifetime cancer risk of 1:1000000.
- NOAEL: no observed adverse effect level.
- PELs: Permissible Exposure Levels.
- ST: Short Term Exposure Levels.
- ↑: means the average was higher than the guideline value.

3.4 Measured SVOCs

The presence of a range of SVOCs in aircraft cabin and cockpit air has been recorded in several studies[69,80,85,89,112-117]. The cabin air supply in most jet aircraft is obtained by extraction of heated and compressed bleed air from the jet engine cores, prior to mixing with filtered recycled cabin air. Furthermore, the aircraft hydraulic reservoir vent is connected to the cabin air ventilation system, making it possible for hydraulic oil aerosols to enter cabin air[118]; they also have other sources as shown by Schuchardt et al[89]. SVOCs have been suspected as the source of hazardous neurotoxic substances and potentially responsible for some of the reported health effects in aircraft cabins and flight decks[19,80,112]. Because of technical difficulties, measurements of SVOCs in aircraft cabins have been in focus only in recent years. Nagda and Rector[15] reported that under normal operating conditions the levels of SVOCs other than tricresyl phosphates (TCPs) (which does not have anything to do with hydraulic systems) but including TMPP and TOCP, originating most likely from engine oil contamination of the cabin air and TBP (tributyl phopsphate) originating from hydraulic oil, are typically below the detection limits. This agrees with the operation of the ventilation system on aircraft. Bleed air is used to pressurize the hydraulic fluid reservoir and fresh-water tank on some aircraft systems. The hydraulic pressurization systems that use bleed air to pressurize the reservoir use dual check-valves to prevent back-flow of hydraulic fluid into the bleed air. In the rare case of a dual check-valve failure, hydraulic fluid could enter the bleed air system. This cannot occur in the B787 because it does not use a bleed air system. During taxi line-up, aircraft ingest exhaust from other aircraft, and TCP is present in aircraft engine exhaust[89,119].

Table 8 provides a summary of the SVOCs that were detected. They are grouped by the measurements performed on the aircraft either in which there was a subjective perception of smell in the cabin, and technical cabin air contamination (TCAC) flights[89], which were attributed to oil entry from leaking engine seals in individual flight phases. Smell-events were documented in nine studies[60,62,66,69-72,80,86] but the smell events could happen not only because of SVOCs. A total of 36 SVOCs were measured, and their concentrations were from below the Limit of Detection (LOD) to 49 μg/m^3. The SVOCs with high concentrations and high frequency of detection were naphthalene (average concentration 1,241±166 ng/m^3), tributyl phosphate (TiBP) (average concentration 495±59 ng/m^3), tris (chloro-isopropyl) phosphate (TCPP) (average concentration 506±0.4 ng/m^3) and trichloroethylene (TCE) (average concentration 483±36 ng/m^3); it is worth mentioning that tributyl phosphate (TiBP) was also detected on discarded cabin air filters at 1 mg/g carbon for filters that had been used for 660 flight hours and at 2 mg/g carbon for filters that had been used for 3,937 flight hours[101]. TMPP was not detected, while TOCP concentrations ranged from 0 to 22,800 ng/m^3 with an average of 50±14 ng/m^3; in the study by Schuchardt et al.[89], TOCP was below LOD.

Among SVOCs for which there were regulations, maximum levels of phosphate cresol mixture and dioctyl sebacate were stipulated in AP-25[40], but they were not measured in the studies included in the present review. Generally, Table 8 also shows that the concentration of SVOCs measured in aircraft cabins with and without events were lower than the statutory limits for the same compounds in buildings.

Table 8 Examples of Indoor Air Guideline Values (IAGVs) for SVOCs proposed by WHO, US and in various countries.

Compounds	Chemical Abstract System (CAS) no.	No events						With events						Relevant regulations and guidelines
		Concentration(ng/m^3)				Number of		Concentration(ng/m^3)				Number of		
		Avg.	SD	Min.	Max.	Study	Flight	Avg.	SD	Min.	Max.	Study	Flight	
Tri-ortho-cresyl phosphate/ Tri-o-cresyl Phosphate (TOCP)	78-30-8	50	14	0	22800	4	163	<LOD	-	-	-	1	177	0.1mg/m^3 [skin] [111] 0.1mg/m^3 8h [110]
Tributyl phosphate (TiBP)	126-73-8	495	59	37	9100	2	149	625	5.4	140	1990	2	194	11mg/m^3 [120] 2.38mg/m^3 8h [110]
Tricresyl phosphates (TCP)	1330-78-5	35	7.7	0.3	14900	4	90	-	-	-	-	-	-	0.1 mg/m^3 [skin] [111]
Naphthalene	91-20-3	1241	166	0	49100	3	83	-	-	-	-	-	-	9µg/m^3 C [93] 10µg/m^3 1year [94,108] 2mg/m^3 [120] 57.8mg/m^3 8h [110] 85.7mg/m^3 15min [110]
Trichloroethylene (TCE)	79-01-6	483	36	0	20100	1	80	-	-	-	-	-	-	537mg/m^3 8h [111] 53.7mg/m^3 8h [110] 134mg/m^3 15min [110]
Triisobutyl phosphate (TBP)	126-71-6	92	9.3	3	1610	1	69	80	0.7	7	220	2	194	50 mg/m^3 [120]
Tris (chloroethyl) phosphate (TCEP)	115-96-8	15	1.0	1	324	1	69	28	1.5	0	70	2	194	0.05 mg/m^3 [109] 0.005 mg/m^3 [109]
Tris (chloro-isopropyl) phosphate (TCPP)	13674-84-5	506	0.4	23	9977	1	69	432	20	0	400	2	194	-
Tris (1,3-dichloro-isopropyl)	13674-87-8	7.7	0.3	1	49	1	69	10	0.5	0	10	2	194	-

phosphate (TDCPP)														
Triphenyl phosphate (TPP)	115-86-6	8.7	0.3	1	119	1	69	14	1.0	11	56	2	194	3mg/m^3 8h [110,111]
Tris (butoxy-ethyl) phosphate (TBEP)	78-51-3	71	4.4	0	642	1	69	249	69	29	2370	2	194	-
Diphenyl-2-ethylhexyl phosphate (DPEHP)	1241-94-7	15	0.2	0	282	1	69	20	0.7	2	155	2	194	-
Tris (ethyl-hexyl) phosphate (TEHP)	78-42-2	< LOD	-	0	88	1	69	11	0.0	1	25	2	194	-
Tri-m-cresyl phosphate (T-m-CP)	563-04-2	4.4	0.3	1	428	1	69	7.5	0.4	-	-	1	177	-
Tri-mmp-cresyl phosphate (T-mmp-CP)	NO	6.5	0.4	1	691	1	69	9.7	0.6	-	-	1	177	-
Tri-mpp-cresyl phosphate (T-mpp-CP)	NO	4.2	0.2	1	339	1	69	6.9	0.4	-	-	1	177	-
Tri-p-cresyl phosphate (T-p-CP)	563-04-2	2.1	0.1	1	57	1	69	2.9	0.2	-	-	1	177	-
Trixylyl phosphate (TXP)	NO	< LOD	-	< LOD	< LOD	1	69	35	0.3	-	-	2	194	-
Acenaphthylene	208-96-8	0.8	0.6	2.6	3.3	2	14	-	-	-	-	-	-	-
Acenaphthene	83-32-9	5.7	4.7	17	24	2	14	-	-	-	-	-	-	-
Fluorene	86-73-7	3.0	2.2	8.8	12	2	14	-	-	-	-	-	-	-
Hexachlorobenzene	118-74-1	0.2	0.2	0.4	2.3	2	14	-	-	-	-	-	-	0.002mg/m^3 8h [110]
Phenanthrene	85-01-8	4.9	3.7	13	21	2	14	-	-	-	-	-	-	0.1mg/m^3 NIOSH 8h [111] 0.2mg/m^3 OSHA 8h [111]
Anthracene	120-12-7	0.3	0.2	0.8	1.1	2	14	-	-	-	-	-	-	0.1mg/m^3 NIOSH 8h [111] 0.2mg/m^3 OSHA 8h [111]
Trimethylolpropane phosphate (TMPP)	1005-93-2	0	-	-	-	1	10	-	-	-	-	-	-	-
Fluoranthene	206-44-0	0.5	0.4	0.0	1.9	2	14	-	-	-	-	-	-	-

Pyrene	129-00-0	2.6	1.9	3.6	15	2	14	-	-	-	-	-	-	0.1mg/m^3 NIOSH 8h [111] 0.2mg/m^3 OSHA 8h [111]
Tri-n-butyl phosphate (TnBP)	NO	330	421	20	4100	1	6	-	-	-	-	-	-	-
Retene	483-65-8	1.4	-	0.8	2.0	1	4	-	-	-	-	-	-	-
cis-Permethrin	61949-76-6	0.9	-	ND	0.9	1	4	-	-	-	-	-	-	-
trans-Permethrin	61949-77-7	1.5	-	1.1	2.0	1	4	-	-	-	-	-	-	-
Seven other PAH compounds	NO	0.9-10.5	-	-	-	1	4	-	-	-	-	-	-	-
2,5-Diphenylbenzoquinone	844-51-9	＜2100	-	NR	NR	1	1	-	-	-	-	-	-	-
Dioctyl phthalate	117-81-7/68515-43-5/8031-29-6	1300	-	NR	NR	1	1	-	-	-	-	-	-	-
Tertiary butylphenol	88-18-6/27178-34-3	＜2100	-	NR	NR	1	1	-	-	-	-	-	-	-
Trimethylpentylphenol	NO	＜2100	-	NR	NR	1	1	-	-	-	-	-	-	-

- NR: not reported.
- ND: not detected.
- C=chronic. Chronic RELs are designed to address continuous exposures for up to a lifetime: the exposure metric used is the annual average exposure.

3.5 Other contaminants and O_3

Table S13 in the SI lists the average concentrations of other contaminants and the ranges of concentration measured in aircraft cabins, together with their maximum recommended levels in regulations and guidelines. These contaminants are: CO, NO, NO_2, NO_X, SO_2, bacteria, fungi, mould, and PM, such as $PM_{2.5}$, PM_{10} and Respirable Suspended Particulates (RSP). The regulations and guidelines apply both to aircraft cabins and buildings. Except for NO_2, the average concentrations of other contaminants were lower than the limits set by regulations and guidelines. The average NO_2 concentration was 12 ppb which is higher than the recommended maximum of 11 ppb for TWA 24 h[108]. Bacteria were at intermediate levels and fungi were at a low level. The maximum measured levels of CO concentration were higher than the permissible level for 15-min exposures.

Ozone (O_3) enters aircraft cabins through the ventilation system. Commercial aircraft typically cruise at an altitude of 18,000 to 41,000 feet (5,490 to 12,500 meters)[63,121,122]. At these cruising altitudes they are in the troposphere in higher latitudes[75], where O_3 is at concentrations ranging from 25 ppb to ~900 ppb[75,123,124]. After entering the cabin, O_3 will decompose on surfaces and may also undergo reactions with other pollutants on surfaces and in the air; the resulting concentration will therefore be lower than in the supply air.

Figure 2 shows the summary of the O_3 levels measured on commercial flights in 11 studies. Figure S2 in SI shows the changes with time in average O_3 concentration reported in different measuring campaigns on non-smoking flights[54,63,65,72,76,86].

Reported ozone levels have been decreasing with time, as more attention has been paid to ozone in aircraft cabins. The O_3 concentrations were reported to have been corrected to compensate for air pressure changes in three studies[62,63,75]; the other eight studies did not report whether this correction had been applied[14,54,57,65,72,76,84,86]. As so few studies reported that corrections had been made, we did not distinguish between the two groups as we did in the case of measurements of CO_2. The reported O_3 levels were between 0 and 275 ppb. The minimum levels reported were between 0 and 20 ppb, with a median minimum O_3 concentration of 2 ppb (Figure 2). The maximum levels reported were between 10 and 275 ppb with a median of 108 ppb (Figure 2). The average concentration of O_3 reported was 38±30 ppb (ranging from 6-80ppb), and the median was 33 ppb (Figure 2). With few exceptions, all of the reported levels were below 250 ppb, which is the limit recommended by the documents prescribing acceptable conditions in aircraft[10,36-41], see Table 1, but 75% of the maximum reported concentrations exceeded 100 ppb[10,36-41]; 87.5% of the reported maximum concentrations and 31% of the reported average O_3 concentrations exceeded 60 ppb[39] (Figure 2). All mean and minimum reported levels were below 100 ppb (Figure 2). However, average concentration exceeded the recommended levels averaged over 8 hours, which were 20 ppb[108], 50 ppb[125] and 50 ppb for heavy workloads[110], and were below the recommended levels in air averaged over an 8 hour working day, which were 100 ppb[111], 80 ppb(acute level) [93], 200 ppb (2-hour average)[110], and 100 ppb and 80 ppb for light and moderate workloads[110]. The World Health Organization[125] defines high levels as 240 $\mu g/m^3$, the interim target as 160 $\mu g/m^3$ and the air quality guideline at 100 $\mu g/m^3$ for 8 hour exposures (conversion factor to ppb is ca. 0.5). ASHRAE 161-2013[36] recommends that in flights on which excessive O_3 levels are likely to occur, O_3 concentrations should be continuously monitored and O_3 converters should be operated to remove O_3. In view of this recommendation, it is probable that the high reported O_3 levels on commercial flights were due to malfunctioning O_3 converters.

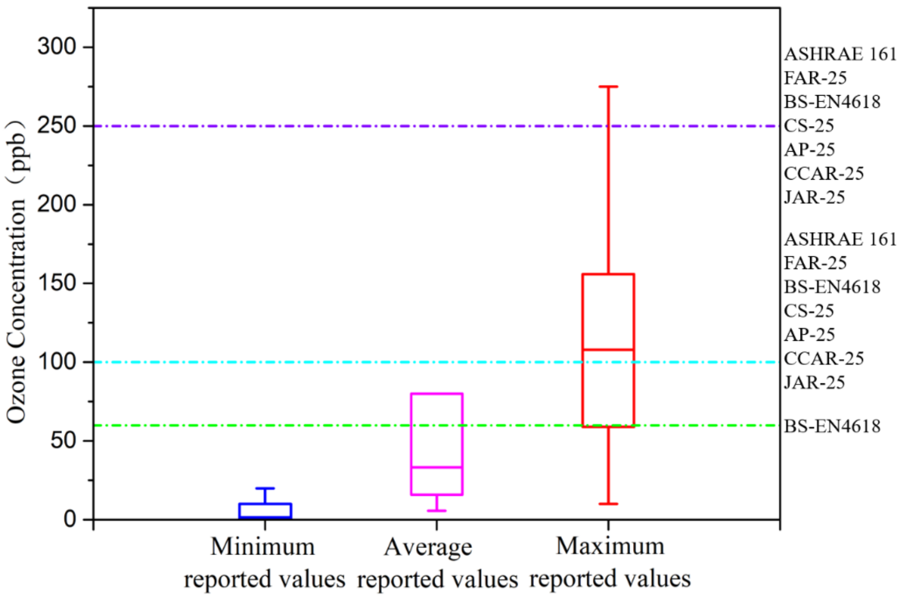

Figure 2 Summary of O_3 concentrations measured on non-smoking aircraft in 11 studies [14,54,57,62,63,65,72,75,76,84,86]. Permissible levels of O_3 prescribed by ASHRAE 161 [36], FAR-25 [37], JAR-25 [38], BS-EN4618 [39] (withdrawn), CS-25 [10], AP-25 [40] and CCAR-25 [41] are also shown.

3.6 Carbon dioxide and ventilation rate

Figure 3 shows a summary of carbon dioxide (CO_2) concentrations measured in 19 studies. The values were automatically or manually corrected to compensate for air pressure changes in seven studies[47,54,57,60-62,88], and in three studies the instruments used were insensitive to pressure changes in the cabin[79,83,90]. The other nine studies[14,52,55,56,59,72-74,86] did not report whether the reported CO_2 concentrations had been compensated for changes in air pressure. The results are consequently divided into two groups: studies that corrected CO_2 measurements for changes in pressure and studies that did not state whether this correction was applied. For the former, the minimum measured CO_2 concentrations were in the range 410-874 ppm, maximum measured CO_2 concentrations were in the range 1,485-3,374 ppm, while average CO_2 concentration was 1,315±232 ppm (the median was 1,387 ppm). For the latter, the minimum measured CO_2 concentrations were in the range 293-1,100 ppm, the maximum measured CO_2 concentrations were in the range between 1,190-5,177 ppm, while the average CO_2 concentration was 1,320±302 ppm (the median was 1,404 ppm). It can be seen that there were only marginal differences in the measured CO_2 between the two groups of studies. The lowest values of minimum measured CO_2 concentrations were lower than the CO_2 concentration in outdoor air, which currently ranges from 365 ppm to 390 ppm[126-129], which may suggest some measurement error.

Compared with the aircraft airworthiness standard (Table 1), all measured CO_2 concentrations, except for one event, were lower than 5,000 ppm[10,37,39-41]. All average and minimum CO_2 concentrations measured were lower than 2,000 ppm[10,37,39-41], although 87% of average CO_2 concentrations were higher than 1,000 ppm, which is generally considered as a target for achieving acceptable air quality in occupied buildings[130].

CO_2 is a product of human metabolism and thus indicates the rate of emission of bioeffluents from passengers and cabin crew in aircraft. It is always present in spaces where humans are present. This applies to most commercial buildings and to passenger transport vehicles, including aircraft[129]. The concentration of CO_2 depends on three factors: number of people, outdoor/ambient air supply rate per person, and ventilation efficiency, i.e., how well the air is mixed within a volume/space[88] CO_2 is an index of ventilation when people are present and can be used to verify whether the recommended rates of outdoor air are being delivered into an aircraft cabin; in this context it is also considered to be a marker of indoor air quality. One study showed that CO_2 concentration was significantly and inversely correlated with ventilation rate ($r=-0.96$, $P< 0.05$) for the same aircraft (Airbus 319)[74] and this was also the case in another study that used data from different aircraft (B777, A330, B787, A320, B737, A320) ($r=-0.93$, $P< 0.05$)[90]. The potential effects of CO_2 on humans are summarized by Fisk et al.[131] and Du et al.[132].

The reported outdoor air supply rates ranged from 1.7 to 39.5 L/s per person with the average and median at 6.0±0.8 L/s/p and 5.8 L/s/p, respectively[47,59,62,72,74,79,83,88,90]. All of the reported average values exceeded the minimum recommended outdoor air supply rate of 3.5 L/s/p[36,37,41], and 97% met the design requirements of 4.7 L/s/p set by[10,38]; 96% of the reported values met the outdoor air supply rate of 5 L/s/p recommended by the ASHRAE handbook[44]. One study reported the total air change rate per hour (ACH)[52] that ranged from 17.7 to 27.5 h^{-1} with an average of 22.6±4.1h^{-1}; this was compatible with the air change rates calculated using outdoor air supply rates[52,56,73].

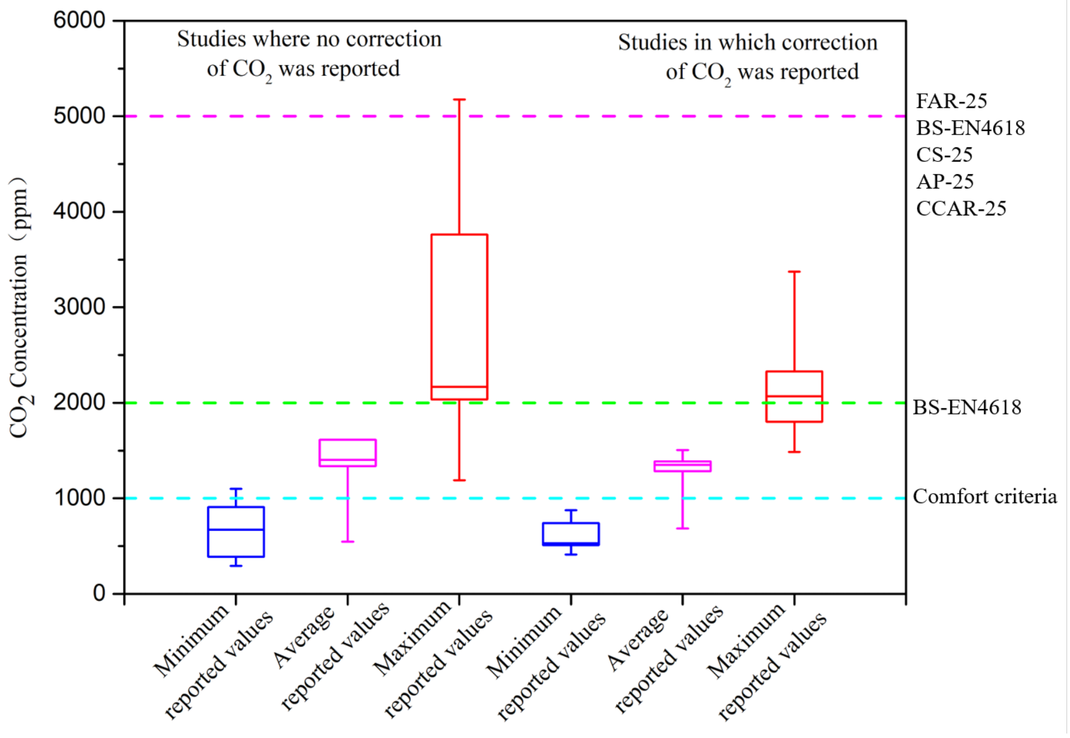

Figure 3 Summary of CO_2 concentrations measured on aircraft in 19 studies[14,47,52,54-57,59-62,72-74,79,83,86,88,90]. The CO_2 limits prescribed by BS-EN4618[39], FAR-25[37], CS-25[10], AP-25[40], CCAR-25[41] and ASHRAE handbook[44] are also shown.

3.7 Temperature and relative humidity in aircraft

Figure 4 shows a summary of the temperatures measured in 14 studies. The minimum measured temperatures were in the range from 17.4ºC to 24.6ºC. The maximum temperatures were in the range from 25.4ºC to 31.0ºC. The average and Standard Deviation (SD) of the measured temperatures were 23.5±0.8°C; the median was 24.0°C. The figure shows additionally that average temperatures were almost within the range recommended by ASHRAE 161[36] and the ASHRAE handbook[44]. The results presented in Figure 4 are from all flight phases and it is impossible to separate the measurements reported in different studies based on the flight phase; it is probable that maximum reported temperatures were measured on the ground with doors open.

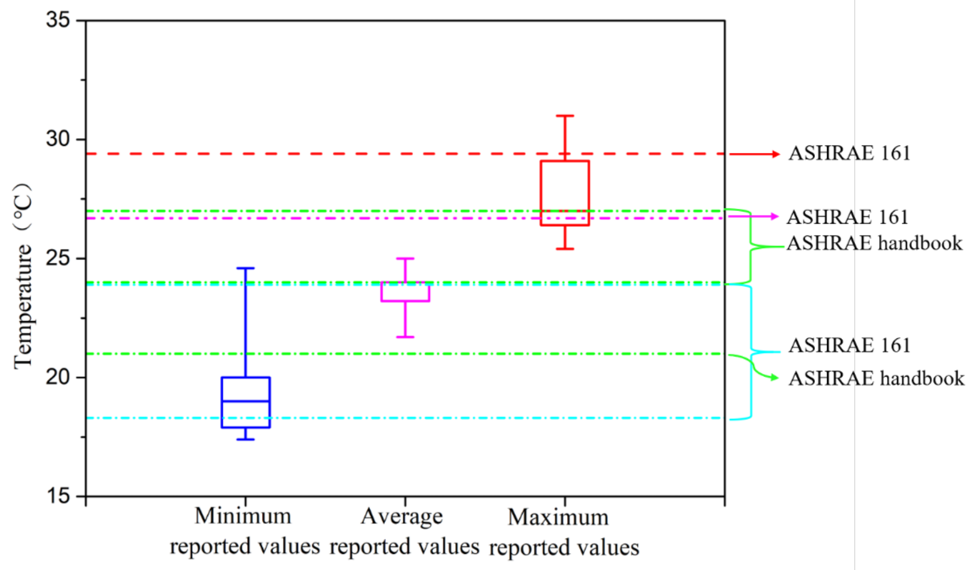

Figure 4 Summary of temperature levels measured on aircraft in 14 studies[6,47,52,54-57,59-62,72,73,86]. The ranges recommended by ASHRAE 161[36] and ASHRAE handbook[44] are also shown.

Figure 5 shows a summary of the relative humidity (RH) levels measured in 17 studies. The minimum measured RH levels were in the range from 0.9% to 15%, the lowest levels representing most likely flights with very few passengers. The maximum measured RH levels were in the range from 13% to 77%. The average and SD of the measured RH values were 16%±5%; the median was 17%. As in the case of temperature, the results presented in Figure 5 are from all flight phases and it is impossible to separate the measurements reported in different studies according to the flight phase, but it is probable that the maximum levels reported were measured on the ground with doors open and the minimum levels were measured at cruising altitude. The main sources of humidity in an aircraft cabin are exhaled air and perspiration from the occupants. ASHRAE 161[36] does not mandate lower and upper humidity requirements. In buildings, ASHRAE 62.1[130] recommends RH should not exceed 65% and EN 16798-1[133] recommends the range of RH from 20 to 70% depending on whether humidification is in operation.

More information on temperature and RH measurements is given in SI. Figures S3 shows that reported average and low humidity level[47,52,54,55,57,59-62,72,73,86] in aircraft cabins were at the low end of what is measured in buildings located in a cold climate in winter. Figure S4 and Table S14 show among others that at the average temperature and RH levels[47,52,54,55,57,59,60,72,86] reported in the literature passengers could be from slightly cool to cold at 0.5 clo and from neutral to slightly cool at 1.0 clo, thus below neutral on the cool side of the thermal sensation scale assuming low air velocities; higher air velocities would move these responses further into cool area and considerably increase the risk of draught.

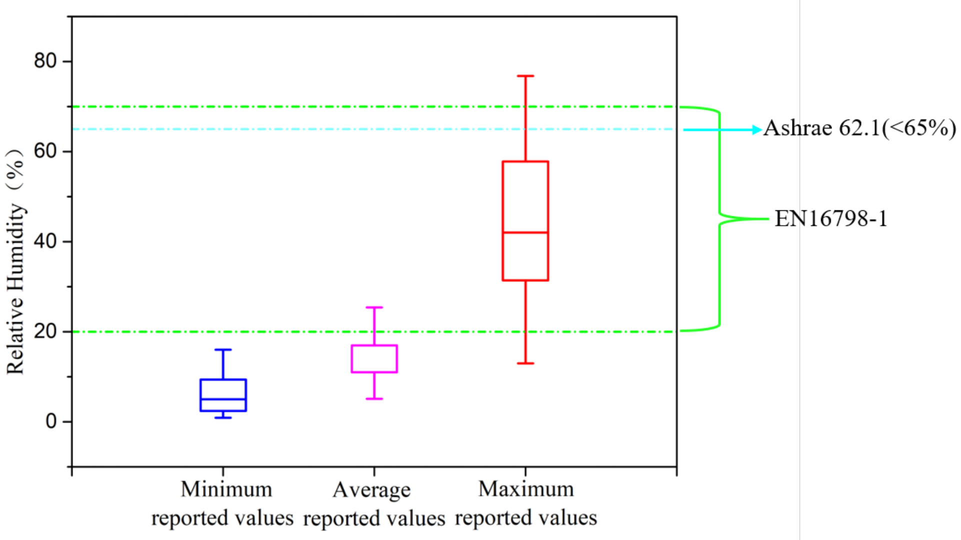

Figure 5 Summary of RH levels measured on aircraft in 17 studies[6,47,52,54-62,72-74,86,91]. The ranges recommended for air-conditioned buildings in ASHRAE 62.1[130] and EN 16798-1[133] are also shown.

3.8 Limitations and general comments

This review summarizes the measurements performed on 2,251 flights. The number of flights is considered to be sufficient for it to be possible to draw reasonable conclusions regarding the air quality conditions on commercial aircraft even though the measurements were made on more than 40 types of aircraft. There was a need for a thorough and data-rich review of cabin air quality to enable broader generalization of the results and definitive conclusions[15]. This work responds to this need.

The VOC and SVOC concentrations we summarize were measured on the non-smoking flights that are typical today. We focused mainly on active sampling and we did not take into account whether it was stated whether an adjustment for cabin pressure had been applied. Applied measuring techniques and QA/QC analysis are presented in detail in Table 9; Table S1 provides information for all types of measurements reported in the present review.

The selection of sampling and analytical methods for VOCs for 25[6,14,47,53,57,59-62,66,69-72,75-78,81-86,89] out of 27 studies[6,14,47,53-55,57,59-62,66,69-72,75-78,81-86,89] was consistent with the recommendations of American Society of Testing Materials (ASTM) D6399[134] among all studies (smoking and non-smoking flights). VOCs sampling and analytical methods for 21[6,14,57,60,62,66,69-72,75-78,81-86,89] out of 22 studies [6,14,54,57,60,62,66,69-72,75-78,81-86,89] on the non-smoking flights was consistent with the recommendations of ASTM D6399[134]. One study[54] was consistent with the recommendations of NIOSH Method (VOCs)[135] and the Environmental Protection Agency (EPA) method TO11-A[136] (formaldehyde and acrolein). ASTM guidance was not available at the time reported by Nagda and Rector[15]. Fifteen studies[6,57,60,62,66,70-72,76-78,81,82,84,85] employed field blanks to characterize any contamination of samples during physical handling and eleven studies[57,60,69-72,75-78,84] used duplicates to characterize precision among 22 studies on the non-smoking flights; only one study[60] reported the quality control results.

The selection of sampling and analytical methods for SVOCs in four[6,14,86,89] out of twelve studies[6,14,60,62,66,69-72,80,86,89] was consistent with the ASTM D6399 method for all studies (smoking and non-smoking flights). SVOCs sampling and analytical methods for four[6,14,86,89] out of eleven studies[6,14,60,62,66,69-72,86,89] on the non-smoking flights was consistent with the recommendations of ASTM D6399[134]. One studies[60] was consistent with the recommendations of EPA Standard Method TO-11A[136]. Two studies[70,71] was consistent with the recommendations of ISO 16000-6[137] and BS EN ISO 16017-1[138]. Four studies[62,66,69,72] was not reported which standard they reference. Seven studies[6,60,62,66,70-72]employed field blanks to characterize any contamination of samples during physical handling and five studies[60,69-72] used duplicates to characterize precision among eleven studies on the non-smoking flights. Only one study[60] reported the quality control results.

Table 9 Description of measuring techniques and QA/QC analysis for VOCs and SVOCs.

Study	Parameter*	VOCs	SVOCs
Dechow et al.[53]	MT	Aldehydes and ketones: TX/(GCMS/AED)/DNPH/(HPLC/UVD); VOCs: AC/SE/GC/FID; TX/SE/GC/ECD; TX/SE/GC/MS; TX/TD/GC/MS	
	QA/QC	A (VOCs and aldehydes)	
	C		
ASHRAE[54]	MT	VOCs: NIOSH Method, CL, TX/GC/FID; Formaldehyde, acrolein: EPA method TO11-A, DNPH/HPLC	
	QA/QC	B (VOCs and aldehydes)	
	C	NR	
Lee et al.[55]	MT	FID by Total Hydrocarbon Analyzer	
	QA/QC	ASTM, ACGIH, APHA, NIOSH, D	
	C		
Fox [6]	MT	Aldehydes and ketones: DNPH/HPLC; VOCs: EC/GC/MS	PUF/XAD/ GC/MS
	FC		MM
	QA/QC	A, B	A, B
	C		
Dumyahn et al.[57]	MT	EC/GC/MS	
	QA/QC	A, B, D	
	C		
Wieslander et al.[59]	MT	VOCs: TX/GCMS; Formaldehyde: DNPH/HPLC;	
	QA/QC	A	
	C		
Nagda et al.[60]	MT	Aldehydes and Ketones: EPA Standard Method TO-11A, DNPH/HPLC; VOCs: EPA Standard Method TO-14A, EC/GCMS	EPA Standard Method TO-11A, PUF/XAD/HPLC
	QA/QC	A, B, D (VOCs and aldehydes)	B, D
	C	M	M
Lindgren and Norbäck[47]	MT	Formaldehyde: glass fiber filters impregnated with DNPH, the diffusive samplers/GCMS	
	QA/QC	A	
	C		
Waters et al.[61]	MT	VOCs: NIOSH Manual of Analytical Methods,TD/GCMS; Aldehydes: NIOSH Manual of Analytical Methods, CPP/GC/FID/MS; Ethanol: NMAM 1400, CL/GC-FID; Aliphatic hydrocarbons: NMAM 1500, CL/GC-FID; Aromatic hydrocarbons: NMAM 1501, CL/GC-FID	
	QA/QC	A	
	C		
Spicer et al.[62]	MT	Passive Sampling; EC (cruise and bleed)/GCMS	A time-integrated adsorbent sample/XAD/GCMS
	FC	MM	MM
	QA/QC	A, B	B
	C	M	M, PC
Muir et al.[66]	MT	TD/GCMS; SPME/GCMS; PID (fume event)	TD/GCMS; SPME/GCMS; PID (fume event)

	QA/QC	A, B	B
	C		
Solbu et al.[69]	MT	TX/TD/GC-EI-MS	Gass adsorbent tube/GC-EI-MS
	QA/QC	A, D	D
	C		
Crump et al.[70]	MT	TVOCs: PID; VOCs: ISO 16000-6 and BS EN ISO 16017-1, Sorbent tube/TD/GC/MS	ISO 16000-6 and BS EN ISO 16017-1 Sorbent tube/TD/GC/MS
	QA/QC	A, B, D	B, D
	C		
Crump et al.[71]	MT	TVOCs: PID; VOCs: ISO 16000-6 and BS EN ISO 16017-1 Sorbent tube/TD/GC/MS	ISO 16000-6 and BS EN ISO 16017-1 Sorbent tube samples/TD/GC/MS
	QA/QC	A, B, D	B, D
	C		
Spengler et al.[72]	MT	VOCs: airlines A: EC/GCMS; airlines B and C: USEPA Compendium Method TO-17, TD/GCM; Aldehyde and ketone: airlines A, B and C: DNPH/HPLC	TCP: Whatman QMA 37 mm quartz filters/SE/GCMS; SVOCs: SKC model 226-143 glass sorbent tubes/XAD/SE/GCMS
	QA/QC	A, B, D	B, D
	C		
Weisel et al.[75]	MT	TX/GC/MS	
	QA/QC	A, D	
	C	C	
Ji and Zhao[76]	MT	TX/TD/GC/MS	
	QA/QC	A, B, D	
	C	PC	
Guan et al.[77]	MT	TX/TD/GC/MS	
	QA/QC	A, B, D	
	C		
Guan et al.[78]	MT	TX/TD/GC/MS	
	QA/QC	A, B, D	
	C		
Ree et al.[80]	MT		Wipe samples/GCMS
	QA/QC		
	C		
Wang et al.[81]	MT	EPA, TX/TD/GCMS	
	QA/QC	A, B	
	C	M	
Wang et al.[82]	MT	EPA, TX/TD/GCMS	
	QA/QC	A, B	
	C	M	
Guan et al.[83]	MT	TVOCs: a ppbRAE 3000-PID	
	QA/QC	A	
	C	NSP	

Gao et al.[84]	MT	TX/TD/GC/MS	
	QA/QC	A, B, D	
	C	C	
Rosenberger et al.[85]	MT	Aldehydes: DNPH/HPLC-UV	
	FC	MM	
	QA/QC	A, B	
	C		
Schuchardt et al.[86]	MT	Aldehydes: DIN ISO 16000-3, DNPH/HPLC/UV; VOCs: DIN ISO 16000-6-TX/MS/FID	ISO 16000-31/2014 Indoor air - Part 31, PUR/SE/GCMS
	QA/QC	A	A
	C	C	C
Rosenberger[14]	MT	VOCs: TX/TD/GCMS; Aldehydes: DNPH/HPLC/UV/VIS; TVOCs: PID	PUR/GCMS
	QA/QC	A, ISO 16000 series, D	A, ISO 16000 series
	C		
Schuchardt et al.[89]	MT	VOCs: ISO 16000-3/2011 Indoor air – Part 6, TX/TD/GC/MS or MS-FID. Aldehydes: ISO 16000-3/2011 Indoor air – Part 3, DNPH/HPLC/UV	TCP:ISO 16000-31, 2014-Part 31, PUR/SE/GC/MS
	FC	MM	
	QA/QC	A, ISO 16000-6: 2011	A, ISO 16000-6: 2011
	C		

* MT-measuring technique (AC, activated carbon sorbent; CL, a charcoal sorbent tube; DNPH, 2,4-dinitrophenylhydrazine-coated sorbent; EC, evacuated canister; ECD, electron capture detector; FID, flame ionization detector; GC, gas chromatography; HPLC, high performance liquid chromatography; AED, atomic-emission detector; UVD, UV-detector; MM, mass flowmeter; MS, mass spectrometry; PID, photoionization detector; EI, electron ionization; IC, Ion Chromatograph; CPP, coated porous polymer; PUF, polyurethane foam sorbent; SE, solvent elution; TD, thermal desorption; TX: Tenex sorbent; SPMF, Solid Phase Microextract Fibres; OPC, optical particle counter; CPC, condensed particle counter; NDIR, Non-dispersive infrared spectrometry; PCR, Polymerase chain reaction technology).

FC-Flow control.

QA/QC-quality assurance/quality control (A, consistent with recommendations of ASTM D6399; B, field blanks; D, duplicate samples).

C-Calibration (M, multipoint calibration; NRC, no pressure calibration; PC, pressure calibration; CSG, calibrated by standard gases; NSP, not sensitive to pressure).

NR - not reported.

Most measurements of VOCs and SVOCs were performed only once using integrating samplers and the sensors and samplers were positioned in only one location in the cabin. In order to obtain more accurate data, the number of samples should be increased in space and time in future research and a method for real-time monitoring data instead of intermittent sampling should be used.

The quality of the measured data included in the present review can be discussed. With respect to the measurements of temperature and RH the studies included in the present review included only partial details of the measurement technique, range, resolution, accuracy and whether the instruments were calibrated or not. In general, it was reported that the measuring instruments had good accuracy for temperature measurements[54,60,62,72-74] and for RH measurements[54,60,62,72,73].

With respect to CO_2 measurements some studies failed to include information on whether a correction for cabin pressure at altitude had been applied. The studies in which no correction for pressure was mentioned used a variety of measuring instruments with an accuracy of about ±3%[72], ±100 ppm CO_2 below 10,000 ppm and above 100 ppm or ±3% at concentrations below 100ppm[73]. The studies in which correction of CO_2 was reported also used a variety of measuring instruments. ASHRAE and CSS [54] and Spicer et al. [62] reported measurements using instruments with an accuracy of ±5%. Cao et al. [88] reported that their CO_2 sensor could provide better accuracy for the lower levels more likely to be encountered in aircraft cabins and in their study, 98% of measured CO_2 concentrations were within this range.

We analysed measured O_3 data only on non-smoking flights. We did not consider the influence of aircraft pressure and altitude on measured concentration as there were very few data. The accuracy of the instruments was greater than 1.0 ppb or 2%[72,75] or greater than 1.5 ppb or 2%[62,65] although some had an accuracy of ±0.1 ppm[54].

The present results can be used for different purposes, e.g., to benchmark the air quality levels in aircraft cabins or to select the target compounds that can be considered as markers of air quality and could constitute an air quality metric. This would however require studies with humans that observed their different responses to changing levels of the selected target pollutants. It would be useful to examine whether there is a relationship between measured concentrations of VOCs and carbon dioxide (CO_2) using the data provided by the literature review. However, the information provided in the reviewed papers was not sufficient to perform such a correlation.

4. Conclusions

We reviewed the literature to identify the airborne pollutants present on commercial aircraft and the regulations regarding air quality on aircrafts. The measurements reported by forty-seven studies on 2,251 flights showed that the majority of measured compounds were alcohols followed by aldehydes, alkanes, terpenes, aromatics and ketones. Among the most prevalent compounds reported were toluene, ethylbenzene, benzene, formaldehyde, acetaldehyde, limonene, nonanal, hexanal, decanal, octanal, acetic acid, acetone, ethanol, butanal, acrolein, isoprene and menthol. Measured VOCs were within the permissible limits where they exist, except for benzene. SVOCs were below the limits prescribed for any indoor environment. Average O_3 concentrations were below air quality guidelines for aircraft cabins but exceeded air quality guidelines for residential buildings or workplaces. Average CO_2 and outdoor air supply rates were within recommended levels. Average temperature was within the limits recommended for thermal comfort while RH values were at the low end of what occurs even in buildings located in cold climates in winter. The present results provide a benchmark reference for airborne pollutants on aircraft in the development of advanced solutions for improving cabin air quality. The present work should continue by relating the measured levels to the responses of crew members and passengers to provide further evidence of the need to improve the control of aircraft cabin air quality and to identify the pollutant levels that should be regulated, as well as smell events and proper risk assessment thereof. The impact of other factors such as the low RH should be considered as well.

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