European Union Aviation Safety Agency

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HEALTH - NEW HEALTH SAFETY MEASURES IN AIRCRAFT

Comprehensive Analysis of Pathogen Transmission and Mitigation Strategies in Aircraft Cabins: Airflow, Surfaces, and Disinfection

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SUMMARY

The report, commissioned by the European Union Aviation Safety Agency (EASA) and prepared by the German Aerospace Center, provides a comprehensive analysis of pathogen transmission and mitigation strategies in aircraft cabins. It examines airflow dynamics, surface contamination, and disinfection measures to enhance health safety during air travel. The review focuses on three core areas: airflow pathogen transmission, surface transmission, and disinfection measures, offering actionable insights to minimize infection risks.

In terms of airflow pathogen transmission, the study highlights the effectiveness of advanced ventilation systems, such as High-Efficiency Particulate Air (HEPA) filters, which can reduce airborne pathogens by up to 99.7%. Computational Fluid Dynamics (CFD) models and experimental validations emphasize the importance of airflow management in mitigating infection risks. Factors like elevated carbon dioxide levels and suboptimal humidity enhance pathogen stability, underscoring the need for optimized environmental controls. Innovations such as personalized ventilation systems and air curtains demonstrate potential in creating localized clean air zones, further reducing droplet transmission.

For surface transmission, the report identifies high-touch areas such as tray tables, armrests, and lavatory fixtures as reservoirs for pathogens, which can persist for extended periods. Material properties play a significant role, with nonfabric surfaces posing higher risks. Enhanced cleaning protocols and antimicrobial coatings are essential for mitigating these risks. However, the need for consistent and standardized practices across airlines remains a critical challenge.

Regarding disinfection measures, the use of Ultraviolet-C (UV-C) technology is recognized as a highly effective method for inactivating airborne and surface pathogens without direct human exposure risks. Electrostatic spraying and chemical disinfectants complement UV-C systems, although proper training is required to ensure safety and compatibility with aircraft materials. Far-UVC light (222 nm) offers a promising solution for continuous disinfection in occupied environments, while antimicrobial surface treatments using materials such as copper, silver, and nanotechnology enhance contamination resistance.

The report also highlights several challenges and provides recommendations for effective implementation. Key actions include the development of standardized global protocols tailored to various aircraft configurations, promotion of sustainable disinfection practices using energy-efficient and environmentally friendly technologies, and leveraging advanced innovations like robotic disinfection devices and self-cleaning surfaces. Dynamic risk-based approaches, adjusting cleaning intensity based on flight duration, passenger density, and epidemiological risks, are also emphasized.

In conclusion, the report underscores the importance of a multi-layered strategy to health safety in aircraft, combining technological innovations, rigorous cleaning protocols, and behavioural interventions. Addressing both airborne and surface transmission routes is vital to ensuring passenger safety and preparing for future global health challenges. Continued research, interdisciplinary collaboration, and real-world testing will be essential for implementing these measures effectively and consistently.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamics
CHDG	Chlorhexidine Digluconate
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease 2019
DHC	Dust Holding Capacity
ESP	Electrostatic Precipitation
FAA	Federal Aviation Administration
HEPA	High-Efficiency Particulate Air
HCAI	Healthcare-Associated Infections
HAS	Head-Mounted Air Supply
HVAC	Heating, Ventilation, and Air Conditioning
IATA	International Air Transport Association
ICU	Intensive Care Unit
MRSA	Methicillin-Resistant Staphylococcus Aureus
MV	Mixing Ventilation
PHEIC	Public Health Emergency of International Concern
PVS	Personalized Ventilation System
RH	Relative Humidity
SARS	Severe Acute Respiratory Syndrome
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SOP	Standard Operating Procedure
UV	Ultraviolet
UV-C	Ultraviolet-C (wavelength)
VOC	Volatile Organic Compounds
WHO	World Health Organization

1. Introduction

1.1 Background

The transmission of pathogens in confined environments, such as aircraft cabins, poses significant challenges for public health and safety, especially in the context of global air travel. The close physical proximity of passengers, combined with shared air circulation and frequently touched surfaces, creates an environment beneficial to the spread of infectious agents. Aircraft could serve as critical vectors in the rapid global dissemination of pathogens, enabling diseases to cross borders within hours and amplifying the risk of widespread global outbreaks. Aircraft cabins, with their controlled ventilation systems and high-touch surfaces, are a microcosm of the complexities involved in managing airborne and contact-based disease transmission. Pathogen transmission in aircraft cabins has been highlighted during past outbreaks, including SARS, influenza, and most notably COVID-19. These events have emphasized the critical importance of developing and implementing effective mitigation strategies. Aircraft cabins represent a unique setting where disease transmission dynamics are influenced by factors such as ventilation systems, surface material properties, and passenger behaviours, which demand comprehensive investigations to find effective and applicable interventions.

Assessing the microbiome in aircraft cabins shows that bacterial communities such as Propionibacterium, *Staphylococcus*, and *Streptococcu*s dominate the environment (Weiss et al., 2019). These microbes are typically harmless under normal conditions; however, their persistence underscores the importance of robust cleaning protocols, particularly to protect vulnerable populations. While the normal microbiome may pose minimal immediate risks, the dynamic nature of emerging threats necessitates vigilance.

The recent 2024 WHO list of emerging pathogens (Ukoaka et al., 2024) highlights the increasing threat posed by novel and re-emerging infectious agents, reinforcing the urgency of robust monitoring and intervention strategies in high-risk environments like aircraft cabins. This updated WHO list underscores a paradigm shift from targeting individual pathogens to a family-focused approach, incorporating "Prototype Pathogens" and "Pathogen X" to guide future research and preparedness efforts. Given that aircraft cabins are critical nodes in global pathogen spread, understanding how these priority pathogens behave in confined, high-traffic environments is essential for developing targeted prevention strategies.

These pathogens, often with high adaptability and resistance profiles, have the potential to cause severe outbreaks in confined environments like aircraft cabins. Climate change further exacerbates this risk by altering pathogen habitats, facilitating spread into new regions, and driving microbial adaptations to higher temperatures (Fisher et al., 2022). For instance, fungi like *Candida auris* have shown increased tolerance to heat, which could be a result of adapting to rising global temperatures, enhancing their potential to infect humans. Historical data shows that aircraft have played pivotal roles in the rapid global spread of pathogens, as evidenced during SARS, H1N1, and more recently, COVID-19 (Mangili & Gendreau, 2005). While statements such as “airborne pathogen transmission in airplanes is rare” (Leder & Newman, 2005) may seem reassuring, they could inadvertently lead to a false sense of security. Emerging pathogens, particularly those with pandemic potential, require proactive measures within the aviation industry to ensure resilience against future outbreaks. By focusing on travel medicine's priority pathogens and leveraging lessons from past pandemics, the aviation sector can prepare for potential uprisings of new infectious threats.

This literature review synthesizes current research to address these challenges and provide actionable insights for the aviation industry.

1.2 Scope of this Literature Review

This report represents deliverable 'D1.1' of the EASA/2023/OP/0003 Horizon Europe Project: HEALTH – New health safety measures in aircraft project, which focuses on assessing pathogen spread potential from contaminated passengers within aircraft cabins.

This literature review systematically examines current and emerging measures designed to mitigate the spread of pathogens in aircraft cabins. Emphasis is placed on identifying the efficacy, constraints, and long-term feasibility of these interventions, including their impact on aircraft materials, crew, and operational requirements. The review also evaluates the critical knowledge gaps and interdisciplinary opportunities to inform future research and policy development in the aviation sector relating to new health safety measures in aircrafts.

The analysis is organized into three core work packages:

WP1.1: Airflow Pathogen Transmission, addressing the role of cabin ventilation systems and airflow dynamics in the dissemination of airborne pathogens.

WP1.2: Surface Transmission, which evaluates the persistence and spread of pathogens on high-touch cabin surfaces.

WP1.3: Disinfection, reviewing chemical and non-chemical cleaning methods for mitigating surface and airborne contamination.

These work packages collectively assess critical factors influencing pathogen spread in aircraft, including passenger behaviour, seating arrangements, and the efficacy of ventilation, surface treatment, and disinfection strategies.

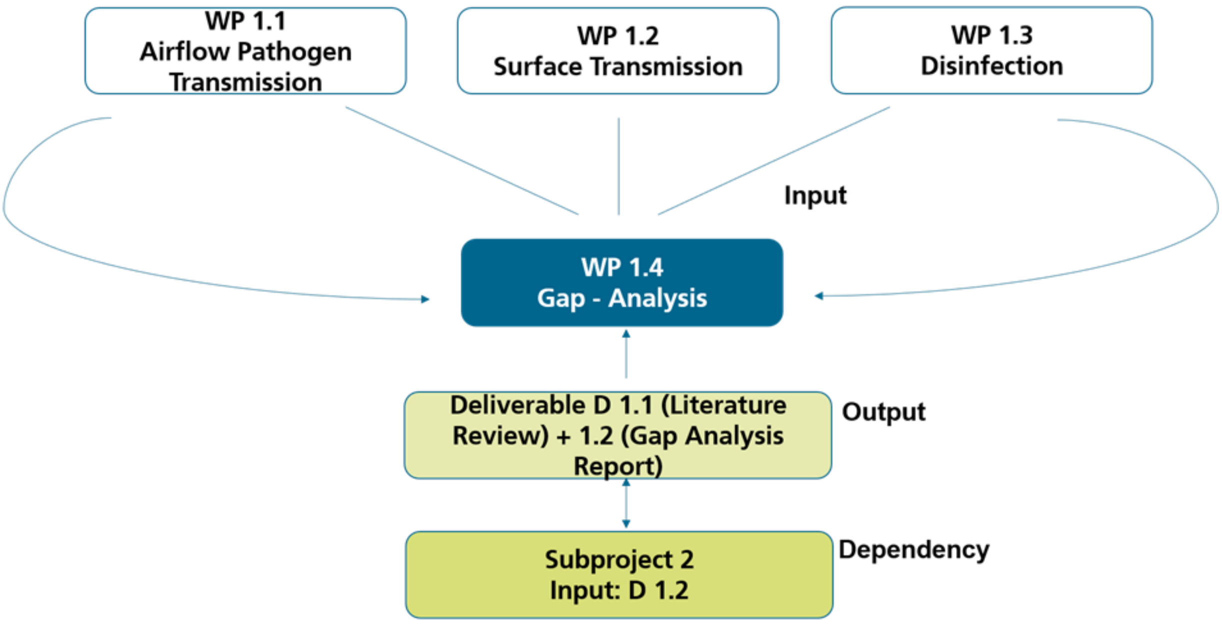

Figure 1: Scope and Framework of Literature Review

2. Literature Analysis

Health Status of Airplane Cabins

Aircraft cabins are enclosed spaces with high passenger turnover, where passengers and crew are in close proximity for extended periods. The limited cubic air volume per passenger and high occupancy rate increases the risk of inhaling airborne pathogens, particularly during long-haul flights (TRANSCOM, 2021). Moreover, the lack of natural ventilation and reliance on recirculated air necessitate robust air filtration systems, such as HEPA filters, which, although effective, cannot entirely eliminate the risk of exposure.

Airborne disease transmission remains a significant concern in confined spaces like aircraft cabins. Pathogens such as SARS-CoV-2 and influenza are primarily transmitted through respiratory droplets and aerosols. CFD studies show that advanced ventilation systems, such as HEPA filters, can remove up to 80% of respiratory particles within minutes, thereby limiting exposure for passengers seated farther from an infected individual (Schmeling et al., 2023; TRANSCOM, 2021). Studies on COVID-19 and other respiratory diseases emphasize the importance of proximity, mask usage, and seating arrangements in reducing transmission risks. For example, the use of N95 masks significantly decreases the number of secondary infections, while optimized airflow systems, such as higher air supply velocities, further reduce exposure risks by over 50% (Gupta et al., 2012; Coșoiu et al., 2022).

Surface transmission also plays a critical role in pathogen transmission within aircraft cabins. High-touch areas, including tray tables, seat armrests, lavatories, and seat-back pockets, serve as reservoirs for pathogens. Research shows that pathogens like *Staphylococcus aureus* and *Escherichia coli* can survive for days on these surfaces. Microbial retention varies by surface material, with textiles harbouring more microbes than leather (Zhao et al., 2019; Fu et al., 2023). Advanced cleaning protocols, antimicrobial coatings, and regular disinfection can mitigate these risks.

The duration of exposure during flights significantly influences the likelihood of infection. A study by CORSICA (2023) found that passengers seated within seven rows of an infected individual on a long-haul flight had a higher probability of contracting airborne diseases, particularly in the absence of effective ventilation and mask usage. Ventilation systems in modern aircraft are generally effective, with air exchange rates of 15–20 times per hour. However, smaller or older aircraft lacking these systems present increased transmission risks (Wang et al., 2022).

Climate change and globalization are accelerating the spread of emerging pathogens. *Candida auris*, a drug-resistant fungus, has been detected in healthcare settings worldwide and poses risks in confined environments like aircraft cabins (CDC, 2024). Similarly, viruses such as Nipah and hantaviruses have emerged as zoonotic threats with pandemic potential (WHO, 2023). These pathogens adapt to changing environmental conditions, such as increased temperatures and humidity, potentially increasing their transmissibility (Fisher et al., 2022). Aircraft serve as conduits for these pathogens, enabling their rapid distribution across continents, as seen during SARS and H1N1 outbreaks (Mangili & Gendreau, 2005).

While HEPA filters are often cited as highly effective, their efficiency can vary based on operational conditions. Increased airflow rates, often required during high-capacity usage, can reduce efficiency and significantly increase pressure drop, impacting overall system performance. Additionally, traditional HEPA filters are not optimized for removing volatile organic compounds (VOCs) or gaseous contaminants, highlighting a need for integrated filtration solutions that address both particulate and gaseous pollutants (Bull et al., 2010). Emerging technologies, such as nanofiber media, offer promise in reducing pressure drops and improving filtration efficiency but face challenges such as poor fire resistance and limited dust-holding capacity (DHC). Innovations like photocatalytic oxidation and electrostatic filters could complement HEPA systems, enhancing their ability to maintain cabin air quality under various conditions (Bull et al., 2010; Zhang et al., 2022).

Given these challenges, it is essential to implement multi-pronged strategies that address both airborne and surface-based transmission routes. These include optimizing air circulation, integrating advanced filtration systems, and adopting innovative disinfection and material technologies. Enhanced cleaning frequency, improved airflow patterns, and collaborative efforts among stakeholders are crucial to developing standardized protocols. Resilience must remain a priority even when the immediate threat seems mitigated.

Combining environmental parameter control, ventilation concepts, infection risk modelling, and pathogen spread analysis is crucial for understanding and mitigating pathogen transmission in aircraft cabins. Recent findings highlight the impact of factors such as CO_2 concentration and relative humidity on pathogen aerostability and immune response, underscoring the importance of improving cabin air quality. Elevated CO_2 levels (>1000 ppm) and suboptimal relative humidity significantly enhance SARS-CoV-2 aerostability and weaken immune response (Haddrell et al., 2024; Guarnieri et al., 2023). Personalized ventilation systems create localized clean air zones, effectively reducing droplet transmission between passengers (Coșoiu et al., 2022; Kurec et al., 2023). Validation of CFD simulations with experiments enables detailed risk assessments for multiple airborne diseases in aircraft cabins (Schmeling et al., 2023; Webner et al., 2024). Studies such as the TRANSCOM report demonstrate the effectiveness of high air exchange rates and HEPA filters in minimizing aerosol exposure risk. Airflow pathogen transmission research highlights the interplay between environmental controls and ventilation systems in reducing infection risks. Optimized airflow management, supported by advanced modelling and experimental validation, is pivotal for mitigating airborne pathogen spread in aircraft cabins.

Building on all of this, we will now present the specific areas of investigation through individual work packages 1.1 – 1.3. These targeted studies explore the mechanisms of pathogen transmission via airflow, surface contact, and countermeasure against pathogen transmission in form of different disinfection methods, providing some more detailed insights into mitigating these risks and improving passenger safety.

Pathogens of Interest and Their Transmission in Aircraft Cabins

Aircraft cabins present a unique environment for pathogen transmission, influenced by high-density seating, shared surfaces, and a controlled ventilation system. There is only limited research on the specific pathogens encountered during air travel and in which abundancy. This section identifies the known key infectious agents, their known incidence rates, and their modes of transmission, along with their environmental survival times and contextualizes them in regards to the risk they pose for airplane passengers and crew.

Overview of most relevant/most cited literature

Analysis of SARS-CoV-2 transmission in airports based on real human close contact behaviors.

Yang, X., Dou, Z., Ding, Y., Su, B., Qian, H., & Zhang, N. (2024). *Journal of Building Engineering, 82*, 108299. https://doi.org/10.1016/j.jobe.2023.108299

3. **Summary:**

- Investigates SARS-CoV-2 transmission risks in airports using real human close contact behavior data.
- Conducts depth sensor measurements and video data collection across nine areas of two airports in China.
- Analyzes more than 44 hours of close contact behaviors, including interpersonal distance, facial orientation, and position.
- Finds that manual check-in areas have the highest close contact ratio (55%), while dining areas pose the greatest virus exposure risk.
- Identifies that maintaining a minimum 1.0m distance could reduce virus exposure by 6.9%–22.0%.
- Uses a semi-supervised machine learning approach to model transmission risks based on real-world human interactions.
- Demonstrates that mask usage and social distancing significantly reduce exposure risks, with N95 masks offering the highest protection.
- Concludes that targeted mitigation strategies, such as spacing markers and mask mandates, are essential for infection control in airport environments.

Risk assessment of airborne infectious diseases in aircraft cabins - PubMed

Gupta, J. K., Lin, C. H., & Chen, Q. (2012). Risk assessment of airborne infectious diseases in aircraft cabins. *Indoor Air, 22*(5), 388–395. https://doi.org/10.1111/j.1600-0668.2012.00773.x

- Based on the study by Gupta et al. (2012), the most significant airborne infectious diseases in aircraft cabins include:
- Influenza (A/B): Highly transmissible through airborne droplets and direct contact, can remain airborne for prolonged periods due to enclosed cabin conditions, infection risk is highest for passengers within 1–2 rows of an infected person
- Severe Acute Respiratory Syndrome (SARS): Airborne and droplet transmission; can spread over greater distances than influenza, higher mortality rate than influenza, airplane ventilation systems play a key role in limiting long-range spread
- Tuberculosis (TB): Primarily airborne transmission through inhalation of infectious aerosols, requires prolonged exposure to an infected individual for transmission, risk is higher on long-haul flights, especially in poorly ventilated sections
- The primary transmission modes: Airborne (SARS, TB), Droplet (Influenza, SARS), Fomite (Influenza, MRSA)

- Infection risk factors: Proximity to infected passengers, duration of flight, and ventilation effectiveness
- Most effective mitigation Strategies: N95 masks, HEPA filtration, hygiene practices, and seating adjustments

Airplanes and Infectious Disease | SpringerLink

Burge, H.A. Airplanes and Infectious Disease. In: Hocking, M. (eds) Air Quality in Airplane Cabins and Similar Enclosed Spaces. The Handbook of Environmental Chemistry, vol 4H. Springer, Berlin, Heidelberg. https://doi.org/10.1007/b107241

- Based on the study by Burge (2005), the most well-documented infectious diseases transmitted in aircraft cabins include:
- Influenza (A/B):

➔ Transmission depends primarily on proximity and duration of exposure rather than ventilation efficiency

- Severe Acute Respiratory Syndrome (SARS):

➔ While airborne transmission is a concern, long-range spread is less emphasized compared to direct exposure risks

- Tuberculosis (TB):

➔ Less likely to spread on short-haul flights, as it requires prolonged exposure—contrary to the general TB risk suggested in Gupta et al. (2012)

- The primary transmission modes: Airborne (SARS, TB), Droplet (Influenza, SARS)
- Ventilation plays a lesser role than passenger proximity and exposure time (contrary to Gupta et al., 2012)
- Infection risk factors: Fomite transmission is downplayed, with greater emphasis placed on airborne and droplet exposure
- Most effective mitigation strategies: Seating arrangements remain the most important factor, but mask-wearing was not a primary recommendation at the time
- Burge (2005) emphasizes that close proximity and flight duration are the primary drivers of infection risk, whereas Gupta et al. (2012) highlights ventilation, surface contamination, and HEPA filtration as additional concerns

Infectious Risks of Air Travel

Mangili A.Vindenes T.Gendreau M.2015.Infectious Risks of Air Travel. Microbiol Spectr3:10.1128/microbiolspec.iol5-0009-2015. https://doi.org/10.1128/microbiolspec.iol5-0009-2015

Based on the study by Mangili & Gendreau (2015), air travel is a major vehicle for the rapid global spread of infectious diseases, including tuberculosis, SARS, influenza, and measles:

- Tuberculosis (TB): Primarily airborne transmission through inhalation of infectious aerosols, prolonged exposure is required for transmission, making long-haul flights a significant risk factor, inadequate ventilation in certain aircraft areas can increase TB exposure
- Severe Acute Respiratory Syndrome (SARS). highly contagious through airborne and droplet transmission, with numerous in-flight outbreaks documented, air travel accelerated global SARS

spread, allowing infected individuals to reach multiple countries before symptoms appeared, risk heightened in crowded flights with prolonged exposure

- Influenza (A/B): Readily transmitted via droplets, airborne particles, and contaminated surfaces, hort incubation period makes infected passengers unknowingly contagious before symptom onset, frequent in-flight outbreaks have been documented
- Measles: One of the most highly infectious airborne diseases, with a high attack rates, low vaccination rates in some regions increase the risk of imported cases through air travel, transmission is possible even several rows away from the index case due to high aerosol stability

•Primary transmission modes: Airborne (TB, SARS, Measles), Droplet (Influenza, SARS), Fomite (Influenza).
•Key risk factors: High passenger density, global travel frequency, and asymptomatic carriers unknowingly spreading infections
•Most effective mitigation strategies: Pre-flight health screening, vaccination enforcement, improved air filtration, and personal protective measures (masks, hand hygiene)

[Infectious diseases and the air travel – a new Pandora's box?](https://doi.org/10.37897/RJID.2020.1.1)
Vâță, A., Miftode, L., Obreja, M., Miftode, R., & Vâță, L. G. (2020). *Ro J Infect Dis, 23(1).* https://doi.org/10.37897/RJID.2020.1.1

•Based on the study by Vâță et al. (2020), air travel is not only a key driver of airborne and droplet-based infections but also contributes to the spread of antibiotic-resistant bacteria and vector-borne diseases, expanding the scope of public health concerns beyond previous studies:

- ➔ Vector-borne diseases (e.g., Malaria, Dengue, Yellow Fever, Chikungunya) can spread through stowaway mosquitoes in aircraft cargo or luggage, potentially establishing outbreaks in new regions ("Airport Malaria" concept)
- ➔ Antibiotic-resistant bacteria (e.g., MDR-TB, MRSA, ESBL-producing Enterobacteriaceae) can be introduced by repatriated patients hospitalized abroad, though in-flight bacterial transmission is not yet confirmed
- ➔ Measles and Influenza outbreaks from air travelers are underreported due to difficulty in tracking passengers and symptom onset delays
- ➔ SARS, MERS, and COVID-19 spread rapidly via air travel, often before containment measures were in place. The 2015 South Korea MERS outbreak started from one infected traveler
- ➔ WHO's two-row transmission rule for airborne diseases may underestimate actual risk, as studies suggest infections can spread up to six rows

- Limitations of current mitigation strategies
- ➔ HEPA filters reduce airborne risk but may not eliminate submicron viral particles (<0.1µm)
- ➔ Passenger screening is ineffective for asymptomatic carriers or diseases with long incubation periods
- ➔ Aircraft disinfection, cleaning & vector control are inconsistently applied, limiting their effectiveness against vector-borne disease introduction

➔ Takeaway: Vâță et al. (2020) emphasize that beyond airborne diseases, air travel is a growing driver of vector-borne disease outbreaks and antimicrobial resistance, requiring improved surveillance and stricter public health measures

[Transmission of the Severe Acute Respiratory Syndrome on Aircraft]

Olsen, S. J., Chang, H.-L., Cheung, T. Y.-Y., Tang, A. F.-Y., Fisk, T. L., Ooi, S. P.-L., Kuo, H.-W., et al. (2003). *The New England Journal of Medicine, 349*(25), 2416–2422. DOI: 10.1056/NEJMoa031349

- Investigates the risk of in-flight transmission of severe acute respiratory syndrome (SARS) on three commercial flights carrying SARS-infected passengers.
- Flight 1 (90 minutes, Hong Kong to Taipei): Carried a presymptomatic SARS case; no secondary infections detected, suggesting low risk of transmission before symptom onset.
- Flight 2 (3 hours, Hong Kong to Beijing): Carried a symptomatic SARS patient; 22 passengers developed SARS, with the highest risk observed for those sitting within three rows in front of the index case (relative risk: 3.1, 95% CI: 1.4–6.9).
- Flight 3 (90 minutes, Hong Kong to Taipei): Carried four symptomatic SARS patients; only one potential secondary case, suggesting variability in transmission risk.
- Transmission risk was higher for symptomatic patients and linked to seating proximity to the infected individual.
- WHO's two-row contact tracing guideline underestimated risk, as SARS transmission extended up to three rows.
- Airborne and droplet transmission likely contributed, with 56% of infections occurring outside the immediate two-row range.
- HEPA filters and aircraft ventilation helped but did not eliminate risk, indicating that in-flight transmission is possible despite modern air circulation systems.
- Public health implications: Findings supported later disease control strategies, including pre-flight health screenings, mandatory masking, enhanced disinfection, and revised contact tracing policies.
- Findings remain relevant for understanding airborne infectious disease risks in air travel, including COVID-19, influenza, and tuberculosis.

[Usefulness and Applicability of Infectious Disease Control Measures in Air Travel]

Huizer, Y. L., Swaan, C. M., Leitmeyer, K. C., & Timen, A. (2015).
Travel Medicine and Infectious Disease, 13(1), 19-30. https://doi.org/10.1016/j.tmaid.2014.11.008

- Providing traveler information, isolation, health monitoring, hygiene measures, and vector control are the most effective and applicable measures to prevent disease spread
- Entry/exit screening, quarantine, and travel restrictions were found to be least effective, requiring high resources with limited success in preventing disease transmission
- Entry and exit screening (e.g., thermal scanners, health declarations) were generally ineffective as asymptomatic travelers could still spread diseases
- During the 2009 H1N1 pandemic, screening only identified 0.02% of infected travelers in China, while in Singapore, 88% of cases were missed

- Contact tracing is resource-intensive and often ineffective, especially when airlines do not collect sufficient passenger data or when travelers are difficult to track after arrival
- Studies show that contact tracing for tuberculosis cases on flights had limited success, with only a few secondary cases identified
- HEPA air filtration effectively removes airborne pathogens, but the effectiveness decreases when ventilation is turned off (e.g., during boarding and taxiing)
- Face masks reduce infection risk but are not widely accepted by passengers
- Quarantine for air travelers is impractical, requiring excessive resources and disrupting passengers
- Travel bans delay outbreaks but do not prevent spread, as modeling studies show they only postpone disease introduction by days to weeks
- Some countries require aircraft disinfection to prevent mosquito-borne diseases (e.g., dengue, malaria)
- Air curtains on planes can reduce insect entry by 95-100%, minimizing vector-borne disease risk

➔ Study emphasizes that disease control measures should be tailored to specific pathogens, considering factors like transmission mode, incubation period, and feasibility of implementation.

➔ Future research should compare multiple interventions to determine the best combination of control strategies

[Influenza Transmission on Aircraft: A Systematic Literature Review]

Leitmeyer, K., & Adlhoch, C. (2016).

Epidemiology, 27(5), 743-751., DOI: 10.1097/EDE.0000000000000438

- 14 studies identified from 1979-2014 showed evidence of influenza spread on aircraft
- Contact tracing of 2,165 out of 4,252 (51%) passengers found 163 secondary cases, yielding an overall attack rate of 7.5%.
- 42% of secondary cases were seated within two rows of the index case, but others were located farther away, indicating possible airborne or indirect transmission
- Studies used inconsistent contact tracing approaches, making comparisons difficult
- Only 43% of influenza A(H1N1) cases were successfully traced, leading to underestimation of transmission
- Many investigations excluded flight crew, despite their prolonged exposure and mobility in the cabin
- No clear correlation between flight duration and transmission rate was found
- The highest attack rate (64%) was reported on a short-haul flight with a 3-hour ground delay without ventilation
- Functional HEPA filtration and high air exchange rates reduce in-flight airborne transmission risk
- The need for standardized data collection and reporting is critical for improving disease containment strategies
- Misclassification bias due to symptom-based diagnosis rather than laboratory confirmation
- Incomplete tracing of asymptomatic or mildly symptomatic passengers
- Possible alternative exposure sources before and after flights (e.g., airport lounges, border controls)
- The evidence for influenza transmission aboard aircraft is moderate, with documented cases of in-flight spread but limited consistency in study methodologies. Better standardized approaches to contact

tracing and data collection are needed to improve public health responses to airborne disease outbreaks in air travel.

[European Risk Assessment Guidance for Infectious Diseases Transmitted on Aircraft – The RAGIDA Project]

Leitmeyer K. European Risk Assessment Guidance for Infectious Diseases transmitted on Aircraft – the RAGIDA project. Euro Surveill. 2011;16(16):pii=19845. https://doi.org/10.2807/ese.16.16.19845-en

- The Risk Assessment Guidance for Infectious Diseases transmitted on Aircraft (RAGIDA) project, initiated by the European Centre for Disease Prevention and Control (ECDC) in 2007, aims to assist national public health authorities in the European Union (EU) in evaluating risks related to infectious disease transmission on aircraft
- literature review covering 3,700+ peer-reviewed articles and grey literature on 12 infectious diseases known to have transmission potential during air travel
- Disease-specific guidance documents based on expert consultations, assessing the need for contact tracing and public health interventions
- The study reviewed transmission risks for 12 diseases, including:

➔ Tuberculosis (TB), Influenza (Seasonal & Pandemic A/H1N1), Severe Acute Respiratory Syndrome (SARS), Invasive Meningococcal Disease, Measles & Rubella, Diphtheria, Ebola & Marburg Hemorrhagic Fevers, Lassa Fever, Smallpox & Anthrax

- Limited scientific evidence for on-board disease transmission in most cases
- Influenza & SARS showed higher transmission risks, especially during long flights with close proximity seating
- Tuberculosis cases on long-haul flights require contact tracing, especially for those seated near the infected person
- Hemorrhagic fevers (Ebola, Lassa, Marburg) have a low transmission risk but require strict isolation protocols due to high mortality rates
- Standardized airline policies for handling infectious disease cases on flights
- Improved ventilation systems and adherence to HEPA filtration guidelines
- Stronger international cooperation between airlines, health authorities, and WHO
- Better contact tracing mechanisms, including real-time passenger information sharing for public health emergencies

[Behaviors, Movements, and Transmission of Droplet-Mediated Respiratory Diseases During Transcontinental Airline Flights]

Hertzberg, V. S., Weiss, H., Elon, L., et al. (2018). Proceedings of the National Academy of Sciences, 115(14), 3623–3627. https://doi.org/10.1073/pnas.1711611115

- Observational study on 10 transcontinental US flights to assess passenger and crew movements and their impact on disease transmission in single-aisle aircraft.
- Passenger behavior data collected by trained observers, including seat position, movement frequency, lavatory use, and proximity to other passengers.

- Simulation of droplet-mediated transmission showed that the risk of infection is primarily confined to one row in front and behind an infected individual, contradicting the two-row contact tracing guidelines recommended by health agencies.
- Crew members posed a higher risk of spreading infection, with an estimated 4.6 secondary infections per flight if they were infected, due to frequent close interactions with passengers.
- Passenger mobility varied by seat type:
- 38% never left their seat, while 62% moved at least once.
- Aisle seat passengers had the highest number of contacts, making them more vulnerable to transmission.
- Window seat passengers had the fewest close contacts and the lowest exposure risk.
- Environmental sampling for 18 common respiratory viruses (including influenza and coronaviruses) was negative, suggesting low virus shedding or effective disinfection practices.
- Limitations: The study does not account for aerosol transmission, cannot be generalized to long-haul international flights, and assumes droplets as the main mode of transmission.

Probability and estimated risk of SARS-CoV-2 transmission in the air travel system.
Pang, J. K., Jones, S. P., Waite, L. L., Olson, N. A., Armstrong, J. W., Atmur, R. J., & Cummins, J. J. (2021). *Travel Medicine and Infectious Disease, 43*, 102133. https://doi.org/10.1016/j.tmaid.2021.102133

- Analyzes the probability of SARS-CoV-2 transmission in the air travel system using a retrospective risk estimation approach.
- Conducts a literature review from January–September 2020 to identify cases of COVID-19 transmission linked to air travel.
- Develops a novel risk assessment model incorporating correction factors for asymptomatic transmission and underreported cases.
- Estimates that the global risk of transmission during air travel is approximately 1 in 1.7 million passengers, with a range between 1 in 712,000 and 1 in 8 million due to uncertainty in reporting.
- Documents 2866 index passengers traveling in a 1.4 billion passenger population, with fewer than 50 secondary cases identified.
- Reports that mask mandates, increased spacing, and systemic COVID-19 testing likely contributed to a reduced transmission risk in later months of 2020.
- Highlights that environmental controls on aircraft, including high airflow rates and HEPA filtration, contribute to low transmission rates.
- Concludes that the risk of in-flight SARS-CoV-2 transmission is low, even with infectious individuals onboard, and supports the continued use of mitigation measures such as mask-wearing.

Routes of Transmission of Influenza A H1N1, SARS-CoV, and Norovirus in Air Cabin: Comparative Analyses
Lei, H., Li, Y., Xiao, S., Lin, C.-H., Norris, S. L., Wei, D., Hu, Z., & Ji, S. (2018). *Indoor Air: International Journal of Indoor Environment and Health, 28*(4), 394–403. DOI:10.1111/ina.12445

- Study examines transmission dynamics of three infectious diseases—Influenza A H1N1, SARS-CoV, and Norovirus—within airplane cabins using a comparative analysis approach **and** mathematical modeling

- Close contact (large droplet) transmission was dominant for influenza A H1N1 (70**%)**, confirming the higher infection risk for passengers seated within two rows of an infected individual (RR: 13.4, 95% CI: 1.5–121.2).
- Fomite transmission played the primary role for norovirus (85%), with aisle seat passengers experiencing significantly higher infection risk than others (RR: 9.5, 95% CI: 1.2–77.4, P = .022).
- SARS-CoV exhibited a mixed transmission pattern:

➔ Fomite transmission was most significant (50%)**,** followed by close contact (29%) and airborne (21%)**,** emphasizing surface contamination and hand hygiene as critical factors in limiting spread.

- Mathematical modeling of virus spread incorporated:

➔ Spatial patterns of infections using real outbreak data
➔ Transmission probability based on airflow, ventilation, and surface contact
➔ Passenger behavior such as movement, seat location, and lavatory usage

- Key recommendations for in-flight infection control:

➔ Close contact transmission mitigation: Prioritize passenger spacing and ventilation improvements
➔ Fomite route reduction: Regular disinfection of seatbacks, tray tables, lavatories, and aisle seats
➔ Enhanced hygiene practices: Encourage handwashing and limit shared surface contact
➔ Targeted interventions based on disease type: SARS-CoV requires both surface disinfection and close-contact distancing, whereas norovirus demands strict hygiene measures due to its high fomite dependency.

- Findings align with WHO recommendations on limiting in-flight transmission risks through passenger contact tracing, improved aircraft sanitation, and ventilation controls.

[Aerobiology and Its Role in the Transmission of Infectious Diseases]
Fernstrom, A., & Goldblatt, M. (2013). Journal of Pathogens. DOI: 10.1155/2013/493960

- Reviews airborne transmission of infectious diseases, focusing on key aerobiological factors
- Differentiates between droplet (short-range, large particles) and airborne transmission (long-range, small particles)
- Environmental factors like humidity, temperature, and ventilation affect pathogen survival
- Aerobiology enables microorganisms to travel long distances through air currents, with infectious diseases spreading via droplet transmission (large particles that settle quickly) and airborne transmission (small particles that remain suspended)
- Environmental factors like temperature, humidity, and air circulation influence pathogen survival, with low temperatures and dry air favoring virus persistence, while bacteria thrive in high humidity
- HVAC systems in office buildings contribute to airborne transmission by circulating contaminants such as molds, bacteria, and allergens, making effective filtration, maintenance, and pressurization crucial for reducing risks
- In healthcare settings, airborne transmission increases the risk of hospital-acquired infections (10–33% of cases), requiring measures like HEPA filtration, negative pressure rooms, and ultraviolet germicidal irradiation (UVGI) to minimize spread

- Air travel poses a risk due to confined spaces and high passenger density, with transmission influenced by seating proximity, shared surfaces, and ventilation, though modern aircraft achieve 15–20 air changes per hour
- Infection prevention strategies should focus on reducing both airborne and surface transmission through improved ventilation, air filtration, personal protective equipment, and hand hygiene in hospitals, offices, and travel settings.
- Current prevention methods, such as HEPA filtration, have limitations, highlighting the need for better technologies and a deeper understanding of airborne disease transmission to improve control measures.

Key Findings Pathogens of Interest

The literature on pathogen transmission in aircraft cabins provides key insights into how infectious diseases spread during air travel, the primary risk factors, and the effectiveness of mitigation strategies. The following ten points summarize the main findings based on multiple studies.

1) Airborne and droplet transmission are the dominant infection pathways in aircraft cabins. Influenza, SARS-CoV-2, measles, and tuberculosis can spread via droplets and aerosols, with the highest risk within two rows of an infected individual. However, studies indicate transmission can extend up to six rows, depending on airflow patterns and passenger movements (Olsen et al., 2003; Mangili & Gendreau, 2015; Leitmeyer & Adlhoch, 2016).
2) HEPA filtration and ventilation reduce transmission risk but are not absolute barriers. High airflow rates and HEPA filters remove 99.97% of particles as small as 0.3 µm, reducing long-range transmission. However, these systems are less effective when ventilation is reduced during boarding, taxiing, and delays, leading to localized airborne exposure risks (Pang et al., 2021; Gupta et al., 2012).
3) Passenger proximity and seat location significantly impact infection risk. Aisle seat passengers face a higher exposure risk due to increased movement and interaction with both passengers and crew. Close-range transmission remains the primary concern, with crew members acting as potential transmission vectors due to their mobility (Hertzberg et al., 2018; Burge, 2005).
4) Long-haul flights increase exposure risks for certain diseases. Tuberculosis transmission is unlikely on short flights but becomes a concern on flights longer than eight hours due to prolonged exposure. Similarly, SARS-CoV-2 and measles have shown increased transmission likelihood in long-duration confined spaces (Mangili & Gendreau, 2015; Leitmeyer et al., 2011).
5) Surface contamination plays a role in disease spread, particularly for norovirus and SARS-CoV. High-touch surfaces such as tray tables, lavatories, armrests, and seatbacks accumulate pathogens, facilitating fomite transmission. Contamination can spread within 2-3 hours, making frequent disinfection crucial, but cleaning practices vary widely across airlines (Lei et al., 2018; Huizer et al., 2015).
6) Mask-wearing is one of the most effective individual protective measures. Studies show that N95 respirators reduce airborne transmission by up to 99.6%, while surgical masks lower risk by approximately 81.5%. However, mask adherence among passengers is inconsistent, limiting its overall effectiveness (Pang et al., 2021; Gupta et al., 2012).
7) Pre-flight screening and temperature checks have limited effectiveness. Many infectious diseases, including COVID-19, influenza, and tuberculosis, can be transmitted by asymptomatic carriers. Studies

show that screening measures during past pandemics, such as H1N1 and SARS, only identified a small fraction of infected travelers (Mangili & Gendreau, 2015; Huizer et al., 2015).

8) Disease transmission is not limited to respiratory infections; vector-borne and antibiotic-resistant bacteria are emerging concerns. Infected mosquitoes in aircraft cargo can introduce diseases such as dengue and malaria to new regions. Additionally, antibiotic-resistant bacteria such as MRSA and MDR-TB may be introduced by repatriated patients or international travelers, though confirmed in-flight bacterial transmission remains rare (Vâță et al., 2020).
9) Current public health guidelines may underestimate actual transmission risk. The World Health Organization's two-row contact tracing rule for airborne diseases has been questioned by multiple studies, which suggest transmission can occur up to six rows away from an infected passenger. More comprehensive guidelines may be needed to assess and prevent in-flight infections (Olsen et al., 2003; Leitmeyer et al., 2016).
10) Integrated mitigation strategies are required to reduce risks effectively. A combination of ventilation improvements, mask mandates, surface disinfection, and seating adjustments has been shown to minimize infection risk. However, implementation challenges remain, particularly regarding passenger compliance, airline policies, and cost considerations (Hertzberg et al., 2018; Lei et al., 2018).

The reviewed literature highlights that in-flight transmission risks depend on multiple factors, including proximity to infected individuals, ventilation efficiency, passenger movements, and hygiene practices. While HEPA filtration and airflow management help reduce airborne transmission, surface contamination and close contact remain critical concerns. A multi-layered approach combining ventilation, personal protective equipment, targeted disinfection, and updated public health guidelines is essential to mitigate risks and ensure safer air travel.

Pathogen Transmission via Airflow

Combining multiple criteria such as environmental parameter control, ventilation concepts, infection risk modelling, and pathogen spread is essential to understand and mitigate pathogen transmission in aircraft passenger cabins. Haddrell et al. (2024) recently showed that the SARS-CoV 2 virus has a prolonged lifespan in environments with higher CO_2 concentrations (>1000 ppm) and that the aerostability of the virus is also significantly enhanced, leading to a higher risk of infection. Other suboptimal values of environmental parameters, for example of the relative humidity, also increase the aerostability of the pathogen and further weaken the immune system response, making individuals more susceptible to infection (Guarnieri et al.,2023). Improving environmental parameters is one way to combat airborne diseases (Wang et al., 2022). Also, personalized ventilation systems (Coșoiu et al., 2022, Kurec et al., 2023) show the potential to reduce the infection risk as they can create localized clean air zones and effectively reduce droplet transmission between passengers. The validation of CFD simulation with experiments (Schmeling et al., 2023) for multiple ventilation systems provides the future perspective to correctly model pathogen transmission in aircraft passenger cabins and with our new infection risk model (Webner et al., 2024), a detailed analysis of the infection risk of multiple airborne diseases in aircraft cabins can be provided. Combining these concepts will help us identify new guidelines for minimizing the risk of infection associated with pathogen transmission in airflows in future pandemics.

Overview of most relevant/most cited literature

Numerical and experimental study of aerosol dispersion in the Do728 aircraft cabin

Schmeling, D., Shishkin, A., Schiepel, D. et al. Numerical and experimental study of aerosol dispersion in the Do728 aircraft cabin. *CEAS Aeronautical Journal* 14, 509–526 (2023). https://doi.org/10.1007/s13272-023-00644-3

- Investigation of how aerosols spread within an aircraft cabin using both experimental methods and numerical simulations for cabin displacement ventilation (CDV) and mixing ventilation (MV).
- They demonstrated advantages of CDV over MV due to reducing aerosol spreading distances and decreasing aerosol dwell time within the cabin for particles with D < 20 µm
- Total number of particles, 60 and 120 s after the particle injection, the remaining active particles in the cabin amount to 6% and 2% for CDV, while at MV 45% and 17% are still flying in the cabin.

A Direct Infection Risk Model for CFD Predictions and Its Application to SARS-CoV-2 Aircraft Cabin Transmission

Webner, Florian, Shishkin, Andrei, Schmeling, Daniel, Wagner, Claus, A Direct Infection Risk Model for CFD Predictions and Its Application to SARS-CoV-2 Aircraft Cabin Transmission, *Indoor Air*, 2024, 9927275, 18 pages, 2024. https://doi.org/10.1155/2024/9927275

- The study presents an analytic infection risk model based on the inhaled dose of infectious virus, the virus emission rate of an emitter and the dynamics of Lagrangian particle trajectories using CFD.
- The fundamental model can be used in all kinds of cabin geometries and types of airborne diseases to calculate infection risk if biological parameters of the virus are known.
- Superspreading events can be modelled.

TRANSCOM/AMC Commercial Aircraft Cabin Aerosol Dispersion Tests

TRANSCOM Report Final.pdf

- It is difficult to determine the potential exposure risk using available computational fluid dynamics models or contact tracing methods, due to the lack of experimental validation of aerosol transport in the aircraft environment and the lack of detailed tracking of human interactions in aircraft. Using fluorescent aerosol tracers between 1-3 µm and real time optical sensors, coupled with DNA-tagged tracers to measure aerosol deposition.
- This is the largest aircraft aerosol experimental validation testing to date, with 8 days of testing involving both inflight and ground tests on Boeing 777-200 and 767-300 airframes with multiple seat configurations.
- Results from the Boeing 777-200 and 767-300 airframes showed a minimum reduction of 99.7% of 1 µm simulated virus aerosol from the index source to passengers seated directly next to the source using high air exchange rates and downward ventilation design
- They indicate an extremely unlikely aerosol exposure risk for a 12-hour flight when using a 4,000 virion/hour shedding rate and 1,000 virion infectious dose

CORSICA final report : Quantitative microbial risk assessment for aerosol transmission of SARS-CoV-2 in aircraft cabins based on measurement and simulations

Ministry of Infrastructure and Water Management. (n.d.). Bijlage: Non-paper by the Netherlands as input for EC's proposal for Euro 7/VII emission standards. Retrieved from https://open.overheid.nl/documenten/ronl-71aaf3ed-1f4b-4c37-8a23-197a9a621f16/pdf

- Extensive particle dispersion measurements using manikins equipped with nozzles and aerosol sensors, testing multiple variables including cruise and taxi conditions, gasper settings, mask usage, and passenger locations across three different aircraft types (Airbus A320, Boeing 737-800, and Boeing 787-8) to understand how viral particles might spread in aircraft cabins
- CFD simulations incorporating real-world environmental conditions, ventilation systems, and thermal effects, are also validated against the measurements
- For typical cruise flights, the mean risk of contracting COVID-19 through aerosolized SARS-CoV-2 particles ranged from 1/1800 to 1/120 for passengers seated within seven rows of an infected person, with significantly higher risks (up to 1/16) if the infected passenger was a "super shedder," and risks generally increasing with flight duration and proximity to the infected passenger.
- Major factors affecting risk are viral concentration in aerosols and volume of aerosol emission, while face mask usage and flight duration had proportionally smaller effects
- HEPA-filtered ventilation system showed minimal recirculation of aerosols, particularly in the economy class section

Quantitative Microbial Risk Assessment of Contracting COVID-19 Derived from Measured and Simulated Aerosol Particle Transmission in Aircraft Cabins | Environmental Health Perspectives | Vol. 131, No. 8

Schijven, J. F., van Veen, T., Delmaar, C., Kos, J., Vermeulen, L., Roosien, R., Verhoeven, F., Schipper, M., Peerlings, B., Duizer, E., Derei, J., Lammen, W., Bartels, O., van der Ven, H., Maas, R., & de Roda Husman, A. M. (2023). Quantitative microbial risk assessment of contracting COVID-19 derived from measured and simulated aerosol particle transmission in aircraft cabins. *Environmental Health Perspectives, 131*(8), 087011. https://doi.org/10.1289/EHP11495

- This study combines measurement and simulation approaches to assess COVID-19 transmission risk through aerosols in aircraft cabins.
- Comprehensive particle dispersion measurements were conducted, utilizing advanced aerosol sensors and manikins to evaluate airflow patterns, passenger seating arrangements, and mask effectiveness.
- CFD models were validated against real-world conditions, incorporating factors such as ventilation dynamics, thermal effects, and aerosol behaviour.
- Results indicated that viral aerosol concentration and passenger proximity to an infected individual are the primary determinants of transmission risk, while mask usage and flight duration had comparatively smaller impacts.
- HEPA-filtered ventilation systems demonstrated a high efficiency in minimizing aerosol recirculation, particularly in economy class sections, reducing the probability of airborne infection to significantly low levels under typical flight conditions.
- The study emphasizes the importance of integrated ventilation strategies and mitigation measures to further reduce infection risks in aircraft environments.

Ambient carbon dioxide concentration correlates with SARS-CoV-2 aerostability and infection risk

Haddrell, A. E., Oswin, H., Otero-Fernandez, M., Robinson, J. F., Cogan, T. A., Alexander, R. W., Mann, J. F. S., Hill, D. J., Finn, A. H. R., Davidson, A. D., & Reid, J. P. (2024). Ambient carbon dioxide concentration correlates with SARS-CoV-2 aerostability and infection risk. *Nature Communications, 15*, Article 3487. https://doi.org/10.1038/s41467-024-47777-5

- They measured the infectivity of the SARS-CoV-2 over time under different CO_2 conditions to determine the impact on viral aerostability.
- Even moderate CO_2 concentrations significantly enhance the aerostability of SARS-CoV-2, leading to a higher risk of infection.
- Effective ventilation strategies are needed to maintain low indoor CO_2 levels, to mitigate the transmission of airborne diseases

Relative Humidity and Its Impact on the Immune System and Infections

Guarnieri, G., Olivieri, B., & Senna, G. (2023). Relative humidity and its impact on the immune system and infections. *International Journal of Molecular Sciences, 24*(11), 9456. https://doi.org/10.3390/ijms24119456

- The aim of this review is to outline the consequences for health of suboptimal relative humidity (RH) in the environment and how to limit this negative impact.
- Suboptimal RH does not only affect the infection risk and aerostability of airborne pathogens it also decreases the effectiveness of the immune system and response to infections, and allergies and it lowers the respiratory health

Personalized Ventilation as a Possible Strategy for Reducing Airborne Infectious Disease Transmission on Commercial Aircraft

Coșoiu, L., Bălănică, F., & Bălan, M. (2022). Personalized ventilation as a possible strategy for reducing airborne infectious disease transmission on commercial aircraft. *Applied Sciences, 12*(4), 2088.https://doi.org/10.3390/app12042088

- The authors numerically investigated the possibility of introducing a personalized ventilation diffuser, combined with mixing ventilation, to improve air quality and thermal comfort and reduce the risk of airborne diseases.
- Mixing ventilation achieves good air-flow distribution but does little to combat airborne disease transport
- The Personalized Ventilation System (PVS) system created a localized microenvironment around each passenger, supplying cleaner and fresher air compared to traditional mixing ventilation systems.

Investigation of thermal comfort on innovative personalized ventilation systems for aircraft cabins: A numerical study with computational fluid dynamics

Bhangar, S., Adams, R. I., Pasut, W., Huffman, J. A., Arens, E. A., Taylor, J. W., & Nazaroff, W. W. (2021). Indoor emissions of human bioeffluents: Understanding the building ecology of indoor microbiomes. *Cell Reports Medicine, 2*(10), 100242. https://doi.org/10.1016/j.xcrm.2021.100242

- Six PVS are numerically investigated towards thermal comfort and flow velocities in a Boeing 767 aircraft cabin using CFD.

- Only PVS-1 could successfully maintain an acceptable thermal comfort with outlets at both sides of the passenger head.
- PVS-1 can improve the RH by 12% in the breathing zones without the risk of air drafts, and provides the freshest air with the lowest age of air time.

Aganovic, A., Cao, G., Kurnitski, J., Melikov, A., & Wargocki, P. (2022). Zonal modeling of air distribution impact on the long-range airborne transmission risk of SARS-CoV-2. *Applied Mathematical Modelling, 112*, 800-821. https://doi.org/10.1016/j.apm.2022.08.027

• A novel zonal modeling approach was developed to extend the traditional Wells-Riley model.

• Interzonal mixing factors were introduced based on previous experimental data to refine infection risk calculations.

• Three ventilation systems were analyzed: incomplete mixing, displacement ventilation, and protected-zone ventilation.

• Results showed that assuming complete air mixing misestimates airborne infection risk in spaces with stratified airflow.

• Displacement ventilation reduces infection risk in occupied zones but depends on temperature differences and airflow rates.

• Protected-zone ventilation isolates airflow, reducing transmission risk in certain areas while increasing it in others.

• The Wells-Riley model overestimates risk in well-ventilated spaces and underestimates it in areas with poor air circulation.

• Zonal modeling offers a more accurate approach for assessing airborne disease transmission in confined spaces.

Use of wearable ventilation for reducing the infection risk of healthcare workers in isolation wards: A numerical study

Guo, X., Li, Y., Wang, Y., & Chen, Q. (2024). Numerical investigation on the effectiveness of displacement ventilation and personalized ventilation in mitigating airborne disease transmission. *Building and Environment, 242*, 110861. https://doi.org/10.1016/j.buildenv.2024.110861

- Investigation of the protective effectiveness of a head-mounted air supply (HAS) on healthcare workers in contact with COVID-19 using CFD.
- Infection probability reduced by using HAS in a coughing event from 30% to 0.18%.
- Infection probability of the wearer with HAS lower than with masks.

Air curtain as a SARS-CoV-2 spreading mitigation method in a small aircraft cabin

Kurec K, Olszański B, Gumowski K, et al. Air curtain as a SARS-CoV-2 spreading mitigation method in a small aircraft cabin. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*. 2023;237(11):2480-2504. doi:10.1177/09544100231153703

- Discrete particle simulations to model the movement of respiratory droplets emitted during coughing within the cabin environment.
- An air curtain system is introduced designed to create a barrier that limits the spread of droplets between passengers.

- The air curtain inhibits the transmission process of medium droplets but not small droplets.
- Improved removal efficiency of virus-laden droplets has been achieved using the air curtain together with supplementary suction surfaces introduced on the front seat backrest.

HEPA filters for airliner cabins: State of the art and future development

Zhang X, Liu J, Liu X, Liu C, Chen Q.HEPA filters for airliner cabins: State of the art and future development. *Indoor Air*. 2022; 32:e13103. doi: 10.1111/ina.13103

- experimental study on 23 different HEPA filters with glass fiber media that are used in different commercial airliner models
- median filtration efficiency of >99.97% for particles with a diameter of 0.3–0.5 µm
- pressure drop of 134–412 Pa
- DHC of 32.2–37.0 g/m2
- comments on the usability of nano fiber or polymer fiber HEPA filters
- huge amount of detailed data of all HEPA filters

Indoor Air Quality Control for Airborne Diseases: A Review on Portable UV Air Purifiers

Sankurantripati, S., & Duchaine, F. (2024). Indoor Air Quality Control for Airborne Diseases: A Review on Portable UV Air Purifiers. *Fluids*, *9*(12), 281. https://doi.org/10.3390/fluids9120281

- A throughout review of indoor ventilation methods and air purification technologies.
- While HEPA and ESP filters focus on trapping airborne particles, UV radiation can inactivate pathogens by disrupting their RNA without interacting with the flow.
- The review reveals a lack of studies of UV air purifiers on their efficacy and effectiveness in real-world settings.
- A thorough investigation is necessary, focusing on purifier placement, airflow dynamics, UV dosage, safety, weight compared to HEPA filters.

Monitoring of indoor air quality at a large sailing cruise ship to assess ventilation performance and disease transmission risk

Cheung, H. Y. W., Kumar, P., Hama, S., Emygdio, A. P. M., Wei, Y., Anagnostopoulos, L., et al. (2025). Monitoring of indoor air quality at a large sailing cruise ship to assess ventilation performance and disease transmission risk. *Science of The Total Environment, 962*, 178286. https://doi.org/10.1016/j.scitotenv.2024.178286

- Ventilation performance was experimentally assessed in 9 spaces on a sailing cruise ship
- Private cabins and theatre are over-ventilated; pub and restaurant require increased ventilation.
- Temperature (22 ± 1.4 ◦C) and RH (68 ± 5.3 %), imply the vessel was over-air-conditioning.
- Indoor CO_2 rises in berths indicated port-related emissions have increased ambient CO_2
- The probability of airborne infection in a speaking normal condition is low and < 3%

Analysis of aerosol spreading in a German Inter City Express (ICE) train carriage

Schmeling, D., Kühn, M., Schiepel, D., Dannhauer, A., Lange, P., Kohl, A., Niehaus, K., Berlitz, T., Jäckle, M., Kwitschinski, T., & Tielkes, T. (2022). Analysis of aerosol spreading in a German Inter City Express (ICE) train carriage. *Building and Environment, 223*, 109363. https://doi.org/10.1016/j.buildenv.2022.109363

- Experimental study of aerosol dispersion in a long-distance ICE train carriage.
- Application of tracer-gas and particle concentration for multiple configurations.
- Spreading occurs over a restricted space and is reduced by wearing a mask.
- Direct transmission is more than one order of magnitude larger than indirect one.
- Decay time-constant of local particle concentration is maximal 5 min.

Recent progress on studies of airborne infectious disease transmission, air quality, and thermal comfort in the airliner cabin air environment

Wang, F., You, R., Zhang, T., & Chen, Q. (2022). Recent progress on studies of airborne infectious disease transmission, air quality, and thermal comfort in the airliner cabin air environment. *Indoor Air, 32*(4), e13032. https://doi.org/10.1111/ina.13032

- Current environmental control systems in airliner cabins do little to prevent airborne disease transmission.
- Cabin air quality is generally satisfactory, but passengers still report symptoms like dry eyes and headaches.
- Thermal comfort, especially with respect to temperature and low humidity, remains a challenge, and better models are needed.
- There is a growing interest in improving personalized and displacement ventilation systems to enhance both air quality and thermal comfort.

Indoor Air Quality Strategies for Air-Conditioning and Ventilation Systems with the Spread of the Global Coronavirus (COVID-19) Epidemic: Improvements and Recommendations

Elsaid, A. M., & Ahmed, M. S. (2021). Indoor air quality strategies for air-conditioning and ventilation systems with the spread of the global coronavirus (COVID-19) epidemic: Improvements and recommendations. *Environmental Research, 199*, 111314. https://doi.org/10.1016/j.envres.2021.111314

- Indoor air quality is important in our society and provides healthy human comfort.
- Increasing the temperatures and humidity dampen the activity of the COVID-19.
- The air carries suspended particles of the COVID-19, which leads to an increase in infected cases.
- Improper use of filters leads to spread of the bacterial and viruses' indoor environment.
- Mandatory recommendations are drawn to benefit the global community to limit the spread of the deadly COVID-19.

Efficacy of antimicrobial and anti-viral coated air filters to prevent the spread of airborne pathogens

Watson, R., Oldfield, M., Bryant, J. A., et al. (2022). Efficacy of antimicrobial and anti-viral coated air filters to prevent the spread of airborne pathogens. *Scientific Reports, 12*, 2803. https://doi.org/10.1038/s41598-022-06579-9

- Development and testing of antimicrobial air filters coated with chlorhexidine digluconate (CHDG) to combat airborne pathogens like bacteria, fungi, and SARS-CoV-2.
- Filters inactivate 91% of SARS-CoV-2 within 30 seconds and 100% in 1 minute.

- Effective against *E. coli*, Multi-resistant *S. aureus* (MRSA), and *Candida albicans*, killing pathogens within 1 minute.
- Airflow and filter structure remain unaffected by the CHDG coating.
- No significant leaching of the biocide over time; durability maintained for 240+ hours.
- On UK trains, CHDG-coated filters fully eliminated microbial contamination, unlike standard filters.
- Conclusion: CHDG-coated filters are highly effective and durable, compatible with existing HVAC systems, and ideal for reducing airborne pathogen spread.

A Review of Methods Applied to Study Airborne Biocontaminants inside Aircraft Cabins - Conceição - 2011 - International Journal of Aerospace Engineering

Conceição, S. T., Pereira, M. L., & Tribess, A. (2011). A review of methods applied to study airborne biocontaminants inside aircraft cabins. *International Journal of Aerospace Engineering, 2011*, 824591. https://doi.org/10.1155/2011/824591

- Indoor-cross infection of expiratory contaminants is still a concern, worsened by the SARS outbreak in 2003 and recent cases of influenza strains (H1N1, avian flu, etc.).
- A variety of methods to study the airborne spread of expiratory contaminants have been worked out, including the use of tracer gas, particle generators, and CFD simulations.
- In this context, the main objective of this work is reviewing methods to evaluate airborne dispersion of contaminants, more specifically those related to cross infection of expiratory droplets inside aircraft cabins.
- This literature review provides guidance in developing methods and choosing equipment for future studies.
- This study gathers knowledge developed so far in a common source, serving as a guideline for researchers who work in this area.

Key Findings Airflow Transmission

The literature review on pathogen airflow transmission synthesizes current research on air filtration systems, airflow dynamics, and advanced technologies aimed at reducing pathogen transmission in enclosed environments, with a focus on aircraft cabins. Key findings from selected studies are summarized:

1) Advantages of Displacement Ventilation: Schmeling et al. (2023) demonstrated that cabin displacement ventilation (CDV) is superior to mixing ventilation (MV) in reducing aerosol spread and dwell times. CDV retained only 6% and 2% of particles after 60 and 120 seconds, respectively, compared to 45% and 17% for MV.
2) Infection Risk Modelling: Webner et al. (2024) developed a computational model linking inhaled virus doses to infection risks. This adaptable model accounts for different cabin geometries, types of airborne diseases, and superspreading events.
3) Experimental Validation of Aerosol Dispersion: The TRANSCOM study conducted extensive tests using fluorescent tracers and DNA-tagged aerosols, showing a 99.7% reduction in virus-sized particles under high air exchange rates in Boeing 777-200 and 767-300 aircraft (TRANSCOM, 2021).

4) Risk Assessment for COVID-19 Transmission: The CORSICA report identified key factors influencing infection risk, including viral concentration and passenger proximity to infected individuals. It highlighted HEPA filters' effectiveness in reducing aerosol recirculation, particularly in economy-class cabins.
5) Effect of CO_2 on Viral Stability: Haddrell et al. (2024) revealed that elevated CO_2 levels enhance SARS-CoV-2 aerostability, emphasizing the need for effective ventilation to maintain low CO_2 concentrations and reduce infection risks.
6) Impact of Relative Humidity: Guarnieri et al. (2023) highlighted that suboptimal RH not only increases pathogen aerostability but also weakens immune system responses, making individuals more susceptible to infections.
7) Innovative Ventilation Approaches: Personalized ventilation systems (Coșoiu et al., 2022) and air curtains (Kurec et al., 2023) showed potential to create localized clean air zones and reduce droplet transmission between passengers effectively.
8) HEPA Filters' Efficiency: Zhang et al. (2022) confirmed that HEPA filters exceed 99.97% efficiency for particles as small as 0.3 µm, with potential improvements using nanofiber or polymer materials for enhanced performance.
9) Integration of UV Air Purifiers: Sankurantripati and Duchaine (2024) reviewed UV air purifiers, which effectively inactivate pathogens but require further real-world validation for optimal placement and usage in confined spaces.
10) Broader Applications in Public Transport: Studies in other confined spaces, such as cruise ships (Cheung et al., 2025) and trains (Schmeling et al., 2022), demonstrated that airflow management and passenger behaviour significantly influence pathogen spread, providing insights for cross-sector applications.

The reviewed literature highlights significant advancements in understanding and mitigating pathogen transmission through innovative filtration and ventilation technologies, but continued interdisciplinary collaboration is necessary to implement effective solutions and ensure safe environments in aircraft and similar enclosed spaces.

Pathogen Transmission via Surfaces

Research on pathogen transmission in aircraft cabins reveals that high-touch surfaces, particularly in seat areas and lavatories, are frequently contaminated with potentially hazardous microorganisms (Bin Zhao et al., 2019). Surface contamination can spread rapidly, with most high-touch surfaces contaminated within 2-3 hours and nearly all touchable surfaces within 5-6 hours (Lei et al., 2017). The airplane cabin microbiome is largely composed of human skin and oral commensals, as well as environmental generalist bacteria, with significant flight-to-flight variability (Weiss et al., 2018). Despite concerns about in-flight disease transmission, studies suggest a low probability of direct transmission to passengers not seated in close proximity to an infectious individual (Hertzberg et al., 2018). However, passenger and crew movements may facilitate disease spread (Hertzberg et al., 2018). These findings highlight the importance of surface cleaning and hand hygiene in reducing the risk of pathogen transmission in enclosed environments like aircraft cabins.

Overview of most relevant/most cited literature

[Microorganisms @ materials surfaces in aircraft: Potential risks for public health? – A systematic review - ScienceDirect](https://doi.org/10.1016/j.tmaid.2018.07.011)

Zhao, B., Dewald, C., & Jandt, K. D. (2019). Microorganisms on materials surfaces in aircraft: Potential risks for public health? – A systematic review. *Travel Medicine and Infectious Disease, 28*, 24–31. https://doi.org/10.1016/j.tmaid.2018.07.011

- The microbial dependences (adhesion, colonization, tenacity and transmission) on the materials surfaces of aircraft interiors are systematically reviewed.
- The interior materials surface in aircraft are generally colonized by various types of potentially hazardous microorganisms, which could pose health risks by causing infectious diseases.
- Within the aircraft cabin, there are infectious hotspots such as tray tables, armrests, seat covers, door knobs and toilet flush buttons in the lavatories.
- Surprisingly, little reliable data is available about the number of microbes on interior commercial aircraft materials surfaces.
- The types of materials and their surface physicochemical properties affect microbial tenacity and transmission within the aircraft cabin.
- They propose strategies to interrupt surface-related infection chains in aircraft.

[PDF] Logistic growth of a surface contamination network and its role in disease spread | Semantic Scholar

Lei, H., Li, Y., Xiao, S., Yang, X., Lin, C.-H., Norris, S. L., Wei, D., Hu, Z., & Ji, S. (2017). Logistic growth of a surface contamination network and its role in disease spread. *Scientific Reports, 7*. https://doi.org/10.1038/srep10591179

- The study found that surface contamination can spread rapidly in a logistic growth pattern, leading to possible rapid disease transmission.
- Pathogens can spread quickly through a network of contaminated surfaces, as far as people move between them.
- The surface contamination network in aircraft cabins exhibits a community structure, with small communities connected by high-touch surfaces like aisle seatbacks and toilets.

The Airplane Cabin Microbiome | Microbial Ecology

Weiss, H., Hertzberg, V. S., Dupont, C., & others. (2019). The airplane cabin microbiome. *Microbial Ecology, 77*(1), 87–95. https://doi.org/10.1007/s00248-018-1191-3

- Core Microbiome: Bacteria like Propionibacterium, Staphylococcus, and Streptococcus were common, posing minimal risk under normal conditions, but potentially problematic for immunocompromised individuals.
- Variability Between Flights: Each flight showed unique bacterial communities, suggesting that cabins inherit microbial profiles from their passengers.
- Air vs. Surface Microbiomes: Clear distinctions were found between air and surface bacterial communities, though no significant changes were detected from pre- to post-flight samples.
- Cleaning Implications: The study suggests that a robust cleaning routine could reduce the inherited microbiome from passengers, helping mitigate disease spread in aircraft.

[Persistence of Pathogens on Inanimate Surfaces: A Narrative Review](https://doi.org/10.3390/microorganisms9020343)

Wißmann, J. E., Kirchhoff, L., Brüggemann, Y., Todt, D., Steinmann, J., & Steinmann, E. (2021). Persistence of Pathogens on Inanimate Surfaces: A Narrative Review. *Microorganisms*, *9*(2), 343. https://doi.org/10.3390/microorganisms9020343

- Many common nosocomial pathogens can survive for days to weeks on inanimate surfaces, potentially leading to outbreaks through fomite-mediated transmission.
- Hygiene measures based on the knowledge of pathogen persistence on surfaces are essential for infection prevention.
- The origin of various infectious disease outbreaks has been linked to fomite-mediated transmission.

The role played by contaminated surfaces in the transmission of nosocomial pathogens - PubMed

Otter, J. A., Yezli, S., & French, G. L. (2011). The role played by contaminated surfaces in the transmission of nosocomial pathogens. *Infection Control & Hospital Epidemiology, 32*(7), 687–699. https://doi.org/10.1086/660363

- Studies have found that hospital surfaces can become contaminated with nosocomial pathogens and contribute to their transmission, in contrast with earlier studies that suggested surfaces played a negligible role.
- Contaminated surfaces play an important role in the transmission of several major nosocomial pathogens, including *Clostridium difficile*, vancomycin-resistant enterococci, methicillin-resistant *Staphylococcus aureus*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and norovirus.
- Improving environmental decontamination can contribute to the control of nosocomial infection outbreaks.

Microbial Virulence Factors, Antimicrobial Resistance Genes, Metabolites, and Synthetic Chemicals in Cabins of Commercial Aircraft - PMC

Fu, X., Zhang, M., Yuan, Y., Chen, Y., Ou, Z., Hashim, Z., Hashim, J. H., Zhang, X., Zhao, Z., Norbäck, D., & Sun, Y. (2023). Microbial virulence factors, antimicrobial resistance genes, metabolites, and synthetic chemicals in cabins of commercial aircraft. *Metabolites, 13*(3), 343. https://doi.org/10.3390/metabo13030343

- Study analysed dust samples from commercial aircraft cabins, highlighting the presence of microbial virulence factors (VFs) and antimicrobial resistance genes (ARGs).
- Showed that microbes associated with respiratory infections, such as *Haemophilus parainfluenzae* and *Streptococcus pneumoniae*, are prevalent on aircraft surfaces, especially on textile seats.
- Study emphasized the importance of surface material choices (textile vs. leather) as they play a role in shaping microbial diversity, potentially impacting passenger health.

Fomite Transmission in Airports Based on Real Human Touch Behaviours

Zhuang, L., Ding, Y., Zhou, L., Liu, R., Ding, J., Wang, R., Huang, W., Shang, S., Qian, H., & Zhang, N. (2023). Fomite transmission in airports based on real human touch behaviours. *Buildings, 13*(10), 2582. https://doi.org/10.3390/buildings13102582

- Study investigates the spread of infectious diseases through surfaces (fomites) in airports, focusing on how passengers interact with these surfaces.

- Touch Behaviour Data: Researchers recorded 21.3 hours of video at three airports and analysed 25,925 surface touches. The highest touch rates were observed in self-service check-in areas (473.5 touches/hour).
- Health Risks: Passengers in airport restaurants had higher rates of touching their mucous membranes (10.3 times/hour) compared to other areas (1.6 times/hour), increasing the risk of fomite-based disease transmission.
- Preventive Measures: The study found that mask-wearing significantly reduced the viral intake fraction by up to 97.4%, and disinfecting public surfaces or hands twice per hour could reduce fomite-based transmission by 27.7% and 15.4%, respectively.
- Highlights the importance of targeted cleaning protocols and public health interventions to reduce surface-based transmission in busy airport environments.

Survival and inactivation of human norovirus GII.4 Sydney on commonly touched airplane cabin surfaces

Djebbi-Simmons, D., Alhejaili, M., Janes, M., King, J., & Xu, W. (2020). Survival and inactivation of human norovirus GII.4 Sydney on commonly touched airplane cabin surfaces. *AIMS Public Health, 7*(3), 574–586. https://doi.org/10.3934/publichealth.2020046

- HuNoV can survive for up to 30 days on common airplane surfaces when organic matter is present. - Commonly used disinfectants are highly ineffective against HuNoV when surfaces are soiled. - Airline companies and public health authorities need to develop better procedures to reduce the risk of HuNoV transmission to passengers on airplanes.

Routes of transmission of influenza A H1N1, SARS CoV, and norovirus in air cabin: Comparative analyses - Lei - 2018 - Indoor Air - Wiley Online Library

Lei, H., Li, Y., Xiao, S., Lin, C.-H., Norris, S. L., Wei, D., Hu, Z., & Ji, S. (2017). Routes of transmission of influenza A H1N1, SARS-CoV, and norovirus in air cabins: Comparative analyses. *Indoor Air, 28*(2), 394–408. https://doi.org/10.1111/ina.12445

- For influenza A H1N1, the airborne and close contact routes are more important than the fomite route.
- For SARS-CoV, all three transmission routes (airborne, close contact, and fomite) are important.
- For norovirus, the fomite route is likely the dominant transmission route.

Effects of Surface Material, Ventilation, and Human Behaviour on Indirect Contact Transmission Risk of Respiratory Infection - PMC

Sze-To, G. N., Yang, Y., Kwan, J. K., Yu, S. C., & Chao, C. Y. (2014). Effects of surface material, ventilation, and human behaviour on indirect contact transmission risk of respiratory infection. *Risk Analysis, 34*(5), 818–830. https://doi.org/10.1111/risa.12144

- Reducing hand contact rates on contaminated surfaces and mucous membranes could significantly reduce the infection risk from indirect contact transmission.
- Contacting nonfabric surfaces poses a much higher indirect contact transmission risk compared to contacting fabric surfaces, especially for RSV and rhinovirus.

- Increasing ventilation rate does not necessarily reduce the indirect contact transmission risk for all occupants, as it can change the airflow patterns and lead to higher deposition of infectious particles in some regions.

[Infectious Risks of Air Travel | Microbiology Spectrum]

Mangili, A., Vindenes, T., & Gendreau, M. (2015). Infectious risks of air travel. Microbiology Spectrum, 3(5), 1–17. https://doi.org/10.1128/microbiolspec.iol5-0009-2015

- Transmission Dynamics: Discusses how infectious agents spread in confined spaces like aircraft cabins, with particular focus on respiratory droplets.
- Pathogen Behaviour: Investigates the survival and transmission rates of common airborne pathogens.
- Mitigation Strategies: Evaluates measures such as air filtration, mask-wearing, and seating arrangements to reduce in-flight infection risks.
- Case Studies: Provides examples of past in-flight disease transmissions.

[Risk assessment of airborne infectious diseases in aircraft cabins - PubMed]

Gupta, J. K., Lin, C. H., & Chen, Q. (2012). Risk assessment of airborne infectious diseases in aircraft cabins. *Indoor Air, 22*(5), 388–395. https://doi.org/10.1111/j.1600-0668.2012.00773.x

- The use of N95 respirator masks by passengers can significantly reduce the number of secondary influenza infections in an aircraft cabin.
- The comprehensive approach used in this study to assess airborne infection risk can be applied to other enclosed environments beyond just aircraft cabins.
- The findings of this study will be useful for the airline industry in protecting passengers and crew, as well as for assessing infection risk in other enclosed spaces.

Key Findings Surface Transmission

The literature review on pathogen surface transmission synthesizes research on surface contamination, pathogen persistence, and mitigation strategies in enclosed environments, focusing specifically on aircraft cabins. Key findings from selected studies are summarized below:

1) Surface Contamination and Disease Spread: Zhao et al. (2019) identified high-touch surfaces such as tray tables, armrests, and lavatory fixtures as hotspots for microbial colonization. These surfaces pose significant health risks due to the adhesion and persistence of pathogens. The study emphasized material properties' role in microbial transmission and proposed strategies for interrupting surface-related infection chains.
2) Rapid Surface Contamination: Lei et al. (2017) found that surface contamination in aircraft cabins follows a logistic growth pattern, spreading rapidly to most high-touch surfaces within 5–6 hours. This highlights the importance of timely and targeted cleaning to mitigate disease transmission.
3) Cabin Microbiome Composition: Weiss et al. (2018) revealed that the airplane cabin microbiome primarily consists of human skin and oral commensals, alongside environmental bacteria. While these microbes pose minimal risk under normal conditions, variability between flights suggests the need for consistent cleaning practices.

4) Pathogen Persistence: Wißmann et al. (2021) demonstrated that many pathogens, including nosocomial ones, can persist on inanimate surfaces for days to weeks, emphasizing the need for hygiene measures to prevent fomite-mediated disease transmission.
5) Role of High-Touch Surfaces: Otter et al. (2011) highlighted the role of contaminated surfaces in spreading pathogens like MRSA and *C. difficile* in healthcare settings, drawing parallels to similar risks in aircraft cabins.
6) Microbial Virulence and Resistance: Fu et al. (2023) analysed dust samples from aircraft cabins and found microbial virulence factors and antimicrobial resistance genes on surfaces, especially textile seats. Surface material choices significantly influenced microbial diversity and potential health impacts.
7) Airport Surface Transmission: Zhuang et al. (2023) documented high-touch rates in airport self-service areas and restaurants, linking them to increased fomite transmission risks. Frequent disinfection and mask-wearing were effective in reducing transmission.
8) Transmission Pathways in Aircraft: Lei et al. (2018) compared influenza, SARS-CoV, and norovirus transmission routes, finding fomite transmission to be dominant for norovirus, while airborne and close contact routes were more critical for influenza and SARS-CoV.
9) Surface Materials and Ventilation: Sze-To et al. (2014) demonstrated that surface material properties and human behaviour significantly influence fomite transmission risks. Nonfabric surfaces were found to pose higher risks, emphasizing material selection and behavioural interventions in risk mitigation.
10) Mitigation Strategies for Air Travel: Mangili et al. (2015) reviewed transmission dynamics in aircraft cabins, advocating for air filtration, mask-wearing, and strategic seating arrangements to minimize infection risks. Similarly, Gupta et al. (2012) highlighted the effectiveness of N95 masks in reducing airborne infections, providing a framework for broader applications in enclosed environments.

The reviewed literature for WP 1.2 underscores the critical role of surface transmission in pathogen spread within aircraft cabins. High-touch surfaces act as central hubs for contamination, with material properties and passenger behaviour significantly influencing microbial persistence and transmission. While advances in antimicrobial materials and cleaning protocols offer promising mitigation strategies, sustained interdisciplinary research and implementation of standardized guidelines are essential to minimize surface-based transmission risks and enhance passenger safety in enclosed environments.

Key Findings Airflow Transmission

Disinfection Measures inside an Airplane Cabin

Recent research highlights various disinfection methods for reducing microbial contamination in airplane cabins. It is important to differentiate cleaning from disinfection: cleaning refers to the removal of visible dirt, debris, and organic material from surfaces using detergents or water-based solutions, whereas disinfection involves the application of chemical agents or physical methods (such as Ultraviolet-C (UV-C) light) to eliminate or inactivate pathogens, including bacteria and viruses. In practice, cleaning is performed regularly between flights, focusing on high-contact areas such as tray tables, armrests, and lavatories, while disinfection—aimed at eradicating infectious agents—is less frequent and typically occurs after a known contamination event or during scheduled deep maintenance. Ultraviolet-C (UV-C) technology has emerged as a promising approach, offering potential risk mitigation for airborne disease transmission (DeJohn et al., 2024). An innovative system combining UV-C and photocatalysis has demonstrated effectiveness in degrading volatile organic compounds and inactivating pathogenic microorganisms, including viruses and bacteria (Gorvel et al., 2014). UV germicidal irradiation, along with increased ventilation and filtration, can help reduce airborne transmission of pathogens from human sources (Menzies, 2005). Environmental microbial contamination can be addressed through cleaning, germicidal chemicals, or UV irradiation (Menzies, 2005). However, routine disinfection in an operational aircraft fleet is rare due to time constraints between flights, concerns over material compatibility, and the potential for chemical residues to impact passengers and crew. For highly pathogenic agents, specific disinfection procedures are crucial, often requiring the aircraft to be taken out of service for deep decontamination. Guidelines have been developed for selecting aircraft-compatible disinfectants and implementing standardized operating procedures to ensure safe and efficient disinfection of civil aircraft (Klaus et al., 2016).

Overview and short summaries of most relevant/most cited literature

Disinfection of aircraft : Appropriate disinfectants and standard operating procedures for highly infectious diseases - PubMed

Klaus, J., Gnirs, P., Hölterhoff, S., Wirtz, A., Jeglitza, M., Gaber, W., & Gottschalk, R. (2016). Disinfection of aircraft: Appropriate disinfectants and standard operating procedures for highly infectious diseases. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 59*(12), 1544–1548. https://doi.org/10.1007/s00103-016-2460-2

- The study provides guidance on effective disinfection substances and procedures that have been tested and found compatible with aircraft components.
- The study makes publicly available the guidance and standardized operating procedures (SOPs) for aircraft disinfection.
- Current WHO guidelines on aircraft disinfection lack specifics on effective disinfection substances and standardized procedures.

Safety and Effectiveness Assessment of Ultraviolet-C Disinfection in Aircraft Cabins in: Aerospace Medicine and Human Performance Volume 95: Issue 3 | AsMA

Belland, K., Garcia, D., DeJohn, C., Allen, G. R., Mills, W. D., & Glaudel, S. P. (2024). Safety and effectiveness assessment of ultraviolet-C disinfection in aircraft cabins. *Aerospace Medicine and Human Performance, 95*(3), 147–157. https://doi.org/10.3357/AMHP.6350.2024

- Integrating UV-C light in aircraft cabins, when applied with appropriate scientific understanding and engineering safeguards, has the potential to reduce in-flight disease transmission.
- This additional mitigation strategy can work synergistically with existing measures.
- The research and risk-vs.-benefit analysis present strong evidence for the safety and effectiveness of continuous UV-C disinfection in aircraft cabins.

Methods of Aircraft Disinfection to Reduce Airborne Infectious Disease Transmission in: Aerospace Medicine and Human Performance Volume 95: Issue 12 | AsMA

DeJohn, C., Belland, K., & Garcia, D. (2024). Methods of aircraft disinfection to reduce airborne infectious disease transmission. *Aerospace Medicine and Human Performance, 95*(12), 930–936. https://doi.org/10.3357/AMHP.6348.2024

- Chemical disinfectants, ultraviolet germicidal irradiation (UVGI), and electrostatic spraying systems effectively reduce microbial loads when applied correctly.
- A combination of disinfection methods is recommended for optimal effectiveness and coverage.
- Safety measures and training are essential to ensure proper application without compromising aircraft material integrity or personnel safety.
- Standardized disinfection protocols tailored to aircraft configurations are critical for consistent implementation.

Design of air circuit disinfection against COVID-19 in the conditions of airliners - ScienceDirect
Pecho, P., Škvareková, I., Ažaltovič, V., & Hrúz, M. (2020). *Design of air circuit disinfection against COVID-19 in the conditions of airliners. Transportation Research Procedia, 51*, 313–322. https://doi.org/10.1016/j.trpro.2020.11.034

- The authors propose integrating a UV-C disinfection system into the aircraft's air circulation to inactivate airborne pathogens, including SARS-CoV-2.
- Computational simulations indicate that the UV-C system can effectively reduce viral load in recirculated air, enhancing passenger safety.
- Implementation Considerations: The study discusses challenges such as ensuring sufficient UV-C exposure time, maintaining system efficiency, and addressing potential material degradation due to prolonged UV exposure.
- Recommendations include shielding to prevent direct UV exposure to passengers and crew, and regular maintenance to ensure system efficacy.

Far-UVC Light at 222 nm is Showing Significant Potential to Safely and Efficiently Inactivate Airborne Pathogens in Occupied Indoor Locations - Brenner - 2023 - Photochemistry and Photobiology - Wiley Online Library
Brenner, D. J. (2023). Far-UVC light at 222 nm is showing significant potential to safely and efficiently inactivate airborne pathogens in occupied indoor locations. *Photochemistry and Photobiology, 99*(5), 1047–1050. https://doi.org/10.1111/php.13739

- Far-UVC light at 222 nm efficiently inactivates a wide range of airborne pathogens, including viruses and bacteria.
- It is safe for human exposure, as it does not penetrate the outer layers of skin or eyes.
- This technology is ideal for continuous use in occupied indoor environments, such as hospitals and public spaces.
- It provides rapid and effective disinfection while posing minimal health risks when properly applied.

Microbial Contamination in Airplane Cabins:Health Effects and Remediation | SpringerLink
Menzies, D. (2005). Microbial contamination in airplane cabins: Health effects and remediation. In M. Hocking (Ed.), *Air quality in airplane cabins and similar enclosed spaces* (The Handbook of Environmental Chemistry, Vol. 4H). Springer. https://doi.org/10.1007/b107242

- Microorganisms that affect human health are found in airplane cabins.
- Airborne transmission of microbes can be reduced through UV irradiation or increased ventilation.
- Environmental sources of microbial contamination can be prevented or remediated through cleaning, disinfectants, or UV irradiation.

Innovative Germicidal UV and Photocatalytic System Dedicated to Aircraft Cabin Eliminates Volatile Organic Compounds and Pathogenic Micro-Organisms - Gorvel - 2014 - CLEAN – Soil, Air, Water - Wiley Online Library
Gorvel, L., Yver, M., Robert, E., Harmant, M., Rosa-Calatrava, M., Lina, B., Gorvel, J. P., Moulès, V., Albalate, R., & Gaüzère, C. (2014). Innovative germicidal UV and photocatalytic system dedicated to aircraft cabin eliminates volatile organic compounds and pathogenic micro-organisms. *Clean Soil Air Water, 42*(6), 703–712. https://doi.org/10.1002/clen.201300085

- The air purification system was able to degrade major volatile organic compound (VOC) pollutants in aircraft cabins.
- The system inactivated pathogenic viruses (influenza, adenovirus) and bacteria (*Legionella, Burkholderia, Streptococcus, Pseudomonas*) found in aircraft cabins.
- The system demonstrates the ability to improve air quality in indoor confined environments like aircraft cabins and could be applied in hospital settings.

Disinfection of Microbial Aerosols | SpringerLink
Adhikari, A., & Clark, S. (2017). Disinfection of microbial aerosols. In C. Hurst (Ed.), Modelling the transmission and prevention of infectious disease (Advances in Environmental Microbiology, Vol. 4, Springer, Cham. https://doi.org/10.1007/978-3-319-60616-3_3

- Although various disinfection methods have shown promise, they all have some limitations.
- Most of the disinfection methods have only been tested in laboratory settings, and there is a lack of real-world field data to support their effectiveness.
- The disinfection methods have not been adequately tested against actual pathogens, including drug-resistant ones.
- There is not yet a perfect solution for disinfecting all airborne microorganisms.

Key Findings Disinfection Procedures

The literature review on state-of-the-art disinfection measures synthesizes research on state-of-the-art disinfection methods and recent innovations designed to mitigate microbial contamination in aircraft cabins. Key findings from selected studies are summarized below:

1. Guidelines for Effective Disinfection: Klaus et al. (2016) highlighted the need SOPs and effective disinfectants that are compatible with aircraft materials. They identified gaps in WHO guidelines, emphasizing the importance of tailored strategies for highly infectious diseases.
2. UV-C Disinfection**:** Belland et al. (2024) and DeJohn et al. (2024) demonstrated that UV-C disinfection can effectively reduce microbial loads in aircraft cabins, complementing ventilation and filtration systems. Safety measures, such as shielding and training, are critical to ensuring efficacy and material integrity.

3. Far-UVC Technology: Brenner (2023) explored the potential of far-UVC light (222 nm), which is safe for human exposure and effective in inactivating airborne pathogens, making it suitable for continuous use in occupied environments like aircraft cabins.
4. Innovative Disinfection Systems: Gorvel et al. (2014) introduced a system combining UV-C and photocatalysis, which eliminates volatile organic compounds (VOCs) and pathogens. This technology could enhance air quality and reduce microbial risks in enclosed spaces.
5. Comprehensive Air Circuit Disinfection: Pecho et al. (2020) proposed integrating UV-C systems into aircraft air circulation to target airborne pathogens. Computational simulations confirmed its efficacy but highlighted challenges such as material degradation and the need for regular maintenance.
6. Microbial Remediation Strategies: Menzies (2005) emphasized the role of cleaning, germicidal chemicals, and UV irradiation in mitigating microbial contamination. Increased ventilation further supports the reduction of airborne transmission risks.
7. Challenges in Disinfection Methods: Adhikari and Clark (2017) noted that while laboratory studies validate various disinfection methods, their real-world effectiveness remains underexplored. Comprehensive testing against drug-resistant pathogens is necessary to improve strategies.
8. Electrostatic and Chemical Disinfection**:** DeJohn et al. (2024) recommended combining methods such as electrostatic spraying and chemical disinfectants for optimal microbial control, tailored to aircraft configurations and supported by personnel training.

The reviewed literature for WP 1.3 highlights significant advancements in disinfection methods for mitigating microbial contamination in aircraft cabins. UV-C technologies, especially when combined with photocatalysis, offer innovative solutions for improving air quality and inactivating pathogens. However, challenges such as material compatibility, operational validation, and the development of comprehensive SOPs remain. Continued interdisciplinary research and real-world testing are essential to optimize these methods and ensure safe, effective disinfection practices in aviation environments.

Key Findings Airflow Transmission

Additional Aspects

Application of Antimicrobial Surface Treatments in Aircraft Interiors

Antimicrobial surfaces play a vital role in reducing microbial contamination and preventing pathogen transmission across various settings, including healthcare and aviation. These surfaces function through antifouling, bactericidal, or stimuli-responsive mechanisms (Wu et al., 2023), utilizing physical and chemical modifications to alter surface properties like topography and charge (Mahanta et al., 2021). Copper, silver, and advanced materials like nanoparticles and organosilanes have demonstrated antimicrobial efficacy, with light-activated surfaces like TiO_2 offering additional potential (Muller et al., 2016; Page et al., 2009). In aircraft cabins, high microbial loads on textile seats and lavatories necessitate targeted interventions (Zhao et al., 2019; Fu et al., 2023). Materials such as copper and silver, along with innovative coatings and topographical features, can reduce pathogen persistence and improve passenger safety (Paton et al., 2020; Wang et al., 2021). However, further research is needed to address gaps in real-world application and ensure the long-term efficacy of antimicrobial surfaces in both healthcare and aviation.

Antimicrobial surfaces: a review of synthetic approaches, applicability and outlook | Journal of Materials Science

Mahanta, U., Khandelwal, M., & Deshpande, A. S. (2021). Antimicrobial surfaces: A review of synthetic approaches, applicability and outlook. *Journal of Materials Science, 56*(33), 17915–17941. https://doi.org/10.1007/s10853-021-06404-0

- Antimicrobial surfaces can be classified into four main categories: patterned surfaces, functionalized surfaces, super - wettable surfaces, and smart surfaces.
- The review critically discusses the important findings from systems of developing antimicrobial surfaces along with the limitations of the current research and the gap that needs to be bridged before these approaches are put into practice.
- Understanding the interaction between various microbes and surfaces is crucial in the development of effective antimicrobial surfaces.

Recent advances in antimicrobial surfaces via tunable molecular interactions: Nanoarchitectonics and bioengineering applications - ScienceDirect

Wu, M., Liu, J., Wang, X., & Zeng, H. (2023). Recent advances in antimicrobial surfaces via tunable molecular interactions: Nanoarchitectonics and bioengineering applications. *Current Opinion in Colloid & Interface Science, 68*, 101707. https://doi.org/10.1016/j.cocis.2023.101707

- Antimicrobial surfaces can effectively combat the transmission of pathogens and reduce infections.
- The study discusses the fabrication processes and properties of different types of antimicrobial surfaces, as well as their structure-performance relationships.
- The study focuses on the anchoring strategies involving tunable molecular interactions, which are important for the development of antimicrobial surfaces.

Antimicrobial surfaces to prevent healthcare-associated infections: a systematic review - ScienceDirect

Muller, M. P., MacDougall, C., Lim, M., & the Ontario Agency for Health Protection and Promotion (Public Health Ontario) and the Provincial Infectious Diseases Advisory Committee on Infection Prevention and Control (PIDAC-IPC). (2016). Antimicrobial surfaces to prevent healthcare-associated infections: A systematic review. *Journal of Hospital Infection, 92*(1), 7–13. https://doi.org/10.1016/j.jhin.2015.09.008

- Copper surfaces resulted in modest reductions in microbial contamination, with less than a 1 log10 reduction on average.
- A randomized controlled trial of copper surfaces in an ICU demonstrated a 58% reduction in healthcare - associated Infections, but the evidence was considered low-quality due to methodological issues.
- An uncontrolled before-after study of copper-impregnated textiles in a long-term care ward demonstrated a 24% reduction in HCAI, but the evidence was considered very low-quality.

Antimicrobial surfaces for use on inhabited space craft: A review - ScienceDirect

Paton, S., Moore, G., Campagnolo, L., & Pottage, T. (2020). Antimicrobial surfaces for use on inhabited spacecraft: A review. *Life Sciences in Space Research, 26*, 125–131. https://doi.org/10.1016/j.lssr.2020.05.004

- Biodegradation of materials on crewed spacecraft is a significant problem that can cause disruption, loss of function, and lost crew time.
- Cleaning of surfaces is only partially effective due to accessibility and resource concerns.
- The use of antimicrobial and antifouling materials, including traditional surfaces like copper and silver, as well as nanoparticles, long-chain organic molecules, surface topographical features, and novel "smart" technologies, is a potential solution to the problem of biodegradation on spacecraft.

Antimicrobial Surfaces for Applications on Confined Inhabited Space Stations - Wang - 2021 - Advanced Materials Interfaces - Wiley Online Library

Wang, M., Duday, D., Scolan, E., Perbal, S., Prato, M., Lasseur, C., & Hołyńska, M. (2021). Antimicrobial surfaces for applications on confined inhabited space stations. *Advanced Materials Interfaces.* https://doi.org/10.1002/admi.202100118

- The review provides an overview of current antimicrobial surface treatments and coatings for use in confined space stations.
- It reviews antimicrobial coatings used on the International Space Station.
- It presents a selection of commercial and newly developed antimicrobial coatings targeting space applications.

Engineering and Application Perspectives on Designing an Antimicrobial Surface | ACS Applied Materials & Interfaces

Song, B., Zhang, E., Han, X., Zhu, H., Shi, Y., & Cao, Z. (2020). Engineering and application perspectives on designing an antimicrobial surface. *ACS Applied Materials & Interfaces, 12*(19), 21330–21341. https://doi.org/10.1021/acsami.9b19992

- Discusses strategies for designing antimicrobial surfaces to combat infections, biofouling, and contamination in healthcare, food, and marine applications.
- Conventional disinfectants face issues like environmental pollution, drug resistance, and limited biofilm efficacy.
- Prevention microbial adhesion with hydrophobic or hydrophilic coatings.
- The types of antimicrobial agents are distinguished between metal, organic, biological and includes copper, silver, polymers, enzymes, and bacteriophages.
- Combination Approach: Mixing microbicidal and resistant strategies improves efficacy and durability.
- Challenges: Real-world application is limited by regulatory, cost, and durability concerns.

Nano-structured antimicrobial surfaces: From nature to synthetic analogues - ScienceDirect

Elbourne, A., Crawford, R. J., & Ivanova, E. P. (2017). Nano-structured antimicrobial surfaces: From nature to synthetic analogues. *Journal of Colloid and Interface Science, 508*, 603–616. https://doi.org/10.1016/j.jcis.2017.07.021

- Naturally occurring surface topographies, such as those found on insect wings, exhibit high levels of antimicrobial efficacy.
- The antimicrobial activity of these natural surfaces is due to the physical interaction between the nanoscale topography and the pathogenic cells, rather than any specific biochemical properties.
- Synthetic, biomimetic surfaces that mimic the antimicrobial properties of the natural surfaces have been fabricated, leading to increased antimicrobial properties.

Current Developments in Antimicrobial Surface Coatings for Biomedical Applications - PubMed

Elbourne, A., Crawford, R. J., & Ivanova, E. P. (2017). Nano-structured antimicrobial surfaces: From nature to synthetic analogues. *Journal of Colloid and Interface Science*, 508, 603–616. https://doi.org/10.1016/j.jcis.2017.07.021

- Effective antimicrobial surface coatings can be based on anti-adhesive or bactericidal strategies, or a multifunctional approach combining both.
- The future of biofilm control on biomaterial implants and devices will likely involve surface modifications that are non-antibiotic related, as the era of antibiotics to control infectious biofilms is expected to come to an end.

Selection of resistance by antimicrobial coatings in the healthcare setting - ScienceDirect

Pietsch, F., O'Neill, A. J., Ivask, A., Jenssen, H., Inkinen, J., Kahru, A., Ahonen, M., & Schreiber, F. (2020). Selection of resistance by antimicrobial coatings in the healthcare setting. *Journal of Hospital Infection, 106*(1), 115–125. https://doi.org/10.1016/j.jhin.2020.06.006

- The available evidence suggests that the use of antimicrobial surfaces in healthcare settings may lead to the selection and spread of antimicrobial resistant strains, through mechanisms like cross-resistance and co-resistance.
- However, there is a lack of studies directly investigating the development of resistance to antimicrobial surfaces in real-world healthcare settings, and more research is needed in this area.
- Future studies on this topic will need to carefully consider various factors that may influence the development of resistance, such as antimicrobial concentrations, biofilm formation, and environmental conditions.

Recent Advances in Antimicrobial Treatments of Textiles - Yuan Gao, Robin Cranston, 2008

Gao, Y., & Cranston, R. (2008). Recent advances in antimicrobial treatments of textiles. *Textile Research Journal, 78*(1), 60–72. https://doi.org/10.1177/0040517507082332

- Antimicrobial treatments can control the negative effects of microbial growth on textiles. Increasing consumer demand for antimicrobial textiles has driven research and development in this area.
- The review covers the requirements for antimicrobial finishing, evaluation methods, application methods, and recent developments in antimicrobial treatments using various active agents.

Antimicrobial Approaches for Textiles: From Research to Market

Morais, D. S., Guedes, R. M., & Lopes, M. A. (2016). Antimicrobial approaches for textiles: From research to market. *Materials, 9*(6), 498. https://doi.org/10.3390/ma9060498

- Explores various antimicrobial agents, including natural compounds (e.g., chitosan), metal-based agents (e.g., silver, copper), and synthetic chemicals, focusing on their effectiveness in disrupting microbial cells or inhibiting biofilm formation.
- Discusses methods to incorporate antimicrobial properties into textiles, such as surface coatings and embedding biocides during fiber extrusion, emphasizing durability and practical applications.
- Highlights challenges in transitioning these technologies to market, including regulatory barriers, cost concerns, and the need for sustainable and safe solutions to meet growing consumer demand for hygienic textiles.

Key findings from selected studies are summarized below:

1) Antimicrobial Surface Mechanisms: Antimicrobial surfaces utilize antifouling, bactericidal, or stimuli-responsive mechanisms, often through physical and chemical modifications such as topography and charge adjustments (Wu et al., 2023; Mahanta et al., 2021). These surfaces are designed to disrupt microbial adhesion, colonization, and biofilm formation.
2) Materials and Innovations: Materials like copper, silver, nanoparticles, and light-activated surfaces (e.g., TiO_2) demonstrate antimicrobial efficacy. Biomimetic surfaces inspired by natural structures, such as insect wings, offer additional promise by using nanoscale topographical interactions to combat pathogens (Muller et al., 2016; Elbourne et al., 2017).
3) Applications in Confined Environments: In aircraft cabins, high microbial loads on seats and lavatories necessitate targeted interventions. Antimicrobial coatings and materials, such as those used in space applications, can reduce pathogen persistence and enhance safety (Paton et al., 2020; Wang et al., 2021).
4) Challenges and Limitations: Long-term efficacy and real-world application remain significant challenges. Issues like cost, durability, and potential resistance development must be addressed through further research and testing (Pietsch et al., 2020; Song et al., 2020).
5) Textile-Specific Developments: Antimicrobial treatments for textiles, including coatings and embedded biocides, are gaining consumer demand but face regulatory and sustainability hurdles (Gao & Cranston, 2008; Morais et al., 2016).
6) Potential Risks: The use of antimicrobial surfaces may inadvertently promote the selection and spread of resistant strains, emphasizing the need for balanced approaches and comprehensive research in diverse environments (Pietsch et al., 2020).

Antimicrobial surface treatments are crucial for reducing microbial contamination and enhancing hygiene in aircraft interiors. Advances in material science, including light-activated and biomimetic surfaces, offer innovative solutions for mitigating pathogen transmission. However, challenges such as resistance development, material durability, and regulatory barriers must be addressed through continued research and collaboration to optimize real-world application.

Passenger behaviour and Pathogen Transmission in Aircraft Cabins (and Airports): Insights from Recent Studies

The aviation industry has undergone significant transformations in the wake of the COVID-19 pandemic, with emerging research shedding light on the intricate interplay between passenger behaviour, safety measures, and technological advancements. As air travel rebounds, understanding these dynamics becomes crucial for ensuring public health resilience and enhancing the overall travel experience.
Recent research highlights the significant impact of hygiene measures, such as mandatory mask-wearing and hand sanitization, on enhancing passenger confidence in air travel. Additionally, the International Air Transport Association (IATA) emphasizes that effectively addressing passenger concerns through comprehensive safety measures is vital for restoring consumer confidence in air travel. Enhanced disinfection protocols and advanced ventilation systems further reduce in-flight virus transmission risks (de Angelis et al., 2020). Mathematical models affirm that widespread facemask use and diligent hand hygiene in airport settings can markedly lower infection probabilities and mitigate disease spread (de Angelis et al., 2020). The pandemic has also spurred the rapid adoption of digital technologies, creating novel avenues for studying technology-driven behavioural changes during global health crises (Yan et al., 2021).

Behavioural Dynamics and Pathogen Transmission in Aircraft Cabins

Passenger behaviour has emerged as a critical determinant in pathogen transmission dynamics within aircraft cabins. Post-pandemic studies reveal how seating adjustments, such as reclining seatbacks, influence airflow patterns and may inadvertently increase longitudinal aerosol dispersion, elevating infection risks. Human movement within the cabin further complicates the transmission landscape. Activities by passengers and crew disrupt airflow, redirecting aerosols toward the cabin floor and reducing deposition rates. However, this dynamic can increase infection risks for mobile individuals, such as crew members (Han et al., 2014). Additionally, lateral air circulation, a hallmark of modern aircraft cabins, allows aerosols smaller than 28 µm to remain airborne for extended durations, amplifying the likelihood of inhalation-based transmission. Contact transmission, in contrast, is estimated to have a significantly lower probability, two orders of magnitude below that of airborne routes (Wan et al., 2009).

Mitigation Strategies: The Role of Masks and Ventilation

The pivotal role of mask usage in reducing transmission risks cannot be overstated. Studies during the COVID-19 pandemic demonstrated that N95 respirators, when properly used, significantly curtailed secondary infections during airborne disease outbreaks. Gupta et al. (2012) found that widespread adoption of masks among passengers substantially reduced transmission rates, providing robust protection, especially in scenarios involving high aerosol generation, such as coughing or speaking.
Optimizing cabin ventilation systems remains a cornerstone of mitigation efforts. While increased airflow rates dilute airborne pathogens and protect passengers near the infection source, they can inadvertently facilitate pathogen dispersion to distant passengers, as observed by Wan et al. (2009). This paradox highlights the need for a balanced approach that integrates ventilation improvements with passenger education on minimizing movement and adhering to hygiene practices.

The COVID-19 pandemic has accelerated the integration of emerging technologies into air travel, fostering innovations that influence passenger behaviour and enhance safety. Automated reminders for mask-wearing and hand hygiene, along with visual cues promoting physical distancing, have been implemented on certain flights to encourage compliance. These measures align with findings that behavioural interventions, when coupled with advanced disinfection and airflow management strategies, can significantly mitigate transmission risks.

The post-pandemic era offers an opportunity to reimagine air travel through the lens of behavioural insights and technological advancements. By combining evidence-based interventions, such as mask usage and optimized ventilation, with innovative digital tools, the aviation industry can effectively address the challenges of airborne disease transmission. These efforts not only safeguard passenger safety but also strengthen public health systems, ensuring resilience in the face of future global crises.

3. Conclusion

The research on pathogen transmission in aircraft cabins has evolved significantly over the past two decades, combining computational fluid dynamics (CFD) models, empirical experiments, and real-world outbreak data to shape infection control strategies. However, despite notable advancements, several critical misconceptions and research gaps still remain, particularly regarding airborne transmission in connection to passenger behaviour and movement and the challenges of real-world implementation of all interconnected aspects. We found one major misconception in early research in related topics about transmission of pathogens in confined spaces, that underestimated long-range airborne transmission risks. Previous studies, especially those conducted before the COVID-19 pandemic, often assumed that airborne diseases such as influenza and tuberculosis only affected passengers within two rows of an infected individual. However, recent studies, particularly those focusing on SARS-CoV-2 transmission, have demonstrated that aerosols can remain suspended in cabin air for extended periods and travel much farther than initially assumed (Olsen et al., 2003; Haddrell et al., 2024; Pang et al., 2021). This new understanding highlights the importance of optimized ventilation strategies and suggests that real-time air quality monitoring could play a valuable role in mitigating in-flight transmission risks. The role of HEPA filtration in reducing airborne pathogens is well-supported by scientific evidence, with modern aircraft ventilation systems achieving up to 99.97% filtration efficiency for particles as small as 0.3 µm (Zhang et al., 2022). However, HEPA filters alone do not eliminate risk, as their effectiveness depends on airflow patterns, passenger movement, and ventilation settings. Periods of reduced airflow, such as during boarding and taxiing, create potential exposure windows that are often overlooked in real world - risk assessments. Optimizing ventilation protocols—such as increasing fresh air intake, ensuring continuous airflow even when the aircraft is on the ground, and supplementing with localized ventilation solutions—can further reduce transmission risks (Webner et al., 2024; Gupta et al., 2012).

Another critical yet understudied area is the role of passenger behaviour in pathogen spread. Research indicates that aisle seat passengers experience higher exposure risks due to frequent movement and proximity to high-touch surfaces (Hertzberg et al., 2018). Similarly, crew members, who interact with multiple passengers, face an increased likelihood of becoming transmission vectors (Mangili et al., 2015). Despite advancements in aircraft design, real-world human movement disrupts airflow models, altering transmission dynamics beyond what computational simulations predict. Integrating behavioural data into future infection risk models will be essential to improve risk assessment accuracy and mitigation strategies.

Surface transmission via fomites, while not the primary driver of respiratory disease spread, remains a concern, particularly for highly persistent pathogens like norovirus (Djebbi-Simmons et al., 2020) and antibiotic-resistant bacteria (Fu et al., 2023). Studies show that high-touch surfaces such as tray tables and lavatory fixtures can become contaminated within hours (Lei et al., 2017; Zhao et al., 2019), necessitating improved cleaning protocols and the development of antimicrobial surface treatments (Mahanta et al., 2021; Wu et al., 2023). While antimicrobial coatings—such as copper, silver, and nanocoatings—show promise in laboratory settings (Paton et al., 2020; Wang et al., 2021), their real-world effectiveness in aircraft cabins remains underexplored, with concerns about durability, cost, and potential antimicrobial resistance selection.

The 2024 WHO list of priority pathogens reinforces the necessity of preemptive research and preparedness strategies tailored to confined environments such as aircraft cabins. The inclusion of Prototype Pathogens as representative research models enables scientists to anticipate pandemic risks more effectively, while Pathogen X highlights the need for continued surveillance of unknown threats. These factors emphasize that the aviation industry must integrate global public health priorities into its risk assessment frameworks and mitigation strategies.

From a technological perspective, UV-C disinfection, far-UVC (222 nm), and electrostatic spraying have emerged as viable supplementary disinfection strategies (Brenner, 2023; DeJohn et al., 2024). Studies confirm that UV-based disinfection can effectively inactivate airborne and surface pathogens when properly integrated. However, concerns regarding material degradation, energy efficiency, and operational feasibility in aviation settings must be resolved before large-scale adoption (Pecho et al., 2020). Electrostatic spraying and chemical disinfectants have also proven effective, but application inconsistencies and airline compliance challenges hinder widespread use (Klaus et al., 2016; Belland et al., 2024).

At a policy level, the absence of standardized global protocols for disinfection, air quality monitoring, and risk assessment presents challenges for uniform implementation across airlines. While regulatory bodies such as EASA, WHO, and IATA have issued guidelines, compliance varies due to economic considerations, operational complexities, and differing national regulations. To ensure both feasibility and effectiveness, guidelines should be designed to align with the industry's operational realities, balancing safety, efficiency, and cost-effectiveness. The already existing studies behind creating safer airplane cabins is strong, with compelling evidence supporting HEPA filtration, optimized ventilation, mask-wearing, as well of suggesting and researching innovative disinfection methods. However, older misconceptions regarding limited airborne transmission persist, despite new findings confirming that aerosols can travel well beyond the traditional two-row guideline. This reinforces the need for a multi-layered infection prevention approach, where ventilation improvements, real-time monitoring, and behavioural interventions complement existing cleaning and filtration measures.

The COVID-19 pandemic accelerated progress in aviation health safety, but without continuous research, policy adaptation, and technological advancements, existing mitigation measures risk becoming outdated. Future efforts must bridge the gap between theoretical models and practical implementation, ensuring that air travel remains not only efficient and sustainable but also a model for public health resilience. By applying the latest scientific insights in a coordinated and standardized manner, the aviation industry can proactively prepare for emerging health threats while ensuring passenger and crew safety.

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Annex A Summarising Tables

A.1 Overview of Emerging Disinfection Technologies for Aircraft Cabins

Method	Key Features	Challenges	References
Far-UVC Technology (222 nm)	Safe for humans and highly effective at inactivating airborne pathogens. Scalable for continuous use in occupied cabins.	Requires proper shielding to avoid overexposure; implementation costs may be high.	Brenner et al. (2023)
UV-C with photocatalysis	Combines UV-C light and photocatalysis to remove volatile organic compounds (VOCs) and pathogens, enhancing air quality.	Dependent on system design and requires energy efficiency optimization; potential long-term maintenance needs.	Gorvel et al. (2014)
Integrated air circuit disinfection	UV-C systems embedded in air circulation reduce airborne viral loads, but challenges include maintenance and material degradation.	Maintenance-intensive; risk of material degradation over time due to UV exposure.	Pecho et al. (2020)
Electrostatic spraying	Offers a cost-effective, scalable solution for large-scale application with minimal waste, provided operators follow best practices.	Requires proper operator training and material compatibility to avoid damage.	DeJohn et al. (2024)

This table summarizes key disinfection methods under consideration for mitigating microbial contamination in aircraft cabins. Each method's primary features, associated challenges, and supporting references are outlined, offering insights into their potential application and limitations within aviation environments. These technologies represent the forefront of innovation aimed at improving air quality, enhancing passenger safety, and reducing pathogen transmission in confined settings.

A.2 Key Considerations and Actions for Disinfection and Cleaning in Aircraft Cabins

Key aspects mentioned in literature	Key Actions suggested in literature	References
Consistency across operations	• Develop SOPs tailored for aircraft configurations. • Use validated methods like UV-C and electrostatic spraying. • Train staff with standardized global protocols.	Klaus et al., 2016
Cost-effectiveness	• Combine UV-C and chemical cleaning to optimize costs. • Implement adaptive schedules based on flight type and contamination risks.	DeJohn et al., 2024; Menzies, 2005
Sustainability	• Use biodegradable disinfectants and energy-efficient systems (e.g., Far-UVC). • Promote durable antimicrobial coatings for high-touch surfaces.	Brenner, 2023; Gorvel et al., 2014; Paton et al., 2020
Monitoring and validation	• Deploy real-time microbial monitoring tools. • Standardize performance metrics for disinfection effectiveness and reapplication intervals.	DeJohn et al., 2024
Dynamic risk-based disinfection	• Adjust cleaning intensity and methods based on passenger density, flight duration, and epidemiological risks.	Menzies, 2005; DeJohn et al., 2024
Innovative technologies	• Use robotic UV-C devices or drones for automated disinfection. • Integrate self-disinfecting materials like copper, silver, or TiO_2 coatings.	Paton et al., 2020; Gorvel et al., 2014; DeJohn et al., 2024
Standardized materials and training	• Standardize globally compatible disinfectants to avoid material damage. • Establish certification programs for cleaning staff. • Validate combined methods (e.g., UV-C, electrostatic spraying) through long-term studies.	Klaus et al., 2016; Adhikari & Clark, 2017

This table provides an overview of critical aspects identified in the literature for effective disinfection in aircraft cabins, along with corresponding recommended actions. It emphasizes consistency in operations, cost-effectiveness, sustainability, monitoring, dynamic risk-based approaches, innovative technologies, and standardized materials and training to enhance safety and mitigate pathogen transmission. These insights aim to guide the aviation industry in implementing robust and efficient disinfection practices.

A.3 Key Pathogens of Concern and Transmission Risks in Aircraft Cabins

Pathogen	Primary Transmission Mode	Risk in Air Travel	Sources from Health Organizations	Sources from Literature about Transmission Modes
SARS-CoV-2 (COVID-19)	Airborne, Droplets, Fomites	High transmission risk especially in crowded cabins, potential for super-spreader events	ECDC Risk Assessment (2020)	ScienceDirect: Transmission of SARS-CoV-2 in air travel (https://www.sciencedirect.com/science/article/pii/S2352710223024828) ScienceDirect: Probability and estimated risk of SARS-CoV-2 transmission in the air travel system https://www.sciencedirect.com/science/article/pii/S1477893921001745#sec3
Influenza (A/B)	Airborne, Droplets	Frequent in-flight outbreaks, risk of seasonal surges	ECDC Communicable Disease Report (2015)	PLOS ONE: In-flight transmission of Influenza (https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0108850)
Measles	Airborne, Droplets	Highly contagious, can infect passengers beyond two-row proximity	ECDC Hajj Risk Assessment (2019)	Wiley: Measles transmission in air travel (https://onlinelibrary.wiley.com/doi/full/10.1155/2023/9353540)
Tuberculosis (TB)	Airborne	Requires prolonged exposure, higher risk in long-haul flights with poor ventilation	WHO Travel and TB Report (2003)	Oxford Academic: TB risk in air travel (https://academic.oup.com/aje/article/177/6/556/160848)

MERS-CoV (Middle East Respiratory Syndrome)	Airborne, Droplets, Fomites	Risk from travel to endemic areas, low but serious transmission potential	ECDC MERS-CoV Update (2013)	PLOS Pathogens: MERS-CoV transmission (https://journals.plos.org/plospathogens/article?id=10.1371/journal.ppat.1004457)
Ebola Virus	Body Fluids, Direct Contact	Low transmission risk in-flight but high mortality; airport screening advised	WHO Ebola Risk Assessment (2022)	ScienceDirect: Ebola virus risks in travel (https://www.sciencedirect.com/science/article/pii/S1879625716301973)
Dengue Virus	Mosquito-borne	Risk of vector introduction via infected travelers; increasing spread	WHO Dengue Travel Risk Report (2003)	NCBI: Dengue virus and travel risks (https://pmc.ncbi.nlm.nih.gov/articles/PMC6086150/)
Norovirus	Fomite, Oral-Fecal	High transmission risk through contaminated surfaces, food, and lavatories	ECDC Norovirus Transmission Report	ScienceDirect: Norovirus transmission risks (https://www.sciencedirect.com/science/article/pii/S1198743X1460361X)
Oropouche Virus	Mosquito-borne	Emerging threat in South America, potential for spread via infected travelers	ECDC Oropouche Virus Report (2024)	ScienceDirect: Oropouche virus travel risks (https://www.sciencedirect.com/science/article/pii/S2667193X24002230)
Lassa Fever	Rodent-borne, Direct Contact	Risk from travelers to endemic areas, requires strict isolation if detected	ECDC Lassa Fever Risk Report (2016)	ScienceDirect: Lassa Fever transmission (https://www.sciencedirect.com/science/article/pii/S037843712200228X)

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