ASEAN Journal of Science and Engineering

Journal homepage: http://ejournal.upi.edu/index.php/AJSE/

Current Strategies for Mitigating Airborne Pathogen Transmission: An Integrative Review Based on Aerosol Science and Particle Technology to Support the Sustainable Development Goals (SDGs), Complemented by a Bibliometric Analysis

Risti Ragadhita[1], Meli Fiandini[1], Asep Bayu Dani Nandiyanto[1,], Eka Lutfi Septiani[1], Takashi Ogi, Kikuo Okuyama*

[1]Universiti Pendidikan Indonesia, Indonesia
[2]Hiroshima University, Japan
Correspondence: E-mail: nandiyanto@upi.edu

ABSTRACT

Airborne pathogen transmission remains a significant global health challenge, particularly in densely populated and poorly ventilated environments. This integrative review explores current strategies for mitigating airborne transmission through the lens of aerosol science and particle technology. Using a structured literature review approach, the study examines the behavior of viruses, bacteria, and fungi in aerosols, highlighting critical environmental factors such as droplet size, humidity, temperature, and airflow. Advanced detection techniques and air purification technologies (including HEPA filters, UVGI, photocatalysis, and electrostatic precipitation) are analyzed for their efficacy and practical limitations. A bibliometric analysis reveals a post-pandemic surge in research, with dominant themes including ventilation systems and COVID-19 mitigation. The review emphasizes the alignment of mitigation strategies with the United Nations Sustainable Development Goals (SDGs), particularly SDGs 3, 9, 11, and 13. It concludes by advocating for interdisciplinary, policy-driven, and AI-enhanced approaches to improve indoor air quality and reduce the risk of airborne infectious diseases.

ARTICLE INFO

Article History:
Submitted/Received 05 Feb 2025
First Revised 02 Mar 2021
Accepted 04 Jun 2025
First Available online 17 Jun 2025
Publication Date 01 Sep 2025

Keyword:
Airborne pathogen,
Air purification technology,
Infection control,
Real-time detection,
Transmission.

1. INTRODUCTION

The transmission of airborne pathogens remains one of the most pressing public health challenges of the 21st century, as underscored by recent global pandemics such as COVID-19, influenza outbreaks, and the continued burden of tuberculosis [1, 2]. Unlike contact-based or fomite-mediated transmission, airborne pathogens have the unique ability to remain suspended in aerosol particles, allowing them to travel over extended distances and linger in indoor environments for prolonged periods [3]. This mode of transmission increases the potential for rapid and widespread infection and complicates efforts to control disease spread, particularly in poorly ventilated spaces.

Aerosol science and particle technology have provided critical insights into the mechanisms of airborne disease transmission. These disciplines enable the detailed analysis of droplet and aerosol behavior, environmental interactions, and mitigation approaches [4, 5]. Key factors such as droplet size distribution, particle evaporation dynamics, humidity, temperature, ventilation rates, and particulate matter significantly influence the survival and dispersal of pathogens [6]. In response, a range of control technologies has been developed or proposed, including high-efficiency particulate air (HEPA) filtration, ultraviolet germicidal irradiation (UVGI), electrostatic precipitation, and chemical disinfection aerosols [7]. However, despite these advances, the practical and theoretical understanding of airborne pathogen transmission and mitigation remains fragmented. The real-world efficacy of many technologies is still under investigation, particularly in terms of long-term sustainability, scalability, and effectiveness under varying environmental conditions. Additionally, the integration of aerosol science with microbiological and epidemiological data is often lacking in the current literature, leading to disjointed strategies that fail to capture the complexity of airborne pathogen dynamics.

Given that airborne transmission intersects multiple scientific disciplines, including aerosol science, infectious disease biology, environmental engineering, and public health, a cohesive and cross-cutting review is urgently needed to consolidate existing knowledge and guide future research and policy efforts. This review is necessary to establish a coherent framework that not only explains how airborne pathogens spread but also evaluates the performance and limitations of existing mitigation strategies in both laboratory and real-world contexts. The urgency of this review is amplified by the increasing frequency of respiratory pandemics and the growing importance of indoor air quality in densely populated and climate-controlled environments.

Although there have been many studies discussing the transmission and mitigation of airborne pathogens [8-20], important gaps remain. Most of the literature focuses only on the physics of aerosols or the biology of pathogens separately, thus failing to fully explain the relationship between the two. Environmental influences such as temperature, humidity, and airflow are also often studied in isolation, rather than in their complex interactions. In addition, advanced detection technologies such as APS, SMPS, and bioaerosol sensors are still rarely utilized, while conventional approaches such as passive sampling do not adequately capture real-time transmission dynamics. Evaluation of mitigation technologies is also generally limited to laboratory conditions and does not cover more complex real-world situations. These shortcomings underscore the necessity for a review that not only summarizes current approaches but also identifies unresolved challenges and potential pathways forward.

To address these interdisciplinary gaps, this review provides a comprehensive synthesis of current strategies for mitigating airborne pathogen transmission, grounded in aerosol science,

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

particle behavior, engineering innovations, pathogen detection technologies, and public health approaches. The goal is to advance understanding and support the development of scalable, effective, and sustainable interventions to control airborne infectious diseases. The review systematically explores the physicochemical behavior of bioaerosols, environmental and architectural determinants of transmission (e.g., humidity, temperature, ventilation, and airflow), real-time detection and assessment tools (such as SMPS, APS, and predictive models), and the effectiveness of air purification technologies including HEPA filtration, UVGI, electrostatic precipitation, and emerging mitigation techniques. In addition, real-world case studies and global implementation practices are presented to illustrate the practical applications of these strategies, including vaccination programs and integrated public health policies. To enhance contextual relevance, the study incorporates a bibliometric analysis (2015–2024) that maps global research trends and emerging themes, alongside a sustainability perspective aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDGs 3, 9, 11, and 13. Through this combined scientific, bibliometric, and policy-oriented lens, the paper offers an integrated framework for future airborne pathogen control and indoor air quality improvement.

2. METHODS

This study was conducted using a systematic literature review method to gain a deeper understanding of how pathogens, as agents that cause disease, are transmitted through the air and how their spread can be effectively reduced based on the principles of aerosol science and particle-based technologies. The review followed a structured and methodical process to ensure comprehensive, valid, and reliable results. The research stages involved systematically searching scientific databases, applying clearly defined criteria for selecting relevant studies, extracting essential data, and synthesizing information from credible academic and technical sources. Through this approach, the study provides an integrated perspective on airborne pathogen transmission and control strategies, grounded in multidisciplinary scientific evidence.

The reviewed literature was systematically grouped into major thematic areas aligned with the structure of this study. These themes include the classification of airborne pathogens, the mechanisms by which they are transmitted through the air, and comparative insights into how transmission dynamics differ in indoor and outdoor settings. In addition to these core themes, the study explores various contributing factors to pathogen spread, such as human activity, the physicochemical properties of aerosol droplets and bioaerosols, and environmental parameters including temperature, humidity, airflow patterns, and spatial layout. The analysis also emphasizes the significance of ventilation systems and airborne particulates in influencing pathogen dispersion. Furthermore, a detailed review of air purification technologies such as HEPA filtration, ultraviolet germicidal irradiation, photocatalytic oxidation, thermal treatment, and both chemical and behavioral interventions was provided. To contextualize these findings, the study incorporates real-world case studies demonstrating the implementation of control strategies on both national and international scales, while also highlighting existing challenges and identifying directions for future research. This integrated approach aims to offer a scientifically grounded foundation for mitigating the spread of airborne pathogens.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis

To understand the evolution and global attention toward airborne pathogen mitigation, a bibliometric analysis was conducted using the Scopus database. The search query "airborne AND pathogen AND transmission" returned 1,955 relevant documents published between 1959 and 2025. **Figure 1** illustrates the annual distribution of publications over this period. From 1959 through the late 1990s, research on airborne transmission remained sparse and episodic, reflecting limited global focus and technological constraints in the field. A modest but steady increase began in the early 2000s, aligning with global health concerns such as SARS and avian influenza outbreaks. However, the most significant surge occurred after 2020, coinciding with the global outbreak of COVID-19. Publications peaked in 2022 with 187 papers, followed by sustained high output in 2023 (149) and 2024 (175), suggesting long-term scientific engagement beyond the pandemic's peak. This sharp increase reflects not only the urgency of understanding aerosol-mediated transmission but also the convergence of multiple scientific disciplines—environmental engineering, virology, public health, and particle physics—toward this critical issue. The research trend aligns with the global development agenda, particularly the Sustainable Development Goals (SDGs):

(i) SDG 3 (Good Health and Well-being): Promotes infection control and pandemic preparedness.
(ii) SDG 9 (Industry, Innovation, and Infrastructure): Encourages technological advancement in air purification and monitoring systems.
(iii) SDG 11 (Sustainable Cities and Communities): Emphasizes improved ventilation and healthy indoor environments.
(iv) SDG 13 (Climate Action): Addresses air quality as a climate-health nexus.

These bibliometric insights confirm the growing scientific and policy momentum around airborne pathogen control and the relevance of this field to sustainable, health-oriented development strategies worldwide.

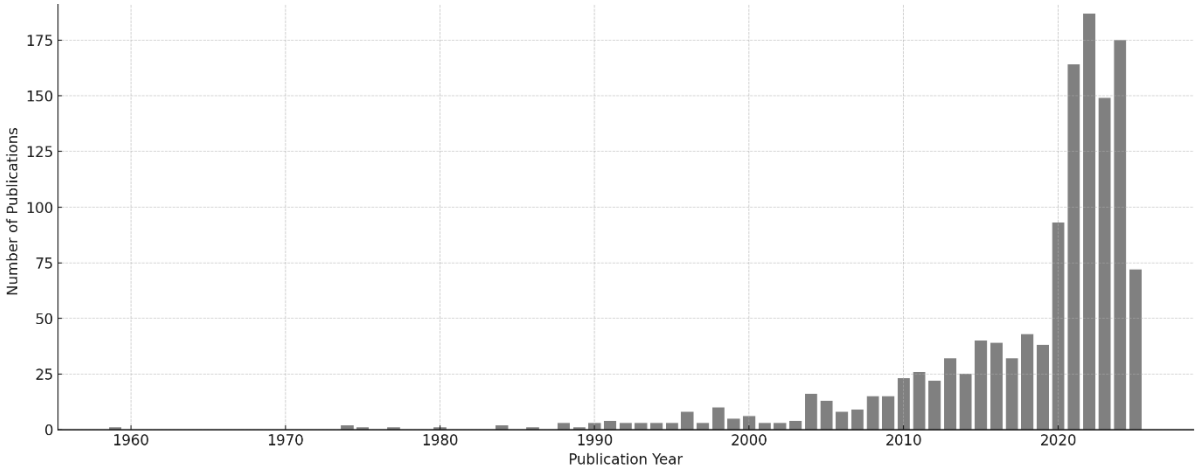

Figure 1. Annual scientific publications on the topic "airborne AND pathogen AND transmission" indexed in Scopus from 1959 to 2025. The sharp post-2020 increase reflects heightened global research activity driven by pandemic events. This trend aligns with the targets of the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health), SDG 9 (Industry and Innovation), and SDG 11 (Sustainable Cities), indicating the critical role of science and technology in responding to airborne infectious threats.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

3.2. Airborne Pathogen and Their Transmission

Airborne pathogens are disease-causing microorganisms that can spread through the air and infect humans when inhaled. Airborne pathogens that are transmitted through the air can be categorized into viruses, bacteria, and fungi. Viruses are very small, non-cellular infectious agents that require a living host to replicate. Unlike viruses, fungi can produce microscopic spores that are light and easily carried by the air. These spores can cause respiratory infections, especially in individuals with weak immune systems. Meanwhile, bacteria are single-celled microorganisms that can live independently or as parasites that can spread through the air [21-23].

These microorganisms are released into the air in the form of droplet particles (d_o > 100 µm), respiratory droplets (10 µm < d_o ≤ 100 µm), and airborne droplets (d_o ≤ 10 µm) as shown in **Figure 2**. Aerosol particles can remain suspended in the air for minutes to hours, especially in closed spaces or with poor ventilation [20]. Droplets, typically larger than 5 µm in diameter, possess sufficient mass to be rapidly pulled down by gravity, causing them to settle on the ground or nearby surfaces shortly after being expelled. As a result, droplet-mediated transmission generally occurs only at close range, typically within one meter of an infected individual [23]. In contrast, aerosols are particles smaller than 5 µm that can remain suspended in the air for extended periods due to their minimal mass. Their lightness allows them to be easily transported by air currents, enabling widespread dispersion throughout an enclosed space (particularly in areas with limited or poor ventilation) [24]. This characteristic makes aerosol-based transmission significantly more concerning in indoor environments such as offices, classrooms, and public transportation.

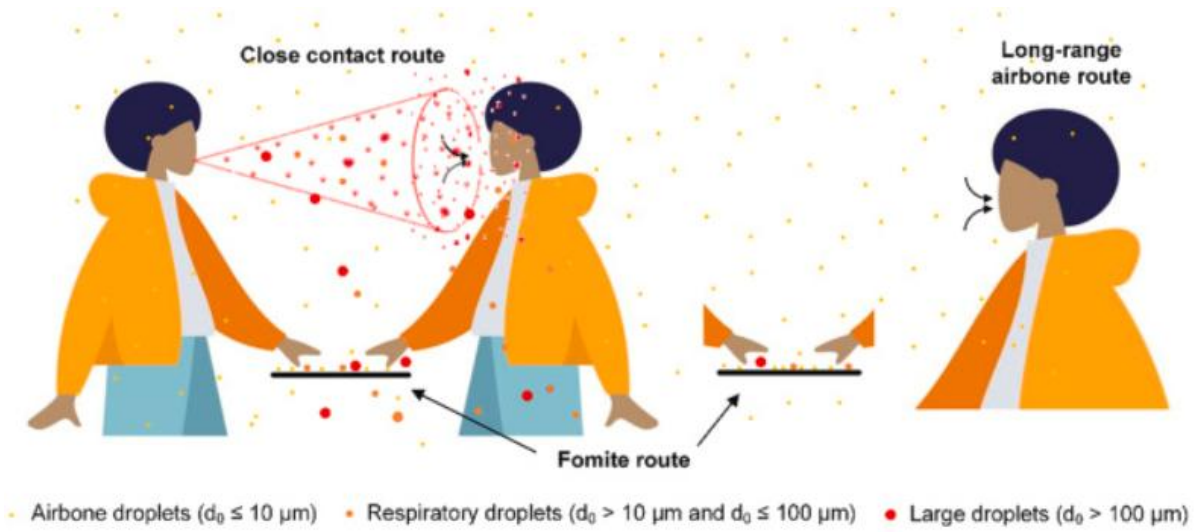

Figure 2. Illustration of airborne pathogen transmission in the form of droplets and aerosol particles (airborne and respiratory droplets) [20].

The difference in particle size plays a critical role in determining how long particles stay and how far they can travel. While larger droplets tend to settle rapidly due to gravity, smaller aerosols can remain suspended in the air for extended periods, allowing them to travel greater distances and accumulate in enclosed or poorly ventilated spaces, and increasing the potential for airborne transmission. A comparative overview of droplet and aerosol transmission mechanisms is provided in **Table 1**.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Table 1. Characteristics of droplet vs. aerosol transmission.

Transmission Mode	Particle Size	Travel Distance	Suspension Time	Example Pathogens
Droplet Transmission	>5 µm	Short-range (<2m)	Seconds to minutes	Influenza, SARS-CoV-2, Common Cold
Aerosol Transmission	<5 µm	Long-range (>2m)	Minutes to hours	Tuberculosis, Measles, SARS-CoV-2

The survival and infectivity of airborne pathogens are significantly affected by various environmental factors, including relative humidity, ambient temperature, airflow patterns, room layout, and so on. Studies show that if the air is too dry (low humidity), then virus particles are more easily suspended in the air and can survive longer. Conversely, if the air is humid (high humidity), virus-carrying droplets tend to fall to the ground quickly. Air temperature also plays a role. Some viruses are more durable and active in cold temperatures. In addition, small particles in the air can act as "vehicles" for viruses, helping them move and spread more widely, increasing the chances of others being exposed [25].

The dynamics of transmission also differ significantly between indoor and outdoor environments. In indoor environments such as hospitals, offices, or public transportation, the risk of airborne transmission is significantly higher due to limited ventilation and continuous air recirculation with minimal fresh air exchange. These conditions facilitate the accumulation of virus-laden particles in the air. In contrast, outdoor environments generally allow better air dispersion, enabling viral particles to dilute and dissipate more rapidly. However, in conditions where the outdoor air is still, such as during calm weather with little wind, and when people gather nearby, the potential for transmission still exists [26].

Airflow or wind circulation plays a crucial role in the transmission of airborne viruses. The better the air circulation, the lower the likelihood of viruses surviving and spreading [27, 28]. When wind speed is high (around 3 m/s), exhaled breath and body heat are disrupted, causing pathogen-laden droplets to be carried rapidly and directly toward other individuals. This increases the risk of infection, even at a greater distance. In contrast, when the wind is weak (around 0.2 m/s), droplets tend to remain around the body and can be inhaled by people standing nearby, particularly at distances less than 0.5 meters. However, if individuals are spaced more than 1.5 meters apart in low-wind conditions, droplets have time to settle or disperse in the air, resulting in a lower risk of exposure [29]. **Figures 3 and 4** show the role of airflow in the transmission of airborne pathogens.

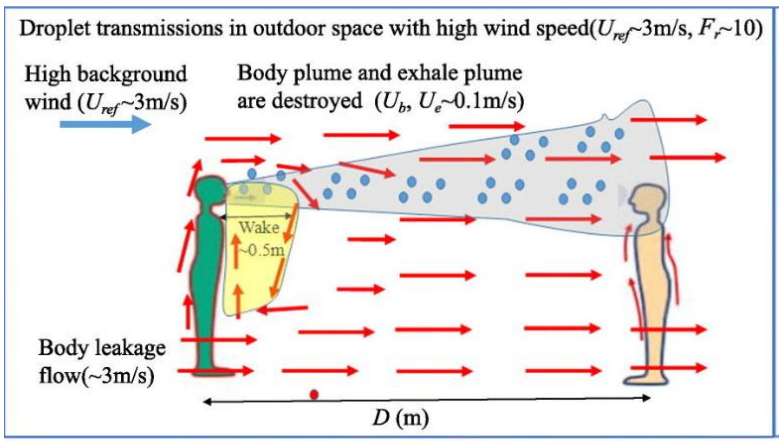

Figure 3. The role of air in carrying airborne pathogens: Highest exposure risk [29].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

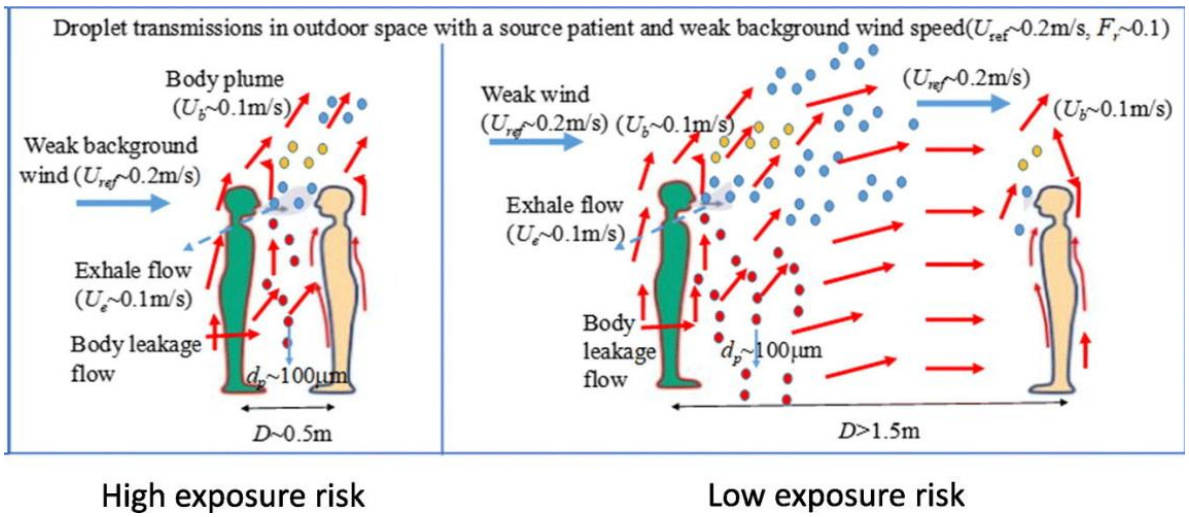

Figure 4. The role of air in carrying airborne pathogens: high and low exposure risk [29].

This section offers a foundational overview of airborne pathogen transmission, emphasizing the fundamental differences between droplet and aerosol pathways, as well as the critical factors that affect pathogen viability and infectivity in the air. It further explores the key environmental and biological variables that influence transmission dynamics, outlines current methods used to assess the risk of airborne spread, and introduces emerging technologies designed to mitigate transmission effectively.

3.2.1. Airborne pathogen types

Airborne pathogens such as viruses, bacteria, and fungi can originate from a range of sources such as infected individuals, healthcare settings, crowded public spaces, and decomposing organic materials. These pathogens are primarily transmitted through the respiratory tract when a person inhales airborne particles containing droplets expelled by an infected individual during coughing, sneezing, or speaking. Additionally, indirect transmission can occur when droplets settle on surfaces and are later transferred to a person's face via hand contact, allowing the pathogen to enter the body (see **Figures 3** and **4**). **Table 2** provides an overview of commonly encountered airborne pathogens, their associated health effects, and the temperatures required to inactivate them.

Airborne pathogenic microorganisms can be found in both outdoor and indoor environments. External sources include building materials, furniture, pets, ornamental plants, organic waste, and human activities such as coughing, sneezing, talking, sweeping, washing, and flushing toilets. These microorganisms can enter the room through windows, ventilation, or be carried by human movement, making them a major source of air contamination in closed spaces, especially in dense areas and with poor ventilation systems. The information presented in **Table 2** is very important as a reference in designing disinfection and air quality control strategies, especially in locations that are vulnerable to the spread of disease, such as hospitals, public facilities, and densely populated residential areas. By understanding the lethal temperature of each pathogen, control measures such as heating, sterilization, and air filtration can be applied more effectively to minimize the risk of infection.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Table 2. Effect of airborne pathogenic microorganisms on health and lethal temperatures for control [30]).

Species	Microorganisms	Health impact	Lethal Temperature (°C)	Reference
Bacteria	*Escherichia coli*	Gastroenteritis	45-56	[31]
		Abdominal cramps		[32]
		Diarrhea		[33]
		Vomiting		[34]
	Pseudomonas fluorescens	Septicemia	45-56	[35]
	Legionella pneumophila	Pneumonia	45-56	[36]
		Pulmonary infections		[37]
		Influenza		[38]
	Staphylococcus epidermidis	Food poisoning	80-180	[39]
	Staphylococcus aureus	Septicemia	80-180	[40]
		Endocarditis		
		Meningitis		
		Osteomyelitis		
	Micrococcus luteus	Endocarditis	80-180	[41]
		Meningitis		
	Mycobacterium	Tuberculosis	45-56	[42]
Fungi	*Aspergillus versicolor*	Gastroenteritis	45-56	[43]
		Abdominal cramps		
		Diarrhea		
		Vomiting		
	Aspergillus niger	Ear infections	45-56	[44]
		Sore throat		
		Bronchitis		
		Skin infections		
	Penicillium citrinum	Renal tumors	45-56	[45]
	Penicillium spinulosum	Septicemia	45-56	
Viruses	Bacteriophage		56-80	
	Measles virus	Measles	45-56	
	NWS/G70C (H11N9)	Pneumonia	56-80	
		Pulmonary infections		
		Influenza		
	Norovirus	Gastroenteritis	56-80	[43]
		Abdominal cramps		
		Diarrhea		
		Vomiting		
	Adenovirus	Ear, respiratory tract, gastrointestinal, and liver infections	56-80	
	Varicella-zoster virus	Chicken pox	56-80	

3.2.2. Infection mechanism

As explained earlier, the transmission of airborne pathogens begins when an infected individual releases microscopic particles into the air through activities such as coughing,

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

sneezing, talking, or even breathing (see **Figures 3** and **4**). These particles can be large droplets that quickly fall to surfaces, or very small aerosols (droplet nuclei) that can remain suspended in the air for long periods, especially in closed spaces with poor ventilation. **Figure 5** illustrates the various routes of pathogen transmission, which include not only airborne transmission but also surface contact and other media.

(i) Droplet and airborne

Airborne transmission is one of the main ways infectious diseases spread from one person to another. When someone coughs, sneezes, talks, or even breathes, they release thousands to tens of thousands of tiny droplets containing microorganisms such as viruses, bacteria, or fungi into the air. Large droplets (>10 microns) usually only stay in the air for about 1–2 meters before falling to the surface, but under certain conditions, especially in closed and humid rooms, droplets can evaporate and turn into very small microparticles (droplet nuclei or aerosols) that can float in the air for several hours. These aerosols can be inhaled by others and cause respiratory infections such as influenza, tuberculosis, and COVID-19 [46].

(ii) Direct and indirect contact

Transmission through direct and indirect contact is also the main route of transmission of various infectious diseases. Direct contact occurs when someone has physical interaction with a source of infection, such as touching an open wound, shaking hands with an infected person, or direct contact with body fluids (for example, in the case of hepatitis A through the fecal-to-oral route). Meanwhile, indirect contact involves intermediaries in the form of objects or surfaces that have been contaminated with microorganisms, such as doorknobs, eating utensils, or medical devices that have not been properly sterilized. In health facilities, medical equipment that is used repeatedly without sterilization can be a source of cross-transmission to other patients [47].

(iii) Foodborne and waterborne

Waterborne and foodborne infections are serious public health threats, especially in areas with poor sanitation. Pathogenic microorganisms such as Enteroviruses, Noroviruses, Adenoviruses, and Rotaviruses are commonly found in groundwater, surface water, or drinking water contaminated with sewage. In the context of food, pathogens such as Listeria monocytogenes, Staphylococcus aureus, Escherichia coli, Salmonella, and Campylobacter are often found in food products that are not properly processed or stored. Waterborne and foodborne diseases include diarrhea, cholera, typhus, hepatitis A, gastroenteritis, and dysentery [48].

(iv) Vector-bone

Vector-borne diseases occur when disease-causing microorganisms are transmitted to humans through the bite of insects or intermediate animals such as mosquitoes, flies, ticks, or other blood-sucking insects. Mosquitoes are the primary vectors of many serious diseases such as malaria, dengue fever, chikungunya, Zika, and filariasis. The life cycle of mosquitoes is highly dependent on the presence of clean stagnant water, making unclean and poorly managed environments ideal breeding grounds for mosquitoes [49-51].

By understanding and intervening in each pathogen transmission pathway appropriately, infectious disease prevention efforts can be carried out in a more comprehensive, targeted, and effective manner because this approach allows for the formulation of strategies that are in accordance with the transmission characteristics of each type of pathogen. For example, for pathogens that spread through the air and droplets, the most effective interventions include implementing good ventilation in closed spaces, using masks with high filtration (such as N95), and maintaining a physical distance of at least 1–2 meters, as well as reducing

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

population density indoors. These efforts can significantly reduce the risk of inhalation of aerosols containing pathogenic microorganisms [46].

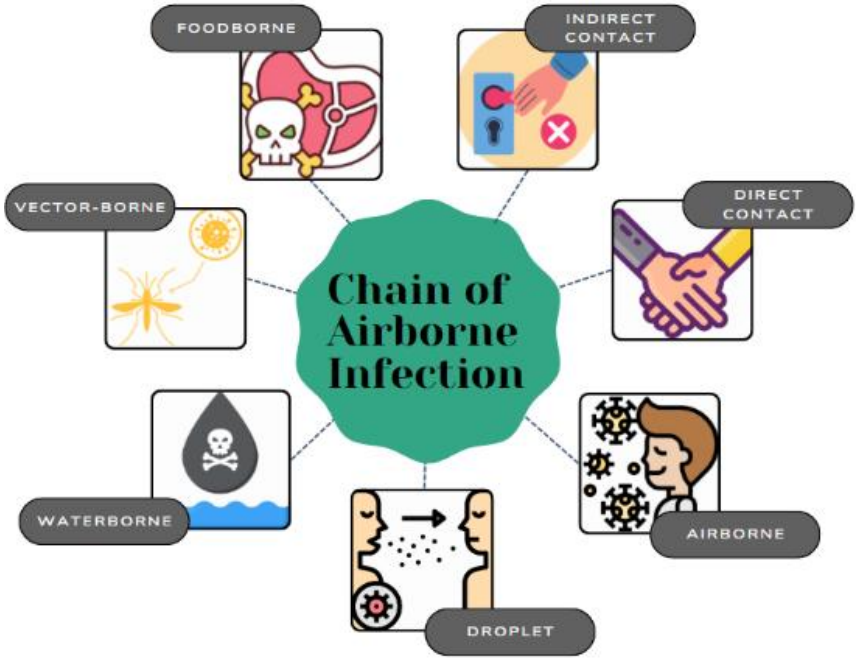

Figure 5. Various ways of disease transmission.

In direct and indirect contact pathways, understanding the touchpoints and routines of human activities is the key to intervention. Interventions can be carried out through education on clean and healthy living behavior, increasing the habit of washing hands with soap, using alcohol-based hand sanitizers, and routine disinfection of frequently touched surfaces such as tables, stair railings, light switches, and medical devices. In the health care environment, sterilization of medical devices and the use of personal protective equipment according to procedures are the main standards for preventing nosocomial infections [47].

In the case of waterborne and foodborne transmission, interventions require an upstream-to-downstream approach. In the water sector, water treatment should be carried out through a combination of techniques such as physical filtration, the use of chemical disinfectants (chlorine, ozone), and high-tech methods such as ultraviolet (UV) irradiation to ensure that pathogenic microorganisms are eliminated. In the food sector, food safety controls must be implemented from the production process, transportation, storage, to serving food. Kitchen sanitation protocols, appropriate storage temperatures, and worker training in the food industry play a critical role in preventing the transmission of pathogens from food to humans [48].

Meanwhile, in vector-based transmission, interventions are dualistic, namely chemical and ecological. The use of insecticides, larvicides, and fogging can eradicate mosquitoes and larvae in high-risk locations, but must be accompanied by environmental management such as draining and covering water reservoirs, recycling waste that can be a breeding ground for mosquitoes (such as used cans, used tires, or flower pots). Community empowerment approaches are also important, such as programs to drain, cover, and bury used goods, mosquito net use campaigns, and community training to recognize and control vector populations around homes [51].

Overall, successful infection prevention relies heavily on a thorough understanding of transmission routes, as each pathogen has different transmission dynamics. By implementing evidence-based interventions at each transmission route, the potential for disease spread can

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

be significantly reduced, even before an outbreak occurs. This approach must be integrative, combining microbiology, epidemiology, public health policy, human behavior, and adequate sanitation infrastructure. Through this synergy, infectious disease resilience systems can be built sustainably and be responsive to potential future pathogen threats.

3.2.3. Mechanism of airborne pathogen transmission through the air

Airborne pathogen transmission occurs through three main stages (see **Figure 6**), namely: (i) generation and respiration; (ii) airborne transport; and (iii) inhalation, deposition, and infection. The initial stage of airborne transmission begins when respiratory activities such as breathing, speaking, and coughing generate aerosols from different regions of the respiratory tract, each contributing to distinct aerosol size distributions. For instance, the bronchioles tend to produce smaller droplets, typically around 4–6 µm, whereas the oral cavity can generate much larger droplets, reaching sizes up to 220 µm. The size of the aerosol particles is closely related to the site of origin within the respiratory system. The deeper the formation site, the smaller the aerosol particles tend to be produced. **Table 3** presents estimated aerosol emission rates for different human activities, illustrating their role in airborne disease spread [52]. The release of virus-laden aerosols during respiratory activities is influenced by various factors, including the stage of illness, age, body mass index (BMI), and individual medical history. For instance, in children, the respiratory system is still developing. Their lungs have a smaller total surface area, fewer bronchioles (small airway branches), and fewer alveoli (air sacs responsible for gas exchange) compared to adults. As a result, the volume of air moved during respiratory activities is generally lower, and the physical forces that generate aerosols. This leads to a lower production and release of respiratory aerosols in children than in adults. However, this does not eliminate the risk of transmission [53, 54].

The second stage is aerosol transport, which is the process of aerosol movement in the air that is influenced by various environmental factors such as temperature, relative humidity, ultraviolet (UV) light exposure, air flow, and ventilation systems. These factors determine how long aerosols can remain in the air and how far they can move from one place to another. When aerosols containing viruses are inhaled by a person, these particles can settle in various parts of the respiratory tract, depending on the size of the particles (see **Table 3**). Meanwhile, aerosols that are not directly inhaled or remain in the air will experience changes in size due to the process of evaporation, coagulation, and precipitation. These processes can change the physical and chemical properties of aerosols, which ultimately affect the ability of aerosols to transport viruses and how long the viruses can survive in the air [52, 55, 56].

Table 3. Aerosol emission rates for different human activities [52].

Activity	Average Aerosol Emission Rate (particles/min)	Example Pathogens
Breathing	100–1,000	Tuberculosis, Influenza
Talking	1,000–10,000	SARS-CoV-2, Common Cold
Coughing/Sneezing	10,000–100,000	Measles, Influenza, Tuberculosis

The third stage describes the settling process of aerosol droplets in the air, which is strongly influenced by particle size and airflow velocity, as illustrated in **Figure 7**. A five-micrometer aerosol released from a height of one point five meters will settle on the ground in approximately thirty-three minutes. In comparison, a one-micrometer aerosol droplet released from the same height can remain suspended in the air for up to twelve hours. This example highlights how the speed and distance of aerosol movement are affected by several key factors. These include the size of the aerosol, where smaller particles take longer to settle,

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

the initial velocity of the airflow that carries the aerosol, such as from coughing or sneezing, and environmental conditions like wind speed in outdoor areas or indoor air movement generated by natural ventilation or mechanical ventilation systems. Once aerosol droplets enter and deposit in the respiratory tract, the body initiates a series of natural clearance mechanisms to eliminate them [56, 57]. These defense responses include the following:

(i) First is mucociliary clearance, where microscopic cilia move mucus containing trapped particles and pathogens toward the throat to be expelled.
(ii) The second is the cough reflex, which helps expel foreign materials from the airways.
(iii) Third is phagocytosis, a process in which immune cells such as alveolar macrophages engulf and neutralize harmful particles and cellular debris.
(iv) Fourth is sneezing, a reflex action that rapidly removes irritants from the upper respiratory tract.
(v) Lastly, the ciliary escalator mechanism moves mucus and particles upward to be expelled from the respiratory system.

These processes work together to protect the lungs from harmful substances and maintain respiratory health.

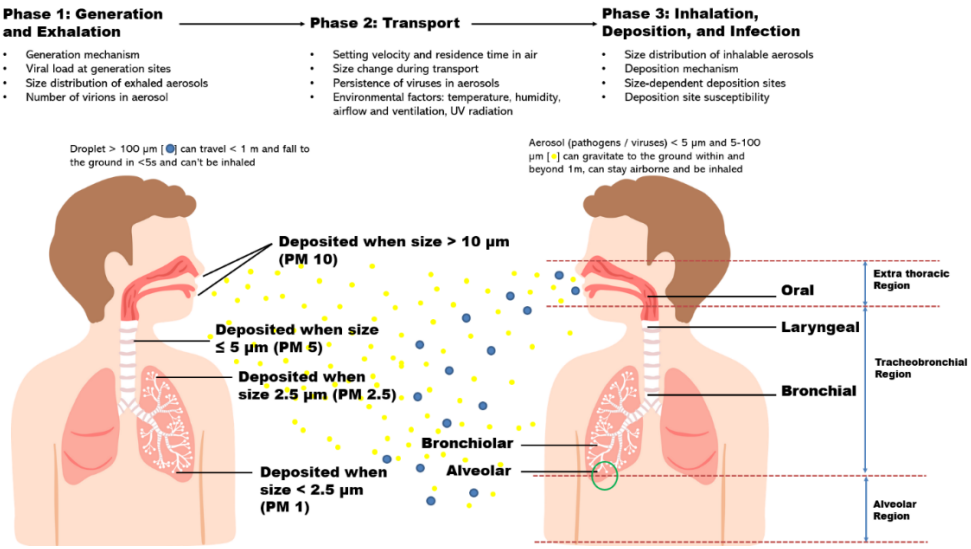

Figure 6. Three components in the process of transmitting pathogenic microorganisms through the air, including (i) generation and exhalation; (ii) transport; and (iii) inhalation, deposition, and infection (modified from literature [52]).

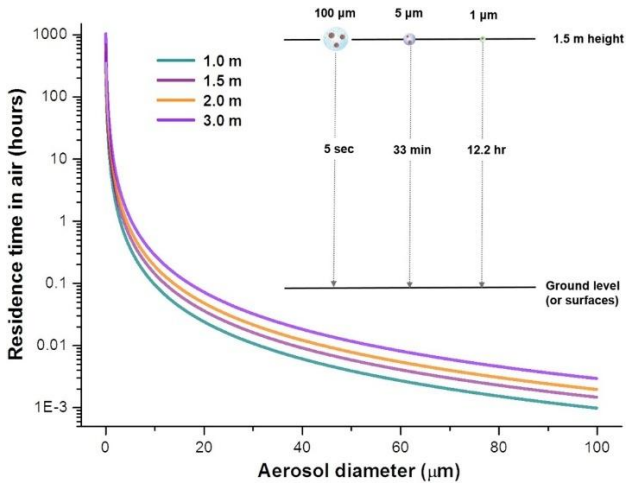

Figure 7. The residence time of aerosols of varying sizes in the air [57].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

3.2.4. Suspension and infectivity times of virus-loaded aerosol

The size and composition of droplets released through respiratory activity greatly determine the fate of the droplets in the air. Smaller droplets (with a radius of less than 50 µm) have a large surface area to volume, making them evaporate quickly. When the water evaporates, the droplets shrink and leave behind a solid residue in the form of droplet nuclei, which are very light and can remain suspended in the air for hours, depending on environmental conditions. In contrast, larger droplets have a higher mass, thus experiencing a greater gravitational force and will settle to the surface before all the water evaporates [55].

An important concept underlying the process of determining the time of droplets in the air is the comparison between the evaporation time and the sedimentation time, which is illustrated in **Figure 8**. If the evaporation time is faster than the sedimentation time (evaporation time < sedimentation time), then the droplets will shrink into droplet nuclei and remain suspended in the air for a long time. Conversely, when the evaporation time exceeds the sedimentation time, larger droplets tend to settle on surfaces before they can evaporate and become aerosols. In this condition, the likelihood of airborne transmission is significantly reduced. The variation in aerosol suspension duration under different environmental conditions is presented in **Table 4** [56].

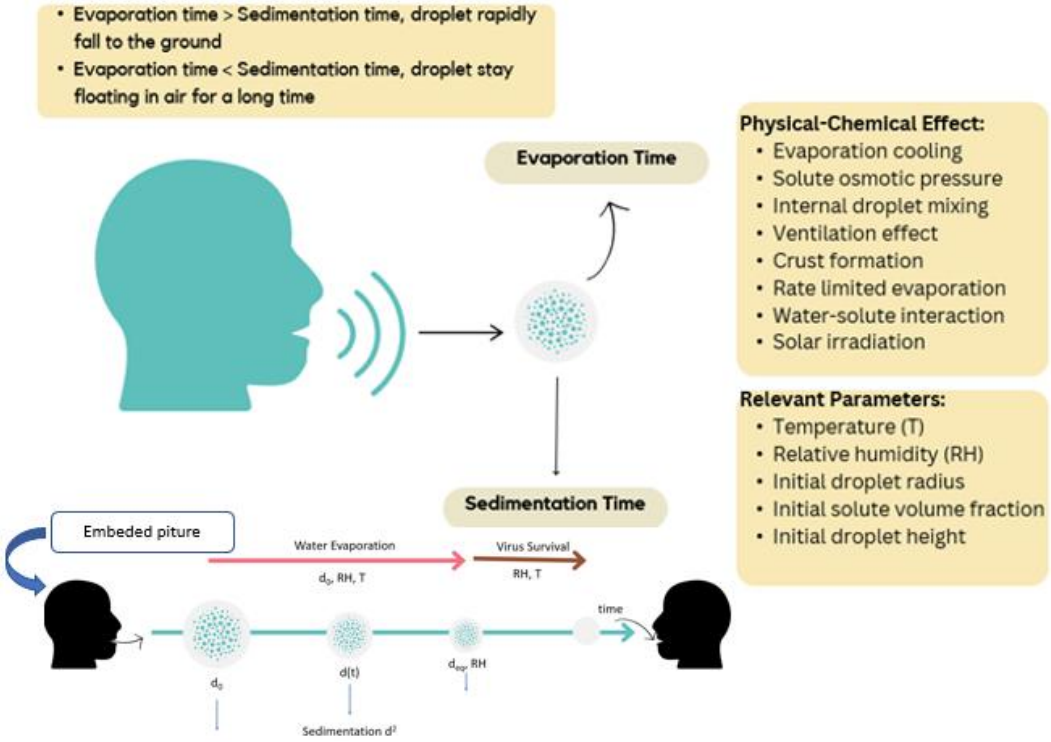

Figure 8. Illustration of the duration respiratory droplets remain suspended in the air, which is a critical factor in understanding airborne transmission of infectious diseases [56].

Furthermore, **Figure 8** explains that the suspension time of droplets depends on various physicochemical factors, including air temperature, relative humidity (RH), initial droplet size, initial release height, and the composition of the solute in the droplet. In addition, the interaction between air ventilation, the effect of sunlight, the osmotic pressure of the solute, and the formation of a crust layer on the surface of the droplet also play a role in the stability and lifetime of viral infection in aerosols. During the suspension, the virus contained in the droplet will also be affected by these environmental factors, which can extend or shorten its infectivity period [56].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

The timeline in the bottom illustration in **Figure 8** shows how the droplet size changes from initial release (d_o), shrinks over time due to evaporation (d(t)), reaches its final size (d_{eq}), and then begins to settle. This process occurs simultaneously with the survival of the virus, which is also strongly influenced by ambient temperature and humidity. Therefore, the indoor microclimate conditions are crucial to whether the virus-carrying aerosol will remain suspended long enough to transmit infection to other individuals. Thus, strategies to prevent aerosol transmission depend not only on controlling the distance between individuals but also on controlling indoor air quality to accelerate the total evaporation and inactivation of the virus before it can be inhaled by others [56].

Table 4. Estimated suspension time of respiratory droplets in air.

Droplet Diameter (µm)	Estimated Suspension Time in Still Air
>100	Falls to the ground in seconds
30–100	Falls within minutes
10–30	Falls within 10–20 minutes
<5	Can remain airborne for hours

3.2.5. Indoor vs. outdoor transmission

Transmission of airborne pathogens is greatly influenced by the environmental conditions in which individuals interact. **Table 5** summarizes the key environmental differences affecting airborne pathogen spread. Indoor environments, such as hospitals, offices, schools, and public transportation, have a higher risk of transmission than outdoor environments. This is due to limited ventilation, recirculated air, and high human density, which cause aerosols containing pathogens to remain in the air for a long time and be inhaled by other individuals [57].

In addition, indoor environments have minimal exposure to ultraviolet (UV) light, which should work to inactivate airborne viruses or bacteria. Indoor humidity, especially in those with air conditioning systems, also tends to be low, which can prolong the life span of aerosol particles in the air. In contrast, in outdoor environments, natural airflow helps disperse and dilute pathogen particles, reducing their concentration and reducing the risk of transmission. Direct sunlight provides UV light that is effective in inactivating viruses and bacteria. Higher humidity also helps reduce the ability of aerosols to persist in the air. However, transmission in outdoor spaces can still occur, especially in dense crowds, stagnant air, or in semi-enclosed areas such as covered markets or stadiums [57].

Differences in airflow that influence pathogen concentration in indoor and outdoor environments are illustrated in **Figure 9**. In outdoor settings, aerosol transmission of the virus generally occurs only at close range, directly behind an infected individual. The person's breath or cough generates aerosols containing viral particles, but these aerosols are rapidly diluted by natural air turbulence such as wind. As a result, the risk of transmission decreases significantly with increasing distance from the source, and the possibility of long-range transmission is minimized. In open-air environments, free airflow effectively disperses the virus, restricting exposure to areas very near the point of emission. In contrast, in indoor spaces, aerosols released by an infected person remain within a confined volume of air and are not easily diluted. Although air turbulence may also occur indoors, limitations in space and ventilation cause the aerosols to persist and spread more extensively. Consequently, there is a risk of both short-range and long-range transmission, as viral particles can circulate throughout the room [58].

Artificial ventilation can assist in reducing airborne viral concentrations, but it is often insufficient to eliminate pathogens, particularly when the system is not operating at optimal

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

capacity. For this reason, in indoor environments, the implementation of preventive measures such as wearing masks, enhancing air circulation, limiting the number of occupants, and reducing the duration of interactions is crucial to minimize the risk of airborne transmission. Moreover, disease prevention strategies must be adapted to the characteristics of the environment. In enclosed spaces, the use of mechanical ventilation systems, high-efficiency particulate air (HEPA) filters, proper humidity regulation, and controlling room occupancy are essential. In contrast, in outdoor settings, maintaining physical distance, avoiding large gatherings, and wearing masks when near others remain important practices to reduce transmission risk [59, 60].

Table 5. Comparison of airborne pathogen transmission in indoor and outdoor environments.

Environment Factor	Indoor	Outdoor
Ventilation and Air Flow	Limited, air is frequently recirculated	Natural air flow is high and freer
Pathogen Dilution	Low aerosols can accumulate in the air	High, particles spread and dilute quickly
UV Ray Exposure	Minimal, limited by walls/roof	High sunlight helps inactivate pathogens
Relative Humidity	Varies, often low in air-conditioned rooms	Generally naturally taller
Human Density	Tends to be high in closed spaces	Usually lower, widely spread
Risk of Pathogen Transmission	High, especially without ventilation mitigation	Low, except in dense crowds or semi-enclosed areas
Location Examples	Hospitals, offices, classrooms, and public transportation	City parks, open streets, sports fields, and pedestrian areas

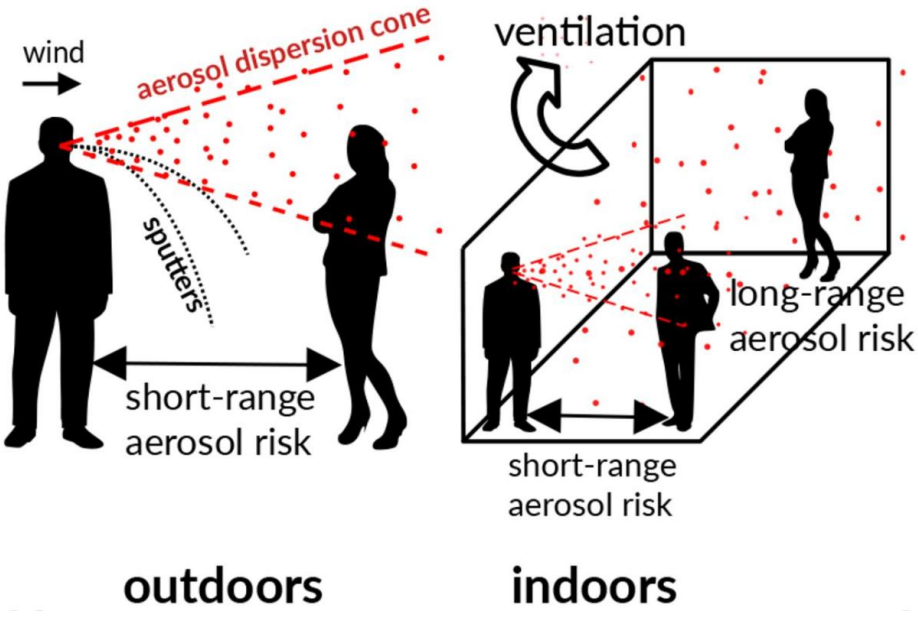

Figure 9. Differences in air flow that affect pathogen concentrations indoors and outdoors [58].

3.3. Influencing Factors in Airborne Pathogen Spread

The ability of airborne viruses to remain suspended in the atmosphere and maintain their infectivity is greatly influenced by several factors, which are explained in detail as follows.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

3.3.1. Human occupancy and activity

The level of occupancy and human activity in a space has a significant influence on the spread of airborne pathogens. High-density areas such as offices, classrooms, hospitals, and public transportation have a greater potential for transmission because humans are the main source of various pathogenic microorganisms, including bacteria, viruses, and fungal spores. These microorganisms are released into the air through everyday activities such as breathing, talking, coughing, and sneezing. In closed environments with limited ventilation, the accumulation of contaminated air particles can increase sharply, increasing the risk of transmission [61].

The size and number of droplets released vary depending on the activity (see **Table 3**). Normal breathing releases small droplets that evaporate quickly, but can form droplet nuclei that remain suspended in the air for long periods. Loud talking and singing generate more droplets due to vocal cord vibrations, increasing the risk in crowded places such as concerts and places of worship. Meanwhile, coughing and sneezing produce a combination of large and small droplets that support both short- and long-range transmission, especially in poorly ventilated spaces [62]. Physical activity, such as exercise, also accelerates bioaerosol emissions and amplifies indoor airflow, which extends the spread of pathogens in the indoor micro-atmosphere [63, 64].

Mitigation efforts to reduce the risk of transmission due to human activities include the implementation of effective ventilation systems, the use of personal protective equipment, reduced occupancy, and behavioral regulation. The use of mechanical ventilation, portable air purifiers, and HEPA filters has been shown to reduce the concentration of aerosols in the air. In addition, the implementation of rotating occupancy schedules, building designs that consider natural air circulation, and regular air quality monitoring are strategic steps to prevent the spread of airborne diseases in high-risk locations. A comprehensive understanding of the role of occupancy and human activities is essential to designing effective control strategies in both public and private spaces [61-64].

3.3.2. Aerosol droplets and bioaerosols

Aerosols and bioaerosols are microscopic particles suspended in the air that play an important role in the spread of infectious diseases through the respiratory tract. The ability of aerosols to transmit pathogens is highly dependent on the physical and chemical properties of the droplets containing disease-causing microorganisms (i.e., viruses, bacteria, and fungi) [65]. These droplets are mostly (more than 99%) water, with the remainder being biological compounds such as enzymes (amylase, lipase), mucus, white blood cells, and lysozyme. Droplets originating from healthy individuals tend to be more stable and less likely to break apart [66]. In contrast, droplets from infected individuals are more susceptible to fragmentation, forming very small particles (<5 microns) that can remain airborne for longer and potentially reach the lower respiratory tract, increasing the risk of infection [67].

Physicochemical characteristics of droplets, such as viscosity, density, and surface tension, greatly influence the size, shape, and behavior of droplets while in the atmosphere [68]. **Figure 10** illustrates three types of deformation that can occur during droplet movement in the air, which result in changes in droplet size [68], including:

(i) Vibrational Changes: Changes in shape due to vibrations from external disturbances, such as air turbulence or unsteady flow. The droplet shape can become temporarily elongated or wavy, without breaking. These vibrations affect the stability of the droplet and the time the particle remains in the air.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

(ii) Translational Changes: Occurs when droplets experience shape distortion while moving through the air due to flow pressure, temperature differences, or speed. These changes are important for understanding how far droplets can travel and their potential for transmission under various environmental conditions.

(iii) Bag Deformation: Occurs when inertial forces exceed surface tension (high Weber number), causing droplets to break into many small particles. These small droplets resulting from fragmentation can remain in the air longer and are more likely to contain active pathogens, especially in closed spaces with poor air circulation.

The chemical composition of bioaerosols also plays an important role in maintaining pathogen infectivity. Respiratory droplets contain water, proteins, salts, and mucus that create a protective environment for pathogens. For example, viruses such as SARS-CoV-2 and influenza show high stability in dry aerosols, while measles virus and tuberculosis bacteria remain active longer in humid environments [69]. In addition to water (90–95%), droplets also contain organic and inorganic compounds that affect the evaporation rate and viability of pathogens. Proteins and lipids in mucus provide protection against temperature changes, drying, and exposure to ultraviolet (UV) light. Meanwhile, electrolytes such as sodium, potassium, and chloride affect the surface tension of droplets, which affects their stability and size distribution. The chemical composition of droplets can also vary depending on the health condition of the individual. In patients with respiratory tract infections, changes in the concentration of components that can increase infectivity have been found [69]. **Table 6** summarizes the main components of respiratory droplets and their roles in supporting pathogen transmission.

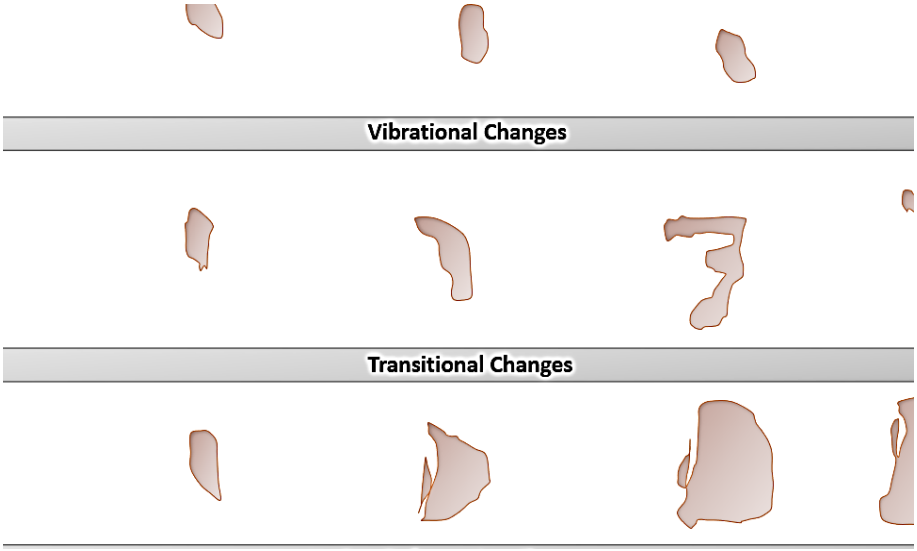

Figure 10. Schematic illustration of the vibrational, transitional, and bag deformation shape changes of water droplets moving in the air [68].

Table 6. Chemical composition of respiratory droplets and their influence on pathogen viability.

Component	Percentage	Function in Pathogen Transmission
Water	90–95%	Determines evaporation rate and droplet size
Proteins	1–5%	Forms protective coating around pathogens
Lipids	<1%	Enhances viral stability and adhesion to surfaces
Salts (Na+, K+, Cl-)	1–3%	Affects droplet surface tension and stability
Mucins	0.5–2%	Increases droplet viscosity, influencing suspension time

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

3.4. Environment Variables

3.4.1. Relative humidity

Relative humidity is an environmental factor that greatly influences the survival and spread of airborne pathogens, including viruses, bacteria, and fungi. **Table 7** summarizes the effects of different humidity levels on airborne pathogen transmission. At low humidity levels (below 40%), droplets containing pathogens will dry out more quickly. This drying can reduce the viability of some viruses that require moisture to survive. However, this condition also causes the formation of smaller aerosols that can stay in the air longer, increasing the risk of long-distance pathogen spread. Some viruses, such as influenza viruses, are known to be more stable and spread more effectively in dry air conditions [70, 71].

In contrast, at moderate humidity (40–60%), the size of aerosol droplets is more controlled, where larger droplets will fall to the surface more quickly, thus reducing the number of infectious particles suspended in the air. At this humidity range, the survival rate of many types of viruses and bacteria also decreases, making it an optimal condition for suppressing the risk of airborne pathogen transmission. In addition, moderate humidity also supports human respiratory comfort because it reduces respiratory tract irritation that often occurs in environments that are too dry or too humid [70, 71].

Meanwhile, at high humidity (above 60%), droplets tend to remain suspended longer before finally falling to the surface, increasing the risk of surface and environmental contamination. High humidity also creates conditions that support the growth of pathogens such as bacteria, viruses, and especially fungi, which thrive in humid environments. This contributes to an increased risk of infection as well as the emergence of other health problems such as allergies due to fungal growth on walls or household furniture [70, 71].

Controlling relative humidity in confined spaces, especially in areas with limited ventilation or in extreme climates, is a challenge. In addition, the optimal humidity level to prevent the spread of pathogens can vary depending on the type of microorganism. Therefore, a balanced and adaptive approach to humidity management is required, including the use of effective humidity control and air purifier systems, accompanied by regular maintenance and monitoring to ensure their effectiveness in creating an environment safe from exposure to airborne pathogens.

Table 7. Impact of relative humidity on airborne pathogen transmission.

Humidity Level	Effect on Droplets	Pathogen Stability	Transmission Risk
<40% (Low Humidity)	Rapid droplet evaporation, formation of smaller aerosols	Increased stability of some viruses (e.g., influenza, SARS-CoV-2)	High, due to prolonged airborne suspension
40–60% (Moderate Humidity)	Optimal conditions for droplet dispersion and deposition	Reduced virus stability	Moderate, as humidity limits long-range transmission
>60% (High Humidity)	Droplet growth, increased gravitational settling	Reduced virus viability, increased bacterial survival	Lower, as airborne transmission is minimized

3.4.2. Temperature

Temperature is a major factor in the spread of airborne pathogens because it plays a direct role in determining the composition and survival of microorganisms in the air [72]. **Table 8** summarizes the effects of different temperature conditions on pathogen stability. High temperatures can generally inactivate various types of pathogens, mainly due to the

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

denaturation process that damages the protein and cell structure of the pathogen, causing death or inactivation. Therefore, high temperatures are often used in sterilization procedures and air treatment technologies such as thermal treatment [73]. Conversely, low temperatures can actually prolong the life span of some viruses, especially respiratory viruses such as influenza, which are more stable and survive longer in cold environments. This explains the increased spread of diseases such as flu during the winter [74].

In addition, low temperatures also slow down the metabolic activity of microorganisms, remaining active longer in the air or on surfaces. Although temperature control can be an effective strategy to inhibit the spread of airborne pathogens, its application in large buildings or public spaces often faces challenges. Temperatures that are too high can cause discomfort to occupants and increase energy costs, while temperatures that are too low also pose a risk of causing health problems [73]. Therefore, temperature regulation in a space must consider the balance between human comfort, pathogen control effectiveness, and energy efficiency.

Table 8. Impact of temperature on airborne pathogen viability.

Temperature Range	Effect on Viral Stability	Effect on Bacterial Survival	Transmission Risk
<10°C (Cold)	High, prolonged survival	Moderate, stable	High, increased airborne spread
10–25°C (Moderate)	Variable, reduced for some viruses	High, optimal for bacteria	Moderate
>25°C (Warm/Hot)	Decreased, rapid inactivation	Decreased, bacterial growth inhibited	Low

3.4.3. Airflow pattern and room layout

Airflow patterns and room layout are important factors that influence the spread of airborne pathogens. The way air moves and disperses (see **Figure 11**) within a room greatly determines how far airborne pathogens can spread. Unidirectional airflow, such as that used in cleanrooms, is designed to move air consistently from clean to dirty areas, minimizing the spread of pathogen particles between areas. In contrast, turbulent or irregular airflow can result in widespread and uneven spread of pathogens, as microorganisms can be randomly dispersed throughout the room and remain airborne longer. In addition, room design, such as asymmetrical room shapes and inappropriate ventilation placement, can create airflow patterns that cause pathogens to concentrate in certain areas, known as “hot zones.” The placement of furniture or other obstructions can also impede air circulation, creating stagnant areas where pathogens can become trapped and accumulate [75, 76].

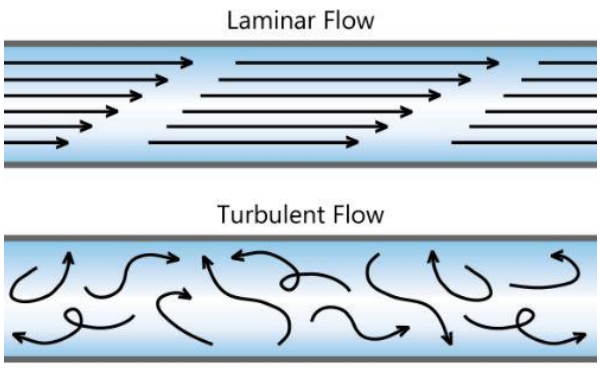

Figure 11. General airflow pattern.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Airflow can be categorized into laminar flow, turbulent flow, and displacement ventilation. Laminar airflow, commonly used in operating rooms and clean rooms, directs air in a controlled, uniform pattern, reducing cross-contamination risks. Turbulent airflow, found in most buildings, involves irregular air movement that can create unpredictable aerosol dispersion, increasing the risk of airborne transmission [77, 78]. Displacement ventilation, which introduces fresh air at low velocities near the floor while exhausting contaminated air at the ceiling, is an effective strategy for reducing airborne pathogen concentration in occupied spaces [79]. **Table 9** compares these airflow patterns and their effectiveness in pathogen control.

The room layout also plays a vital role in pathogen distribution. Enclosed spaces with poor ventilation and high occupancy density pose a greater risk for airborne transmission, particularly in settings such as hospitals, classrooms, and public transportation. Poor room designs, such as narrow hallways, poorly placed air vents, and obstructed airflow, can contribute to localized aerosol buildup, increasing the potential for infection hotspots. Proper airflow management in indoor environments can be achieved through strategic placement of air supply and exhaust vents, use of directional airflow, and incorporation of air purification systems [76]. Ensuring that airflow patterns facilitate contaminant removal rather than recirculation is essential for effective airborne disease prevention. Optimizing room layout and airflow patterns is an essential component of infection control strategies in healthcare facilities, workplaces, and public buildings.

Table 9. Comparison of airflow patterns in indoor environments.

Airflow Type	Description	Effect on Pathogen Dispersion	Common Applications
Laminar Flow	Controlled, unidirectional airflow	Minimizes cross-contamination	Operating rooms, clean rooms
Turbulent Flow	Irregular air movement	High dispersion, increases infection risk	Offices, classrooms, hospitals
Displacement Ventilation	Fresh air introduced at low level, exhausted at high level	Reduces airborne concentration	Theaters, conference rooms

3.4.4. Environmental contamination and surface reaerosolization

Environmental contamination and surface reaerosolization are important factors influencing the spread of airborne pathogens. Once pathogens are released into the air through coughing, sneezing, or other activities, they can settle on surfaces and become a source of ongoing contamination. Highly touched surfaces, such as doorknobs, tables, and shared equipment, have the potential to harbor infectious pathogens. If not thoroughly cleaned, these surfaces can act as reservoirs of pathogens, increasing the risk of disease transmission. Although routine cleaning and disinfection can reduce the level of contamination, some pathogens can persist for long periods on surfaces, depending on the type of material and the biological characteristics of the microorganisms. This increases the possibility of recontamination through direct contact or reaerosolization, which is the return of pathogenic particles to the air due to disturbances on contaminated surfaces, such as human movement or cleaning activities. This is particularly common in high-traffic settings such as offices, shopping centers, or healthcare facilities. Although conventional cleaning methods can reduce the number of pathogens, dust or small particles containing pathogens are often difficult to remove completely, making reaerosolization a challenge in controlling

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

the spread of airborne diseases [80]. The extent of surface contamination depends on factors such as droplet size, surface material, environmental conditions, and cleaning frequency. **Table 10** outlines how different surfaces contribute to pathogen survival and potential reaerosolization.

Table 10. Surface characteristics and their impact on pathogen persistence and reaerosolization.

Surface Type	Pathogen Survival Time	Reaerosolization Potential	Example Pathogens
Smooth (e.g., glass, metal, plastic)	Hours to days	Low to moderate	SARS-CoV-2, Influenza
Porous (e.g., fabric, paper, wood)	Minutes to hours	Low	Rhinovirus, Common Cold
Rough (e.g., carpet, textured surfaces)	Days to weeks	High	Tuberculosis, Fungal Spores

3.5. Ventilation System and Particulate Matter

3.5.1. Ventilation system and their activity

Ventilation plays a crucial role in controlling airborne pathogen transmission by diluting infectious aerosols, increasing air exchange rates, and reducing pathogen concentration in indoor environments [81]. Effective ventilation systems help prevent the accumulation of airborne pathogens by promoting air circulation, filtration, and removal of contaminated air, thereby reducing the risk of respiratory disease spread. The efficiency of ventilation depends on factors such as airflow rate, filtration capacity, air distribution, and outdoor air intake. Understanding these factors is essential for designing infection-resistant indoor environments [10].

Ventilation can be categorized into natural ventilation, mechanical ventilation, and hybrid ventilation systems. Natural ventilation, which relies on open windows, doors, and passive airflow, is effective in reducing airborne pathogens in outdoor or semi-open environments but may be limited in enclosed spaces with poor air circulation. Mechanical ventilation, including heating, ventilation, and air conditioning (HVAC) systems, provides controlled air exchange, ensuring that contaminated indoor air is continuously replaced with fresh outdoor air. Hybrid ventilation systems integrate both natural and mechanical ventilation, optimizing airflow and reducing pathogen concentration while maintaining energy efficiency [10]. **Table 11** compares different ventilation strategies based on their effectiveness in airborne infection control.

Poorly designed or inadequate ventilation systems contribute to airborne disease outbreaks, as seen in hospitals, office buildings, schools, and public transportation, where recirculated air increases pathogen accumulation. The air exchange rate (measured in air changes per hour, ACH) is a key parameter in ventilation design, with healthcare settings requiring 6–12 ACH to minimize airborne contamination [82]. **Figure 12** illustrates how ventilation efficiency affects airborne pathogen dispersion in enclosed environments.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Table 11. Comparison of ventilation strategies for airborne pathogen mitigation.

Ventilation Type	Air Exchange Rate	Airflow Control	Filtration Capability	Effectiveness in Pathogen Removal
Natural Ventilation	Low to moderate	Uncontrolled	No filtration	Limited, depends on external airflow
Mechanical Ventilation (HVAC)	Moderate to high	Controlled	HEPA, MERV, UVGI	High, effective in enclosed environments
Hybrid Ventilation	High	Partially controlled	Depends on system	Optimized for energy efficiency and pathogen control

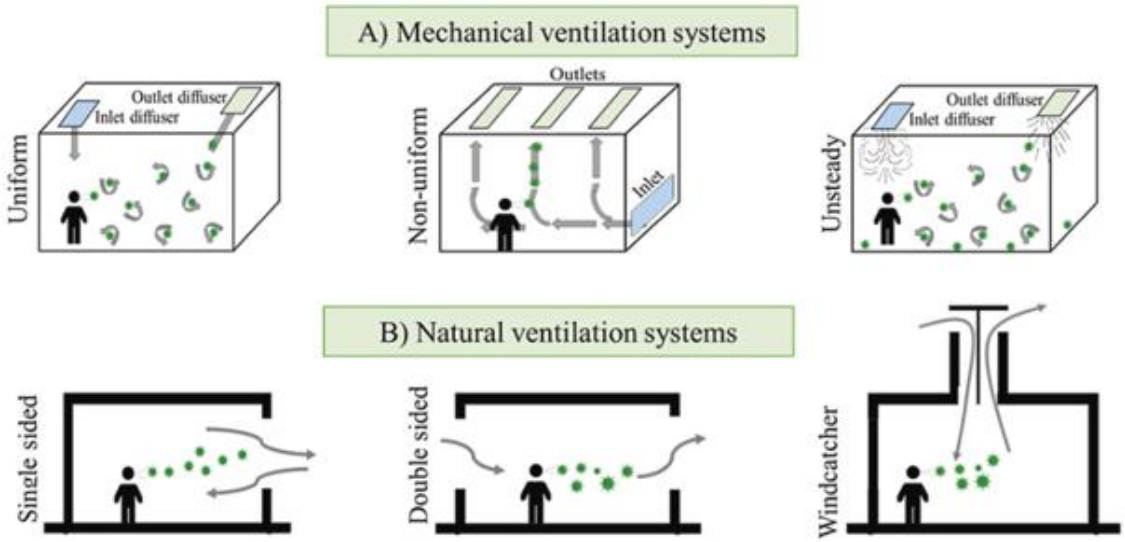

Figure12. Airborne pathogen transmission scenarios through ventilation: (A) mechanical and (B) Natural system [83].

In mechanical ventilation systems, there are three main scenarios: uniform, non-uniform, and unsteady ventilation. Uniform ventilation indicates good air distribution, where fresh air enters through the diffuser inlet and is expelled through the diffuser outlet, creating a homogeneous circulation and is able to effectively dilute and remove bioaerosol particles containing pathogens. In contrast, uneven ventilation creates an unbalanced airflow, causing particle accumulation in certain areas that potentially increase the risk of infection. Unsteady ventilation shows a condition where the airflow pattern is disturbed by pressure changes or technical disturbances, becoming unpredictable and infectious particles can spread widely and persist longer in the air [83].

Meanwhile, in natural ventilation systems, there are three main approaches, namely single-sided ventilation, double-sided ventilation, and windcatchers. Single-sided ventilation only allows air to enter and exit through one opening, such as a window, where air exchange is limited and bioaerosols tend to stay in the room longer. Double-sided ventilation utilizes two openings on opposite sides, creating a more effective cross-ventilation in removing polluted air and replacing it with fresh air, thereby reducing the concentration of pathogens in the air. The windcatcher system uses a wind tower or vertical chimney to capture the flow of outside air and direct it into or out of the room naturally. This system is very effective in encouraging vertical air movement, carrying infectious droplets outside the room efficiently without the help of mechanical devices [83].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

Overall, the effectiveness of ventilation systems, both mechanical and natural, greatly determines the dynamics of the spread of aerosols containing viruses, bacteria, or other pathogens. A well-designed ventilation system can accelerate the removal of infectious particles from a room, reducing the risk of airborne disease transmission. Therefore, in efforts to prevent aerosol-based infections, attention to ventilation design and management is a crucial factor that cannot be ignored.

3.5.2. Role of particulate matter in pathogen spread

Particulate matter is classified based on aerodynamic diameter, with PM10 (particles ≤10 µm) and PM2.5 (particles ≤2.5 µm) being the most relevant to airborne pathogen transmission. Larger particles tend to settle quickly, whereas smaller particles remain suspended for extended periods, enhancing the spread of infectious agents. **Table 12** provides an overview of PM classifications and their interactions with airborne pathogens.

Table 12. Classification of particulate matter and its role in airborne pathogen transmission.

Particulate Matter	Size Range (µm)	Suspension Time	Pathogen Attachment Potential	Example Sources
PM10	≤10 µm	Minutes to hours	Moderate	Dust, pollen, vehicle emissions
PM2.5	≤2.5 µm	Hours to days	High	Combustion byproducts, industrial emissions
Ultrafine PM	≤0.1 µm	Days to weeks	Very high	Engine exhaust, secondary aerosols

Particulate matter (PM) plays a significant role in the transmission and persistence of airborne pathogens. These microscopic solid and liquid particles, suspended in the air, can serve as carriers for viruses, bacteria, and fungal spores, increasing their ability to remain airborne and travel longer distances [84]. The interaction between airborne pathogens and PM is influenced by particle size, composition, and environmental conditions, making it a crucial factor in understanding and mitigating airborne disease transmission as previous explained [85]. The important role of particulate matter (PM) in the transmission and persistence of airborne pathogens is shown in **Figure 13**.

Figure 13 shows that PM play a significant role in the transmission and persistence of airborne pathogens, especially in exacerbating respiratory tract infections. PM originating from sources such as industrial emissions, motor vehicles, and dust storms can be carried into the atmosphere in various sizes, such as PM10, PM2.5, and PM0.1. These particles function as carriers for pathogenic microorganisms such as influenza viruses. When PM10 particles are inhaled and reach the respiratory tract, they can enter human lung epithelial cells (e.g. A549 cells) and cause disruption to the body's biological systems. PM10 has been shown to increase the expression of several genes related to metabolic pathways, such as CYP1A1, ALDH13A, VIPR1, and PPP1R14A, which support virus replication in the body. In addition, PM exposure also decreases the innate immune response, which makes the body more susceptible to infection. As a result, viruses can replicate more rapidly and intensively, exacerbating the severity of respiratory diseases caused. Therefore, the interaction between PM and pathogens is an important factor in understanding and controlling the spread of airborne infectious diseases [86].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

In addition, Studies have shown that viruses, including influenza and SARS-CoV-2, can bind to fine particulate matter (PM2.5 and PM10), extending their environmental stability and facilitating long-range transport. High levels of air pollution have been linked to increased transmission rates of respiratory infections, as polluted air provides a carrier medium for pathogens and compromises human respiratory defenses [87]. The presence of particulate matter also affects respiratory tract deposition. Smaller particles, especially ultrafine PM (≤0.1 µm), can penetrate deep into the alveolar regions of the lungs, carrying infectious agents and toxic compounds directly into the respiratory system. This deep lung penetration increases the likelihood of infection and exacerbates pre-existing respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD) [88].

Mitigation strategies to reduce PM-associated pathogen transmission include air filtration systems (HEPA filters), electrostatic precipitation, and pollution control policies. Reducing ambient PM levels through urban air quality management, emissions control, and indoor air purification can significantly lower the risk of airborne disease transmission. Future research should focus on quantifying the specific role of PM in different airborne disease outbreaks and developing targeted strategies to minimize its impact on public health.

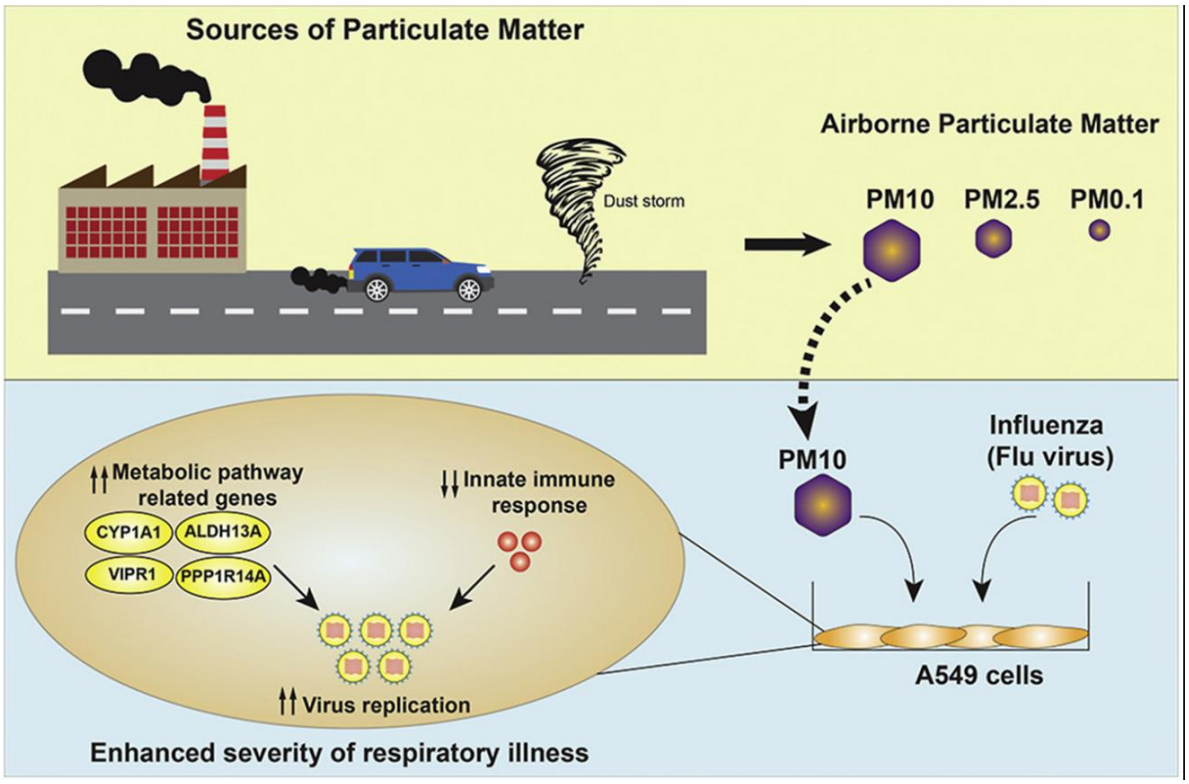

Figure 13. The important role of particulate matter (PM) in the transmission and persistence of airborne pathogens [86].

3.6. Assessing Airborne Pathogen Transmission and Transmission Efficiency

Airborne pathogen transmission has become a major concern in public health and infection control, especially after the emergence of the global pandemic caused by the SARS-CoV-2 virus. To understand the dynamics of airborne pathogen spread, a comprehensive assessment of the transmission efficiency and presence of pathogens in various environments, both indoor and outdoor, is needed. Therefore, various advances in pathogen measurement techniques, assessment model development, and detection devices have been developed. This section reviews recent advances in measurement techniques, challenges in measurement

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

in different environments, evaluation models from qualitative to quantitative approaches, and recent developments in detection devices and measuring instruments such as SMPS, APS, and other new technologies.

3.6.1. Current airborne pathogen detection

Advances in pathogen measurement techniques have played a crucial role in improving the understanding of the dynamics of airborne pathogen transmission. As detection technologies have improved, new methods have enabled the identification of pathogens with greater sensitivity and accuracy, both in indoor and outdoor environments. However, challenges remain in terms of sampling, airborne pathogen stability, and the accuracy of measurement instruments in detecting infectious particles. Therefore, this discussion highlights recent developments in airborne pathogen measurement techniques.

Two main approaches in biosensor technology for detecting pathogens in the air are optical biosensors and electrochemical biosensors as shown in **Figure 14** [89]. Optical biosensors work by detecting changes in optical properties such as color and light due to the interaction between target biomolecules (such as viruses or bacteria) and sensors. The three main techniques in this category are colorimetry, fluorescence, and surface plasmon resonance (SPR) [90-92]. Colorimetry produces a color change that can be seen directly as an indication of the presence of pathogens [93]. Fluorescence is a detection method that uses special substances that can light up (glow) when exposed to certain light. These substances are paired with detection tools, such as antibodies or DNA, that can recognize viruses or bacteria in the air. When these substances meet targets such as viral RNA, they will attach and start emitting light. This light is read as a signal that there is a pathogen in the air. This method is very sensitive and can detect very small amounts of viruses, but it requires special equipment to read the light. Meanwhile, SPR works in a different way [94]. SPR does not use a luminescent substance, but instead measures how light changes when a pathogen attaches to a metal sensor surface, usually gold. When a pathogen such as a virus binds to the sensor, a small change occurs in the reflected light, and this change is read by the device as an indication that the pathogen is present. The advantage of SPR is that it can directly detect binding without any additives, and can show the process directly and quickly. However, this device is more expensive and is usually used in laboratories [95].

Meanwhile, electrochemical biosensors work by detecting electrical signals that change due to reactions between sensors and pathogens. Three commonly used electrochemical techniques are impedance, voltammetry, and amperometry [96, 97]. The impedance method is a technique used to detect the presence of pathogens in the air by measuring changes in electrical resistance. When viruses or bacteria attach to the surface of the sensor, the resistance of the electrical flow in the sensor will change. This change is then read by the device as a sign that there are pathogen particles. This method does not require dyes or other additives, making it simpler and faster [98]. Voltammetry is another method that detects pathogens based on changes in electrical current due to changes in voltage. When pathogens interact with the sensor surface, a chemical reaction (redox reaction) occurs that causes an electric current to flow, and this current is measured to determine how many pathogens are present. Voltammetry is suitable for measuring the number of pathogens more precisely [99]. Furthermore, amperometry works by measuring a stable electric current during a chemical reaction at a certain voltage. This method is very sensitive and fast in responding to the presence of pathogens, even in very small amounts. Due to its speed and accuracy, amperometry is often used for real-time detection [100]. Based on the applications of the optical and electrochemical biosensors, a comparison of these methods with other techniques

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

is shown in **Table 13**. Overall, impedance, voltammetry, and amperometry methods fall into the category of electrochemical biosensors that offer an efficient, fast, and portable way of pathogen detection in various locations such as hospitals, airports, schools, or other enclosed spaces. By combining these technologies with optical methods such as fluorescence and SPR, the detection system becomes more flexible and effective in dealing with the spread of airborne pathogens.

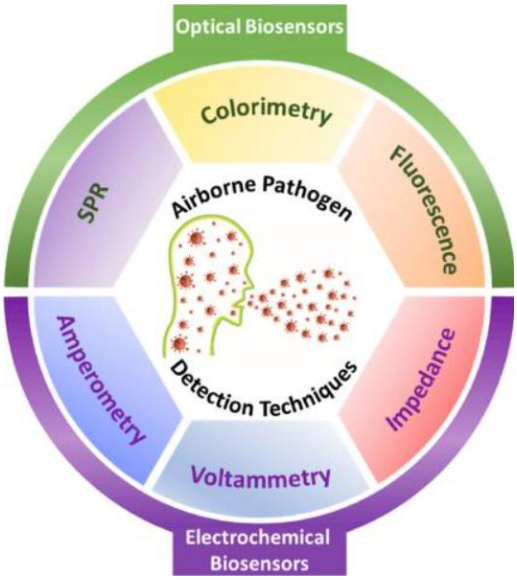

Figure 14. Schematic diagram showing optical and electrochemical biosensors following various mechanisms for airborne pathogen detection [89].

Table 13. A comparative analysis of optical and electrochemical biosensors alongside alternative detection methods [89].

Detection Method	Advantages	Disadvantages
Optic Biosensors	• Direct and fast detection • Suitable for use at point-of-care • High sensitivity • Short detection time	• Very sensitive, can cause errors • Less compatible with various sample condition • Low reproducibility
Electrochemical Biosensor	• Strong and resistant to testing • Easy to carry and use in the field • Capable of detecting very well (low detection limit)	• Susceptible to sample matrix influences • Selectivity is low towards certain targets. • Need trained operators

3.6.2. Development of assessment model

In the face of the threat of airborne infections, such as respiratory viruses and bacteria, it is important to have an effective system to detect and assess the presence of airborne pathogens. Therefore, there is a need to develop assessment models that can identify and quantify the risk of these pathogens quickly, accurately, and efficiently. To understand and predict how airborne infectious diseases (such as TB or COVID-19) spread in closed spaces such as hospitals, scientists have developed mathematical models. These models help us calculate how likely a person is to become infected from another sick person, taking into account factors such as the number of people in the room, how well the air is ventilated, and

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

how much virus is released into the air by the infected person. One of the most well-known models is the Wells–Riley model. It calculates the probability of infection based on the concept of "infection quanta," which are units of the amount of infectious particles in the air that are enough to infect one person. For example, if the room is poorly ventilated and there is one person carrying the virus, the chances of others becoming infected are greater. However, this model assumes that the air in the room is evenly mixed, when in reality this is not always the case. In addition, this model is less suitable for rooms with few people or with uneven air flow [101].

To address these weaknesses, researchers have developed more sophisticated models. One is the stochastic (random) model, which takes into account different probabilities for each scenario. For example, two rooms with the same number of people may have different infection risks depending on the position of the patient, the direction of ventilation, or the duration of exposure. There is also the zonal approach, where the room is divided into several parts (zones), and each zone has a different rate of air exchange. This makes the calculations more realistic than assuming all rooms have perfectly mixed air [102].

Furthermore, this model can also be combined with computer technology such as Computational Fluid Dynamics (CFD), which is a three-dimensional simulation of air flow in a room. With CFD, we can visualize how droplets or aerosols carrying the virus spread when someone coughs or speaks. We can also find out which zones are most at risk, such as right in front of the patient or in areas with slow air flow [103]. Overall, this approach helps us make better decisions in designing ventilation systems, arranging rooms, and protecting medical personnel and patients from exposure to airborne pathogens. Mathematical models provide a scientific picture of the risk of disease spread and help us control infections before they spread further.

3.6.3. Emerging technologies for airborne pathogen detection

To effectively detect airborne pathogens, a device capable of accurately measuring the characteristics of microscopic particles is required. In recent years, various sophisticated airborne detection devices have been developed, including the Scanning Mobility Particle Sizer (SMPS) and the Aerodynamic Particle Sizer (APS), which are used to measure the size, quantity, and distribution of aerosol particles in the air. This section discusses the role, working principles, and advantages and limitations of these devices in detecting airborne pathogens under various environmental conditions.

APS is an aerosol particle measuring device used to measure the aerodynamic diameter of particles measuring between 0.5 and 20 µm. APS works based on the principle of the difference in velocity between particles and the air stream when passing through a narrow nozzle, which is then measured using laser gates. When the air stream carries particles through the nozzle, particles with different sizes and masses will experience different accelerations. Larger or heavier particles will move slower than the air stream, and this difference in velocity is used to determine the aerodynamic diameter of the particle, namely by measuring the size of a spherical particle with a density of 1 g/cm^3 which has the same settling velocity. For effective measurement, dilution of the sample flow (dilution) needs to be done thus the particles are not too dense and do not cover the laser signal. In addition, the particles being measured must have a refractive index high enough to be detected by the laser beam. The smallest size that can be measured by APS is generally around 0.2–0.5 µm, depending on its optical sensitivity. APS can also be used to estimate the mass distribution of aerosols, if the bulk density of the particles is known or assumed. Calibration of APS instruments is generally carried out using laboratory aerosols that are spherical in shape and

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

have standard densities, so that a calibration curve can be produced between particle speed and its aerodynamic size. This is important to maintain measurement accuracy [104].

SMPS is a tool used to measure the electronic mobility diameter of aerosol particles with very small sizes, ranging from 0.025 to 1 µm, and can even be as accurate as 8–200 nanometers, depending on the configuration of the tool and its software. SMPS is a tool with the highest level of accuracy for very fine particle sizes (nano). SMPS consists of two main components [105]:

(i) Differential Mobility Analyzer (DMA): serves to classify particles based on their electrical mobility. This mobility depends on the size and electrical charge of the particle. Only particles with a certain mobility can pass the selection and enter the next stage. Because it relies on direct physical measurements, not just empirical relationships or statistical models, measurements with DMA are considered more accurate.

(ii) Condensation Particle Counter (CPC): used to count the number of particles that have been classified by DMA.

The comparison of APS and SMPS instruments is summarized in **Table 14**. In practice, SMPS is often combined with APS to obtain a wider range of particle size distribution, ranging from tens of nanometers to tens of micrometers, making it suitable for the analysis of complex bioaerosols in air such as mixtures of viruses, bacteria, spores, and other pollutants.

Table 14. Summary of comparison of APS and SMPS instruments [106].

Instrument	Measured Particle Size	Diameter Type	Advantages	Disadvantages
APS	0.5 – 20 µm	Aerodynamic	Suitable for large particles such as bacteria/spores; can estimate mass	Less accurate for particles <0.5 µm; requires particles with high refractive index
SMPS	0.025 – 1 µm	Electric Mobility	Very accurate for small particles (viruses, nanoparticles); physics-based	Complex process; need load and humidity calibration

Based on **Table 14**, overall, SMPS excels in precision and small size, while APS is more suitable for large particles and fast measurements; therefore, both are often used together in aerosol research to produce comprehensive data [106].

For example, to understand the impact of burning biomass on air quality, SMPS and APS are used to measure the concentration and size distribution of particulate matter resulting from burning wood in a small fireplace, as shown in **Figure 15**. The SMPS tool is used to detect very small particles, ranging in size from 1 nanometer to 1 micrometer, while the APS is used to measure larger particles, ranging from 0.5 to 20 micrometers. In this measurement, the two devices are connected simultaneously (tandem) and combined with an exhaust gas dilution system; thus, the measurement results remain accurate even though the particle concentration is high. The results from these two tools were then compared with standard gravimetric methods, namely direct particle filtering and weighing techniques. The results show that SMPS and APS are very effective in measuring small particles, especially those less than 2.5 micrometers in size, with results close to gravimetric methods. However, when the measured particles are larger, the difference in results becomes very significant. SMPS and APS devices record much lower particle concentrations than gravimetric methods, indicating that large particles are more difficult to capture by these systems [107].

In another study, SMPS and APS were also used in the context of measuring the concentration and size distribution of particles produced from e-cigarette liquid (ECIG) with

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

various mixture ratios of propylene glycol (PG) and vegetable glycerin (VG) as illustrated in **Figure 16**. These measurements were carried out in a controlled laboratory exposure chamber, with five variations of the PG/VG ratio (0/100 to 90/10) and for two main particle sizes: PM_1 (≤1 µm) and $PM_{2.5}$ (≤2.5 µm). SMPS is used to measure fine particles <1 µm in size with a differential mobility approach, while APS is used to complete a larger size range, namely 0.5–20 µm, based on the aerodynamic size of the particles. Data from both are combined to obtain real-time particle size distribution and mass concentration, then compared with a gravimetric reference method (mass weighing on the filter). The results show that the SMPS + APS combination is consistent and close to the gravimetric results [108].

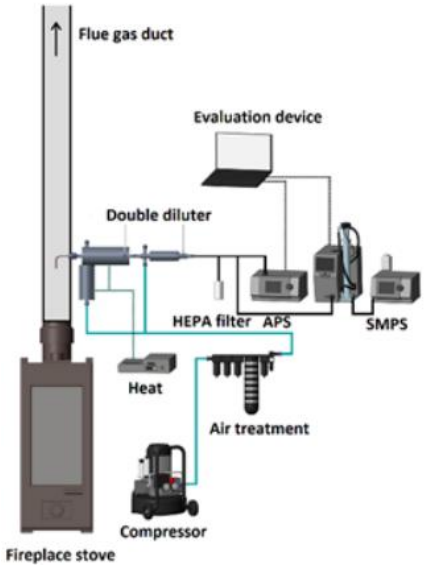

Figure 15. Scheme for measuring biomass burning particulate matter with SMPS-APS [107].

Several studies regarding the use of SMPS and APS concluded that the SMPS and APS methods are very useful in measuring concentrations and describing the particle size distribution of aerosols in real-time. These two instruments complement each other: SMPS is effective in detecting ultrafine particles (<1 µm), while APS can reach larger particles (up to 20 µm). Therefore, overall, SMPS and APS provide deep insight into aerosol dynamics and can be an important tool in air quality research and risk assessment of exposure to fine particles, especially when used in conjunction with appropriate calibration methods.

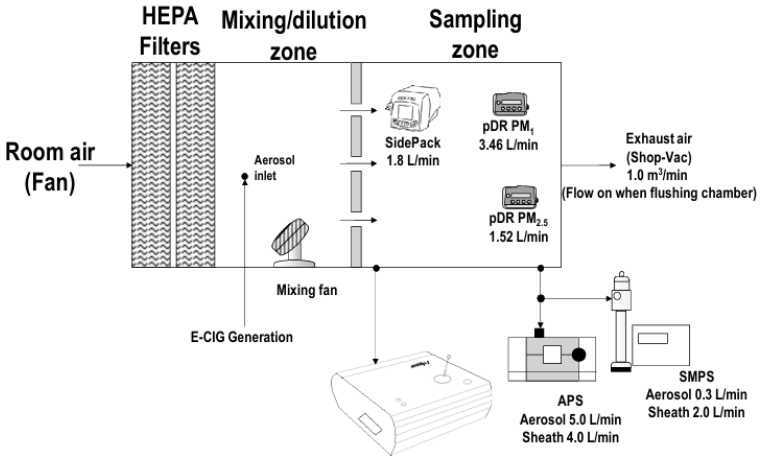

Figure 16. The experimental chamber for measuring ECIG exposure of different mixture ratios using SMPS-APS [108].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

3.7. Advances in Air Cleansing Technologies

Air cleaning technology is an important solution to prevent the transmission of viruses and microorganisms carried in aerosol droplets in the air. In general, these technologies are classified into two main inactivation mechanisms: physicochemical and biochemical (see **Figure 17**). Physico-chemical mechanisms work physically or chemically to inactivate or eliminate particles and pathogens, while biochemical mechanisms utilize biological reactions such as the use of enzymes or microorganisms [109].

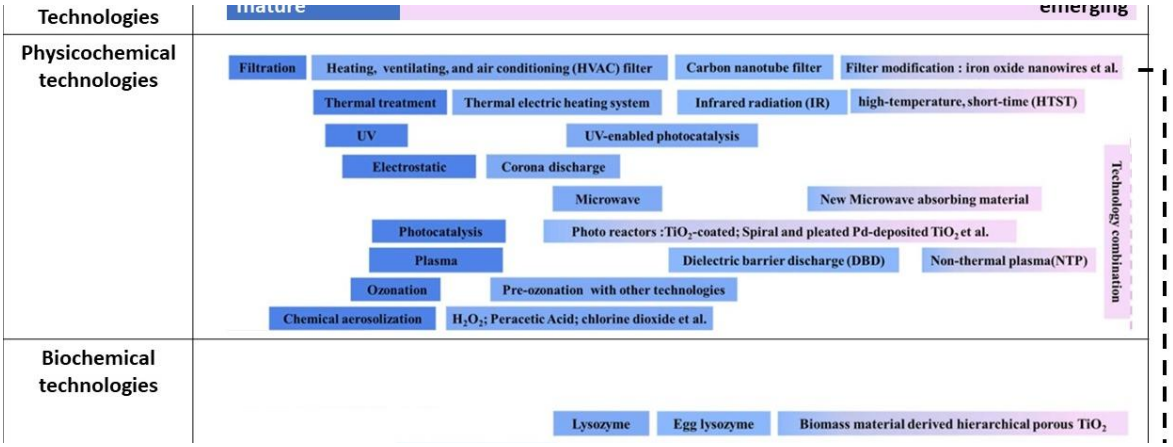

Figure 17. Two types of airborne pathogen inactivation mechanisms [109].

To understand the advantages, disadvantages, and characteristics of each air cleaning technology, **Table 15** summarizes a comparison of various pathogen cleaning technologies based on inactivation mechanisms, range of effectiveness against pathogens, ease of operation, technical challenges in their application, and potential risk of harm. **Table 15** helps in assessing and selecting the most appropriate technology for specific needs in air quality control.

Based on **Table 15**, various air purification technologies can be classified and explained in more detail according to their mechanisms and working principles. To make it easier to understand, the following discussion is divided into several parts.

Table 15. An overview of various air cleansing technologies [109].

Technology	Mechanism	Universal Effectiveness	Operation & Maintenance	Technical Notes	Hazard Risk
HEPA Filtration	Particle removal	N/A	Easy, requires periodic replacement	Less effective for very small microorganisms; potential for secondary contamination	No
Thermal Treatment	Inactivation	Yes	Simple	Not suitable for large or open spaces	No
UVGI (UV-C)	Inactivation	Less effective against spores and protozoa	Easy	Requires safety measures against free radicals and ozone	Yes

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

Table 15 (continue). An overview of various air cleansing technologies [109].

Technology	Mechanism	Universal Effectiveness	Operation & Maintenance	Technical Notes	Hazard Risk
Electrostatic (ESP)	Removal, partial inactivation	Not effective against Gram-positive bacteria	Reliable	Long-term electricity consumption	No
Photocatalysis (PCO)	Inactivation	Yes	Continuous disinfection, requires monitoring	May generate ozone or formaldehyde	Yes
Plasma	Inactivation	Yes	Requires routine maintenance	Operation requires professional technician	No
Ozonation	Inactivation	Yes	Fast, ready for immediate use	Ozone levels must be controlled due to toxicity	Yes
Chemical Aerosolization (H_2O_2)	Inactivation	Depends on disinfectant type	Ready-to-use, evenly distributed	Toxic and corrosive residues; transportation risk	Yes
Biological (enzymes, microbes)	Inactivation	Limited	Stable in acidic conditions, vulnerable in alkaline	Effective but slow; performance depends on environmental conditions	No

3.7.1. Ventilation and air filtration (HEPA)

Air filtration using a High Efficiency Particulate Air (HEPA) filter is one of the most conventional methods, but is still very relevant in modern air purification systems. HEPA filters work based on the principle of mechanical filtration, where particles in the air are captured through several physical mechanisms such as interception, inertial impaction, diffusion, and direct filtration, as shown in **Figure 18**. This combination of mechanisms allows the HEPA filter to capture up to 99.97% of airborne particles measuring ≥0.3 micrometers, which includes a variety of harmful pathogens such as bacteria, viruses, mold spores, pollen, dust, and aerosols [110].

Filtration effectiveness depends on air flow, particle size, and the condition of the filter itself. Particles larger than 0.3 µm are generally captured via impaction and interception, while ultrafine particles (<0.1 µm) tend to be captured via Brownian diffusion. Therefore, even though the 0.3 µm size is known as the "Most Penetrating Particle Size" (MPPS), HEPA filters are still capable of capturing both smaller and larger particles with high efficiency, provided they are under optimal conditions [110].

However, HEPA filters have significant limitations. This technology is not effective in removing gases, chemical vapors, and volatile organic compounds (VOCs), because these particles are molecular and cannot be captured by mechanical filter media. To overcome

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

these limitations, HEPA is often combined with activated carbon or chemical adsorption systems in advanced air cleaning units [111].

Figure 18. Illustration depicting how HEPA filters trap bacteria, viruses, and aerosols in a ventilation system.

Additionally, HEPA efficiency can decrease drastically over time if regular maintenance is not performed. Periodic filter replacement is very important to prevent the buildup of particles that can become a place for microorganisms to grow. If not managed properly, dirty filters can cause secondary contamination, namely the release of microorganisms back into the air due to backflow, filter seal leaks, or degradation of the filter material. Therefore, in HVAC (Heating, Ventilation, and Air Conditioning) systems in health facilities or laboratories, the presence of a HEPA filter must be accompanied by a differential pressure detection system, performance indicators, and standard replacement procedures [110].

In the context of preventing the spread of airborne diseases, HEPA filters have been proven effective in capturing aerosols containing the SARS-CoV-2 virus, influenza and various other airborne pathogens. Therefore, this technology is the main choice in medical isolation rooms, biosafety laboratories, public transportation, and closed work environments with a high risk of exposure. However, for maximum efficiency, HEPA filters need to be paired with a good ventilation system, and in some cases also accompanied by additional disinfection technology to ensure that captured particles no longer pose a risk of infection [112].

3.7.2. Ultraviolet germicidal irradiation (UVGI)

UVGI is an air disinfection technology that works by utilizing UV-C radiation, especially at a wavelength of around 254 nm, to damage the DNA or RNA of microorganisms. Under optimal conditions, UVGI can inactivate more than 99% of pathogens such as Mycobacterium tuberculosis, E. coli, Staphylococcus aureus, influenza viruses, and SARS-CoV-2 [113]. However, its effectiveness is highly dependent on several factors, such as the duration and intensity of exposure, the distance between the UV source and the microorganisms, humidity conditions, and the shape and position of objects that can cause shadowing effects. UVGI is less effective against microorganisms that have strong protective structures such as spores and multicellular protozoa [114]. **Figure 19** illustrates how UVGI inactivates airborne pathogens. UVGI systems are classified into upper-room UVGI, in-duct UVGI, and portable UV disinfection units, each designed for different applications [113]. **Table 16** compares the characteristics and applications of various UVGI systems.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

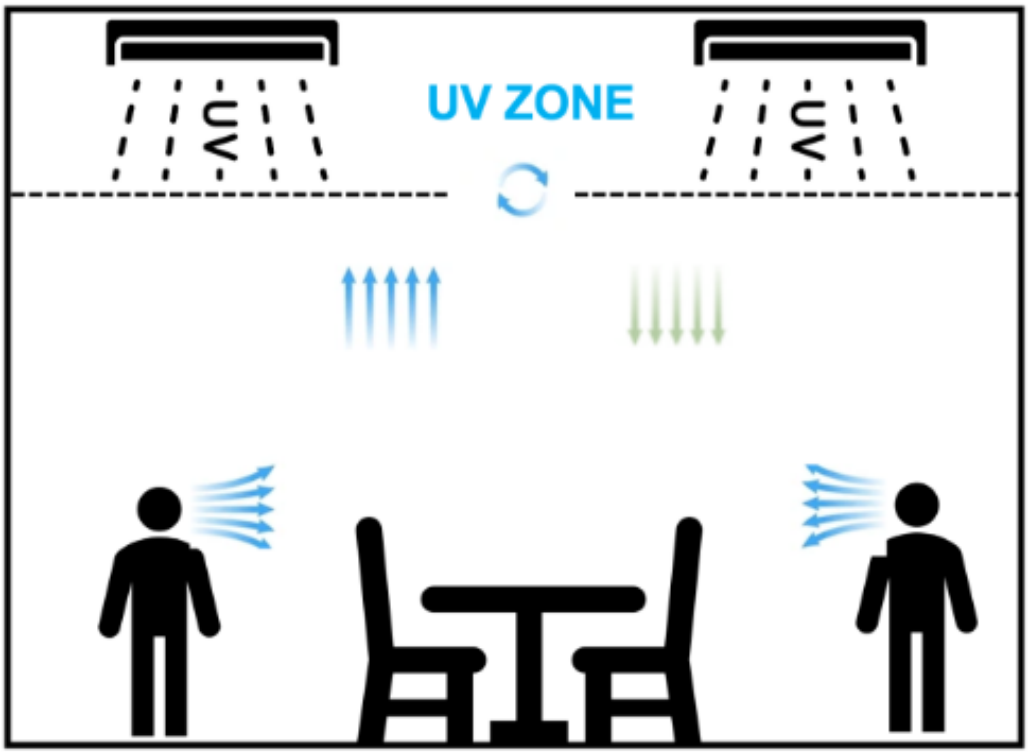

Figure 19. UVGI air disinfection.

Table 16. Comparison of UVGI systems for airborne pathogen control.

UVGI System	Installation Type	Application	Advantages	Limitations
Upper-Room UVGI	Mounted at ceiling level	Hospitals, schools, public spaces	Continuous air disinfection, minimal airflow resistance	Requires proper room design to avoid human UV exposure
In-Duct UVGI	Installed in HVAC systems	Commercial buildings, healthcare facilities	Deactivates pathogens before air distribution	Dependent on air exchange rates and duct reflectivity
Portable UV Disinfection Units	Standalone mobile units	Offices, small rooms, temporary disinfection	Flexible, can be moved to high-risk areas	Limited coverage, requires manual positioning

Although effective, the use of UVGI carries risks to human health, such as skin and eye irritation, as well as the potential for chronic damage due to direct exposure to UV rays. Therefore, UVGI system design must pay attention to safety aspects, such as the use of presence sensors, light shields, or automatic operation when the room is unoccupied [113]. The main advantages of UVGI are its speed in inactivating microorganisms and leaving no chemical residue, making it suitable for applications in ventilation, laboratories, medical facilities and public spaces. However, due to UV's limitations in reaching hidden areas or killing more resistant microorganisms, UVGI is often combined with other technologies such as HEPA filters and ionization plasma to form a comprehensive and safe air disinfection system [115].

3.7.3. Photocatalyst oxidation (PCO)

PCO is an air purification technology that relies on an oxidation process triggered by a photocatalyst, generally titanium dioxide (TiO_2) activated by ultraviolet (UV) light. When the

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

photocatalyst surface is exposed to UV radiation, especially UV-A or UV-C, electron excitation occurs which triggers the formation of hydroxyl radicals (•OH) and superoxide anions (O_2^-•). These radicals are very strong and reactive oxidizing agents, capable of destroying various organic pollutants in the air, including volatile organic compounds (VOCs) as well as membranes and genetic structures of microorganisms such as bacteria and viruses [116, 117].

PCO is known to be effective in reducing VOC concentrations originating from cigarette smoke, chemical solvents, unpleasant odors, and other household compounds. The resulting hydroxyl radicals can decompose these complex molecules into carbon dioxide (CO_2) and water vapor (H_2O), which is much safer [118]. In the context of disinfection, PCO also has the ability to damage the cell walls of microorganisms and degrade important components in viruses, although its level of inactivation against microorganisms is generally lower compared to pure UVGI technology. This is because PCO works more slowly, and its effectiveness is greatly influenced by environmental conditions such as air humidity, contact time, UV light intensity, and photocatalyst surface area [116].

One of the main advantages of PCO is its continuous and passive nature: the oxidation process takes place continuously as long as a UV light source and photocatalyst are present. This technology also does not require regular media replacement like HEPA filters, thereby reducing the need for physical maintenance [119]. Therefore, PCO is often applied in portable air purification device systems and air circulation systems in commercial and household buildings.

However, PCO also has a number of limitations and potential dangers. One of the main problems is the formation of dangerous by-products, such as ozone (O_3) and formaldehyde (CH_2O), which can be released into the air in small amounts but enough to pose a health risk if not controlled. Incomplete oxidative reactions can also produce undesirable intermediate compounds. In addition, a decrease in efficiency can occur over time due to contamination of the catalyst surface, thus the performance of the photocatalyst must be monitored and cleaned periodically [117].

To increase efficiency and safety, PCO technology is currently being developed in the form of closed reactors, layered systems, and combinations with other technologies such as HEPA, UVGI, or activated carbon adsorption. The use of modified photocatalyst materials, such as TiO_2 doped with noble metals (e.g. Ag, Cu, or Pd), is also a recent trend to improve the spectral response to visible light and suppress the formation of by-products [116].

Overall, PO offers an innovative approach to actively and efficiently break down air pollutants, but its implementation needs to be accompanied by careful system engineering to avoid emissions of hazardous substances, maintain long-term stability, and ensure user safety in household and industrial scale applications.

3.7.4. Thermal treatment

Thermal treatment is an air purification technology that works by utilizing high temperatures to deactivate or destroy microorganisms and decompose organic pollutants in the air. This technology takes advantage of the fact that most pathogens, including bacteria, viruses and fungi, cannot survive extreme temperatures. By heating the air to temperatures between 200°C and 500°C, thermal treatment is able to damage the protein structure, cell membranes and genetic material of microorganisms, thereby causing total inactivation [120]. In addition, toxic volatile organic compounds (VOCs) can be broken down into simpler and less dangerous compounds such as carbon dioxide and water vapor [121].

Thermal treatment is known to be very effective in providing thorough sterilization without leaving residue, making it very useful for applications in laboratories, hospitals, isolation

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

facilities, and the pharmaceutical and chemical industries. However, this technology also has several important limitations. One is the high energy requirements to maintain operating temperatures, which makes them less efficient for large spaces or long-term use. In addition, if the heating process is not controlled properly, there is a risk of fire or damage to the ventilation system. The process of burning organic compounds can also produce harmful gas emissions such as carbon monoxide or nitrogen oxide, so this system should be equipped with additional emissions handling units such as scrubbers or activated carbon filters [119].

Even though it has risks, thermal treatment remains a very effective method in air disinfection systems, especially for environments that require a high level of sterilization. To increase efficiency and reduce negative impacts, this technology is often combined with other methods such as pre-filtration or UVGI. With proper control, thermal treatment is able to provide a very reliable and comprehensive air sterilization solution [122].

3.7.5. Electrostatic precipitator, plasma, and ozonation

Electrostatic Precipitator (ESP), Plasma Ionization, and Ozonization are three air purification technologies based on electrochemical and oxidation principles that are widely used to remove fine particles and deactivate microorganisms and chemical pollutants in the air. These three technologies work on different principles, but have similarities in terms of electric fields utilization to clean the air [123].

ESP is a device that works by providing an electric charge to particles in the air using a high voltage electric field. Once ionized, these charged particles are directed towards a counter-charged metal plate, where they stick and separate from the air flow [123]. ESP is very effective for removing solid particles and aerosols with an efficiency of between 80–99%, especially micrometer to submicrometer sized particles. The advantages of ESP are low energy consumption and relatively easy maintenance. However, one drawback that must be considered is the potential for the formation of ozone (O_3) during the ionization process, which can be toxic if the concentration exceeds the safe exposure limit. In addition, the effectiveness of the ESP can decrease if the device is not cleaned regularly because particles will accumulate on the collection plate [123].

Plasma ionization is a development of ESP technology which not only precipitates particles, but also deactivates microorganisms and breaks down chemical compounds in the air. This technology works by creating cold plasma (non-thermal plasma), which is a mixture of ions, electrons, and high-energy free radicals. When this plasma comes into contact with contaminated air, an intense chemical reaction occurs [124]. Hydroxyl ions and radicals produced from plasma can damage the cell walls of microorganisms and destroy their genetic material, as well as oxidize volatile organic compounds (VOC) into CO_2 and H_2O [123]. The main advantages of plasma ionization are its speed and efficiency in inactivating various types of pathogens, as well as its ability to operate without a physical filter. However, like ESP, this technology also has the potential to produce by-products such as ozone and other reactive compounds (Reactive Oxygen Species/ROS), which can be dangerous if not strictly controlled. Therefore, modern plasma systems are often equipped with ozone sensors and automatic emission controllers [125-127].

Ozonization, on the other hand, is an air purification method that directly utilizes ozone (O_3) as a powerful oxidizing agent. Ozone is able to damage the structure of proteins, lipids and nucleic acids of microorganisms, causing rapid and complete inactivation. In addition, ozone can also react with VOCs and other chemical pollutants, breaking them down into simpler, less harmful compounds. The effectiveness of ozonation is very high, especially in killing bacteria, viruses and fungi in the air and on surfaces [123]. However, this strength is

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

also the main weakness of ozone: direct human exposure can cause respiratory tract irritation, headaches, and even long-term lung damage. Therefore, the use of ozone in air purification systems must be done carefully, such as only activating it when the room is empty (disinfection mode), or with a closed system that is able to neutralize residual ozone before it is released back into the environment [125].

Table 17 shows comparison of electrostatic precipitators. Overall, ESP, plasma ionization, and ozonation are technologies that have great potential for improving air quality, especially in terms of eliminating micro particles, microorganisms, and chemical pollutants. However, this high effectiveness must be balanced with safe system design, strict emission controls, and continuous monitoring to ensure that users are not exposed to health-harming byproducts. The combination of these three technologies, when applied with good control, can provide a comprehensive solution for air purification in high-risk environments such as hospitals, laboratories and closed public spaces.

Table 17. Comparison of electrostatic precipitators with other filtration technologies.

Technology	Mechanism	Pathogen Removal Efficiency	Advantages	Limitations
HEPA Filtration	Captures particles in fine mesh	99.97% for ≥0.3 µm particles	Highly effective, passive filtration	Requires frequent filter replacement
Electrostatic Precipitator (ESP)	Electrically charges and collects airborne particles	95–99% for fine particles	Reusable collector plates, low airflow resistance	May generate ozone, requires periodic cleaning
Plasma-Based Purification	Generates ionized plasma to disrupt microbial structures	90–99% for airborne pathogens	Kills bacteria and viruses directly	Requires high energy input
Ozonation	Produces ozone (O_3) to oxidize airborne pathogens	Variable, depends on concentration	Effective for odor and chemical neutralization	Can be hazardous to humans at high exposure

3.7.6. Chemical aerosolization and behavioral approaches

Chemical aerosolization is an air disinfection method that uses chemical compounds in the form of aerosols or steam to spread throughout the room and completely inactivate microorganisms. One of the most common chemical agents in this technology is hydrogen peroxide (H_2O_2), which is used in the form of vapor (Vaporized Hydrogen Peroxide/VHP) or micro mist (aerosol). The main mechanism of action is oxidation, namely H_2O_2 reacts with cell membranes, proteins and nucleic acids (DNA/RNA) of microorganisms, causing fatal damage to the cell structure and resulting in effective microbial death [128]. **Table 18** summarizes commonly used chemical aerosols for air disinfection [129].

This technology is superior in killing various types of pathogens, including Gram-positive and Gram-negative bacteria, enveloped and non-enveloped viruses, as well as resistant bacterial spores, with an efficacy level of more than 99.99% (log 4–6 reduction) under optimal conditions. Because it spreads evenly as a gas or aerosol, H_2O_2 aerosol is able to reach hidden areas such as room corners, the back surface of furniture, and small crevices that are difficult to clean manually [129].

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

However, the use of H_2O_2 in high concentrations carries significant risks. H_2O_2 is corrosive to metals and sensitive materials, and toxic to humans if inhaled at high levels, because it can cause respiratory tract, eye and skin irritation. Therefore, aerosolization systems must be designed with very precise concentration control, good ventilation systems, and strict safety protocols. Typically, this process is carried out when the room is unoccupied and can only be re-entered once the residue concentration has dropped to a safe level. In addition, the storage and transportation of H_2O_2 requires special attention because it is easily decomposed and reactive to heat and other chemicals [130].

Chemical aerosolization is frequently applied in medical facilities, biosafety laboratories, patient isolation rooms, ambulance vehicles, and operating rooms, where thorough disinfection is crucial. In the context of the COVID-19 pandemic, this technology is used to sterilize public spaces, airplane cabins and mass transportation. For large-scale use, H_2O_2 aerosol can be combined with other disinfection systems such as UVGI or HEPA filtration to increase effectiveness while reducing the risk of excess chemical exposure [131].

Behavioral strategies complement technological and chemical interventions by modifying human activities to reduce the risk of airborne infection [132]. The integration of chemical aerosolization and behavioral adaptations has been particularly successful in hospitals, aircraft cabins, and pandemic response settings. Key behavioral measures include:

(i) Mask Usage and Respiratory Etiquette: Wearing N95, FFP2, or surgical masks reduces airborne particle emission and inhalation. Proper coughing and sneezing techniques prevent droplet dispersion in public spaces.
(ii) Social Distancing and Occupancy Control: Reducing crowd density in enclosed environments lowers airborne pathogen concentration, minimizing exposure risks.
(iii) Ventilation Optimization: Encouraging natural ventilation by opening windows and ensuring proper airflow management in workplaces and public transport.
(iv) Hand Hygiene and Surface Cleaning: Frequent handwashing and surface disinfection prevent pathogens from re-entering the air through reaerosolization.

3.8. Case Studies and Real-Life Implementation of Airborne Pathogen Control Strategies

National and global airborne pathogen control strategies have developed rapidly, especially after the COVID-19 pandemic exposed the weakness of the global health system in dealing with the massive spread of viruses through the air. Various countries implement a combination of science-based policies and social approaches to prevent the spread of respiratory infections, which are explained in more detail as follows.

3.8.1. National and global strategies

Strategies to prevent the spread of airborne infectious diseases, such as COVID-19, influenza and tuberculosis, have been widely implemented in various countries around the world, both in health systems, public transportation, schools and other public buildings. These concrete steps provide an illustration of how policy and technology can work together to reduce the risk of disease transmission in densely populated environments or confined spaces.

Countries such as South Korea [133], Germany [134], Japan [135], and the United States [136] have combined various strategies such as improving ventilation systems, installing air purifying technology such as UVGI and HEPA filters, mass vaccination programs and public education. These actions not only reduce infection rates, but also demonstrate the importance of collaboration between technology, government policy and societal behavior.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Table 19 summarizes real-world case studies of airborne infection control measures implemented in different regions.

Table 19. Real-life implementations of airborne pathogen control strategies.

Country/Region	Strategy Implemented	Effectiveness	Main Points
South Korea	High-efficiency HVAC systems, UVGI in public buildings	Reduced airborne transmission in public spaces	Early adoption of advanced air purification led to lower case numbers
Germany	Ventilation mandates in schools and offices, CO_2 monitoring systems	Decreased indoor infection risk	Government-funded ventilation upgrades improved air quality
Japan	Widespread mask usage, HEPA filtration in public transport	Significant reduction in respiratory infections	Cultural acceptance of masks enhanced overall disease prevention
United States	HEPA and UVGI integration in hospitals, improved ICU ventilation	Reduced nosocomial infections	Hospital air quality upgrades led to lower healthcare-associated infections

Apart from technology, vaccination and public education are important parts in controlling the spread of airborne infectious diseases. Vaccines work by training the body's immune system to fight certain viruses or bacteria. If someone is exposed, their body can respond more quickly and prevent disease from developing [137]. One of the great benefits of vaccination is the creation of herd immunity, that is, when most people are immune to a disease, people who cannot be vaccinated, such as babies or people with immune disorders, are also protected. This helps stop the chain of disease spread and reduces the burden on the health system, especially during an outbreak [138]. **Table 20** summarizes the actual implementation of vaccination strategies and control of airborne infectious diseases in several Southeast Asian countries. However, there are still many challenges in implementing vaccination, such as inequality in vaccine distribution, especially in developing countries; public doubts about vaccines (vaccine hesitancy) due to lack of education or the rise of false information; as well as special logistics requirements such as storing vaccines at a certain temperature (cold chain) to remain effective.

Table 20. Implementation of vaccination and communal immunity strategies in Southeast Asia [139-141].

Country	Implemented Strategy	Goals and Focus	Special Challenges and Notes
Indonesia	Mass vaccination against COVID-19 and influenza-Vaccine outreach as a protection measure	Reducing mortality and morbidity rates and protecting vulnerable groups through herd immunity	Distribution challenges in remote areas and public doubts about vaccines
Malaysia	National primary and booster vaccination for COVID-19 vaccine	Increase the effectiveness of protection and reduce infection rates in a sustainable manner	Focus on the effectiveness of boosters and public education to increase vaccination awareness
Thailand	Promotion of mass vaccination and expansion of national immunization coverage	Achieve national herd immunity and protect all age groups	Intensive public education and community involvement as well as a focus on the sustainability of the vaccination program

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

3.8.2. Integrating science approaches

Controlling airborne infections cannot be done with just one approach. Interdisciplinary collaboration, including public health, environmental engineering, digital technology, and microbiology is needed to control infections. The application of this integrated science has produced real solutions in the field and helped reduce infection rates in various environments, especially in congested areas, hospitals and public facilities. **Table 21** summarizes examples of real implementation of integrated science in airborne pathogen control. Although this approach is effective, several challenges still need to be overcome for wider adoption such as ensuring this solution is affordable, integrated, and supported by health-conscious public behavior.

Table 21. Examples of real implementation of integrated science in controlling airborne pathogens [142-144].

Initiative / Location	Technology / Strategy	Results and Impact
NASA	Development of air purification and antimicrobial surface coating technologies for space missions	Adapted to hospitals and clean rooms to help significantly reduce airborne microbes
Modern Hospital	Combination of real-time bioaerosol sensor, HEPA filter, and UVGI	Reducing nosocomial infections (HAIs); technology that enables automatic responses when microbial levels increase
Airports, Stations and Public Spaces	AI-based ventilation system and smart sensors that adjust airflow based on density	Preventing the spread of disease in crowded place, improve ventilation efficiency, and respiratory safety

3.8.3. Case-specific example of airborne pathogen control

Control of airborne pathogens depends largely on the type of environment where transmission occurs. Each type of place, from industry, agriculture, health facilities, public transportation, to educational institutions, has different risk characteristics, so it requires specific mitigation strategies. **Table 22** summarizes airborne pathogen control strategies based on environment.

Table 22. Summary of airborne pathogen control strategies based on environment.

Environment	Airborne Pathogen Source	Mitigation Strategy
Industry and Agriculture	Spores of Bacillus anthracis, Leuconostoc, E. coli from livestock manure, Legionella from coolants, as well as toxic gases and biological dust	Industrial ventilation system + HEPA, HVAC maintenance, use of personal protective equipment (masks, gloves), work hygiene, disinfection of work areas
Non-Industrial Environment	Cigarette smoke, poor ventilation, microbes from occupants (bacteria such as Staphylococcus, fungi such as Aspergillus, Penicillium)	Natural/mechanical ventilation, humidity control, regular cleaning, hygiene education
Public transport	Viruses and bacteria from passengers, vehicle pollutants, closed air circulation (eg at airports, stations, MRT)	Intelligent ventilation design, regular cleaning, UV disinfection, passenger density regulation, use of masks

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

Table 22 (continue). Summary of airborne pathogen control strategies based on environment.

Environment	Airborne Pathogen Source	Mitigation Strategy
Campus	Microorganisms from students and users of public facilities (toilets, gyms, classrooms, canteens, dormitories)	Ventilation of closed spaces, health education, sanitation and disinfection protocols, provision of hand sanitizer
Offices and Company Buildings	Contamination from user interactions and shared objects such as telephones, tables, air conditioners, keyboards	Ventilation with a filter system, surface disinfection, worker education, provision of hand sanitizer and clean work space
Restaurants and Food Services	Pathogens from raw materials, workers, kitchen surfaces: Salmonella, E. coli, Listeria, Toxoplasma, Hepatitis A/E, Norovirus	Worker hygiene, hygiene training, sanitation of tools and surfaces, use of safe temperatures when cooking, HACCP system
Medical Facilities	Aerosols from patients (coughs, sneezes), medical procedures (intubation), pathogens such as M. tuberculosis, Klebsiella, Candida, Aspergillus, etc.	Negative/positive pressure ventilation, UVGI, HEPA filtration, equipment and surface disinfection, full PPE, nosocomial infection protocols

3.9. Challenges and Future Outlook

Although various airborne pathogen control strategies have been widely implemented in clinical, industrial, educational, and public facility contexts, there are still major challenges that need to be overcome to ensure long-term effectiveness and sustainability. These challenges include: (i) limitations of current technology; (ii) the need for interdisciplinary integration; (iii) technical challenges (such as economic and social); and (iv) gaps in regulations and policies that have not fully accommodated the urgency of controlling air infections globally.

In the future, airborne pathogen control technology will develop in a more intelligent, energy efficient and digitally integrated direction. The main focus of innovation will be towards real-time data-driven automation, sustainable materials, and systems that can respond adaptively to infection threats as summarized in **Table 23**.

Table 23. Key innovations in emerging airborne pathogen control technologies.

Innovation Field	Description
Smart Purification Systems	Combining AI and IoT in an adaptive ventilation/filtration system that can adjust flow and disinfection according to airborne pathogen levels.
Hybrid Technologies	Combination of technologies such as HEPA + UVGI + plasma in one compact unit that is energy efficient and efficient.
Nanotechnology for Sustainable Filtration	Development of a HEPA filter made from antimicrobial nanofiber that can self-clean and lasts a long time with minimal maintenance.
Real-Time Airborne Pathogen Surveillance	Installation of biosensors and automated pathogen detection networks in public facilities to detect and warn of potential airborne outbreaks.

3.9.1. Gaps in current research and technology

Despite much progress in airborne pathogen control technology, there are still a number of fundamental gaps that limit the effectiveness, widespread application and adaptation of

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

this technology in various sectors of life. Most research on airborne pathogen control still focuses on clinical settings, such as hospitals or laboratories. In fact, non-clinical environments such as schools, offices, transportation centers, restaurants or prayer rooms also have a high risk of airborne transmission, but this has not been explored in depth. This creates a data vacuum to develop relevant and contextual solutions for public spaces.

Currently, there are almost no commercially available real-time airborne pathogen monitoring systems. The majority of air purification systems (e.g. HEPA, UVGI, photocatalysis) operate statically and are blind to actual conditions, resulting in wasteful energy use or are even ineffective when contamination spikes occur.

Smart technologies such as artificial intelligence (AI)-based control systems, Internet of Things (IoT)-based air quality monitoring, and biosensors for detecting microbial pathogens in the air have actually experienced rapid development in research environments and laboratory scales. However, the real-world application of these technologies is still very limited. Most of them are still at the testing or prototype stage, so they are not yet ready for widespread use on a commercial or public scale. Even in developed countries, access to this technology is still limited to certain institutions that have large resources. In addition, the use of this smart technology requires complex supporting infrastructure, such as a stable and fast data network, comprehensive integration with building ventilation systems (HVAC), and the availability of accurate and sensitive air quality sensors. Unfortunately, this kind of infrastructure is not yet available evenly, especially in remote areas or developing countries. This makes smart technology difficult to access, expensive, and not yet suitable for mass use, even though it has enormous potential to detect and respond to airborne infection threats automatically and efficiently.

3.9.2. Need for integrated science-based approach

To effectively address the challenges of air infection control, an integrated and science-based approach across disciplines is needed. Currently, most approaches are carried out sectorally, for example, technical approaches are carried out without considering human behavior, or regulations are made without referring to epidemiological data and the latest technology. Therefore, synergy is needed between public health, environmental engineering, microbiology, data science and public policy. This integration will encourage the development of air control systems that are not only technically reliable, but also socially and economically sustainable. For example, the implementation of a smart ventilation system must be accompanied by an understanding of local epidemiology and public education about the risk of aerosol infection.

3.9.3. Regulatory developments and policy consideration

To encourage global adoption of air infection control, comprehensive, science-based regulations and policies are needed. Currently, most regulations only regulate indoor chemical pollution, not yet covering bioaerosols such as viruses and bacteria. Effective airborne pathogen control efforts require a strong regulatory foundation, financial support from the government, and active community participation. The synergy of the three will enable widespread and sustainable application of air infection control technology, as well as improve global preparedness for future pandemics.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

3.10. Contribution to the Sustainable Development Goals (SDGs)

The findings and synthesis presented in this review contribute directly to several targets within the United Nations SDGs, demonstrating how scientific advancement in aerosol science and airborne pathogen mitigation can support global sustainability efforts:

(i) First and foremost, this study aligns with SDG 3: Good Health and Well-being, by addressing the need for effective strategies to reduce airborne transmission of infectious diseases. By evaluating technologies such as HEPA filtration, UVGI, and electrostatic precipitation, this review informs health interventions that protect populations in both clinical and community settings.

(ii) Second, the paper supports SDG 9: Industry, Innovation and Infrastructure, through its focus on emerging technologies in air purification and real-time detection. The analysis of engineering-based solutions—ranging from particle sensors to ventilation modeling—highlights the role of innovation in strengthening public health infrastructure and occupational safety.

(iii) In the context of urban planning and public environments, the study contributes to SDG 11: Sustainable Cities and Communities, by emphasizing the importance of indoor air quality, especially in densely populated and climate-controlled settings such as schools, public transportation systems, and offices.

(iv) Lastly, the environmental implications of airborne particles and ventilation systems relate to SDG 13: Climate Action. Efficient air management strategies not only reduce pathogen exposure but also intersect with efforts to mitigate climate-sensitive health risks and energy-efficient building practices.

By integrating scientific knowledge, bibliometric insights, and public health imperatives, this review bridges disciplines and reinforces the importance of linking pathogen mitigation strategies with global sustainability goals. Finally, this adds new information regarding SDGs as reported elsewhere [145-152].

4. Conclusion

The increasing prevalence of airborne infectious diseases highlights the urgent need for comprehensive and adaptive pathogen mitigation strategies. This review has summarized key findings that underscore how airborne pathogens, especially those in aerosol form smaller than 5 µm, can remain suspended in enclosed environments for extended periods, significantly increasing the risk of long-range transmission. Environmental factors such as humidity, ventilation quality, airflow patterns, and human activity and physicochemical characteristics of airborne pahogen contribute to the complexity of airborne pathogen spread, particularly in poorly ventilated indoor spaces.

Advancements in detection technologies (such as bioaerosol samplers, AI-powered sensors, and computational modelling) offer promising improvements in real-time pathogen monitoring. However, widespread implementation remains hindered by cost, technical limitations, and uneven access across regions. Similarly, while progress in air cleansing technologies like HEPA filtration, UVGI, photocatalytic oxidation, electrostatic precipitation, and plasma purification has been substantial, these systems often require high energy inputs and lack integration with smart monitoring networks. Behavioral interventions, such as mask-wearing and managing indoor occupancy, serve as important complements to technological solutions.

Despite these developments, challenges persist in the form of high operational costs, lack of global ventilation and air quality standards, and limited public awareness. Moving forward, innovation must prioritize the development of AI-integrated, energy-efficient purification

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

systems, sustainable filtration materials, and adaptive ventilation technologies tailored for diverse public settings.

To ensure long-term impact, governments, healthcare providers, and research institutions must work collaboratively to: (i) expand access to affordable and efficient air purification systems; (ii) integrate real-time pathogen detection into public health infrastructure; (iii) establish enforceable international air quality and ventilation standards; and (iv) promote public education to build awareness of airborne disease risks and the importance of preventive practices.

A multidisciplinary, science-driven, and policy-supported approach will be essential in building global resilience against future airborne health threats.

5. References

[1] De Gaetano, S., Ponzo, E., Midiri, A., Mancuso, G., Filippone, D., Infortuna, G., and Biondo, C. (2025). Global trends and action items for the prevention and control of emerging and re-emerging infectious diseases. *Hygiene*, *5*(2), 18.

[2] Aghayan, S.K. (2025). Moghadas hosseinzadeh F. The impact of traveling on infectious diseases transmission with a focus on air travel: A Narrative Review. *International Journal Travel Media Global Health*, *13*(1), 33-41.

[3] Wang, C.C., Prather, K.A., Sznitman, J., Jimenez, J.L., Lakdawala, S.S., Tufekci, Z., and Marr, L.C. (2021). Airborne transmission of respiratory viruses. *Science*, *373*(6558), eabd9149.

[4] Friedlander, S.K., and Pui, D.Y. (2004). Emerging issues in nanoparticle aerosol science and technology. *Journal of Nanoparticle Research*, *6*(2), 313-320.

[5] Khlystov, A., Stanier, C., and Pandis, S.N. (2004). An algorithm for combining electrical mobility and aerodynamic size distributions data when measuring ambient aerosol special issue of aerosol science and technology on findings from the fine particulate matter supersites program. *Aerosol Science and Technology*, *38*(S1), 229-238.

[6] Tang, J.W. (2009). The effect of environmental parameters on the survival of airborne infectious agents. *Journal of the Royal Society Interface*, *6(suppl_6)*, S737-S746.

[7] Liu, F., Ma, Q., Marjub, M.M., Suthammanont, A. K., Sun, S., Yao, H., and Zhang, W. (2023). Reactive air disinfection technologies: Principles and applications in bioaerosol removal. *ACS ES&T Engineering*, *3*(5), 602-615.

[8] Qiu, G., Zhang, X., deMello, A. J., Yao, M., Cao, J., and Wang, J. (2023). On-site airborne pathogen detection for infection risk mitigation. *Chemical Society Reviews*, *52*(24), 8531-8579.

[9] Olatunji, A.O., Olaboye, J.A., Maha, C.C., Kolawole, T.O., and Abdul, S. (2024). Environmental microbiology and public health: Advanced strategies for mitigating waterborne and airborne pathogens to prevent disease. *International Medical Science Research Journal*, *4*(7), 756-770.

[10] Nair, A. N., Anand, P., George, A., and Mondal, N. (2022). A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality. *Environmental Research*, *213*, 113579.

[11] Saeedi, R., Ahmadi, E., Hassanvand, M.S., Mohasel, M.A., Yousefzadeh, S., and Safari, M. (2023). Implemented indoor airborne transmission mitigation strategies during COVID-

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

19: a systematic review. *Journal of Environmental Health Science and Engineering*, *21*(1), 11-20.

[12] Tsang, T.W., Wong, L.T., and Mui, K. W. (2024). Experimental studies on airborne transmission in hospitals: A systematic review. *Indoor and Built Environment*, *33*(4), 608-640.

[13] Salman, A., Sattineni, A., Azhar, S., and Leousis, K. (2022). A systematic review of building systems and technologies to mitigate the spread of airborne viruses. *Journal of Facilities Management*, *20*(3), 369-384.

[14] Bertran, K., Clark, A., and Swayne, D. E. (2018). Mitigation strategies to reduce the generation and transmission of airborne highly pathogenic avian influenza virus particles during processing of infected poultry. *International Journal of Hygiene and Environmental Health*, *221*(6), 893-900.

[15] Klompas, M., Milton, D. K., Rhee, C., Baker, M. A., and Leekha, S. (2021). Current insights into respiratory virus transmission and potential implications for infection control programs: a narrative review. *Annals of Internal Medicine*, *174*(12), 1710-1718.

[16] Salman, A., Sattineni, A., Azhar, S., and Leousis, K. (2022). A systematic review of building systems and technologies to mitigate the spread of airborne viruses. *Journal of Facilities Management*, *20*(3), 369-384.

[17] Aliabadi, A.A., Rogak, S.N., Bartlett, K.H., and Green, S.I. (2011). Preventing airborne disease transmission: Review of methods for ventilation design in health care facilities. *Advances in Preventive Medicine*, *2011*(1), 124064.

[18] Li, Y., Leung, M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., and Yuen, P.L. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment–a multidisciplinary systematic review. *Indoor Air*, *17*(1), 2-18.

[19] Delikhoon, M., Guzman, M.I., Nabizadeh, R., and Norouzian Baghani, A. (2021). Modes of transmission of severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) and factors influencing on the airborne transmission: A review. *International Journal of Environmental Research and Public Health*, *18*(2), 395.

[20] Janczarek, M., Ślosarczyk, A., Klapiszewska, I., Riha, J., Jesionowski, T., and Klapiszewski, Ł. (2024). Airborne bioaerosols in healthcare facilities–transmission routes and mitigation strategies. A review. *Journal of Building Engineering*, 111015.

[21] Acharya B., Acharya A., Gautam S., Ghimire S.P., Mishra G., Parajuli N., and Sapkota B. (2020). Advances in the diagnosis of Tuberculosis: An update into molecular diagnosis of Mycobacterium tuberculosis. *Molecular Biology Reports*, *47*, 4065-4075.

[22] Kim S.M., Kim J., Noh S., Sohn H., and Lee T. (2020). Recent development of aptasensor for influenza virus detection. *BioChip Journal*, *14*, 327-339.

[23] Lee J.I., Jang S.C., Chung J., Choi W.-K., Hong C., Ahn G.R., Kim S.H., Lee B.Y., and Chung W.-J. (2021). Colorimetric allergenic fungal spore detection using peptide-modified gold nanoparticles. *Sensors and Actuators B: Chemical*, *327*, 128894.

[23] Randall, K., Ewing, E. T., Marr, L. C., Jimenez, J. L., and Bourouiba, L. (2021). How did we get here: what are droplets and aerosols and how far do they go? A historical perspective on the transmission of respiratory infectious diseases. *Interface Focus*, *11*(6), 20210049.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

[24] Delikhoon, M., Guzman, M. I., Nabizadeh, R., and Norouzian Baghani, A. (2021). Modes of transmission of severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) and factors influencing on the airborne transmission: A review. *International journal of Environmental Research and Public Health*, *18*(2), 395.

[25] Wolkoff, P., Azuma, K., and Carrer, P. (2021). Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation. *International Journal of Hygiene and Environmental Health*, *233*, 113709.

[26] Zhao, X., Liu, S., Yin, Y., Zhang, T., and Chen, Q. (2022). Airborne transmission of COVID-19 virus in enclosed spaces: an overview of research methods. *Indoor Air*, *32*(6), e13056.

[27] Jonges, M., Van Leuken, J., Wouters, I., Koch, G., Meijer, A., and Koopmans, M. (2015). Wind-mediated spread of low-pathogenic avian influenza virus into the environment during outbreaks at commercial poultry farms. *PloS One*, *10*(5), e0125401.

[28] Coşkun, H., Yıldırım, N., and Gündüz, S. (2021). The spread of COVID-19 virus through population density and wind in Turkey cities. *Science of the Total Environment*, *751*, 141663.

[29] Yang, X., Yang, H., Ou, C., Luo, Z., and Hang, J. (2021). Airborne transmission of pathogen-laden expiratory droplets in open outdoor space. *Science of The Total Environment*, *773*, 145537.

[30] Kim S.M., Kim J., Noh S., Sohn H., and Lee T. (2020). Recent development of aptasensor for influenza virus detection. *BioChip Journal*, *14*, 327-339.

[31] Rowe B. (1979). The role of Escherichia coli in gastroenteritis. *Clinics in Gastroenterology*, *8*(3), 625-644.

[32] Mouratidis P.X., and Ter Haar G. (2022). Latest advances in the use of therapeutic focused ultrasound in the treatment of pancreatic cancer. *Cancers*, *14*(3), 638.

[33] Al-Abri, S. S., Al-Jardani, A. K., Al-Hosni, M. S., Kurup, P. J., Al-Busaidi, S., and Beeching, N. J. (2011). A hospital acquired outbreak of Bacillus cereus gastroenteritis, Oman. *Journal of Infection and Public Health*, *4*(4), 180-186.

[34] Song, H., Sandie, R., Wang, Y., Andrade-Navarro, M.A., and Niederweis, M. (2008). Identification of outer membrane proteins of Mycobacterium tuberculosis. *Tuberculosis*, *88*(6), 526-544.

[35] Aziz S.A.A.A., Mahmoud R., and Mohamed M.B.E.D. (2022). Control of biofilm-producing Pseudomonas aeruginosa isolated from dairy farm using Virokill silver nano-based disinfectant as an alternative approach. *Scientific Reports*, *12*(1), 9452.

[36] Kostic A., Cukovic K., Stankovic L., Raskovic Z., Nestorovic J., Savic D., Simovic A., Prodanovic T., Zivojinovic S., and Andrejevic S. (2022). The different clinical courses of legionnaires' disease in newborns from the same maternity hospital. *Medicina*, *58*(9), 1150.

[37] Yoshida, M., Furuya, N., Hosokawa, N., Kanamori, H., Kaku, M., Koide, M., and Fujita, J. (2018). Legionella pneumophila contamination of hospital dishwashers. *American Journal of Infection Control*, *46*(8), 943-945.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

[38] Hussain H.H., Ibraheem N.T., Al-Rubaey N.K.F., Radhi M.M., Hindi N.K.K., and AL-Jubori R.H.K. (2022). A review of airborne contaminated microorganisms associated with human diseases. *Medical Journal of Babylon*, *19*(2), 115-122.

[39] Banerjee K., Chatterjee M., Sandur R., Nachimuthu R., Madhyastha H., and Thiagarajan P. (2021). Azadirachta indica A. Juss (Neem) oil topical formulation with liquid crystals ensconcing depot water for anti-inflammatory, wound healing and anti-methicillin resistant Staphylococcus aureus activities. *Journal of Drug Delivery Science and Technology*, *64*, 102563.

[40] Navarro P. P., Vettiger A., Ananda V. Y., Llopis P. M., Allolio C., Bernhardt T. G., and Chao L. H. (2022). Cell wall synthesis and remodelling dynamics determine division site architecture and cell shape in Escherichia coli. *Nature Microbiology*, *7*(10), 1621-1634.

[41] Chruściel J.J. (2022). Modifications of textile materials with functional silanes, liquid silicone softeners, and silicone rubbers—A Review. *Polymers*, *14*(20), 4382.

[42] Deb C., Lee C.M., Dubey V.S., Daniel J., Abomoelak B., Sirakova T.D., Pawar S., Rogers L., and Kolattukudy P.E. (2009). A novel in vitro multiple-stress dormancy model for Mycobacterium tuberculosis generates a lipid-loaded, drug-tolerant, dormant pathogen, *PloS one*, *4*(6), e6077.

[43] Song, L., Zhou, J., Wang, C., Meng, G., Li, Y., Jarin, M., Wu, Z., and Xie, X. (2022). Airborne pathogenic microorganisms and air cleaning technology development: A review. *Journal of Hazardous Materials*, *424*, 127429.

[44] Jasim, S.A., Mohammadi, M.J., Patra, I., Jalil, A.T., Taherian, M., Abdullaeva, U.Y., and Alborzi, M. (2024). The effect of microorganisms (bacteria and fungi) in dust storm on human health. *Reviews on Environmental Health*, *39*(1), 65-75.

[45] Guo W., Zhao M., Chen Q., Huang L., Mao Y., Xia N., Teng J., and Wei B. (2019). Citrinin produced using strains of Penicillium citrinum from Liupao tea. *Food Bioscience*, *28*, 183-191.

[46] La Rosa G., Fratini M., Libera S.D., Iaconelli M., and Muscillo M. (2013). Viral infections acquired indoors through airborne, droplet or contact transmission. *Annali dell'Istituto Superiore di Sanita*, *49*, 124-132.

[47] Li Y. (2021). Basic routes of transmission of respiratory pathogens—A new proposal for transmission categorization based on respiratory spray, inhalation, and touch. *Indoor Air*, *31*(1), 3.

[48] Habibi-Yangjeh A., Asadzadeh-Khaneghah S., Feizpoor S., and Rouhi A. (2020). Review on heterogeneous photocatalytic disinfection of waterborne, airborne, and foodborne viruses: can we win against pathogenic viruses?. *Journal of Colloid and Interface Science*, *580*, 503-514.

[49] Okoro O.J., Deme G.G., Okoye C.O., Eze S.C., Odii E.C., Gbadegesin J.T., Okeke E.S., Oyejobi G.K., Nyaruaba R., and Ebido C.C. (2023). Understanding key vectors and vector-borne diseases associated with freshwater ecosystem across Africa: Implications for public health. *Science of the Total Environment*, *862*, 160732.

[50] Bardosh, K.L., Ryan, S.J., Ebi, K., Welburn, S., and Singer, B. (2017). Addressing vulnerability, building resilience: community-based adaptation to vector-borne diseases in the context of global change. *Infectious Diseases of Poverty*, *6*, 1-21.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

[51] Rani Z., Abbas A., Saeed Z., Zaheer H., and Abbas R. (2023). Strategies and advancements for control of vector borne diseases of public health concern. *One Health Triad, Unique Scientific Publishers, Faisalabad, Pakistan*, *1*, 168-174.

[52] Wang C.C., Prather K.A., Sznitman J., Jimenez J.L., Lakdawala S.S., Tufekci Z., and Marr L.C. (2021). Airborne transmission of respiratory viruses. *Science*, *373*(6558), eabd9149.

[53] Edwards D.A., Ausiello D., Salzman J., Devlin T., Langer R., Beddingfield B.J., Fears A.C., Doyle-Meyers L.A., Redmann R.K., and Killeen S.Z. (2021). Exhaled aerosol increases with COVID-19 infection, age, and obesity. *Proceedings of the National Academy of Sciences*, *118*(8), e2021830118.

[54] Riediker M., and Morawska L. (2020). Low exhaled breath droplet formation may explain why children are poor SARS-CoV-2 transmitters. *Aerosol and Air Quality Research*, *20*(7), 1513-1515.

[53] Lin K., and Marr L.C. (2019). Humidity-dependent decay of viruses, but not bacteria, in aerosols and droplets follows disinfection kinetics. *Environmental Science & Technology*, *54*(2), 1024-1032.

[54] Yang W., and Marr L.C. (2011). Dynamics of airborne influenza A viruses indoors and dependence on humidity, *PloS one*, *6*(6), e21481.

[55] Rasheed, A., Sharma, S., Kabi, P., Saha, A., Chaudhuri, S., and Basu, S. (2021). Precipitation dynamics of surrogate respiratory sessile droplets leading to possible fomites. *Journal of Colloid and Interface Science*, *600*, 1-13.

[56] Merhi T., Atasi O., Coetsier C., Lalanne B., and Roger K. (2022). Assessing suspension and infectivity times of virus-loaded aerosols involved in airborne transmission. *Proceedings of the National Academy of Sciences*, *119*(32), e2204593119.

[57] Rowe, B. R., Canosa, A., Drouffe, J. M., and Mitchell, J. B. A. (2021). Simple quantitative assessment of the outdoor versus indoor airborne transmission of viruses and COVID-19. *Environmental Research*, *198*, 111189.

[58] Poydenot, F., Abdourahamane, I., Caplain, E., Der, S., Haiech, J., Jallon, A., and Andreotti, B. (2022). Risk assessment for long-and short-range airborne transmission of SARS-CoV-2, indoors and outdoors. *PNAS Nexus*, *1*(5), pgac223.

[59] Morawska, L., Tang, J. W., Bahnfleth, W., Bluyssen, P. M., Boerstra, A., Buonanno, G., and Yao, M. (2020). How can airborne transmission of COVID-19 indoors be minimised?. *Environment International*, *142*, 105832.

[60] Gao, X., Wei, J., Lei, H., Xu, P., Cowling, B. J., and Li, Y. (2016). Building ventilation as an effective disease intervention strategy in a dense indoor contact network in an ideal city. *PLoS One*, *11*(9), e0162481.

[61] Kumar P., Singh A., and Singh R. (2021). Seasonal variation and size distribution in the airborne indoor microbial concentration of residential houses in Delhi and its impact on health. *Aerobiologia*, *37*(4), 719-732.

[62] Ruiz-Gil T., Acuña J.J., Fujiyoshi S., Tanaka D., Noda J., Maruyama F., and Jorquera M.A. (2020). Airborne bacterial communities of outdoor environments and their associated influencing factors. *Environment International*, *145*, 106156.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

[63] Onchang, R., and Panyakapo, M. (2016). The physical environments and microbiological contamination in three different fitness centres and the participants' expectations: Measurement and analysis. *Indoor and Built Environment*, *25*(1), 213-228.

[64] Boonrattanakij, N., Yomchinda, S., Lin, F.J., Bellotindos, L.M., and Lu, M.C. (2021). Investigation and disinfection of bacteria and fungi in sports fitness center. *Environmental Science and Pollution Research*, *28*(37), 52576-52586.

[65] Le Cann, P., Bonvallot, N., Glorennec, P., Deguen, S., Goeury, C., and Le Bot, B. (2011). Indoor environment and children's health: recent developments in chemical, biological, physical and social aspects. *International Journal of Hygiene and Environmental Health*, *215*(1), 1-18.

[66] Dima, C., Assadpour, E., Dima, S., and Jafari, S.M. (2020). Bioavailability of nutraceuticals: Role of the food matrix, processing conditions, the gastrointestinal tract, and nanodelivery systems. *Comprehensive Reviews in Food Science and Food Safety*, *19*(3), 954-994.

[67] Vadivukkarasan M., Dhivyaraja K., and Panchagnula M.V. (2020). Breakup morphology of expelled respiratory liquid: From the perspective of hydrodynamic instabilities, *Physics of Fluids*, *32*(9), 094101.

[68] Argyropoulos C.D., Skoulou V., Efthimiou G., and Michopoulos A.K. (2023). Airborne transmission of biological agents within the indoor built environment: a multidisciplinary review. *Air Quality, Atmosphere & Health*, *16*(3), 477-533.

[69] Jiayu, C., Qiaoqiao, R., Feilong, C., Chen, L., Jiguo, W., Zhendong, W., and Guoxia, Z. (2019). Microbiology community structure in bioaerosols and the respiratory diseases. *Journal of Environmental Science and Public Health*, *3*(3), 347-357.

[70] Cunliffe, A.J., Wang, R., Redfern, J., Verran, J., and Wilson, D.I. (2023). Effect of environmental factors on the kinetics of evaporation of droplets containing bacteria or viruses on different surfaces. *Journal of Food Engineering*, *336*, 111195.

[71] Redrow, J., Mao, S., Celik, I., Posada, J. A., & Feng, Z. G. (2011). Modeling the evaporation and dispersion of airborne sputum droplets expelled from a human cough. *Building and Environment*, *46*(10), 2042-2051.

[72] Ruiz-Gil, T., Acuña, J.J., Fujiyoshi, S., Tanaka, D., Noda, J., Maruyama, F., and Jorquera, M. A. (2020). Airborne bacterial communities of outdoor environments and their associated influencing factors. *Environment International*, *145*, 106156.

[73] Roos, Y.H. (2020). Water and pathogenic viruses inactivation—food engineering perspectives. *Food Engineering Reviews*, *12*(3), 251-267.

[74] Jaakkola, K., Saukkoriipi, A., Jokelainen, J., Juvonen, R., Kauppila, J., Vainio, O., and KIAS-Study Group. (2014). Decline in temperature and humidity increases the occurrence of influenza in cold climate. *Environmental Health*, *13*, 1-8.

[75] Jeong, D., Yi, H., Park, J.H., Park, H.W., and Park, K. (2022). A vertical laminar airflow system to prevent aerosol transmission of SARS-CoV-2 in building space: Computational fluid dynamics (CFD) and experimental approach. *Indoor and Built Environment*, *31*(5), 1319-1338.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

[76] Sadrizadeh, S., Aganovic, A., Bogdan, A., Wang, C., Afshari, A., Hartmann, A., and Cao, G. (2021). A systematic review of operating room ventilation. *Journal of Building Engineering*, *40*, 102693.

[77] Mizuno, M., Yori, K., Takeuchi, T., Yamaguchi, T., Watanabe, K., Tomaru, Y., and Sekiya, I. (2023). Cross-contamination risk and decontamination during changeover after cell-product processing. *Regenerative Therapy*, *22*, 30-38.

[78] Aghniaey, S., Williams, J.G., Chaitow, S.D., and Rivera, L. (2021). Investigating air distribution designs for doas systems to reduce cross-contamination in open offices. *ASHRAE Transactions*, *127*(1), 214-224.

[79] Ghaddar, N., and Ghali, K. (2022). Ten questions concerning the paradox of minimizing airborne transmission of infectious aerosols in densely occupied spaces via sustainable ventilation and other strategies in hot and humid climates. *Building and Environment*, *214*, 108901.

[80] Otter, J.A., Yezli, S., and French, G.L. (2011). The role played by contaminated surfaces in the transmission of nosocomial pathogens. *Infection Control & Hospital Epidemiology*, *32*(7), 687-699.

[81] Ganegoda, N.C., Wijaya, K.P., Amadi, M., Erandi, K.H., and Aldila, D. (2021). Interrelationship between daily COVID-19 cases and average temperature as well as relative humidity in Germany. *Scientific Reports*, *11*(1), 11302.

[82] Izadyar, N., and Miller, W. (2022). Ventilation strategies and design impacts on indoor airborne transmission: A review. *Building and Environment*, *218*, 109158.

[83] Al-Rikabi, I.J., Karam, J., Alsaad, H., Ghali, K., Ghaddar, N., and Voelker, C. (2024). The impact of mechanical and natural ventilation modes on the spread of indoor airborne contaminants: A review. *Journal of Building Engineering*, *85*, 108715.

[84] Zhang, X., Li, Z., Hu, J., Yan, L., He, Y., Li, X., and Xu, H. (2021). The biological and chemical contents of atmospheric particulate matter and implication of its role in the transmission of bacterial pathogenesis. *Environmental Microbiology*, *23*(9), 5481-5486.

[85] Liu, H., Zhang, X., Zhang, H., Yao, X., Zhou, M., Wang, J., and Hu, B. (2018). Effect of air pollution on the total bacteria and pathogenic bacteria in different sizes of particulate matter. *Environmental Pollution*, *233*, 483-493.

[86] Zhang, X., Li, Z., Hu, J., Yan, L., He, Y., Li, X., and Xu, H. (2021). The biological and chemical contents of atmospheric particulate matter and implication of its role in the transmission of bacterial pathogenesis. *Environmental Microbiology*, *23*(9), 5481-5486.

[87] Burbank, A.J. (2023). Risk factors for respiratory viral infections: a spotlight on climate change and air pollution. *Journal of Asthma and Allergy*, *16*, 183-194.

[88] Nandiyanto, A.B.D., Ragadhita, R., Setiyo, M., Al Obaidi, A.S.M., and Hidayat, A. (2023). Particulate matter emission from combustion and non-combustion automotive engine process: Review and computational bibliometric analysis on its source, sizes, and health and lung impact. *Automotive Experiences*, *6*(3), 599-623.

[89] Sivakumar, R., and Lee, N.Y. (2022). Recent advances in airborne pathogen detection using optical and electrochemical biosensors. *Analytica Chimica Acta*, *1234*, 340297.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

[90] Liu, Y., Zhang, L., Wei, W., Zhao, H., Zhou, Z., Zhang, Y., and Liu, S. (2015). Colorimetric detection of influenza A virus using antibody-functionalized gold nanoparticles. *Analyst*, *140*(12), 3989-3995.

[91] Wang, S., Deng, W., Yang, L., Tan, Y., Xie, Q., and Yao, S. (2017). Copper-based metal–organic framework nanoparticles with peroxidase-like activity for sensitive colorimetric detection of Staphylococcus aureus. *ACS Applied Materials & Interfaces*, *9*(29), 24440-24445.

[92] Xu, L., Wang, R., Kelso, L. C., Ying, Y., and Li, Y. (2016). A target-responsive and size-dependent hydrogel aptasensor embedded with QD fluorescent reporters for rapid detection of avian influenza virus H5N1. *Sensors and Actuators B: Chemical*, *234*, 98-108.

[93] Zhang, X., Wu, D., Zhou, X., Yu, Y., Liu, J., Hu, N., and Wu, Y. (2019). Recent progress in the construction of nanozyme-based biosensors and their applications to food safety assay. *TrAC Trends in Analytical Chemistry*, *121*, 115668.

[94] Weng, X., and Neethirajan, S. (2016). A microfluidic biosensor using graphene oxide and aptamer-functionalized quantum dots for peanut allergen detection. *Biosensors and Bioelectronics*, *85*, 649-656.

[95] Zhou, J., Fu, R., Tian, F., Yang, Y., Jiao, B., and He, Y. (2020). Dual enzyme-induced Au–Ag alloy nanorods as colorful chromogenic substrates for sensitive detection of Staphylococcus aureus. *ACS Applied Bio Materials*, *3*(9), 6103-6109.

[96] Sun, Y., He, X., Ji, J., Jia, M., Wang, Z., and Sun, X. (2015). A highly selective and sensitive electrochemical CS–MWCNTs/Au-NPs composite DNA biosensor for Staphylococcus aureus gene sequence detection. *Talanta*, *141*, 300-306.

[97] Bai, C., Lu, Z., Jiang, H., Yang, Z., Liu, X., Ding, H., and Shao, N. (2018). Aptamer selection and application in multivalent binding-based electrical impedance detection of inactivated H1N1 virus. *Biosensors and Bioelectronics*, *110*, 162-167.

[98] Bekir, K., Barhoumi, H., Braiek, M., Chrouda, A., Zine, N., Abid, N., and Mansour, H.B. (2015). Electrochemical impedance immunosensor for rapid detection of stressed pathogenic Staphylococcus aureus bacteria. *Environmental Science and Pollution Research*, *22*, 15796-15803.

[99] Eissa, S., Alhadrami, H.A., Al-Mozaini, M., Hassan, A.M., and Zourob, M. (2021). Voltammetric-based immunosensor for the detection of SARS-CoV-2 nucleocapsid antigen. *Microchimica Acta*, *188*(6), 199.

[100] Waller, D.F., Hew, B. E., Holdaway, C., Jen, M., and Peckham, G.D. (2016). Rapid detection of Bacillus anthracis spores using immunomagnetic separation and amperometry. *Biosensors*, *6*(4), 61.

[101] Noakes, C.J., and Sleigh, P.A. (2009). Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. *Journal of the Royal Society Interface*, *6(suppl_6)*, S791-S800.

[102] Beggs, C.B., Shepherd, S.J., and Kerr, K.G. (2010). Potential for airborne transmission of infection in the waiting areas of healthcare premises: stochastic analysis using a Monte Carlo model. *BMC Infectious Diseases*, *10*, 1-8.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

[103] Sheikhnejad, Y., Aghamolaei, R., Fallahpour, M., Motamedi, H., Moshfeghi, M., Mirzaei, P. A., and Bordbar, H. (2022). Airborne and aerosol pathogen transmission modeling of respiratory events in buildings: An overview of computational fluid dynamics. *Sustainable Cities and Society*, *79*, 103704.

[104] McMurry, P. H. (2000). A review of atmospheric aerosol measurements. *Atmospheric Environment*, *34(12-14)*, 1959-1999.

[105] Shen, S., Jaques, P. A., Zhu, Y., Geller, M. D., and Sioutas, C. (2002). Evaluation of the SMPS–APS system as a continuous monitor for measuring PM2. 5, PM10 and coarse (PM2. 5− 10) concentrations. *Atmospheric Environment*, *36*(24), 3939-3950.

[106] Friehmelt, R., Büttner, H., and Ebert, F. (2000). On-line Characterisation of Aerosols–Comparability and Combination of Selected Measuring Devices. *KONA Powder and Particle Journal*, *18*, 183-193.

[107] Holubčík, M., Jandačka, J., Ďurčanský, P., and Čaja, A. (2020). Particulate matter measurement by using the particle sizers APS and SMPS. *EAI Endorsed Trans. Energy Web*, *8*, 166000.

[108] Close, A., Blackerby, J., Tunnell, H., Pender, J., Soule, E., and Sousan, S. (2023). Effects of e-cigarette liquid ratios on the gravimetric filter correction factors and real-time measurements. *Aerosol and Air Quality Research*, *23*(10), 230011.

[109] Song L., Zhou J., Wang C., Meng G., Li Y., Jarin M., Wu Z., and Xie X. (2022). Airborne pathogenic microorganisms and air cleaning technology development: A review. *Journal of Hazardous Materials*, *424*, 127429.

[110] Liu, G., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., and Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. *Sustainable Cities and Society*, *32*, 375-396.

[111] Salthammer, T. (2004). Emissions of volatile organic compounds from products and materials in indoor environments. *Air Pollution: Indoor Air Pollution*, *4*, 37-71.

[112] Ueki, H., Ujie, M., Komori, Y., Kato, T., Imai, M., and Kawaoka, Y. (2022). Effectiveness of HEPA filters at removing infectious SARS-CoV-2 from the air. *Msphere*, *7*(4), e00086-22.

[113] Luo, H., and Zhong, L. (2021). Ultraviolet germicidal irradiation (UVGI) for in-duct airborne bioaerosol disinfection: Review and analysis of design factors. *Building and Environment*, *197*, 107852.

[114] Mata, T.M., Martins, A.A., Calheiros, C.S., Villanueva, F., Alonso-Cuevilla, N.P., Gabriel, M.F., and Silva, G.V. (2022). Indoor air quality: A review of cleaning technologies. *Environments*, *9*(9), 118.

[115] Bono, N., Ponti, F., Punta, C., and Candiani, G. (2021). Effect of UV irradiation and TiO2-photocatalysis on airborne bacteria and viruses: an overview. *Materials*, *14*(5), 1075.

[116] Liu, Y., Li, L., Hu, T., Zhu, X., Wang, H., Zhang, W., and Li, Y. (2025). Enhanced photocatalytic performance of multifunctional composite Ag-Ag2Se@ CdSe/3DOM TiO2 with dual Z-scheme heterostructures coupling Ag NPs: Degradation, hydrogen production and antibacterial activity. *Journal of Alloys and Compounds*, *1021*, 179571.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

[117] Foster, H.A., Ditta, I.B., Varghese, S., and Steele, A. (2011). Photocatalytic disinfection using titanium dioxide: spectrum and mechanism of antimicrobial activity. *Applied Microbiology and Biotechnology*, *90*, 1847-1868.

[118] Bogdan, J., Zarzyńska, J., and Pławińska-Czarnak, J. (2015). Comparison of infectious agents susceptibility to photocatalytic effects of nanosized titanium and zinc oxides: a practical approach. *Nanoscale Research Letters*, *10*, 1-15.

[119] Fujishima, A., and Zhang, X. (2006). Titanium dioxide photocatalysis: present situation and future approaches. *Comptes Rendus Chimie*, *9*(5-6), 750-760.

[120] Jonges, M., Liu, W.M., van der Vries, E., Jacobi, R., Pronk, I., Boog, C., and Soethout, E. (2010). Influenza virus inactivation for studies of antigenicity and phenotypic neuraminidase inhibitor resistance profiling. *Journal of Clinical Microbiology*, *48*(3), 928-940.

[121] Bertrand, I., Schijven, J.F., Sánchez, G., Wyn-Jones, P., Ottoson, J., Morin, T., and Gantzer, C. (2012). The impact of temperature on the inactivation of enteric viruses in food and water: a review. *Journal of Applied Microbiology*, *112*(6), 1059-1074.

[122] Vlaskin, M.S. (2022). Review of air disinfection approaches and proposal for thermal inactivation of airborne viruses as a life-style and an instrument to fight pandemics. *Applied Thermal Engineering*, *202*, 117855.

[123] Tao, S., Zhu, Y., Chen, M., and Shangguan, W. (2024). Advances in electrostatic plasma methods for purification of airborne pathogenic microbial aerosols: Mechanism, modeling and application. *Environment & Health*, *2*(9), 596-617.

[124] Lim, S.W.Y., Ow, S.Y., Sutarlie, L., Lee, Y.Y., Suwardi, A., Tan, C.K.I., and Su, X. (2024). Bioaerosol inactivation by a cold plasma ionizer coupled with an electrostatic precipitator. *Microorganisms*, *12*(9), 1923.

[125] Guo, H., Chen, J., Wang, L., Wang, A.C., Li, Y., An, C., and Wang, Z.L. (2021). A highly efficient triboelectric negative air ion generator. *Nature Sustainability*, *4*(2), 147-153.

[126] de Aquino Lima, F., and Guerra, V.G. (2024). Collection of nanoparticles by electrostatic precipitation operating over a wide range of electric fields. *Separation Science and Technology*, *59*(5), 848-865.

[127] Jaworek, A., Marchewicz, A., Sobczyk, A.T., Krupa, A., and Czech, T. (2018). Two-stage electrostatic precipitators for the reduction of PM2. 5 particle emission. *Progress in Energy and Combustion Science*, *67*, 206-233.

[128] Patial, S., Nazim, M., Khan, A.A.P., Raizada, P., Singh, P., Hussain, C.M., and Asiri, A.M. (2022). Sustainable solutions for indoor pollution abatement during COVID phase: A critical study on current technologies & challenges. *Journal of Hazardous Materials Advances*, *7*, 100097.

[129] Clausen, P.A., Frederiksen, M., Sejbæk, C.S., Sørli, J.B., Hougaard, K.S., Frydendall, K.B., and Wolkoff, P. (2020). Chemicals inhaled from spray cleaning and disinfection products and their respiratory effects. A comprehensive review. *International Journal of Hygiene and Environmental Health*, *229*, 113592.

[130] Bokare, A.D., and Choi, W. (2014). Review of iron-free Fenton-like systems for activating H2O2 in advanced oxidation processes. *Journal of Hazardous Materials*, *275*, 121-135.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938

[131] Rai, N. K., Ashok, A., and Akondi, B. R. (2020). Consequences of chemical impact of disinfectants: safe preventive measures against COVID-19. *Critical Reviews in Toxicology*, *50*(6), 513-520.

[132] Calcagni, N., Venier, A. G., Nasso, R., Boudin, G., Jarrige, B., Parneix, P., and Quintard, B. (2023). Respiratory infection prevention: perceptions, barriers and facilitators after SARS-CoV-2. *Infection, Disease & Health*, *28*(1), 54-63.

[133] Koo, J., Jo, Y. M., Lee, T. J., Park, S., and Song, D. (2023). Ventilation strategy for simultaneous management of indoor particulate matter and airborne transmission risks–A case study for urban schools in South Korea. *Building and Environment*, *242*, 110575.

[134] Lu, G., Razum, O., Jahn, A., Zhang, Y., Sutton, B., Sridhar, D., and Müller, O. (2021). COVID-19 in Germany and China: mitigation versus elimination strategy. *Global Health Action*, *14*(1), 1875601.

[135] Li, T., Liu, Y., Li, M., Qian, X., and Dai, S. Y. (2020). Mask or no mask for COVID-19: A public health and market study. *PloS one*, *15*(8), e0237691.

[136] Roberts, J. D., and Tehrani, S. O. (2020). Environments, behaviors, and inequalities: reflecting on the impacts of the influenza and coronavirus pandemics in the United States. *International Journal of Environmental Research and Public Health*, *17*(12), 4484.

[137] Rauch, S., Jasny, E., Schmidt, K.E., and Petsch, B. (2018). New vaccine technologies to combat outbreak situations. *Frontiers in Immunology*, *9*, 1963.

[138] Mantel, C., and Cherian, T. (2020). New immunization strategies: adapting to global challenges. *Bundesgesundheitsblatt-Gesundheitsforschung-Gesundheitsschutz*, *63*(1), 25-31.

[139] Hafidzhah, M.A., Wijaya, R.M., Probojati, R.T., Kharisma, V.D., Ansori, A.N.M., and Parikesit, A. A. (2021). Potential vaccine targets for covid-19 and phylogenetic analysis based on the nucleocapsid phosphoprotein of indonesian SARS-CoV-2 isolates. *Indonesian Journal of Pharmacy/Majalah Farmasi Indonesia*, *32*(3), 328-337.

[140] Wong, M.T.J., Dhaliwal, S.S., Balakrishnan, V., Nordin, F., Norazmi, M.N., and Tye, G.J. (2023). Effectiveness of booster vaccinations on the control of covid-19 during the spread of omicron variant in Malaysia. *International Journal of Environmental Research and Public Health*, *20*(2), 1647.

[141] Kuai, Y.H., and Ser, H.L. (2021). COVID-19 situation in Thailand. *Progress In Microbes & Molecular Biology*, *4*(1), 1-8.

[142] Pirich, R., Weir, J., and Leyble, D. (2008). Self-cleaning and anti-contamination coatings for space exploration: an overview. *Optical System Contamination: Effects, Measurements, and Control 2008*, *7069*, 99-106.

[143] Gupta, N., Abd EL-Gawaad, N.S., and Mallasiy, L. O. (2024). Hospital-borne hazardous air pollutants and air cleaning strategies amid the surge of SARS-CoV-2 new variants. *Heliyon*, *10*(20).

[144] Yigitcanlar, T., Desouza, K. C., Butler, L., and Roozkhosh, F. (2020). Contributions and risks of artificial intelligence (AI) in building smarter cities: Insights from a systematic review of the literature. *Energies*, *13*(6), 1473.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2775-6793 e- ISSN 2775-6815

[145] Nurramadhani, A., Riandi, R., Permanasari, A., and Suwarma, I.R. (2024). Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *9*(2), 261-286.

[146] Krishnan, A., Al-Obaidi, A.S.M., and Hao, L.C. (2024). Towards sustainable wind energy: A systematic review of airfoil and blade technologies over the past 25 years for supporting sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *9*(3), 623-656.

[147] Djirong, A., Jayadi, K., Abduh, A., Mutolib, A., Mustofa, R.F., and Rahmat, A. (2024). Assessment of student awareness and application of eco-friendly curriculum and technologies in Indonesian higher education for supporting sustainable development goals (SDGs): A case study on environmental challenges. *Indonesian Journal of Science and Technology*, *9*(3), 657-678.

[148] Waardhani, A.W., Noviyanti, A.R., Kusrini, E., Nugrahaningtyas, K.D., Prasetyo, A.B., Usman, A., Irwansyah, F.S., and Juliandri, J. (2025). A study on sustainable eggshell-derived hydroxyapatite/CMC membranes: Enhancing flexibility and thermal stability for sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *10*(2), 191-206.

[149] Yustiarini, D., Soemardi, B.W., and Pribadi, K.S. (2025). Integrating multi-stakeholder governance, engineering approaches, and bibliometric literature review insights for sustainable regional road maintenance: Contribution to sustainable development goals (SDGs) 9, 11, and 16. *Indonesian Journal of Science and Technology*, *10*(2), 367-398.

[150] Merzouki, M., Khibech, O., Fraj, E., Bouammali, H., Bourhou, C., Hammouti, B., Bouammali, B., and Challioui, A. (2025). Computational engineering of malonate and tetrazole derivatives targeting SARS-CoV-2 main protease: Pharmacokinetics, docking, and molecular dynamics insights to support the sustainable development goals (SDGs), with a bibliometric analysis. *Indonesian Journal of Science and Technology*, *10*(2), 399-418.

[151] Namoussa, T.Y., Boucerredj,L., Khechekhouche, A., Kemerchou, I., Zair, N., Jahangiri, M., Miloudi, A., and Siqueira, A. (2025). Innovative nanofluid encapsulation in solar stills: Boosting water yield and efficiency under extreme climate supporting sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *10*(3), 419-426.

[152] Glovatskii, O., Kalimbetov, B., Ergashev, R., Kholbutaev, B., Pardaev, M., Ergasheva, G., Nasirova, N., and Khimmataliev, D.O. (2025). Modernization of Submersible Pump Designs for Sustainable Irrigation: A Bibliometric and experimental contribution to sustainable development goals (SDGs). *Indonesian Journal of Science and Technology*, *10*(3), 427.

DOI: https://doi.org/10.17509/ajse.v5i2.86303
p- ISSN 2776-6098 e- ISSN 2776-5938