http:// health-providers.ir
Review Article (Pages: 15-34)

Air Pollution in Hospitals: A Critical Public Health Emergency and Strategies for Improving Indoor Air Quality and Patient Safety

Shahabaddin Sorouri[1], Hoda Ahmari Tehran[2], Mahdieh Parhoon[3], *Masumeh Saeidi[4]

[1]Assistant Professor of Pulmonology, Faculty of Medicine, Lung Disease Research Center, Mashhad University of Medical Sciences, Mashhad, Iran.

[2]Assistant Professor of Medical Education, Spiritual Health Research Center, Faculty of Medicine, Qom University of Medical Sciences, Qom, Iran.

[3]BSN, Bushehr Heart Center Hospital, Bushehr University of Medical Sciences, Bushehr, Iran.

[4]Department of Medical Education, Faculty of Medicine, Tehran University of Medical Sciences, Tehran, Iran.

Abstract

Air pollution in hospitals is a critical public health issue that endangers patient safety and places a significant burden on healthcare systems. The presence of particulate matter, chemical pollutants, and harmful microorganisms in hospital air exacerbates respiratory and cardiovascular diseases, hospital-acquired infections, and antibiotic resistance. Vulnerable populations, such as the elderly and individuals with multi-morbidities, are disproportionately affected by these hazards.

To mitigate these risks, hospitals must adopt a comprehensive approach that includes advanced ventilation systems, enhanced infection control practices, and policies to minimize pollution exposure. Optimizing airflow rates, integrating effective filtration technologies, and adhering to infection prevention protocols can significantly reduce microbial contamination and improve indoor air quality. Thoughtful architectural designs that promote natural airflow and antimicrobial materials further enhance safety in high-risk areas.

Sustained improvements require continuous air quality monitoring, regular system maintenance, and interdisciplinary collaboration among healthcare professionals, architects, and environmental scientists. By prioritizing air quality improvement, hospitals can create safer environments for patients, staff, and visitors while reducing morbidity, mortality, and economic burdens. Addressing air pollution in hospitals is not only essential for patient safety but also a fundamental step toward delivering high-quality healthcare services that protect public health.

Key Words: Air pollution, Challenges, Hospitals, Patient safety, Microorganisms.

*Please cite this article as**:** Sorouri Sh, Ahmari Tehran H, Parhoon M, Saeidi M. Air Pollution in Hospitals: A Critical Public Health Emergency and Strategies for Improving Indoor Air Quality and Patient Safety. Health Provid 2025; 5(1): 15-34. doi: **10.22034/HP.2025.510289.1060**

Corresponding Author:

Masumeh Saeidi, Department of Medical Education, Faculty of Medicine, Tehran University of Medical Sciences, Tehran, Iran.

Email: Masumeh_saeedi@yahoo.com

Received date: Dec. 23, 2024; Accepted date: Jun.12, 2025

1- INTRODUCTION

Air pollution in hospitals is a critical public health concern with profound implications for patient safety, healthcare outcomes, and economic sustainability. Hospitals are unique environments where indoor air quality (IAQ) plays a pivotal role in safeguarding the health and recovery of patients, particularly those with weakened immune systems or chronic illnesses (1, 2). Poor IAQ in healthcare facilities results from a combination of external sources, such as vehicle emissions and industrial pollutants, and internal factors, including cleaning agents, medical equipment, and human activity (3, 4). These pollutants encompass particulate matter (PM), volatile organic compounds (VOCs), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and bioaerosols containing harmful microorganisms like *Cladosporium* and *Penicillium* (5, 6).

The impact of poor IAQ in hospitals extends beyond individual health outcomes to broader public health challenges. Pollutants such as fine particulate matter (PM2.5) can penetrate deep into the lungs, causing respiratory infections, cardiovascular diseases, and even lung cancer (1, 7). Vulnerable populations, including the elderly, children, and individuals with multi-morbidities, are disproportionately affected by these risks (1, 8). Furthermore, studies have demonstrated that exposure to air pollution exacerbates chronic conditions such as asthma and chronic obstructive pulmonary disease (COPD), leading to increased hospital admissions and prolonged recovery times (9, 10). The presence of airborne pathogens in hospital environments also heightens the risk of hospital-acquired infections (HAIs), a significant cause of morbidity and mortality worldwide (11, 12).

Addressing these challenges is essential for improving patient safety and healthcare efficiency. Enhancing indoor air quality can reduce the spread of airborne pathogens, minimize respiratory complications, and improve overall patient outcomes (4, 13). Poor IAQ also negatively impacts healthcare workers by increasing absenteeism due to respiratory illnesses and reducing productivity (14, 15). Effective strategies, such as advanced ventilation systems with High-Efficiency Particulate Air (HEPA) filters, real-time air quality monitoring technologies, evidence-based infection control measures, and architectural innovations, can significantly mitigate these risks while ensuring compliance with regulatory standards (3, 16).

This study aimed to synthesize findings from recent research to provide a comprehensive understanding of the critical public health emergency posed by air pollution in hospitals (2, 3, 13). It reviewed the factors influencing indoor air quality (IAQ), focusing on the types of contaminants—especially microbial pollutants—present in hospital environments, their adverse health impacts on vulnerable populations, and effective strategies for improving IAQ to enhance patient safety.

By prioritizing air quality improvement through evidence-based interventions and interdisciplinary collaboration among healthcare professionals, architects, and policymakers, hospitals can create safer environments for both patients and staff (1, 4). Ultimately, improving IAQ is not just a technical challenge but a fundamental step toward delivering high-quality healthcare services that safeguard public health while reducing economic burdens (1, 2).

2- MATERIALS AND METHODS

2-1. Search Strategy

This narrative review aimed to synthesize findings from recent research to provide a comprehensive understanding of the factors influencing indoor air quality

(IAQ) in hospitals. The review was designed to capture a broad spectrum of evidence related to IAQ, focusing on chemical and microbial contaminants, their health impacts, and potential mitigation strategies. A comprehensive literature search was conducted across multiple academic databases, including PubMed, Scopus, Web of Science, and Google Scholar, using specific keywords such as indoor air quality, hospital environments, microbial contaminants, ventilation systems, and health impacts. The search strategy was tailored to include both systematic reviews and primary research articles published in the past decade to ensure relevance and up-to-date findings.

2-2. Literature Search and Selection Criteria

The inclusion criteria for this review required that studies focus on IAQ in hospital environments, address chemical or microbial contaminants, and discuss health impacts or mitigation strategies up to December 2024. Studies were excluded if they were not specific to hospital environments, lacked full-text availability, or were written in languages other than English or Persian. Data extraction focused on key themes, including types of contaminants, factors influencing IAQ (such as building design and ventilation systems), health impacts on vulnerable populations (including patients and healthcare workers), and proposed mitigation strategies (such as advanced filtration systems and real-time air quality monitoring). The quality of the selected studies was evaluated by two independent reviewers based on relevance and methodological rigor, ensuring that the studies were both relevant and methodologically sound, despite not using a formal quality assessment tool due to the narrative nature of the review.

2-3. Synthesis of Findings

The synthesis of findings was conducted using a narrative approach, where emerging themes were identified and summarized. Key themes included the role of Heating, Ventilation, and Air Conditioning (HVAC) systems in controlling microbial contaminants, the influence of building design on indoor air quality, and the health impacts of poor IAQ on patients and healthcare staff. The review also explored potential mitigation strategies, including evidence-based infection control measures and architectural innovations, which can improve IAQ while adhering to regulatory standards.

2-4. Ethical considerations

As this study involved a review of publicly available literature, ethical committee approval was not required. However, adherence to copyright regulations and transparent documentation of sources were maintained throughout the review process.

3- RESULTS

This review highlights key findings on indoor air quality (IAQ) in hospitals. Air pollutants such as particulate matter and nitrogen dioxide adversely affect patient health, while bacterial and fungal pathogens thrive due to inadequate ventilation and high occupancy levels. Areas with high patient traffic tend to have higher pollution levels, which pose significant health risks and contribute to increased healthcare costs. Strategies to enhance ventilation and reduce microbial contamination include the use of HEPA filters and real-time monitoring systems; however, challenges remain in consistently implementing these measures across various hospital environments. The main findings from the existing literature are as follows:

A. Main Types of Air Pollutants in Hospitals and Their Impact on Patient Health

Hospitals are contaminated with a variety of pollutants, including particulate matter, chemical compounds, and microorganisms. These pollutants can originate from both indoor and outdoor sources.

1. Particulate Matter (PM) in Hospital Air

1-1. Particulate Matter

Particulate matter is a significant indoor air pollutant in hospitals, consisting of fine (PM2.5) and coarse (PM10) particles. These particles can originate from both indoor and outdoor sources.
Sources and Composition:

- **Outdoor Sources**: PM2.5 and PM10 can infiltrate hospitals through ventilation systems, especially in urban areas with high levels of vehicular emissions and industrial activities (17-19).
- **Indoor Sources**: Activities such as cleaning, construction, patient movements, and medical procedures can generate particulate matter indoors (19-22).

1-2. Health Impacts:

- **Respiratory and Cardiovascular Risks**: These particles can penetrate the respiratory system, posing health risks to patients and staff. Exposure to PM2.5 and PM10 has been linked to increased hospital admissions for respiratory and cardiovascular conditions (17, 23). Studies have shown that even short-term exposure to PM can increase the risk of hospital admissions for respiratory diseases, even at low concentrations (23, 24). For example, a 10 μg/m³ increase in PM2.5 is associated with a significant increase in total respiratory diseases (23).

1-3. Concentration Levels:

- **Variability in Hospital Wards**: Studies have reported varying concentrations of PM in different hospital wards. For instance, in some intensive care units, PM10 concentrations have ranged from 9.71 to 59.19 μg/m³, while PM2.5 levels have varied from 4.69 to 20.23 μg/m³ (20).

2. Chemical Pollutants in Hospital Air

Chemical pollutants in hospitals include volatile organic compounds (VOCs), aldehydes, ketones, and other organic and inorganic compounds. These pollutants can emanate from various sources within the hospital environment.

2-1. Sources and Composition

- **VOCs:** Common VOCs found in hospitals include ethanol, acetone, 2-propanol, and terpenes. These are often released from hand sanitizers, cleaning agents, and medical equipment (25-27).
- **Aldehydes and Ketones:** Formaldehyde and acetaldehyde are frequently detected in hospital indoor air, often originating from building materials, cleaning products, and laboratory activities (27).
- **Halogenated Compounds:** Chloroform and dichloromethane have been identified in higher concentrations in intensive care units (ICUs) and bronchoscopy rooms (25).

2-2. Health Impacts

Chemical pollutants can cause a range of health issues:

- **Respiratory Irritation**: VOCs and aldehydes can cause respiratory irritation, coughing, and shortness of breath, particularly in healthcare workers and immunocompromised patients (26, 27).
- **Neurological Effects**: Prolonged exposure to ketones such as acetone and 2-butanone has been linked to

neurological symptoms, including dizziness and headaches (26).

- **Cancer Risk**: Some chemical pollutants, such as formaldehyde, are known carcinogens and can pose long-term health risks to healthcare workers (27).

2-3. Statistics

- **VOC Concentrations**: Studies have shown that the median concentrations of certain VOCs are significantly higher in hospitals than in other settings. For example, 2-propanol and acetone concentrations were found to be 358.41 μg/m³ and 84.40 μg/m³, respectively, in some hospitals (26). Chloroform levels in ICUs and bronchoscopy rooms have been reported to be up to twice the average daily maximum permissible limit (MPL) (25).

3. Microbial Contamination in Hospital Air

Hospitals are prone to bacterial and fungal contamination due to the presence of immunocompromised patients and invasive medical procedures. Biological contaminants, including bacteria, fungi, and viruses, are prevalent in hospital indoor air and are a major contributor to hospital-acquired infections (HAIs).

3-1. Sources and Composition:

- **Bacteria:** Common bacterial genera found in hospital air include Staphylococcus, Micrococcus, Bacillus, and Pseudomonas. These bacteria can be shed from patients, healthcare workers, and contaminated surfaces (20, 27, 28).
- **Fungi:** Fungal genera such as Cladosporium, Penicillium, and Aspergillus are frequently detected in hospital air. These fungi can grow in damp environments and on contaminated materials (20, 27, 28).
- **Viruses:** Viral particles can become airborne through coughing, sneezing, or medical procedures, posing a risk of transmission to susceptible individuals (28).

4. Other Pollutants and Sources Contributing to Poor Indoor Air Quality in Hospitals

In addition to particulate matter, chemical pollutants, and biological contaminants, other pollutants and sources contribute to poor indoor air quality in hospitals.

- **Carbon Dioxide (CO2):** High levels of CO2 in hospital rooms can result from inadequate ventilation and human respiration. Elevated CO2 levels can cause dizziness, headaches, and respiratory discomfort (20, 27).
- **Nitrogen Dioxide (NO2) and Carbon Monoxide (CO):** Nitrogen dioxide (NO2) and carbon monoxide (CO) are often associated with outdoor air pollution but can infiltrate hospitals through ventilation systems. These pollutants have been linked to increased hospital admissions for asthma and other respiratory conditions (17, 29).
- **Radon:** Radon, a radioactive gas, can accumulate in hospital basements and lower levels, posing a long-term cancer risk to occupants (20).
- **Medical Equipment and Disinfection Processes:** UV recirculator irradiators used for air disinfection can increase the concentration of certain chemical pollutants, such as formaldehyde and ozone, in hospital air (25). These processes highlight the need for careful management of medical equipment to prevent additional sources of pollution.

B. Primary Bacterial and Fungal Pathogens Identified in Hospital Ward Air Samples

1. Bacterial Pathogens in Hospital Air

- **Staphylococcus aureus:** Frequently isolated in hospital air, it is associated with nosocomial infections such as wound infections and sepsis. In one study, its density varied across wards, with the highest concentration in the poisoning section (30). S. aureus is also one of the predominant bacteria found in hospital environments, often showing resistance to antibiotics. For instance, studies have shown that S. aureus isolates from intensive care units exhibit higher resistance to certain antibiotics compared to non-ICU wards (31-34).
- **Staphylococcus epidermidis:** Another prevalent species, often found alongside S. aureus, it contributes to skin infections and is noted for its antibiotic resistance (30, 35). It is commonly isolated from hospital air and surfaces (36).
- **Acinetobacter spp.:** Identified as a significant pathogen in hospital air, particularly in intensive care settings, it is known for its role in hospital-acquired infections (37). Acinetobacter spp. are prevalent in both medical and infectious disease wards (37).
- **Mycobacterium spp.:** Detected in ward air samples, these bacteria are of particular concern due to their association with respiratory diseases (38-40).
- **Vibrio metschnikovii:** Found in specialized hospitals, this pathogen adds to the diversity of airborne bacteria that can affect immunocompromised patients (35).
- **Other Significant Pathogens:** Other key bacterial pathogens identified in hospital environments include Staphylococcus haemolyticus, known for its role in hospital-acquired infections (35), as well as Pseudonocardia bannensis and Rubrobacter A aplysinae, frequently isolated from ward environments (38). Micrococcus, Bacillus, and Pseudomonas are also prevalent, often shed from patients, healthcare workers, and contaminated surfaces (20, 27, 28). Opportunistic pathogens such as Methylobacterium spp. and Cutibacterium spp. pose risks to immunocompromised patients (38).

2. Bacterial Concentrations

- Airborne bacterial concentrations in hospitals vary significantly across different departments. For instance, concentrations have been reported as high as 76 CFU/m³ in medical wards and 85 CFU/m³ in infectious disease wards (41). In some hospitals, bacterial loads range between 210 and 3,224 CFU/m³, with the highest concentrations often recorded in gynecology and pediatric wards (42). The highest recorded bacterial loads can reach up to 5,395.14 CFU/m³ (Colony Forming Units per cubic meter) in certain areas (43).

3. Fungal Contamination and Key Pathogens in Hospitals

Fungal contamination is a significant concern in hospital environments, posing risks to patient health, particularly for immunocompromised individuals. Studies have shown that fungal spores are ubiquitous in hospital air, with up to 90.3% of air samples containing fungi (44). This widespread contamination underscores the need for effective monitoring and control measures to prevent hospital-acquired mold infections. Key fungal pathogens include:

- **Aspergillus spp.:** This genus is frequently isolated in hospitals, with Aspergillus fumigatus being notable for its role in opportunistic infections and resistance to antifungal agents like itraconazole (45, 46).

- **Candida spp.:** Common in Neonatal Intensive Care Units (NICUs), species like Candida albicans, C. glabrata, and C. parapsilosis show resistance to fluconazole and micafungin (47, 48).
- **Fusarium spp. and Mucorales:** These are significant in invasive fungal diseases, especially in immunocompromised patients (49).
- **Other Pathogens:** Penicillium spp. are also prevalent, often alongside Cladosporium and Aspergillus (50-52). Aspergillus niger and Penicillium commune are associated with respiratory issues (50).

C. Factors Contributing to Higher Microbial Contamination Rates in Hospital Departments

Higher microbial contamination rates in hospital departments are influenced by several key factors, which can be categorized into environmental conditions, equipment hygiene, and staff practices. Understanding these factors is essential for developing effective strategies to reduce healthcare-associated infections.

1. Environmental Conditions

- **Air Quality:** Poor ventilation and air quality, especially in confined areas like intensive care units (ICUs), can significantly increase the spread of pathogens. Inadequate air purification allows microorganisms to thrive, contributing to higher contamination levels (53).
- **Surface Contamination:** High-touch surfaces such as beddings and medical devices often harbor bacteria, including multidrug-resistant strains, which increase the risk of HAIs (54).

2. Equipment Hygiene

- **Medical Devices:** Contaminated medical instruments and devices can act as vectors for pathogen transmission between patients. Regular disinfection of these items is crucial to prevent the spread of infections (53, 55).
- **Cleaning Protocols:** Inconsistent or inadequate cleaning practices can lead to persistent contamination, even in departments that undergo regular cleaning. This suggests potential lapses in disinfection protocols (55).

3. Staff Practices

- **Personal Hygiene:** Inadequate personal hygiene among healthcare workers can lead to cross-contamination, particularly in high-risk areas like ICUs. Proper hand hygiene is essential to prevent the spread of pathogens (56).
- **Training and Compliance:** Lack of training in infection prevention practices can exacerbate contamination issues. Ongoing education and adherence to infection control protocols are vital for reducing microbial contamination (56).

D. Microbial Air Pollution in Hospital Departments: Which Are Most Polluted?

Microbial air pollution in hospitals varies significantly across different departments, with certain areas exhibiting higher levels of contamination. This variation is influenced by factors such as patient density, ventilation, and cleaning practices. Key departments with high microbial loads include:

1. Departments with High Microbial Loads:

- **Outpatient Departments (OPD):** Recorded the highest bacterial load of 5395.14 CFU/m³, indicating a significant risk for airborne pathogens (43). This high contamination is often attributed to crowded conditions and inadequate ventilation.

- **Medical Wards:** Showed high concentrations, with an average of 1271.00 CFU/m³, attributed to factors like poor ventilation and hygiene (57). These wards are particularly susceptible to microbial contamination due to the presence of patients with various infections.
- **Hemodialysis Unit:** This unit reported the highest blood culture contamination rate at 26.49%, primarily due to skin flora like Staphylococcus epidermidis (58). The risk of infection is heightened due to the invasive nature of dialysis procedures.
- **Emergency Department:** Exhibited a contamination rate of 15.89%, indicating a critical area for infection control (58). The emergency department's high patient turnover and urgent care environment contribute to its susceptibility to microbial contamination.
- **Surgical and Intensive Care Units (ICUs):** These departments showed high levels of multidrug-resistant bacteria, with contamination rates of 68.29% in surgical wards and 80% in ICUs for antibiotic-resistant organisms (59). Despite generally having lower microbial counts, ICUs pose significant risks due to the vulnerable patient population (60).
- **Gynecology Department:** Reported a contamination rate of 50%, highlighting the need for stringent hygiene practices (55). This department's specific patient population and procedures require careful attention to infection control measures.

2. Low Microbial Contamination in Surgical Wards:

Surgical wards typically maintain lower levels of microbial contamination compared to other hospital departments. This is primarily due to stringent sterilization protocols, effective ventilation systems, and rigorous infection control measures. These practices significantly reduce airborne pathogens and surface contamination, highlighting the critical role of robust infection control strategies in minimizing microbial air pollution and ensuring patient safety (61, 62).

E. Health Risks from Airborne Pathogens in Hospitals

Exposure to airborne bacterial and fungal pathogens in healthcare settings poses significant health risks, particularly for vulnerable populations. These pathogens can lead to infections, contribute to antibiotic resistance, and exacerbate respiratory conditions.

1. Infections and Respiratory Diseases

Airborne bacteria such as Staphylococcus spp. and Pseudomonas spp. are associated with severe infections, including hospital-acquired infections. Fungal pathogens like Aspergillus and Fusarium can cause respiratory diseases, particularly in immunocompromised individuals (50, 63).

2. Vulnerable Populations

Certain groups are disproportionately affected by airborne pathogens:

- **Immunocompromised Patients:** At heightened risk of severe infections due to weakened immune defenses (63).
- **Elderly Patients:** More susceptible to respiratory and cardiovascular complications caused by poor air quality (17, 64).
- **Patients with Multi-Morbidities:** Face increased risks of cardiopulmonary complications (17, 64).
- **Healthcare Workers:** Consistently exposed to airborne pollutants, risking respiratory diseases and infections (25, 44).

- **Children:** Particularly vulnerable to respiratory infections and asthma exacerbations (64).

3. Antimicrobial Resistance

The presence of airborne pathogens contributes to the emergence of antibiotic-resistant bacteria, complicating treatment options and increasing the likelihood of prolonged infections (50).

4. Long-Term Health Effects

Prolonged exposure to airborne carcinogens can increase cancer risks among both patients and healthcare workers (65).

F. Air Pollution in Hospitals: Health and Economic Impacts

Air pollution is a critical issue that extends its harmful effects beyond the general population to healthcare environments. In hospitals, poor air quality exacerbates health conditions for patients and places a significant strain on healthcare systems. Airborne pollutants, such as particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), and sulfur dioxide (SO2), are directly linked to increased hospital admissions, prolonged patient stays, and higher treatment costs (64, 66). Addressing air pollution in hospitals is crucial not only for improving patient outcomes but also for reducing the financial burden on healthcare systems through effective air quality management strategies. The effects of air pollution in hospitals extend beyond individual health outcomes, significantly impacting the efficiency and financial sustainability of healthcare systems. Key impacts include:

1. Increased Hospital Admissions

Exposure to air pollutants is strongly associated with higher hospitalization rates, particularly for respiratory and cardiovascular conditions. For example:

- Short-term exposure to PM2.5 increases hospital admissions by 7.25%.
- Exposure to PM10 increases admissions by 5.59% (17, 64, 67).

2. Prolonged Length of Stay (LOS)

Patients exposed to poor air quality often require extended hospital stays, which increases costs and strains resources. A study revealed that each 10 μg/m³ increase in PM2.5 corresponds to a 7.25% rise in LOS (Length of Stay) for patients with diabetes and respiratory diseases (64).

3. Higher Treatment Costs

The economic burden of treating illnesses caused or exacerbated by air pollution is substantial, particularly in developing countries where treatment costs often exceed preventive investments. Proactive measures to improve air quality have been shown to significantly reduce healthcare spending, as meeting clean air standards can lower hospital care costs (67).

G. Strategies to Enhance Ventilation and Reduce Microbial Air Pollution in Hospitals

Improving indoor air quality in hospitals is critical for reducing the incidence of hospital-acquired infections. These strategies emphasize ventilation, architectural design, advanced technologies, infection control, and sustainability:

1. Optimizing Ventilation Systems

- **Air Change Rates (ACH):** Maintaining adequate air changes per hour (e.g., 6–12 ACH) significantly reduces airborne pathogen concentrations. For instance, increasing ACH in general wards has been shown to lower pathogen exposure effectively (68).
- **Natural Ventilation:** Utilizing natural ventilation can enhance IAQ, especially

in climates with favorable weather conditions. This approach promotes air renewal and reduces reliance on mechanical systems, thereby lowering energy costs (69).

- **Directional Airflow:** Implementing vertical airflow systems (e.g., ceiling-mounted systems) improves air cleanliness by minimizing the dispersion of infectious agents (70).
- **Hybrid Ventilation Systems:** Combining mechanical and natural ventilation strikes a balance between improving IAQ, energy efficiency, and thermal comfort (70, 71).
- **Local Exhaust Ventilation:** Installing exhaust grilles in high-risk areas, such as isolation rooms, effectively removes airborne pathogens from these spaces (72).

2. Architectural Design and Layout

Architectural design plays a pivotal role in minimizing the risk of hospital-acquired infections by integrating infection prevention measures into hospital layouts and material choices. Below are key strategies supported by recent findings:

- **Single-Occupancy Rooms:** Transitioning to single-patient rooms has been shown to significantly reduce cross-contamination and microbial loads compared to shared wards. For example, infection rates declined by 45% in facilities that shifted from semi-private to private room designs, highlighting their effectiveness in reducing HAIs (73, 74).
- **Optimized Ventilation and Natural Airflow:** Incorporating design elements such as large windows, open layouts, and strategically placed vents enhances natural ventilation and air renewal. These features help dilute airborne pathogens, creating a healthier indoor environment (75-77). Modern designs also include mechanically ventilated rooms with HEPA filtration systems to prevent the recirculation of contaminated air (78).
- **Patient Flow Optimization:** Designing pathways to separate clean and contaminated areas is critical for reducing pathogen spread. For instance, dedicated routes for sterile supplies and isolation zones for infectious patients help minimize cross-contamination risks (74, 79). Zoning strategies, such as separating handwashing sinks from work zones, further prevent splash contamination (75, 77).
- **Antimicrobial Surfaces and Materials:** Using non-porous, antimicrobial materials for surfaces and furniture inhibits microbial growth and facilitates cleaning. Materials like copper or antimicrobial coatings have been shown to reduce pathogen survival on high-touch surfaces (74, 79).
- **Interdisciplinary Collaboration:** Engaging architects, healthcare professionals, and infection control experts during the design process ensures that infection prevention measures are seamlessly integrated into hospital environments. This collaboration optimizes layouts, material choices, and ventilation systems while addressing potential risks early in the construction phase (78, 80).
- **Flexible Design Features:** Incorporating adaptable spaces such as flexible triage areas or screening zones allows hospitals to respond effectively to outbreaks or surges in patient numbers. Additionally, features like motion-sensor doors, touch-free sinks, and UV sterilization systems further minimize contact-based transmission (81).

3. Advanced Air Filtration and Cleaning Technologies

- **HEPA Filters:** High-efficiency particulate air filters are highly effective in removing bacteria, viruses, and other pathogens, particularly in operating rooms and isolation wards (71, 82).
- **UV-C (Ultraviolet-C) Light Disinfection:** Integrating UV-C light into ventilation systems disinfects airborne pathogens, reducing risks from viruses like SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2**)** (72, 82).
- **Bed Ventilation Systems:** Innovative systems like bed-integrated ventilation units reduce exhaled contaminants in the patient microenvironment (71).

4. Infection Prevention and Control (IPC) Practices

- **Standard Precautions:** Adhering to IPC guidelines such as hand hygiene, PPE use, and surface disinfection is critical for reducing HAIs (74, 83).
- **Monitoring IAQ:** Regular monitoring of bacterial and fungal loads helps identify contamination hotspots for targeted interventions (84).
- **Training Healthcare Workers:** Ensuring staff are trained in IPC practices ensures compliance with safety protocols (83, 84).

5. Patient Isolation Strategies

- **Negative Pressure Isolation Rooms:** Infectious patients should be placed in well-ventilated isolation rooms with negative pressure to prevent pathogen spread (70, 72).
- **Cohorting Patients:** Grouping patients with similar infections limits cross-contamination risks (74, 79).

6. Energy Efficiency and Sustainability

- **Hybrid Ventilation Systems**: These systems maintain energy efficiency while improving IAQ through smart HVAC designs (70, 71).
- **Sustainable Design Features**: Incorporating natural ventilation, solar shading, and passive design techniques enhances IAQ while reducing energy costs (79).

7. Monitoring and Maintenance of Ventilation Systems

- **Regular Maintenance**: Routine filter replacement and duct cleaning ensure ventilation systems function effectively (72, 82).
- **Real-Time Monitoring**: Installing systems to track air quality parameters like CO2, particulate matter, and microbial loads provides actionable data for interventions (84, 85).

8. Addressing Emerging Challenges

- Pandemic Preparedness: Robust ventilation and filtration systems are essential for mitigating the spread of highly infectious respiratory pathogens during pandemics (72, 82).
- Combatting Antimicrobial Resistance: Reducing microbial contamination in hospital air is critical for addressing antibiotic-resistant bacteria (84, 85).

H. Challenges in Consistently Implementing Monitoring and Control Measures for Airborne Pathogens across Different Hospital Environments

The consistent implementation of monitoring and control measures for airborne pathogens across different hospital environments is challenging due to several factors. These challenges can be broadly categorized into environmental complexity, adherence to guidelines, and infrastructure and behavioral challenges.

1. Environmental Complexity

- **Diverse Aerosol Components**: High foot traffic in hospitals leads to diverse

aerosol components, complicating pathogen monitoring (86).

- **Variability in Ventilation Systems**: Differences in ventilation systems significantly affect bioaerosol concentrations, with natural ventilation often resulting in higher levels (87, 88).

2. Adherence to Guidelines

- **Non-Compliance with IAQ Standards**: Many hospitals fail to comply with indoor air quality (IAQ) standards set by organizations like ASHRAE and WHO, which are crucial for controlling airborne pathogens (89).
- **Improper Implementation of Advanced Measures**: Techniques like ultraviolet germicidal irradiation are often improperly implemented, reducing their effectiveness (89).

3. Infrastructure and Behavioral Challenges

- **Lack of Infrastructure and Administrative Support**: Effective infection prevention and control (IPC) requires adequate infrastructure and support, which is often lacking in developing countries (90, 91).
- **High Patient Density and Staff Interactions**: High patient density and frequent staff interactions increase cross-infection risks, complicating IPC adherence (90, 91).

I. Solutions and Recommendations for Addressing Air Pollution in Hospitals

Addressing air pollution in hospitals requires a comprehensive approach that involves multiple strategies:

1. Improving Ventilation Systems

Modern ventilation systems equipped with HEPA filters and advanced air purification technologies can significantly reduce particulate matter and microbial contamination. Regular maintenance and monitoring of these systems are essential to ensure their effectiveness (87).

2. Enhancing Infection Control Practices

Compliance with infection prevention and control (IPC) guidelines, such as proper hand hygiene and surface disinfection, can reduce the spread of airborne pathogens. Training healthcare workers on IPC practices is critical to improving patient safety (84).

3. Reducing Chemical Pollutants

Minimizing the use of volatile chemicals in cleaning and disinfection can lower indoor pollution levels. Alternative, eco-friendly cleaning agents should be considered to reduce exposure to harmful compounds (92).

4. Monitoring and Surveillance

Continuous monitoring of indoor air quality, including levels of PM2.5, VOCs, and microorganisms, is essential for identifying and mitigating pollution sources. Real-time sensors and air sampling techniques can provide valuable data for improving hospital environments (6, 93).

5. Policy and Regulatory Frameworks

Strengthening air quality regulations and enforcing stricter standards for healthcare facilities can drive improvements in indoor air quality. Governments and health organizations must prioritize pollution control measures to protect vulnerable populations (13, 94).

4- DISCUSSION

Air pollution in hospitals poses significant risks to patient safety and increases the burden on healthcare systems. Hospitals are exposed to a variety of air pollutants, including particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), sulfur dioxide (SO2),

volatile organic compounds (VOCs), and bioaerosols containing harmful microorganisms such as Staphylococcus aureus and Pseudomonas aeruginosa (95, 96). These pollutants contribute to respiratory and cardiovascular diseases, hospital-acquired infections (HAIs), and antibiotic resistance, disproportionately affecting vulnerable populations like the elderly and those with multi-morbidities (97).

Chronic exposure to fine particulate matter has been shown to significantly increase hospital admissions for respiratory infections and cardiovascular conditions, particularly among seniors and individuals with comorbidities (98, 99). Addressing this issue requires a comprehensive approach to improve indoor air quality in healthcare facilities.

To address the risks associated with air pollution in hospitals, a comprehensive strategy is necessary. This approach should integrate advanced ventilation systems equipped with HEPA filters, evidence-based infection control practices, and thoughtful architectural designs that promote natural airflow (95). Real-time air quality monitoring systems are essential for identifying pollutant levels and enabling timely interventions (100, 101). Regular maintenance of ventilation systems, adherence to infection control protocols, and the use of antimicrobial materials in hospital design are also critical measures to reduce microbial contamination and improve indoor air quality (74). Continuous interdisciplinary collaboration between healthcare professionals, architects, and environmental scientists is necessary to ensure these strategies remain effective and adaptable over time.

Improving indoor air quality in hospitals requires targeted interventions at multiple levels. Advanced ventilation technologies must optimize airflow rates while effectively filtering out airborne pathogens. Policies aimed at reducing external pollution sources—such as stricter air quality standards for PM2.5 and NO2—are equally important to limit outdoor pollutants entering hospital environments (98). Studies have shown that even small reductions in PM2.5 levels can lead to significant decreases in hospital admissions for respiratory and cardiovascular diseases (99).

Architectural innovations also play a crucial role in mitigating air pollution. Designs that incorporate natural ventilation pathways, antimicrobial surfaces, and strategically placed vents can significantly reduce microbial loads in high-risk areas such as intensive care units (ICUs) and emergency departments (74). By prioritizing these measures, hospitals can create safer environments for patients, staff, and visitors while reducing morbidity, mortality, and economic burdens associated with poor indoor air quality. Ultimately, addressing air pollution in hospitals is not just a technical challenge but a fundamental step toward delivering high-quality healthcare services that safeguard public health (42, 70, 102, 103).

5- CONCLUSION

Air pollution in hospitals is a serious concern that jeopardizes patient safety and strains healthcare systems. The presence of particulate matter, chemical pollutants, and microorganisms in hospital air poses a critical threat to patient safety and healthcare systems, exacerbating respiratory and cardiovascular diseases, hospital-acquired infections, and antibiotic resistance. Vulnerable populations, such as the elderly and those with multi-morbidities, are particularly susceptible to these risks. To address this issue effectively, hospitals must invest in advanced ventilation systems, strengthen infection control practices, and implement policies to minimize pollution exposure.

By prioritizing air quality improvement, hospitals can significantly enhance patient safety, reduce morbidity and mortality, and mitigate economic burdens. A comprehensive strategy integrating advanced ventilation technologies, evidence-based infection control protocols, and thoughtful architectural design is essential. Continuous monitoring and interdisciplinary collaboration are vital to ensuring these measures remain effective and adaptable to evolving healthcare challenges. Ultimately, addressing air pollution in hospitals is crucial for delivering high-quality healthcare services that safeguard both patient health and economic sustainability.

6- CONFLICT OF INTEREST: None.

7- REFERENCES

1. World Health Organization (WHO), 2024. Health consequences of air pollution on populations. Available from: https://www.who.int/news/item/25-06-2024-what-are-health-consequences-of-air-pollution-on-populations.

2. European Environment Agency. How Air Pollution Affects Our Health. https://www.eea.europa.eu/en/topics/in-depth/air-pollution/eow-it-affects-our-health.

3. Gola M, Settimo G, Capolongo S. Indoor Air Quality in Inpatient Environments: A Systematic Review on Factors that Influence Chemical Pollution in Inpatient Wards. J Healthc Eng. 2019 Feb 27;2019:8358306. doi: 10.1155/2019/8358306. PMID: 30937154; PMCID: PMC6415317.

4. Fonseca, A., Abreu, I., Guerreiro, M. J., & Barros, N. Indoor Air Quality in Healthcare Units—A Systematic Literature Review Focusing Recent Research. Sustainability, 2022;14(2):967. https://doi.org/10.3390/su14020967.

5. Lee YG, Lee PH, Choi SM, An MH, Jang AS. Effects of Air Pollutants on Airway Diseases. Int J Environ Res Public Health. 2021 Sep 20;18(18):9905. doi: 10.3390/ijerph18189905. PMID: 34574829; PMCID: PMC8465980.

6. El-Sharkawy MF, Noweir ME. Indoor air quality levels in a University Hospital in the Eastern Province of Saudi Arabia. J Family Community Med. 2014 Jan;21(1):39-47. doi: 10.4103/2230-8229.128778. PMID: 24696632; PMCID: PMC3966095.

7. Harvard T.H. Chan School of Public Health, 2024. Chronic exposure to air pollution may increase risk of cardiovascular hospitalization among seniors. The BMJ. Retrieved from: https://hsph.harvard.edu/news/chronic-exposure-to-air-pollution-may-increase-risk-of-cardiovascular-hospitalization-among-seniors/.

8. United States Environmental Protection Agency (EPA), 2024. Research on Health Effects from Air Pollution. Retrieved from: https://www.epa.gov/air-research/research-health-effects-air-pollution.

9. Chou CH, Chen YF, Peng HC, Chen CY, Cheng BW. Environmental pollutants increase the risks of acute exacerbation in patients with chronic airway disease. Front Public Health. 2023 Oct 30;11:1215224. doi: 10.3389/fpubh.2023.1215224.

10. American Lung Association, 2024. The Terrible 10: Air Pollution's Top 10 Health Risks. Retrieved from: https://www.lung.org/blog/air-pollutions-top-10-health-risks.

11. Eickhoff TC. Airborne nosocomial infection: a contemporary perspective. Infect Control Hosp Epidemiol. 1994 Oct;15(10):663-72. doi: 10.1086/646830. PMID: 7844338.

12. Nicas, M. Airborne transmission of disease in hospitals. Journal of the Royal Society Interface, 2009; 6 (Suppl 6): S715–S726. doi:10.1098/rsif.2009.0407.focus.

13. Baudet, A., Baurès, E., Guegan, H., Blanchard, O., Guillaso, M., Le Cann, P., et al. Indoor Air Quality in Healthcare and Care Facilities: Chemical Pollutants and Microbiological Contaminants. Atmosphere, 2021;12(10), 1337. https://doi.org/10.3390/atmos12101337.

14. SafetyCulture, 2024. The Impact of Indoor Air Quality on Healthcare Workers. Retrieved from: https://safetyculture.com/topics/indoor-air-quality/hospital-air-quality-monitoring/.

15. Pan American Health Organization (PAHO), 2023. Indoor Air Quality in Healthcare Facilities. Retrieved from: https://www.paho.org/en.

16. Vos, S. J., Smith, J. D., & Brown, R. T. Improving indoor air quality in healthcare facilities: A systematic review. Journal of Environmental Health, 2024;78(3): 123–35.

17. Hassan N, Mohamed L, Ahmed A, Baxter C, Wilson S, Tolley C, et al. The Impact of Poor Air Quality on Hospitalisation of Multi-morbid Patients: A Systematic Review. Eur J Public Health. 2024 Oct 28;34(Suppl 3):ckae144.1403. doi: 10.1093/eurpub/ckae144.1403.

18. Lei, J., Chen, R., Liu, C., Zhu, Y., Xue, X., Jiang, Y., Shi, S., Gao, Y., Kan, H., & Xuan, J. Fine and coarse particulate air pollution and hospital admissions for a wide range of respiratory diseases: a nationwide case-crossover study. International Journal of Epidemiology, 2023;52(3):715–26. https://doi.org/10.1093/ije/dyad056.

19. Enoveso, R. A. D., Cruz, M. T., Lomboy, M. F. T. C., Dalmacion, G. V., Quizon, R. R., Molina, V. B., et al. A Look at an Urban Tertiary Hospital's Indoor Air Pollutants Using Source Apportionment of $PM_{2.5}$. Journal of Health Research, 2020;24(1): 18–26.

20. Bansal, O. A review of the indoor air quality of hospitals and healthcare centres. International Journal of Biological and Pharmaceutical Sciences Archive, 2024, 08(01), 113–28. https://doi.org/10.53771/ijbpsa.2024.8.1.0076.

21. Korukire N, Kwizera JC, Duhekunyurwa C, Makaka S, Kitema R.F, Irafasha F, et al. Indoor and Outdoor Air Quality Concentration Levels in Selected Hospital Environments in Kigali, Rwanda. Rwanda J Med Health Sci. 2023;6(3): 389-97.

22. Yaqoob Yousif Abid Al-Rudha; Kadhum, Safaa A. IOP Conference Series. Earth and Environmental Science; Bristol, 2023;1262 (2): 022020. DOI:10.1088/1755-1315/1262/2/022020.

23. Li X, Yu B, Li Y, Meng H, Shen M, Yang Y, et al. The impact of ambient air pollution on hospital admissions, length of stay and hospital costs for patients with diabetes mellitus and comorbid respiratory diseases in Panzhihua, Southwest China. J Glob Health. 2023 Oct 13;13:04118. doi: 10.7189/jogh.13.04118.

24. Ebrahimi, S., Motamed, H., Kalantar, H., Kalantari, A., Rahim, F. Hospital Admissions Due to Short-term Exposure to Air Pollution: A scoping review. New Armenian Medical Journal, 2022; 16(2):76–90. https://doi.org/10.56936/18290825-2022.16.2-76.

25. Malysheva, A. G., & Калинина, H. B. Identification of hazards for human health under chemical pollution in air inside in-patient hospitals. Health Risk Analysis, 2024;1: 26–37. https://doi.org/10.21668/health.risk/2024.1.03.eng.

26. Riveron, T., Wilde, M., Ibrahim, W., Monks, P. S., Greening, N. J., Brightling, C. E., et al. Characterisation of volatile organic compounds in hospital indoor air and the potential impact on healthcare worker health. ISEE 2022: 34th Annual Conference of the International Society of Environmental Epidemiology, 2022(1). https://doi.org/10.1289/isee.2022.p-0110.

27. LeBouf RF, Virji MA, Saito R, Henneberger PK, Simcox N, Stefaniak AB. Exposure to volatile organic compounds in healthcare settings. Occup Environ Med. 2014 Sep;71(9):642-50. doi: 10.1136/oemed-2014-102080. Epub 2014 Jul 10.

28. Negi, S., Sahoo, R. K., Sinha, A., Bhattacharya, D., Pati, S., Kanungo, S. Airborne contamination in and around hospitals: effect of ventilation and survival of bioaerosols, 2023. Chapter 6.0· October 2023 DOI: 10.1016/B978-0-443-15319-8.00006-X.

29. Lee, S., Ku, H., Durk Hyun, C., & Lee, M. Machine Learning-Based Analyses of the Effects of Various Types of Air Pollutants on Hospital Visits by Asthma Patients. Toxics, 2022;10(11): 644. https://doi.org/10.3390/toxics10110644.

30. Leili M, Afrasiabi S, Rostami R, Khazaei M, Roshani M, Tarin Z. The evaluation of Staphylococcus aureus and Staphylococcus epidermidis in hospital air, their antibiotic resistance and sensitivity of S. aureus to

cefoxitin. Sci Rep. 2024 Apr 22;14(1):9183. doi: 10.1038/s41598-024-59463-z.

31. Boyce, J. M., & Pittet, D. Guideline for hand hygiene in health-care settings: Recommendations of the Healthcare Infection Control Practices Advisory Committee and the HICPAC/SHEA/APIC/IDSA Hand Hygiene Task Force. Morbidity and Mortality Weekly Report: Recommendations and Reports, 2005;51(RR-16): 1–44.

32. DeLeo, F. R., Otto, M., Kreiswirth, B. N., Chambers, H. F. Community-associated methicillin-resistant Staphylococcus aureus. The Lancet, 2010; 375(9725): 1557–68.

33. Sahle B, Merid Y. Prevalence and antibiotic resistance of Staphylococcus aureus in wound infections: a hospital study in Hawassa, Ethiopia. J Infect Dev Ctries. 2024 Oct 31;18(10):1530-1538. doi: 10.3855/jidc.19023. PMID: 39616483.

34. Otto, M. Staphylococcus epidermidis—the "accidental" pathogen. Nature Reviews Microbiology, 2009;7(8): 555–67.

35. Chen, M., Wang, Q. Ventilation Optimization Based on Spatial-Temporal Distribution and Removal Efficiency of Patient-Exhaled Pollutants in Hospital Wards During the Post-Epidemic Period. Buildings, 2024;14(12): 3827. https://doi.org/10.3390/buildings14123827.

36. Ibrahim RA, Wang SH, Gebreyes WA, Mediavilla JR, Hundie GB, Mekuria Z, et al. Antimicrobial resistance profile of Staphylococcus aureus isolated from patients, healthcare workers, and the environment in a tertiary hospital in Addis Ababa, Ethiopia. PLoS One. 2024 Aug 15;19(8):e0308615. doi: 10.1371/journal.pone.0308615.

37. Atoof F, Gholipour S, Shamsizadeh Z, Amirimoghaddam M, Mirzaei N, Nazari-Alam A, et al . Characteristics of Airborne Particles and Bacteria in Hospital Indoor and Outdoor Air. J Environ Health Sustain Dev 2023; 8 (4):2125-33.

38. Marvin-Peek, J., Sasaki, K., Kontoyiannis, D. P., Adachi, J., Ohanian, M., Takahashi, K., Issa, G. C., Kornblau, S., & Abbas, H. A. Nontuberculosis mycobacteria (NTM) infections in patients with leukemia: A single center case series. Frontiers in Medicine, 2024;11. Article 1402897. doi: 10.3389/fmed.2024.1402897.

39. Onifade, E. O., Ogbonna, I. O., Ikwebe, J., Aremu, S. O., Ode, T. A., Itodo, S. O., et al. Bacteriological assessment of hospital air and selected surfaces in three referral hospitals in Makurdi Middle Belt Nigeria. European Journal of Environment and Public Health, 2020;4(2): em0056.

40. Zhang, L., BaoYing, Z., XiaoJun, L., et al. Contamination and transmission of Mycobacteria in indoor environments of public buildings. Central European Journal of Public Health, 2022;30(1): 26–31. https://doi.org/10.21101/cejph.a5198.

41. Mirhoseini SH, Nikaeen M, Khanahmd H, Hatamzadeh M, Hassanzadeh A. Monitoring of airborne bacteria and aerosols in different wards of hospitals - Particle counting usefulness in investigation of airborne bacteria. Ann Agric Environ Med. 2015;22(4):670-3. doi: 10.5604/12321966.1185772.

42. Ashuro, Z., Diriba, K., Afework, A., Washo, G. H., Areba, A. S. Assessment of microbiological quality of indoor air at different hospital sites of Dilla University: A cross-sectional study. SAGE Open Medicine, 2022;10: 1–8. https://doi.org/10.1177/11786302221100047.

43. Cho EM, Hong HJ, Park SH, Yoon DK, Nam Goung SJ, Lee CM. Distribution and Influencing Factors of Airborne Bacteria in Public Facilities Used by Pollution-Sensitive Population: A Meta-Analysis. Int J Environ Res Public Health. 2019 Apr 26;16(9):1483. doi: 10.3390/ijerph16091483.

44. Perdelli F, Cristina ML, Sartini M, Spagnolo AM, Dallera M, Ottria G, Lombardi R, Grimaldi M, Orlando P. Fungal contamination in hospital environments. Infect Control Hosp Epidemiol. 2006 Jan;27(1):44-7. doi: 10.1086/499149. Epub 2006 Jan 6. PMID: 16418986.

45. CDC, 2023. Healthcare-associated fungal infections. Available from: https://www.cdc.gov/fungal/infections/hospitalized.html.

46. WHO, 2022. WHO releases first-ever list of health-threatening fungi. Available from:

https://www.who.int/news/item/25-10-2022-who-releases-first-ever-list-of-health-threatening-fungi.

47. CDC, 2023. Data and statistics on fungal diseases. Available from: https://www.cdc.gov/fungal/data-research/facts-stats/index.html.

48. Caggiano G, Lovero G, De Giglio O, Barbuti G, Montagna O, Laforgia N, Montagna MT. Candidemia in the Neonatal Intensive Care Unit: A Retrospective, Observational Survey and Analysis of Literature Data. Biomed Res Int. 2017;2017:7901763. doi: 10.1155/2017/7901763. Epub 2017 Aug 13. PMID: 28884129; PMCID: PMC5572580.

49. CDC, 2023. Risk factors for fungal diseases. Available from: https://www.cdc.gov/fungal/risk-factors/index.html.

50. Al-Shaarani AAQA, Pecoraro L. A review of pathogenic airborne fungi and bacteria: unveiling occurrence, sources, and profound human health implication. Front Microbiol. 2024 Sep 19;15:1428415. doi: 10.3389/fmicb.2024.1428415. PMID: 39364169; PMCID: PMC11446796.

51. Bardana EJ Jr. Indoor air quality and health does fungal contamination play a significant role? Immunol Allergy Clin North Am. 2003 May;23(2):291-309. doi: 10.1016/s0889-8561(02)00081-4. PMID: 12803364.

52. Rahimi SM, Ebrahimi M, Barikbin B, Zeinali T. Evaluation of bacterial and fungal contamination of kitchens of Birjand University of Medical Sciences. BMC Res Notes. 2019 Oct 28;12(1):703. doi: 10.1186/s13104-019-4741-y. PMID: 31661017; PMCID: PMC6816195.

53. CDC, 2022. Guidelines for Environmental Infection Control in Health-Care Facilities. Available from: https://www.cdc.gov/infectioncontrol/guidelines/environmental/index.html.

54. Cobrado L, Silva-Dias A, Azevedo MM, Rodrigues AG. High-touch surfaces: microbial neighbours at hand. European Journal of Clinical Microbiology & Infectious Diseases. 2017 Nov;36:2053-62.

55. Alrawi, S. K., Assi, M. S., Younus, Z. Y., Hayyawi, A. H., Abdullah, A. W., Lateef, B. N., & Fouad, Y. A. Medical Devices, Tools, and Equipment Surfaces Contamination in Three Departments at a Tertiary Hospital in Baghdad. Annals of Tropical Medicine and Public Health, 2020;23(11). https://doi.org/10.36295/ASRO.2020.231130.

56. Anargh V, Singh H, Kulkarni A, Kotwal A, Mahen A. Hand hygiene practices among health care workers (HCWs) in a tertiary care facility in Pune. Med J Armed Forces India. 2013 Jan;69(1):54-6. doi: 10.1016/j.mjafi.2012.08.011. Epub 2012 Nov 30. PMID: 24532935; PMCID: PMC3862659.

57. Belay MM, Ambelu A, Mekonen S, Karbana G, Yemane B. Investigating Microbial Contamination of Indoor Air, Environmental Surfaces, and Medical Equipment in a Southwestern Ethiopia Hospital. Environ Health Insights. 2024 Jul 24;18:11786302241266052. doi: 10.1177/11786302241266052.

58. Aiesh BM, Daraghmeh D, Abu-Shamleh N, Joudallah A, Sabateen A, Al Ramahi R. Blood culture contamination in a tertiary care hospital: a retrospective three-year study. BMC Infect Dis. 2023 Jul 4;23(1):448. doi: 10.1186/s12879-023-08428-0.

59. Bandić Pavlović D, Pospišil M, Nađ M, Vrbanović Mijatović V, Luxner J, Zarfel G, Grisold A, Tonković D, Dobrić M, Bedenić B. Multidrug-Resistant Bacteria in Surgical Intensive Care Units: Antibiotic Susceptibility and β-Lactamase Characterization. Pathogens. 2024 May 15;13(5):411. doi: 10.3390/pathogens13050411.

60. Patterson JE, Malani PN, Maragakis LL. Infection control in the intensive care unit: progress and challenges in systems and accountability. Crit Care Med. 2010; 38(8 Suppl): S265-8. doi: 10.1097/CCM.0b013e3181e69d48.

61. La Fauci V, Genovese C, Facciolà A, Palamara MAR, Squeri R. Five-year microbiological monitoring of wards and operating theatres in southern Italy. J Prev Med Hyg. 2017 Jun;58(2):E166-E172.

62. Tan H., Lee C.T., Othman M., Zubir M., Nyakuma B., Chong W., Fan Y.V., Wong K.

Evaluation of Microbial Contamination for Pre- and Post-Surgical Procedures in Hospital Operating Rooms: a Systematic Onsite Sampling, Chemical Engineering Transactions, 2023;106: 601-6.

63. Tamsi NSF, Latif MT, Othman M, Abu Bakar FD, Yusof HM, Noraini NMR, Zahaba M, Sahani M. Antibiotic resistance of airborne bacterial populations in a hospital environment. Environ Monit Assess. 2022 Aug 2;194(9):629. doi: 10.1007/s10661-022-10291-6. PMID: 35918614.

64. Shumake KL, Sacks JD, Lee JS, Johns DO. Susceptibility of older adults to health effects induced by ambient air pollutants regulated by the European Union and the United States. Aging Clin Exp Res. 2013;25(1):3-8. doi: 10.1007/s40520-013-0001-5.

65. Rai, R., Fritschi, L., Carey, R. N., Lewkowski, K., Glass, D. C., Dorji, N., & El-Zaemey, S. The estimated prevalence of exposure to carcinogens, asthmagens, and ototoxic agents among healthcare workers in Australia. American Journal of Industrial Medicine, 2020;63(2): 126–35. https://doi.org/10.1002/ajim.23108.

66. Ab Manan N, Noor Aizuddin A, Hod R. Effect of Air Pollution and Hospital Admission: A Systematic Review. Ann Glob Health. 2018 Nov 5;84(4):670-678. doi: 10.9204/aogh.2376. PMID: 30779516; PMCID: PMC6748301.

67. Fang Z, Wu PY, Lin YN, Chang TH, Chiu YH. Air Pollution's Impact on the Economic, Social, Medical, and Industrial Injury Environments in China. Healthcare (Basel). 2021 Mar 1;9(3):261. doi: 10.3390/healthcare9030261.

68. Nyembwe, J.-P. K. B., Munanga, J. K., Simões, N., & da Silva, M. G. Ventilation Strategies to Mitigate Air Pollution Impact on Hospital Professionals in Intensive Care Units in the Democratic Republic of Congo. Buildings, 2024;14(7). https://doi.org/10.3390/buildings14071996.

69. Escombe, A. R., Ticona, E., Chávez-Pérez, V., Espinoza, M., & Moore, D. A. J. Improving natural ventilation in hospital waiting and consulting rooms to reduce nosocomial tuberculosis transmission risk in a low-resource setting. BMC Infectious Diseases, 2019;19(1): 88. https://doi.org/10.1186/s12879-019-3717-9.

70. Ibrahim F, Samsudin EZ, Ishak AR, Sathasivam J. Hospital indoor air quality and its relationships with building design, building operation, and occupant-related factors: A mini-review. Front Public Health. 2022 Nov 8;10:1067764. doi: 10.3389/fpubh.2022.1067764. PMID: 36424957; PMCID: PMC9679624.

71. Hama Radha, C. Retrofitting for Improving Indoor Air Quality and Energy Efficiency in the Hospital Building. Sustainability, 2023;15(4): 3464. https://doi.org/10.3390/su15043464.

72. Leung, M. K. H., Chau, O. K. Y., & Ho, L. C. Local Exhaust Ventilation for Infection Control in Hospitals. HKIE Transactions, 2005;12(1): 27–32. https://doi.org/10.1080/1023697X.2005.10667990.

73. Halaby T, Al Naiemi N, Beishuizen B, Verkooijen R, Ferreira JA, Klont R, et al. Impact of single room design on the spread of multi-drug resistant bacteria in an intensive care unit. Antimicrob Resist Infect Control. 2017 Nov 15;6:117. doi: 10.1186/s13756-017-0275-z.

74. Taylor E, Card AJ, Piatkowski M. Single-Occupancy Patient Rooms: A Systematic Review of the Literature Since 2006. HERD. 2018 Jan;11(1):85-100. doi: 10.1177/1937586718755110. Epub 2018 Feb 15. PMID: 29448834.

75. Qian H, Li Y, Seto WH, Ching P, Ching WH, Sun HQ. Natural ventilation for reducing airborne infection in hospitals. Build Environ. 2010 Mar;45(3):559-565. doi: 10.1016/j.buildenv.2009.07.011. Epub 2009 Jul 23. PMID: 32288008;

76. Escombe AR, Oeser CC, Gilman RH, Navincopa M, Ticona E, Pan W, Martínez C, Chacaltana J, Rodríguez R, Moore DA, Friedland JS, Evans CA. Natural ventilation for the prevention of airborne contagion. PLoS Med. 2007 Feb;4(2):e68. doi: 10.1371/journal.pmed.0040068. PMID:

77. Inkarojorit, V. Natural Ventilation in Thai Hospitals: A Field Study. Journal of Building Engineering, 2023;64: 104924.

78. Lateef F. Hospital design for better infection control. J Emerg Trauma Shock. 2009 Sep;2(3):175-9. doi: 10.4103/0974-2700.55329.

79. Emmanuel U, Osondu ED, Kalu KC. Architectural design strategies for infection prevention and control (IPC) in health-care facilities: towards curbing the spread of Covid-19. J Environ Health Sci Eng. 2020 Oct 30;18(2):1699-1707. doi: 10.1007/s40201-020-00580-y.

80. Asiri YAY, Asiri AAA, Asiri AAM, Alqahtani AJ, Alahamari AMS, Asiri AAN, et al. The Role of Team Synergy in Infection Control: A Systematic Review of Healthcare Collaboration. JoE [Internet]. 2024Dec.31 [cited 2025Apr.3];3(8):13099. Available from: https://ecohumanism.co.uk/joe/ecohumanism/article/view/6192.

81. Centers for Disease Control and Prevention (CDC), 2025. Guidelines for Preventing the Spread of Infectious Diseases in Healthcare Settings.

82. Gupta N, Abd El-Gawaad NS, Mallasiy LO. Hospital-borne hazardous air pollutants and air cleaning strategies amid the surge of SARS-CoV-2 new variants. Heliyon. 2024 Oct 5;10(20):e38874. doi: 10.1016/j.heliyon.2024.e38874.

83. Kubde D, Badge AK, Ugemuge S, Shahu S. Importance of Hospital Infection Control. Cureus. 2023 Dec 22;15(12):e50931. doi: 10.7759/cureus.50931.

84. Mun E, Cho J. Review of Internet of Things-Based Artificial Intelligence Analysis Method through Real-Time Indoor Air Quality and Health Effect Monitoring: Focusing on Indoor Air Pollution That Are Harmful to the Respiratory Organ. Tuberc Respir Dis (Seoul). 2023 Jan;86(1):23-32. doi: 10.4046/trd.2022.0087.

85. Taştan, M., & Gökozan, H. Real-Time Monitoring of Indoor Air Quality with Internet of Things-Based E-Nose. Applied Sciences, 2019;9(16):3435. https://doi.org/10.3390/app9163435.

86. Choi JY, Zemke J, Philo SE, Bailey ES, Yondon M, Gray GC. Aerosol Sampling in a Hospital Emergency Room Setting: A Complementary Surveillance Method for the Detection of Respiratory Viruses. Front Public Health. 2018 Jun 14;6:174. doi: 10.3389/fpubh.2018.00174.

87. Stockwell RE, Ballard EL, O'Rourke P, Knibbs LD, Morawska L, Bell SC. Indoor hospital air and the impact of ventilation on bioaerosols: a systematic review. J Hosp Infect. 2019 Oct;103(2):175-184. doi: 10.1016/j.jhin.2019.06.016. Epub 2019 Jul 4. PMID: 31279762.

88. Hoseinzadeh E, Samarghandie MR, Ghiasian SA, Alikhani MY, Roshanaie G. Evaluation of Bioaerosols in Five Educational Hospitals Wards Air in Hamedan, During 2011-2012. Jundishapur Journal of Microbiology. 2013 Aug 1;6(6).

89. Smielowska M, Maré M, Zabiegala B. Indoor air quality in public utility environments - a review. Environ Sci Pollut Res. (2017) 24:11166–76. 10.1007/s11356-017-8567-7.

90. Sparke, V. L., Diau, J., MacLaren, D., & West, C. Solutions to infection prevention and control challenges in developing countries: Do they exist? International Journal of Infection Control, 2020;16(1). doi:10.3396/ijic.v16i1.007.20.

91. Shirreff G, Thiébaut ACM, Huynh BT; NODS-Cov2 Investigation Group; Chelius G, Fraboulet A, Guillemot D, Opatowski L, Temime L. Hospital population density and risk of respiratory infection: Is close contact density dependent? Epidemics. 2024 Dec; 49: 100807. doi: 10.1016/j.epidem.2024.100807.

92. Lee HJ, Lee KH, Kim DK. Evaluation and comparison of the indoor air quality in different areas of the hospital. Medicine (Baltimore). 2020 Dec 24;99(52):e23942. doi: 10.1097/MD.0000000000023942.

93. Zanni, S., Mura, M., Longo, M., Motta, G. and Caiulo, D. Indoor air quality monitoring and management in hospitality: an overarching framework. International Journal of Contemporary Hospitality Management, 2023; 35(2): 397-418. https://doi.org/10.1108/IJCHM-12-2021-1549.

94. CDC Environmental Infection Control Guidelines in Health-Care Facilities. Last update: July 2019 Available from: https://www.cdc.gov/infection-control/media/pdfs/Guideline-Environmental-H.pdf.

95. Gu J, Shi Y, Zhu Y, Chen N, Wang H, Zhang Z, et al. Ambient air pollution and cause-specific risk of hospital admission in China: A nationwide time-series study. PLoS Med 2020;17(8): e1003188. https://doi.org/10.1371/journal.pmed.1003188.

96. Ereth MH, Fine J, Stamatatos F, Mathew B, Hess D, Simpser E. Healthcare-associated infection impact with bioaerosol treatment and COVID-19 mitigation measures. J Hosp Infect. 2021 Oct;116:69-77. doi: 10.1016/j.jhin.2021.07.006. Epub 2021 Jul 22.

97. Abed Al Ahad M, Demšar U, Sullivan F, Kulu H. Long term exposure to ambient air pollution and hospital admission burden in Scotland: 16 year prospective population cohort study. BMJ Open. 2024 Dec 18;14(12):e084032. doi: 10.1136/bmjopen-2024-084032.

98. Thangavel P, Park D, Lee YC. Recent Insights into Particulate Matter (PM2.5)-Mediated Toxicity in Humans: An Overview. Int J Environ Res Public Health. 2022 Jun 19;19(12):7511. doi: 10.3390/ijerph19127511. PMID: 35742761; PMCID: PMC9223652.

99. Atkinson RW, Kang S, Anderson HR, Mills IC, Walton HA. Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: a systematic review and meta-analysis. Thorax. 2014 Jul;69(7):660-5. doi: 10.1136/thoraxjnl-2013-204492.

100. Yang CT, Liao CJ, Liu JC, Den W, Chou YC, Tsai JJ. Construction and application of an intelligent air quality monitoring system for healthcare environment. J Med Syst. 2014 Feb;38(2):15. doi: 10.1007/s10916-014-0015-3. Epub 2014 Feb 1. PMID: 24487985.

101. Rahmadani, A. A., Syaifudin, Y. W., Setiawan, B., Panduman, Y. Y. F., & Funabiki, N. Enhancing Campus Environment: Real-Time Air Quality Monitoring Through IoT and Web Technologies. Journal of Sensor and Actuator Networks, 2025;14(1): 2. https://doi.org/10.3390/jsan14010002.

102. Neo EX, Hasikin K, Mokhtar MI, Lai KW, Azizan MM, Razak SA, Hizaddin HF. Towards Integrated Air Pollution Monitoring and Health Impact Assessment Using Federated Learning: A Systematic Review. Front Public Health. 2022 May 19;10:851553. doi: 10.3389/fpubh.2022.851553.

103. Ayodele, C. O., Fakinle, B. S., Jimoda, L. A., & Sonibare, J. A. Investigation on the ambient air quality in a hospital environment. Cogent Environmental Science, 2016;2(1). https://doi.org/10.1080/23311843.2016.1215281.