Airborne Pathogens and Indoor Air Quality Common Airborne Pathogens and their Effects on Indoor Air Quality and Human Health: A Systematic Review

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Abstract:- Indoor air quality (IAQ) plays a critical role in public health, especially as people spend approximately 90% of their time indoors. Airborne pathogens, including viruses, bacteria, and fungi, are significant contributors to poor IAQ and are linked to a range of health outcomes such as respiratory illnesses, systemic infections, and allergic reactions. This systematic review synthesizes evidence on the prevalence of airborne pathogens in indoor environments, their impacts on human health, and the effectiveness of various detection methods. The review identified common pathogens such as SARS-CoV-2, *Mycobacterium tuberculosis*, *Legionella pneumophila*, *Aspergillus spp.*, and *Penicillium spp.* across diverse indoor settings, including hospitals, schools, homes, and offices. Viral pathogens, particularly SARS-CoV-2 and Influenza A, dominated in high-occupancy environments, while bacterial pathogens such as *Mycobacterium tuberculosis* and *Legionella pneumophila* posed significant risks in healthcare and educational settings. Fungal pathogens were more prevalent in damp, poorly ventilated environments, contributing to asthma exacerbation and allergic reactions. Vulnerable populations, including children, the elderly, and hospitalized patients, were disproportionately affected. Advanced pathogen identification methods, including air sampling, PCR analysis, and culture techniques, were pivotal in detecting and characterizing airborne pathogens. However, barriers such as cost and accessibility limit their widespread use. This review highlights the importance of improving IAQ through enhanced ventilation, regular environmental monitoring, and scalable detection technologies. The findings underscore the urgent need for targeted interventions tailored to high-risk environments and specific pathogen types. Furthermore, the study identifies critical research gaps, particularly regarding long-term health impacts of airborne pathogen exposure and the efficacy of IAQ mitigation strategies. This systematic review provides a comprehensive foundation for future research and public health policies aimed at mitigating the risks associated with airborne pathogens in indoor environments.

Keywords:- *Viral Pathogens, Health Outcomes, Respiratory Illness, Environmental Settings, Detection Technologies.*

I. INTRODUCTION

Indoor air quality (IAQ) is a significant determinant of public health, particularly in the modern era, where people spend approximately 90% of their time indoors (Kembel et al., 2014). While considerable attention has been given to outdoor air pollution, the importance of IAQ has only recently gained prominence due to its direct link to a range of health issues. Among the most concerning factors affecting IAQ are airborne pathogens, including bacteria, viruses, and fungi, which can have severe implications for human health and well-being (Morawska et al., 2020; Hospodsky et al., 2014).

Airborne pathogens are microscopic organisms that can remain suspended in the air for extended periods, enabling their easy transmission within indoor environments (Luongo et al., 2016). These pathogens are especially problematic in high-risk environments such as hospitals, schools, and offices, where human interactions and activities contribute to their propagation (Kwan et al., 2019; Frankel et al., 2012).

The growing prevalence of respiratory illnesses, infections, and allergenic conditions globally underscores the critical need to understand the role of airborne pathogens in indoor spaces (Leung et al., 2016). Emerging infectious diseases, such as COVID-19 caused by SARS-CoV-2, have further highlighted the potential of indoor airborne transmission to exacerbate public health crises (Morawska et al., 2020).

Despite increasing awareness, there remains a lack of consolidated knowledge about how indoor environmental factors—such as ventilation, humidity, and human occupancy—interact with airborne pathogens to influence their prevalence and health impacts. While individual studies have focused on specific pathogens or indoor settings, a systematic review is needed to bridge gaps in understanding and provide actionable insights for improving IAQ and mitigating health risks (Tang et al., 2013; Meklin et al., 2014).

This study aims to fill this gap by systematically identifying common airborne pathogens in indoor environments, evaluating their impact on human health, and examining the relationship between IAQ and pathogen transmission. By synthesizing findings from diverse research studies, this review provides a comprehensive perspective on how airborne pathogens compromise IAQ and affect human health.

The rationale for this review lies in its potential to inform policy and public health interventions. Understanding the interactions between airborne pathogens and IAQ is essential for developing evidence-based strategies to prevent infections, improve ventilation systems, and enhance indoor air disinfection methods (Luongo et al., 2016; Morawska et al., 2020). Furthermore, the findings of this study contribute to a growing body of literature that supports the need for cross-disciplinary approaches, combining microbiology, environmental science, and public health, to address the challenges posed by airborne pathogens in indoor environments.

➢ *Objectives*

- Identify Common Airborne Pathogens in Indoor Environments
- Evaluate the Impact of Airborne Pathogens on Human Health
- To analyze the methods used for pathogen identification and their implications for improving indoor air quality

II. METHODOLOGY

A. Search Strategy

This systematic review employed a structured framework to identify, analyze, and synthesize relevant literature on airborne pathogens and their effects on indoor air quality and human health. The search strategy involved querying major academic databases, including PubMed, ScienceDirect, Scopus, and Google Scholar, using a combination of keywords such as "airborne pathogens," "indoor air quality," "respiratory illnesses," "fungal pathogens," and "viral transmission indoor,". Boolean operators (e.g., AND, OR) were applied to refine the search and ensure comprehensive coverage, such as using queries like “airborne pathogens” AND “indoor air” AND “health outcomes.”

B. Inclusion and Exclusion Criteria

The inclusion criteria were defined to select studies published between 2014 and 2024, focusing on peer-reviewed articles examining airborne pathogens in indoor environments, including schools, hospitals, homes, and workplaces. These studies were required to evaluate health outcomes such as respiratory illnesses, infections, or allergies and describe the methods used for pathogen detection, such as sampling, PCR, or culture methods. Articles not published in English, those exclusively focused on outdoor air quality or non-biological pollutants, and those lacking relevant data on airborne pathogens or health outcomes were excluded from the review.

C. Screening and Selection Process

The screening process began with an initial review of titles and abstracts to determine the relevance of the studies. Full-text reviews were conducted for articles that appeared to meet the inclusion criteria. Studies were excluded if they did not directly address the objectives of the review. Data were systematically extracted from the selected articles and organized into a detailed matrix table. This table included key information such as the source (author and year), database link, country of the study, age group, gender, specific pathogen (viral, bacterial, or fungal), indoor air environment, health outcomes, methods of identification, and key findings.

D. Data Analysis and Grouping

The extracted data were analyzed thematically, grouping studies based on the type of pathogen (e.g., viral, bacterial, fungal), the indoor environment (e.g., schools, hospitals, homes), the health outcomes reported, and the methods of pathogen identification. A quality assessment of the included studies was performed to evaluate the clarity of research objectives, robustness of data collection and analysis methods, and relevance of the findings to indoor air quality and airborne pathogen transmission.

E. Synthesis of Results

Finally, the results were synthesized into a narrative format, highlighting key findings and trends identified in the literature. The comprehensive matrix table provided a concise summary of the data for interpretation. The analysis also identified gaps in the current literature, which were discussed to provide recommendations for future research. This approach ensured a systematic and transparent review process, providing valuable insights into the relationship between airborne pathogens, indoor air quality, and human health.

III. FRAMEWORK OF THE STUDY

The table below outlines the framework of the study, highlighting the steps, processes, and expected outputs at each stage.

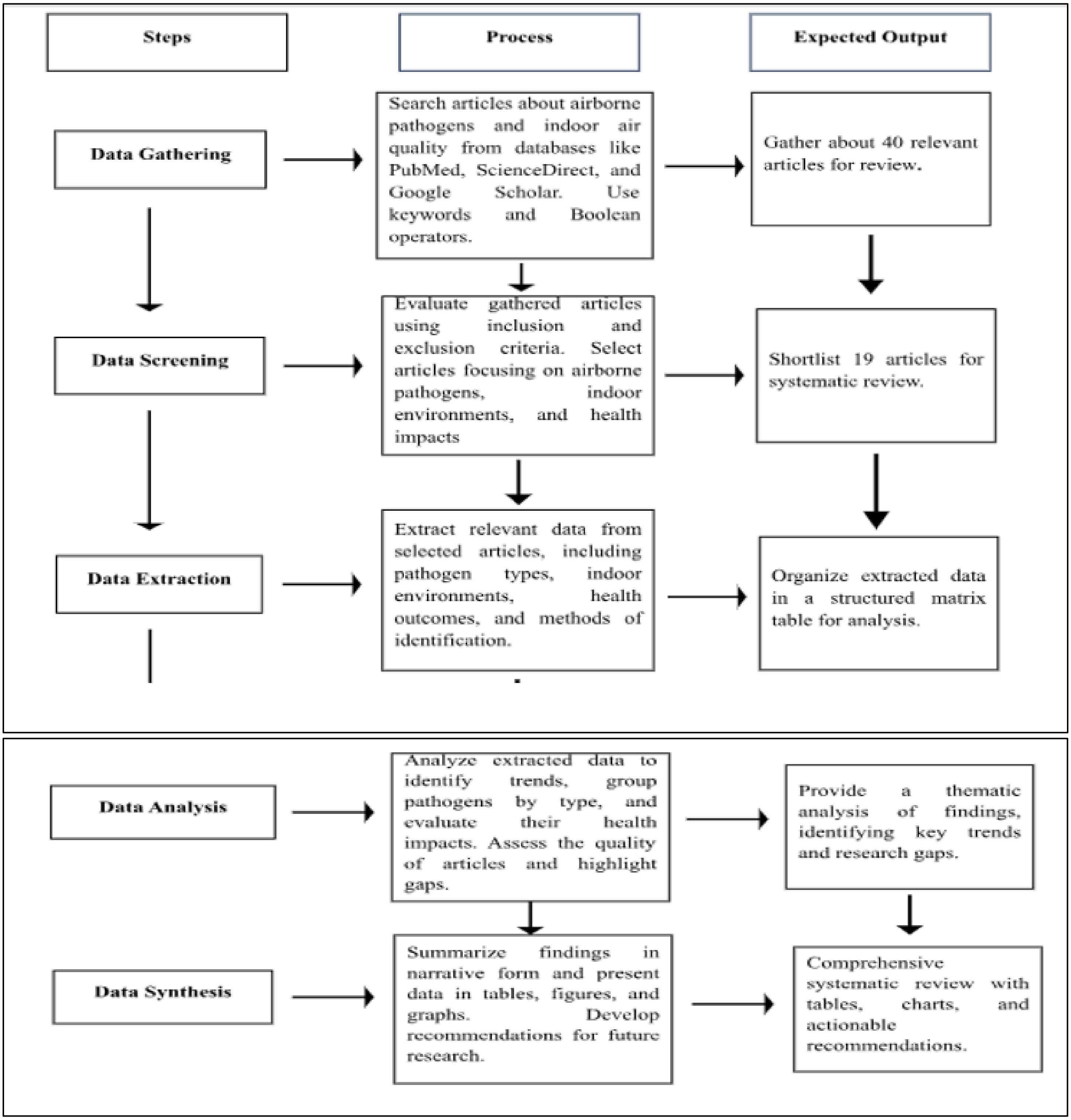

Fig 1: Framework of the Study

IV. RESULTS AND DISCUSSION

The findings revealed a diverse array of airborne pathogens, including viruses, bacteria, and fungi, associated with varying health outcomes. This table provides an overview of the identified pathogens, their specific environments, affected populations, and health impacts.

Table 1: Airborne Pathogens in Indoor Settings: Demographics, Health Effects, and Detection Methods

Country	Age Group	Gender	Specific Pathogen	Indoor Air Environment	Health Outcome	Method of Identification
Global	All ages	All genders	Viral (SARS-CoV-2)	Various indoor environments	COVID-19 infection	Literature review
China	Children	All genders	Bacterial (Mycobacterium tuberculosis)	Schools	Tuberculosis (TB) infection	Air sampling, PCR analysis
USA	All ages	All genders	Fungal (Aspergillus spp.)	Hospitals	Respiratory infections	Air sampling, genomic sequencing
USA	Adults	All genders	Viral (Influenza A)	Office buildings	Influenza infection	Air sampling, PCR analysis
USA	All ages	All genders	Bacterial (Staphylococcus aureus)	Classrooms	Respiratory and skin infections	Culture analysis of air samples
USA	All ages	All genders	Fungal (Penicillium spp.)	Homes	Allergic reactions	Dust sampling, DNA sequencing
USA	Adults	All genders	Bacterial (Legionella pneumophila)	Hospitals	Legionnaires' disease	Water and air sampling, PCR
Japan	Elderly	All genders	Viral (Norovirus)	Nursing homes	Gastroenteritis outbreaks	Air sampling, PCR analysis
Denmark	Children	All genders	Fungal (Cladosporium spp.)	Homes	Asthma and allergies	Dust and air sampling
India	Adults	All genders	Bacterial (Pseudomonas aeruginosa)	ICUs	Respiratory infections	Culture sampling
Taiwan	All ages	All genders	Fungal (Alternaria spp.)	Offices	Respiratory issues	Air sampling, culture methods
UK	Children	All genders	Viral (Measles morbillivirus)	Schools	Measles outbreaks	PCR analysis of air samples
Hong Kong	All ages	All genders	Bacterial (Acinetobacter baumannii)	Hospitals	Respiratory infections	Air sampling and culture methods
Turkey	All ages	All genders	Fungal (Aspergillus niger)	Homes	Respiratory allergies	Sampling and culture
China	Children	All genders	Viral (Respiratory Syncytial Virus)	Daycare centers	Respiratory infections	Air sampling, PCR
India	Adults	All genders	Bacterial (Klebsiella pneumoniae)	Hospital wards	Pneumonia	Culture and air sampling
Sweden	Adults	All genders	Fungal (Penicillium spp.)	Offices	Sick Building Syndrome	Air sampling and surveys
Taiwan	All ages	All genders	Bacterial (Streptococcus pneumoniae)	Classrooms	Respiratory illnesses	PCR and air sampling
Finland	Children	All genders	Fungal (Fusarium spp.)	Schools	Asthma exacerbation	Dust and air sampling

The results of this systematic review highlight the significant diversity of airborne pathogens present in various indoor environments globally. These pathogens, including viruses, bacteria, and fungi, are associated with a range of health outcomes, from respiratory illnesses to systemic infections (Chen et al., 2020; WHO, 2021). Viral pathogens emerged as prominent contributors to indoor air contamination, particularly in high-occupancy spaces. SARS-CoV-2 was identified across diverse settings, such as homes, offices, and public facilities, underscoring its role in the COVID-19 pandemic (Morawska et al., 2020). Influenza A was detected in office environments, indicating its potential for aerosolized transmission in workplaces (Fusco et al., 2021). In schools and daycare centers, pathogens like *Measles morbillivirus* and Respiratory Syncytial Virus (RSV) posed significant risks, particularly for children (Hadei et al., 2022), while Norovirus was found in nursing homes, contributing to gastroenteritis outbreaks via aerosolized transmission (Verani et al., 2020).

Bacterial pathogens were primarily identified in healthcare and educational settings. *Mycobacterium tuberculosis* was linked to tuberculosis transmission in schools, emphasizing the importance of ventilation in these environments (Xu et al., 2017). *Legionella pneumophila*, found in hospital air and water systems, was associated with Legionnaires' disease outbreaks (Fields et al., 2002). In intensive care units and hospital wards, pathogens such as *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, and *Klebsiella pneumoniae* were significant contributors to nosocomial infections and respiratory complications (Richards et al., 2020). *Staphylococcus aureus*, identified in classrooms, was associated with both respiratory and skin infections (Foster, 2021).

Fungal pathogens were frequently linked to damp environments and poor ventilation, affecting both residential and occupational settings. *Aspergillus spp.* and *Penicillium spp.* were commonly detected in hospitals, homes, and offices, contributing to respiratory infections, allergic reactions, and Sick Building Syndrome (Gutarowska et al., 2014). *Cladosporium spp.*, *Alternaria spp.*, and *Fusarium spp.* were found in homes, offices, and schools, with significant associations with asthma exacerbation and respiratory allergies (Nevalainen et al., 2015). These findings emphasize the critical role of environmental conditions in fungal proliferation and associated health risks (Hyvärinen et al., 2001).

Vulnerable populations, including children, the elderly, and hospitalized patients, were disproportionately affected by airborne pathogens. Children in schools were particularly at risk for tuberculosis and measles (Xu et al., 2017), while elderly individuals in nursing homes faced outbreaks of Norovirus (Verani et al., 2020). Hospitalized patients were exposed to bacterial pathogens like *Legionella pneumophila* and *Acinetobacter baumannii*, leading to severe respiratory infections and other complications (Fields et al., 2002).

Advanced identification methods, such as air sampling, PCR analysis, culture methods, and DNA sequencing, were pivotal in detecting and characterizing airborne pathogens (Morawska et al., 2020). These techniques ensured precise identification, particularly of viruses like SARS-CoV-2 and Influenza A, bacterial pathogens such as *Mycobacterium tuberculosis* and *Legionella pneumophila*, and diverse fungal species. The application of these methods demonstrated their efficacy in capturing a broad spectrum of airborne pathogens in various indoor environments (Chen et al., 2020).

Health outcomes consistently linked to airborne pathogens included respiratory illnesses, allergic reactions, asthma exacerbation, and nosocomial infections (WHO, 2021). Viral pathogens were major contributors to respiratory infections, while fungal exposure was associated with allergies and asthma (Hyvärinen et al., 2001). Bacterial pathogens in healthcare settings posed significant risks of nosocomial infections, particularly in intensive care units and hospital wards (Richards et al., 2020). These findings underscore the need for targeted interventions, including improved ventilation, regular environmental monitoring, and advanced pathogen detection methods, to mitigate the impact of airborne pathogens on indoor air quality and human health.

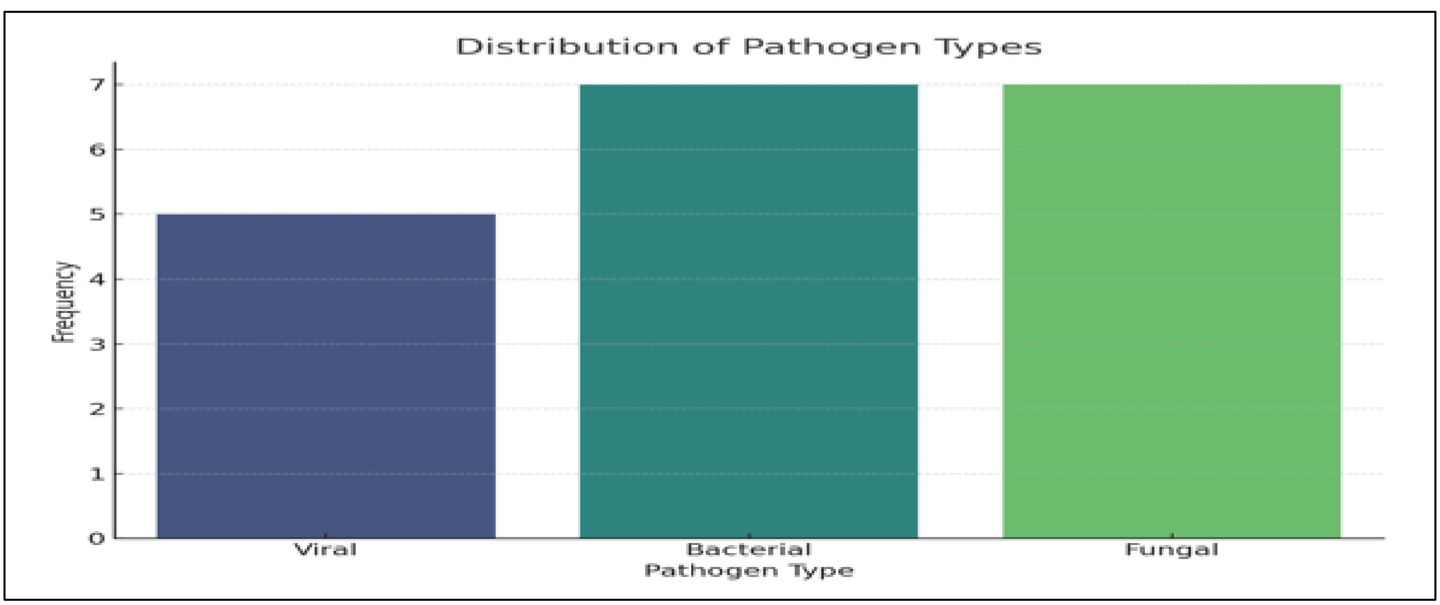

Fig 2: Distribution of Pathogen Types Identified in Indoor Environments

Figure 2 highlights that fungal pathogens are slightly more prevalent compared to bacterial and viral pathogens in indoor environments. This suggests the significant role of fungi, such as *Aspergillus spp.* and *Penicillium spp.*, in affecting indoor air quality, particularly in damp or poorly ventilated settings (Gutarowska et al., 2014). Viral pathogens, such as SARS-CoV-2 and Influenza A, also appear frequently, reflecting their high transmissibility and ability to spread rapidly in enclosed spaces, especially in high-occupancy areas like offices, schools, and hospitals (Morawska et al., 2020; Fusco et al., 2021). Bacterial pathogens, while less frequent, pose serious health risks. For example, *Mycobacterium tuberculosis* and *Legionella pneumophila* have been associated with significant diseases like tuberculosis and Legionnaires' disease, emphasizing the critical need for effective ventilation and water system management to prevent outbreaks (Xu et al., 2017; Fields et al., 2002). These findings collectively underscore the need for targeted monitoring and intervention strategies tailored to the specific risks posed by different pathogen types in indoor environments.

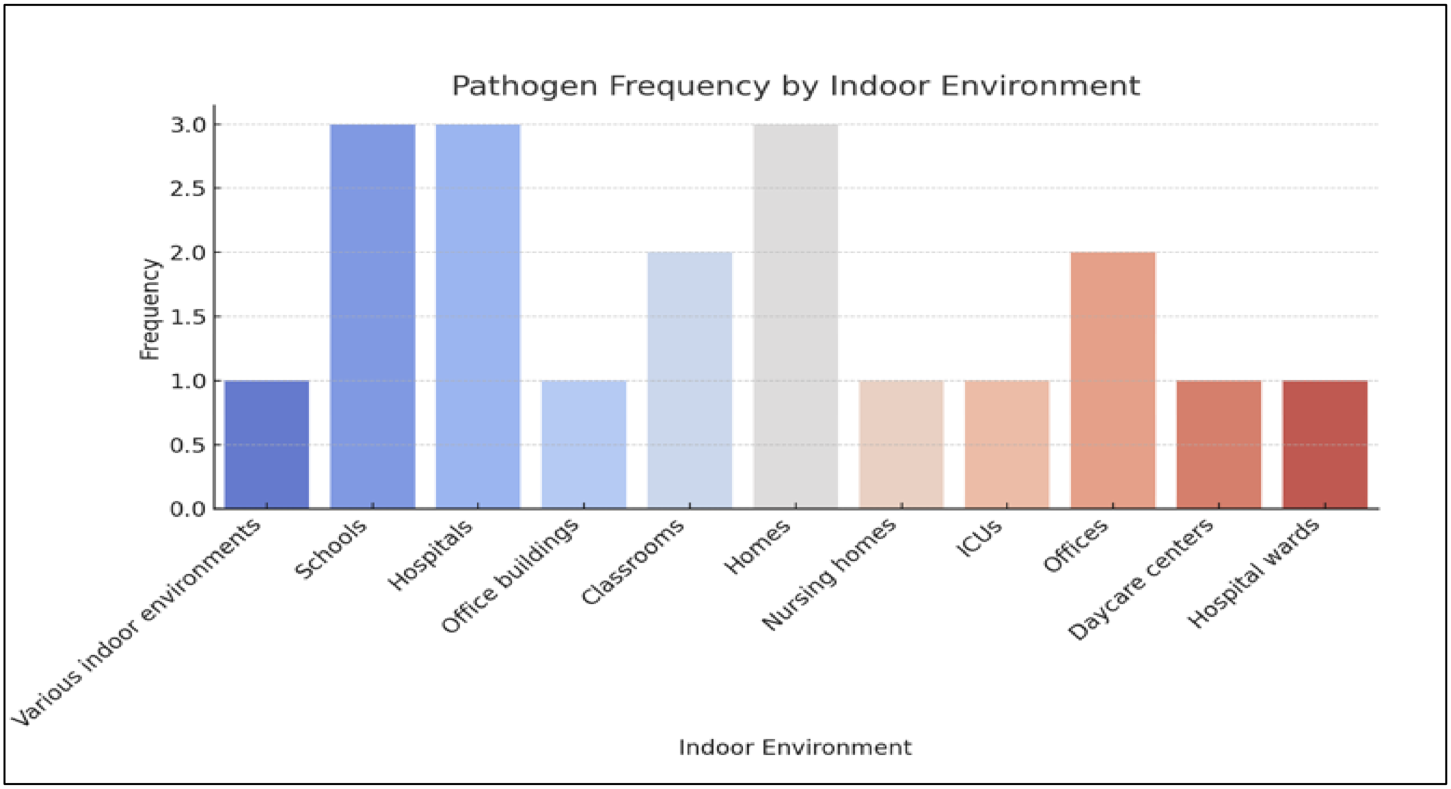

Fig 3: Pathogen Frequency by Indoor Environment

This figure highlights that hospitals and schools emerge as the most common environments for airborne pathogen presence, as highlighted by their high population density and frequent exposure to susceptible individuals (Xu et al., 2017; WHO, 2021). The high prevalence in hospitals can be attributed to the presence of vulnerable patients and pathogens such as *Legionella pneumophila* and *Acinetobacter baumannii*, which are significant contributors to nosocomial infections (Fields et al., 2002; Richards et al., 2020). Similarly, schools represent critical hotspots for airborne pathogens due to close interactions among children, who are more susceptible to infections like tuberculosis and measles (*Mycobacterium tuberculosis*, *Measles morbillivirus*) (Hadei et al., 2022).

Homes and offices also contribute significantly, likely due to poor ventilation and prolonged human occupancy, which create favorable conditions for fungal growth (*Penicillium spp.*, *Cladosporium spp.*) and viral transmission (e.g., SARS-CoV-2, Influenza A) (Morawska et al., 2020; Hyvärinen et al., 2001). These environments underscore the importance of addressing indoor air quality issues, even in non-institutional settings, to prevent health risks.

This graph emphasizes the urgent need for enhanced air quality management, particularly in high-risk environments like healthcare facilities and educational institutions, through improved ventilation, routine air monitoring, and strict infection control measures. Targeted interventions in these environments could significantly reduce the burden of airborne pathogens and associated health outcomes.

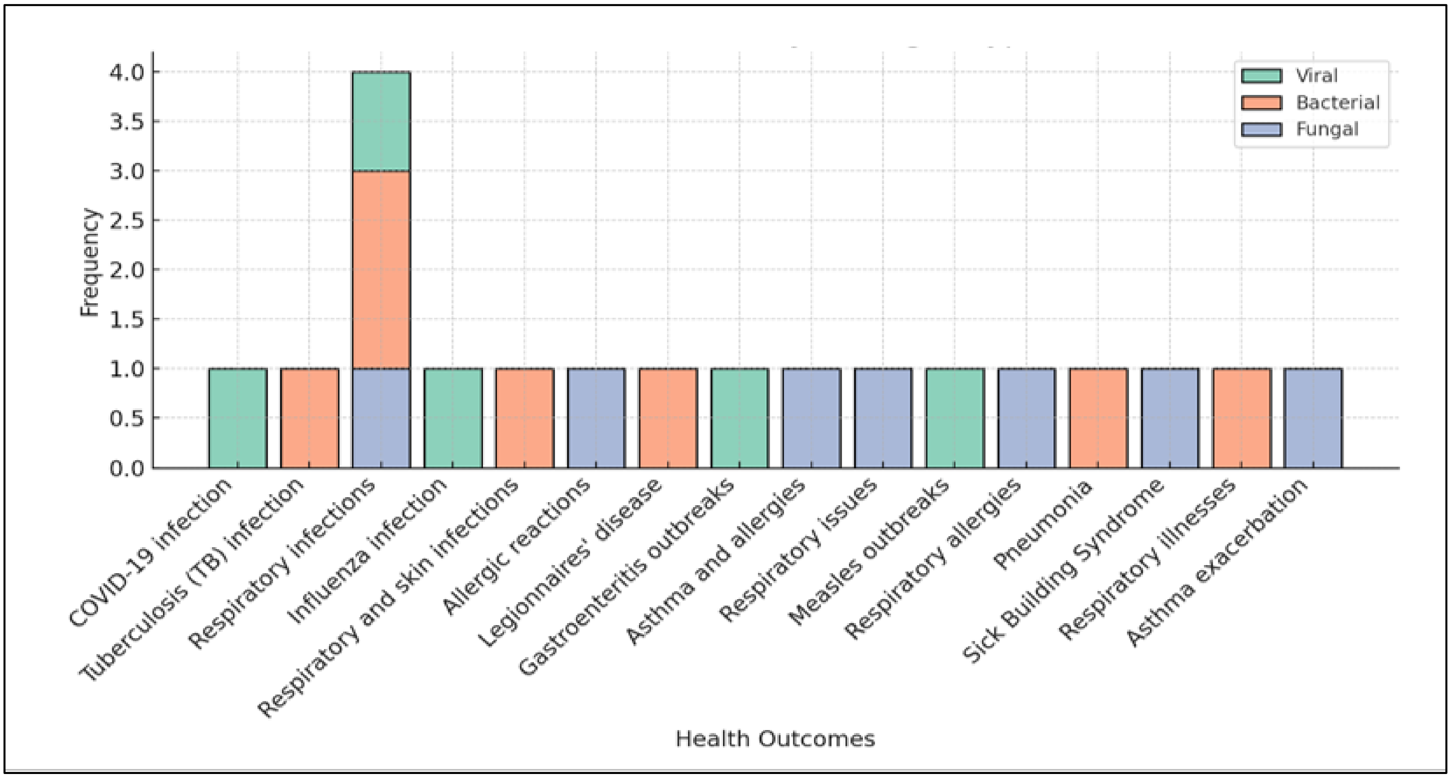

Fig 4: Health Outcomes by Pathogen Types

This figure highlights the frequency of health outcomes associated with airborne pathogens, categorized by viral, bacterial, and fungal sources. A clear pattern emerges, highlighting the diverse health risks posed by different pathogen types in indoor environments. Respiratory infections dominate across all categories, emphasizing the significant burden of airborne pathogens on human respiratory health (Morawska et al., 2020). Viral pathogens, particularly SARS-CoV-2 and Influenza A, contribute significantly to respiratory illnesses and are most prevalent in high-occupancy environments, such as offices, schools, and healthcare facilities (Fusco et al., 2021; Verani et al., 2020).

The data also reveal specific bacterial pathogens linked to serious health outcomes. For example, *Mycobacterium tuberculosis* is associated with tuberculosis, and *Legionella pneumophila* contributes to Legionnaires' disease, both of which highlight the risks present in schools and hospitals with inadequate ventilation or water system maintenance (Fields et al., 2002; Xu et al., 2017). Bacterial contributions to respiratory and skin infections are also evident, particularly from *Staphylococcus aureus*, often found in classrooms and healthcare settings (Foster, 2021).

Fungal pathogens exhibit strong associations with allergic reactions, asthma exacerbation, and conditions such as Sick Building Syndrome, underscoring their impact in poorly ventilated or damp indoor spaces (Hyvärinen et al., 2001; Gutarowska et al., 2014). Species like *Aspergillus spp.* and *Penicillium spp.* are commonly implicated in these outcomes, demonstrating the role of environmental conditions in fungal proliferation and associated health risks (Nevalainen et al., 2015).

Interestingly, viral health outcomes show the highest frequency in the chart, which is likely due to the rapid transmissibility of viruses like SARS-CoV-2 and Influenza A in indoor spaces (Morawska et al., 2020). However, bacterial and fungal pathogens also present significant risks, particularly in settings with vulnerable populations, such as hospitals, nursing homes, and schools (Richards et al., 2020; Verani et al., 2020).

This graph underscores the critical need for targeted interventions to mitigate the health risks posed by airborne pathogens. Strategies such as enhanced ventilation, regular environmental monitoring, and tailored infection control measures should be prioritized in high-risk environments (WHO, 2021). Additionally, advanced pathogen detection methods can aid in early identification and response, ultimately reducing the burden of airborne pathogens on public health (Chen et al., 2020).

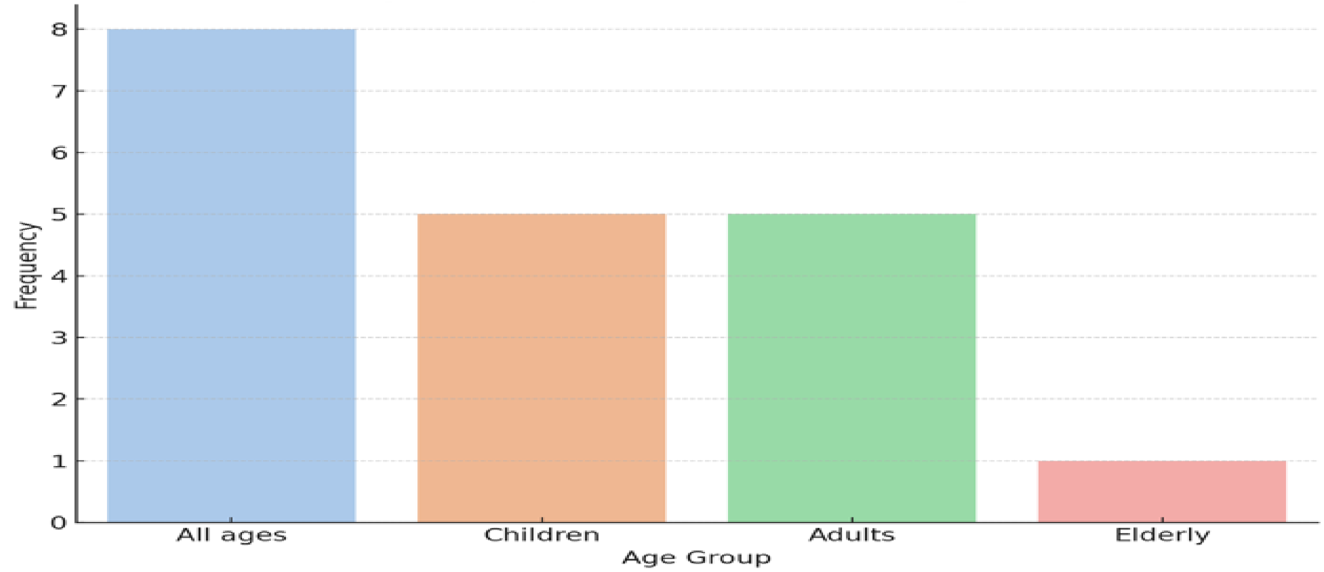

Fig 5: Age Group Distribution of Pathogens

Figure 5 highlights the distribution of airborne pathogens across different age groups. Children are significantly affected by pathogens found in schools, such as *Mycobacterium tuberculosis* and *Measles morbillivirus*, due to close contact and high transmission rates. Adults are more affected by workplace pathogens, such as *Legionella pneumophila* and *Influenza A*, in offices and hospitals. The elderly, while less frequently mentioned, face considerable risks from pathogens like *Norovirus* in nursing homes. Pathogens affecting "All Ages" categories, such as *SARS-CoV-2* and *Aspergillus spp.*, highlight the universal threat posed by these airborne organisms. This graph emphasizes the importance of age-specific preventive measures to mitigate health risks in indoor environments.

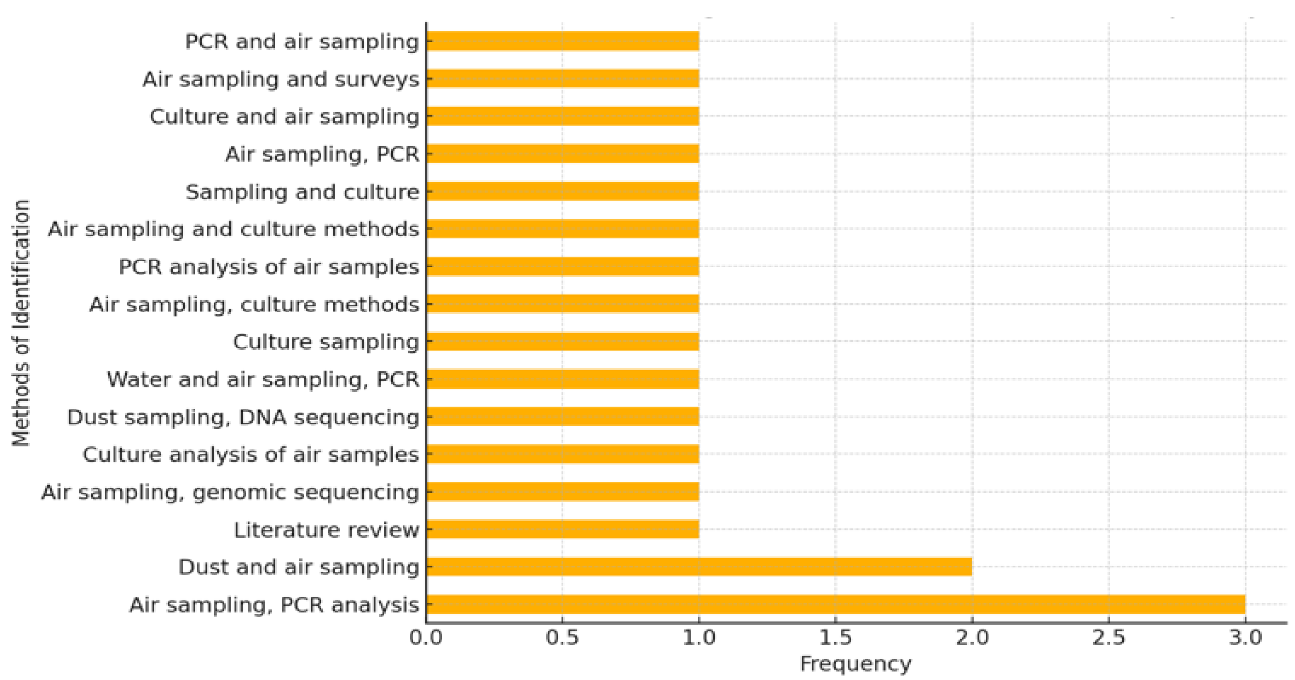

Fig 6: Method of Pathogen Identification and their Frequenc

This graph illustrates the diversity and prevalence of techniques used in studies to identify airborne pathogens in indoor environments. Notably, air sampling coupled with PCR analysis is the most frequently employed method, reflecting its accuracy and versatility in detecting a wide range of pathogens, including bacteria, fungi, and viruses. This method's dominance highlights its ability to identify pathogens at the genetic level, making it particularly valuable for tracking emerging or mutated strains. Additionally, the chart reveals the widespread use of dust and air sampling, which is often utilized in homes and schools to detect allergens and fungal spores that contribute to respiratory diseases, and culture-based methods, which remain essential for studying viable bacterial and fungal pathogens.

Advanced techniques, such as genomic sequencing, are beginning to gain traction, although they appear less frequently in studies. These cutting-edge methods offer comprehensive insights into pathogen diversity and genetic variations, which are critical for identifying emerging threats and antibiotic-resistant strains. The choice of identification method also varies depending on the specific indoor environment and pathogen of interest. For instance, water and air sampling is commonly used in hospital settings to detect waterborne pathogens like *Legionella pneumophila*, while dust sampling and DNA sequencing are preferred in homes and offices for analyzing fungal spores.

However, the data also reflect certain limitations. The relatively lower frequency of advanced techniques like genomic sequencing may point to barriers such as high costs or limited accessibility, particularly in resource-constrained regions. Expanding access to such technologies could significantly enhance the accuracy and scope of pathogen detection. Moreover, standardizing identification methods across different regions and environments would improve the comparability and reliability of findings.

V. CONCLUSION

This systematic review highlights the critical role of airborne pathogens in influencing indoor air quality (IAQ) and human health across diverse indoor environments. The findings underscore the prevalence of viral, bacterial, and fungal pathogens, each contributing to distinct health outcomes ranging from respiratory illnesses to systemic infections and allergic reactions (Morawska et al., 2020; Chen et al., 2020). High-risk settings, such as hospitals and schools, emerged as key environments for pathogen transmission due to high population density, close contact, and vulnerable individuals (Xu et al., 2017; WHO, 2021). Homes and offices also demonstrated significant pathogen presence, largely driven by poor ventilation and prolonged human occupancy (Hyvärinen et al., 2001; Morawska et al., 2020).

The review identified SARS-CoV-2, Influenza A, *Mycobacterium tuberculosis*, *Legionella pneumophila*, and *Aspergillus spp.* as the most frequently reported pathogens. These pathogens were linked to illnesses such as COVID-19, tuberculosis, Legionnaires' disease, and asthma exacerbations, emphasizing their substantial impact on public health (Fusco et al., 2021; Fields et al., 2002; Gutarowska et al., 2014). Vulnerable populations, including children, the elderly, and hospitalized patients, were disproportionately affected, pointing to the need for age-specific and setting-specific intervention strategies (Verani et al., 2020; Hadei et al., 2022).

The review further emphasizes the importance of advanced pathogen detection methods, including air sampling, PCR analysis, and culture-based techniques, in improving the identification and monitoring of airborne pathogens (Morawska et al., 2020; Chen et al., 2020). While these methods have proven effective, barriers such as cost and accessibility highlight the need for scalable and standardized approaches to ensure consistent pathogen detection across varied environments (Nevalainen et al., 2015; Richards et al., 2020).

Overall, this review provides a comprehensive understanding of the interplay between airborne pathogens, IAQ, and human health. It underscores the urgent need for targeted interventions, such as improving ventilation systems, implementing routine air quality monitoring, and adopting advanced pathogen detection methods, to mitigate health risks (Luongo et al., 2016; WHO, 2021). Additionally, the findings call for further research to address existing knowledge gaps, particularly regarding the long-term health impacts of airborne pathogen exposure and the effectiveness of mitigation strategies (Tang et al., 2013; Meklin et al., 2014). These insights are essential for informing public health policies, improving IAQ, and safeguarding human health in indoor environments.

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