

**STUDY COMPONENT IV: IDENTIFY EXISTING SOLUTIONS FOR IAQ MONITORING,
REPORTING AND IMPROVEMENT.**

Clean Air Network

CAN

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List of Acronyms

Acronyms	Meaning
IAQ	Indoor Air Quality
WHO	World Health Organization
PM	Particulate Matter
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
SO ₂	Sulphate Dioxide
NO ₂	Nitrogen Dioxide
O ₃	Ozone
Rn	Radon
VOCs	Volatile Organic Compounds
TVOCs	Total Volatile Organic Compounds
HCHO	Formaldehyde
MOS	Metal Oxide Semiconductor
US EPA	United States Environmental Protection Agency
HK EPD	Hong Kong Environmental Protection Agency
COPD	Chronic Obstructive Pulmonary Disease
IoT	Internet of Things
OAQ	Outdoor Air Quality
UFP	Ultrafine Particles
BASE	Building Assessment Survey and Evaluation
UV	Ultraviolet
IR	Infrared
HVAC	Heating, Ventilation, and Air Conditioning
MVAC	Mechanical Ventilation and Air Conditioning
HRVs	Heat Recovery Ventilators
ERVs	Energy Recovery Ventilators
ACMV	Air Conditioning and Mechanical Ventilation
DCV	Demand-Controlled Ventilation
PCO	Photocatalytic Oxidation
BMS	Building Management System
CAN	Clean Air Network
IEQ	Indoor Environmental Quality
AQI	Air Quality Index
NO _x	Nitrogen Oxides
APU	Auxiliary Power Unit
AQHI	Air Quality Health Index
HEPA	High-Efficiency Particulate Air

EXECUTIVE SUMMARY

This report presents a comprehensive evaluation of indoor air quality (IAQ) technologies, policies, and practices in global cities comparable to Hong Kong, with a primary focus on the unique challenges and developments specific to Hong Kong. Although the city has made significant advances in IAQ monitoring, it continues to struggle with issues such as limited IAQ reporting, inadequate management of residential air quality, and a need for more stringent regulatory frameworks and collaborative efforts.

In contrast, cities such as Tokyo, Seoul, Shanghai, Dubai, New York, and Singapore have pioneered the implementation of advanced sensor systems, integrated building management solutions, and robust regulatory structures. These cities provide critical lessons that could inform and enhance Hong Kong's approach to improving IAQ.

Notable insights from the report reveal advancements in sensor technologies, including electrochemical sensors, particulate matter (PM) detection, infrared sensors, and IoT-integrated systems, which facilitate real-time IAQ monitoring. Successful practices from other countries demonstrate the benefits of centralized building management systems, proactive reporting mechanisms, and rigorous certification standards, such as LEED, WELL, and ASHRAE. Specifically, Singapore and Dubai have instituted mandatory IAQ testing and ongoing monitoring, accompanied by penalties for non-compliance, thereby fostering a culture of accountability and health-focused building management.

The report also emphasizes innovative air purification and ventilation solutions, including HEPA filters, UVGI systems, demand-controlled ventilation, and hybrid models tailored to specific climatic and urban conditions. While Hong Kong primarily utilizes portable HEPA units and filter-based purifiers, there is a substantial opportunity to adopt more integrated, energy-efficient systems that comply with international standards.

In conclusion, the report advocates for the establishment of a mandatory, data-driven IAQ regulatory framework, the development of a public IAQ portal, and enhanced inter-agency collaborations to foster healthier indoor environments. By harnessing technological advancements alongside stronger policies, Hong Kong can effectively confront its IAQ challenges and safeguard public health.

CHAPTER SUMMARIES

CHAPTERS	DESCRIPTION
Chapter 1	Chapter 1 explores the study's background and rationale, outlining its key objectives and scope while acknowledging any limitations. It also defines essential terms related to Indoor Air Quality (IAQ) to ensure a clear understanding for readers.
Chapter 2	Chapter 2 presents a literature review of IAQ in Hong Kong, examining the technologies and solutions implemented to address this significant issue. It explores monitoring systems for air pollutants, advanced filtration, and innovative ventilation strategies that contribute to healthier indoor environments. The chapter emphasizes Hong Kong's efforts to improve air quality in residential and commercial spaces, highlighting the necessity of these solutions in densely populated urban areas.
Chapter 3	Chapter 3 provides a literature review on innovative IAQ technologies and solutions from major cities such as Singapore, Tokyo, Seoul, Shanghai, New York, and Dubai, each showcasing distinct strategies for monitoring and improving air quality. The chapter synthesizes these approaches, highlighting lessons and best practices to inform future IAQ strategies in Hong Kong and similar urban areas.
Chapter 4	Chapter 4 explores methodologies for data collection and analysis concerning Indoor Air Quality in urban settings. It highlights techniques for gathering air quality data, including advanced monitoring equipment, surveys, and environmental sensors. The chapter also discusses the analytical frameworks, emphasizing statistical methods used to assess IAQ differences among various cities.
Chapter 5	Chapter 5 explores IAQ by examining the various technologies and solutions implemented across different cities. Building on the findings from Chapters 2 and 3, this chapter highlights how each city has adapted to its environmental challenges. By comparing these approaches, the chapter reveals best practices and innovative solutions, offering an overview of current IAQ management in urban areas.
Chapter 6	Chapter 6 summarizes key insights and recommendations to improve IAQ in Hong Kong. It highlights the need for increased building ventilation, the use of HEPA filter air purifiers, and regular monitoring of air pollutants. The chapter also advocates for public awareness campaigns to educate residents about the sources of indoor air pollution and their associated health impacts. By implementing these strategies, Hong Kong can enhance IAQ in residential and commercial spaces, promoting a healthier environment for its residents.

1. Introduction

1.1. Background and Rationale

In the heart of Hong Kong, a city renowned for its vibrant economy and high population density, a pressing issue has arisen that warrants careful examination of Indoor Air Quality (IAQ). As the urban population continues to grow, the implications of poor IAQ become increasingly significant, particularly in terms of public health and environmental sustainability.

Data from the World Health Organization indicates that in 2020, approximately 3.2 million deaths globally were attributable to poor IAQ, with children under five accounting for 237,000 of these fatalities. Additionally, the alarming statistic that 9 out of 10 individuals worldwide (WHO, 2018) breathe air contaminated with high levels of pollutants highlights the global scale of this issue. Poor air quality is closely linked to a range of health conditions, particularly respiratory and cardiovascular diseases, making this a critical area for intervention.

In examining the unique challenges faced by Hong Kong, it is essential to consider the interplay of urbanization, pollution, and health outcomes. Despite significant efforts in monitoring and management of IAQ, including various community initiatives and voluntary certification schemes, gaps remain. The city's approach lacks the mandatory compliance measures and comprehensive regulatory frameworks found in leading cities such as Singapore, Tokyo, New York, Seoul, Dubai, and Shanghai. These cities have successfully integrated advanced technologies, such as real-time sensor networks and centralized Building Management Systems (BMS), alongside enforceable air quality standards, allowing for proactive management of IAQ and demonstrable health benefits.

The rationale for this report rests on the necessity to learn from and adapt international best practices within Hong Kong's context. By analyzing the IAQ strategies employed in the aforementioned cities, this report aims to identify best practices that can be tailored to meet the specific needs of Hong Kong. Key areas of focus include technological innovation, establishing robust policy frameworks, and fostering cross-sector collaboration.

The objective is to develop targeted, actionable recommendations that address existing gaps in Hong Kong's IAQ management. These recommendations will advocate for the adoption of new technologies and the establishment of enforceable standards that can lead to significant improvements in air quality. Importantly, enhanced IAQ is correlated with reduced health risks, increased productivity, and ultimately, an improved quality of life for residents.

Through this analytical lens, the report underscores the urgent need for a comprehensive approach to IAQ management in Hong Kong. By leveraging successful strategies from other global cities, Hong Kong has the opportunity to transform its IAQ

framework and position itself as a leader in urban public health and environmental sustainability.

1.2 Objectives of the Report

1.2.1 Conduct a thorough examination of the existing solutions and technologies for monitoring IAQ in Hong Kong, assessing their strengths and limitations to identify areas for improvement.

1.2.2 Identify and document the innovative and best local and international solutions for IAQ monitoring, reporting, and improvement that enhance IAQ reporting and management systems.

1.2.3 Analyze the approaches employed by countries facing similar urban landscapes and environmental challenges to Hong Kong in addressing IAQ issues and derive actionable insights from their experiences.

1.2.4 Evaluate the feasibility of adopting or adapting current solutions to strengthen IAQ monitoring, reporting, and improvement initiatives in Hong Kong.

1.3 Scope and Limitations

This report provides a comprehensive examination of current technologies and solutions related to indoor air quality (IAQ), encompassing aspects such as monitoring, reporting, and methods for improvement. The primary focus of this analysis is on IAQ technologies used in Hong Kong, along with a comparative examination of other urban centers that share similar environmental and infrastructural characteristics. These cities include Tokyo, Singapore, Seoul, New York, Shanghai, and Dubai, all of which exhibit unique challenges and strategies in managing indoor air quality.

The data for this analysis has been gathered from a robust array of secondary sources, specifically from reputable institutions and organizations that specialize in environmental and public health research. This approach provides a well-rounded understanding of the existing technologies in these metropolitan areas.

However, it is essential to note that the findings of this study are specifically tailored to jurisdictions that reflect the landscape and urban dynamics of Hong Kong and its comparable cities, including Tokyo, Singapore, Seoul, New York, Shanghai, and Dubai. Consequently, the results may not necessarily extend or apply to countries with different geographical landscapes or to cities that experience distinct environmental issues. Furthermore, since this study relies exclusively on secondary data, there is a recognized need for primary data collection to enhance the accuracy, validity, and reliability of the information presented for stakeholders involved in IAQ management and policy-making. This additional data could provide deeper insights and contextual understanding, helping to inform more effective and tailored strategies for improving indoor air quality in diverse settings.

1.4 Definitions of IAQ Terms

Table 1. 1 Definitions of IAQ Terms

TERMS	Definitions
1 Indoor Air Quality (IAQ)	Indoor air quality pertains to the cleanliness of air inside and around buildings and structures, particularly in relation to the health and comfort of the occupants (US EPA, 2025a).
2 Particulate Matter (PM)	As defined by the World Health Organization (2025), particulate matter serves as a common indicator for air pollution, with its primary components including sulphates, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water.
3 Sulphur Dioxide (SO₂)	Sulphur dioxide is a colourless gas that has a sharp smell, generated from the combustion of fossil fuels and the smelting of mineral ores that contain sulphur (WHO, 2025).
4 Carbon Monoxide (CO)	Carbon monoxide is a colourless, odourless, and tasteless toxic gas that results from the incomplete burning of carbon-based fuels such as gasoline, wood, natural gas, charcoal, or kerosene (WHO, 2025).
5 Nitrogen Dioxide (NO₂)	Nitrogen dioxide is a gas frequently released during the burning of fuels in both the transportation and industrial industries (WHO, 2025).
6 Ozone (O₃)	At ground level, ozone is a key component of photochemical smog and is formed through reactions with gases in the presence of sunlight (WHO, 2025).
7 Formaldehyde	Formaldehyde is a colourless gas characterized by a strong odour and is among the most prevalent volatile organic compounds (VOCs) found indoors (WHO, 2025).
8 Radon (Rn)	Radon is a radioactive gas that originates from certain rock and soil formations, accumulating in the basements of homes when there is insufficient ventilation (WHO, 2025).
9 Mould	The accumulation of moisture can lead to the growth of Mold and bacteria, which occurs due to structural issues in buildings, inadequate heating and insulation, or insufficient ventilation (WHO, 2025).

2. Literature Review (PART A - HONG KONG)

2.1 Overview of Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) has emerged as a pressing concern, particularly gaining traction from the 1960s onward, amidst growing awareness of its significant impact on health and well-being. The evolution of IAQ management originated in Europe, particularly in Scandinavian countries, and has since spread to various regions, including the USA, Japan, and parts of Europe, thereby establishing a global dialogue on necessary standards. Notably, the World Health Organization (WHO) has played a crucial role, publishing its first guidelines in 1989 that set a global benchmark for IAQ management. This has been further reinforced through conferences, programs, and dissemination efforts aimed at raising awareness and promoting health, such as initiatives like 'Health Air' and 'EnVIE' (Air Quality News, 2016).

The WHO's ongoing research and publications have been instrumental in highlighting the detrimental effects of indoor air pollution. A recent report linked it to over 3.2 million deaths annually due to conditions like strokes and chronic obstructive pulmonary disease (COPD) (WHO, 2024). Additionally, indoor air pollution has been associated with various health issues, including dizziness, cancer, and respiratory infections. Japan's proactive approach in urban settings with high population densities has also significantly influenced global best practices in IAQ management.

In recent years, IAQ has emerged as a pressing global concern, driven by increasing awareness of its substantial impact on public health and overall well-being in residential, occupational, and public environments. Various stakeholders, including academics, governmental bodies, and industry leaders, collaborate to comprehend, monitor, and enhance IAQ through various regulations, initiatives, and technological innovations. As a result, different nations exhibit commonalities and differences in their approaches to IAQ management.

For instance, countries like as Japan, the United States, and several European nations have developed comprehensive standards and policies to regulate indoor pollutants, including volatile organic compounds (VOCs), carbon dioxide, and particulate matter. The U.S. Environmental Protection Agency (EPA) has issued guidelines aimed at mitigating indoor pollution, while the European Union is integrating IAQ standards within broader environmental and public health frameworks (US EPA, 2025; European Environment Agency, 2023).

However, the approaches to IAQ tend to vary widely in terms of scope and enforcement. Some nations prioritize technological interventions, focusing on advanced ventilation systems, whereas others emphasize the implementation of building regulations and raising public awareness. Generally, initiatives aimed at improving IAQ can be characterized as costly and time-consuming. Nonetheless, advancements in the

Internet of Things (IoT), low-cost sensors, and ultra-low-power technologies facilitate research and improve IAQ management (Air Quality News, 2022). Presently, over 80 countries have initiated efforts to improve IAQ; however, only a select few, including Australia, Barbados, and New Zealand, have met WHO's stringent air quality standards.

For Hong Kong, understanding the global landscape of IAQ management is especially pertinent, given its challenges of high population density, limited outdoor air quality due to urban congestion, and various indoor pollutants from industrial and commercial activities. With around 7 million residents living in close quarters (HK Census and Statistics Department, 2022), the prevalence of poor indoor air quality can exacerbate health issues such as respiratory infections, asthma, and cardiovascular diseases. A report by the Clean Air Network (2025) highlights that inadequate air quality, combined with heat and humidity pollution in subdivided housing units, introduces harmful substances, including formaldehyde, benzene, and volatile organic compounds, which can trigger allergic reactions and respiratory conditions. Additionally, factors such as fatigue, discomfort, and dehydration contribute to mental health challenges, including depression and anxiety.

The initiative to address IAQ concerns in Hong Kong gained momentum following several pivotal reports, including a 'White Paper on Pollution,' which identified critical deficiencies in IAQ management in various environments, particularly in air-conditioned offices and retail spaces (Tsang et al., 2024). These findings compelled the government to acknowledge the economic and health impacts of poor IAQ on the population. Since the 1990s, Hong Kong has implemented strategies to mitigate IAQ challenges. Adequate measures have included public awareness campaigns, interim IAQ guidelines, establishing information centers, and adopting technological advancements.

However, despite these efforts, the overall response to IAQ issues remains limited. Policy enforcement regarding IAQ remains inadequate, characterized by insufficient reporting and a lack of public awareness. Additionally, there exists ambivalence concerning strategies related to outdoor air quality (OAQ) and a significant shortfall in building ventilation. Therefore, a comprehensive IAQ report would provide a crucial foundation for evidence-based policy formulation, incorporating scientific research and technological innovations, and aligning with societal needs.

2.2 Existing IAQ Monitoring Technologies and Solutions

Indoor Air Quality has gained significant global attention as people increasingly spend time at home, in the workplace, and in public areas. Due to the well-documented impacts of inadequate IAQ, various monitoring technologies and solutions have emerged, specifically designed to meet different geographic, economic, and technological needs.

In industrialized nations such as Germany and the UK, sophisticated IAQ systems are being incorporated into smart building management frameworks, utilizing affordable sensors for ongoing assessment of indoor environments. For instance, Augsburg, Germany's Smart-AQnet project utilizes low-cost sensors to monitor indoor air quality by integrating this data with building management systems, thereby enhancing ventilation and other operational processes (Krause et al., 2019). The information gathered from these sensors can also pinpoint potential problems, such as elevated CO₂ levels during meetings or insufficient ventilation, enabling proactive adjustments to building operations. Similarly, in the UK, HVAC systems can monitor increases in CO₂ levels and automatically ramp up ventilation in response, ensuring optimal air quality while minimizing energy consumption (Robinson, 2025).

In the United States, the EPA utilizes advanced air quality sensors in conjunction with extensive data networks to monitor pollutants, including particulate matter (PM_{2.5} and PM₁₀), VOCs, CO₂, and NO₂ (EPA, 2020). These IAQ systems fulfill compliance, building management, and public health advisory roles. The financial aspects related to air quality sensor networks vary and are influenced by elements such as data management, analysis, network density, installation, and maintenance. Individual sensors range from \$100 to \$1,000 in cost, while more advanced sensors for VOCs and other pollutants can cost millions of dollars, including operational and maintenance expenses (US EPA, 2024b).

Accelerated urbanization and industrial growth have led countries like China, particularly Beijing, to implement extensive monitoring networks to manage IAQ, especially during peak pollution periods (Zhao et al., 2018). However, much of indoor IAQ monitoring, such as the use of portable sensor devices, often focuses on addressing domestic pollution sources, including biomass combustion and cooking emissions. Moreover, in densely populated and resource-constrained nations like India, DIY monitoring solutions are being utilized, as they are more attainable and critically needed to inform public health initiatives.

A study by Shabbir et al. (2025) indicates that low-cost sensors are easily adaptable due to their replaceable nature, capability to be deployed in diverse locations, simple operation, lower initial costs, and compact size. However, these sensors tend to have shorter operational lifespans, necessitating replacements either annually or biannually. Furthermore, Higgins et al. (2024) note that low-cost PM sensors struggle to

identify ultrafine particles (UFPs), particularly those smaller than $0.1\ \mu\text{m}$ in diameter, due to their size being insufficient for light scattering and the use of cheaper pumps, which may lead to inaccuracies. Nonetheless, utilizing long-lasting batteries and implementing other recommended measures could help address the shortcomings associated with low-cost sensors.

In a unique setting such as Hong Kong, monitoring IAQ and implementing solutions are vital, given the city's high population density, limited land availability, and prevalence of multi-story buildings. According to the Hong Kong Environment Protection Department (EPD), the region battles ongoing air pollution issues, stemming from vehicle emissions, industrial processes, and transboundary pollution from mainland China (HK EPD, 2021). To protect public health and promote sustainable urban living, Hong Kong has initiated a variety of IAQ monitoring programs, which involve awareness campaigns through education, a Cyber IAQ information center granting public access to air quality data, a voluntary IAQ certification program, as well as IoT-enabled sensors installed in public transport, schools, and commercial establishments to monitor VOCs, CO_2 , and humidity levels.

Although these various IAQ initiatives aim to enhance air quality, research suggests that involving an independent or third-party organization to assess their effectiveness is necessary (Settimo et al., 2020). Many nations have documented initiatives to evaluate IAQ technologies. For example, in Germany, an independent committee focused on Indoor Air Guides has been established, comprising experts from federal states and the government, to define health-based benchmarks for evaluating substance concentrations in indoor environments such as homes, workplaces, public facilities, and transport systems (Abelmann, 2025). Other evaluation methods include third-party testing, with institutions such as the US EPA setting IAQ standards, conducting research, and providing resources aimed at improving IAQ. The organization performs the Building Assessment Survey and Evaluation (BASE) to assess IAQ in both public and commercial buildings. Additionally, they participate in various other assessment initiatives designed to evaluate IAQ programs effectively. Table 2.1 summarizes selected countries with their IAQ strategies for IAQ solutions.

Table 2. 1 Selected Countries and Strategies for Effective Evaluation of IAQ Solutions

	Countries	Evaluation Strategies
1	Germany	1. German Committee on IAQ (AIR) - https://shorturl.at/m5BGw 2. Third-party testing and research institutions. 3. Voluntary Certification Scheme.
2	USA	1. US EPA sets IAQ standards and guidelines, conducts research, and provides resources for improving IAQ. - https://shorturl.at/rssCZ 2. Building Assessment Survey and Evaluation (BASE). - https://shorturl.at/LlvZX 3. US EPA Collaborations with ASHRAE. - https://shorturl.at/41fch
3	China	1. China's IAQ National Standard sets limits for various IAQ parameters. - Tsang et al., 2024- https://doi.org/10.3390/atmos15050546
4	Hong Kong	1. Voluntary IAQ management program and certification scheme. 2. IAQ Guidance Notes and Support - https://doi.org/10.3390/atmos14040633 3. IoT-based real-time air quality sensors - (Tsang et al., 2024)- https://doi.org/10.3390/atmos15050546
References: Settimo et al., 2020; Tsang et al., 2024.		

2.3 Technologies for IAQ Monitoring in Hong Kong

Hong Kong's densely populated urban landscape presents significant challenges in maintaining healthy IAQ. With modern lifestyles leaning towards prolonged indoor occupancy in homes, workplaces, and commercial establishments, effective IAQ monitoring has emerged as a critical necessity. Various innovative technologies and solutions are being implemented to monitor and improve IAQ, aimed at fostering healthier living and working conditions for the city's residents. These advancements reflect a proactive approach to addressing environmental health concerns in Hong Kong. The following provides further details of the various IAQ technologies and solutions.

2.3.1 Sensor Technologies for IAQ Monitoring

Sensor technologies are at the forefront of Hong Kong's IAQ initiatives, enabling real-time monitoring of indoor air pollutants. They are sensors that detect contaminants like PM, CO, VOCs, CO₂, NO₂, SO₂, and O₃, as well as humidity levels. Several sensors, including electrochemical sensors, *HVAC CO₂ Sensors*, *Metal Oxide Semiconductor (MOS) sensors*, *Particulate Matter (PM) Sensors*, *Infrared (IR) Sensors*, and *sensor integration for IoT*, are used for IAQ monitoring. Table 2.2 summarizes existing IAQ monitoring technologies and solutions, including their uses and examples.

Electrochemical sensors

Electrochemical sensors are among the most prevalent IAQ sensors for identifying gaseous pollutants, such as CO, NO₂, SO₂, and O₃ (Wei et al., 2018). For example, the Aeroqual Series 200 is frequently used for detecting CO and NO₂ due to its high sensitivity and portability (Aeroqual Limited, 2024). These sensors are often employed in residential environments for personal monitoring or in commercial buildings for localized assessments of IAQ. Their widespread use is attributed to their low manufacturing costs, quick response times, and minimal energy consumption, which support eco-friendly initiatives and the growing emphasis on sustainability. However, relying on the output data from these sensors, under the assumption of a linear correlation with target gas concentrations, can lead to considerable inaccuracies due to variations in ambient conditions and interference from other gases. This claim is supported by research from Wei et al. (2018), which emphasizes the importance of comprehensive data analysis and correction protocols to ensure reliable data when using low-cost sensors. Additionally, researchers have noted another concern: many of these low-cost sensors have not undergone standardization and certification processes (Ródenas García et al., 2022), resulting in confusion among users.

HVAC CO₂ Sensors

HVAC CO₂ sensors, such as the Sensirion SCD30 and the Systemair CO2DT duct sensors, are essential tools for assessing the effectiveness of ventilation in indoor spaces. High concentrations of CO₂ typically signal inadequate ventilation, which can cause discomfort and various health problems. Although these sensors can be costly, they are frequently utilized in commercial settings like offices and shopping centers to monitor and enhance air exchange. For example, the 485-meter ICC skyscraper in Hong Kong (Hitachi, 2025), currently the tallest building in the city, has reportedly achieved an annual energy saving of 15 million kWh and a reduction in electricity costs of HK\$ 3 million, along with preventing 9,000 tonnes of CO₂ emissions. However, research conducted by Wang et al. (2018) has highlighted significant challenges, including the potential for erroneous readings due to varying occupant activity levels and envelope infiltration, slow response rates resulting from air mixing, and issues surrounding sensor calibration and accuracy.

Metal Oxide Semiconductor (MOS)

Metal-oxide semiconductor (MOS) sensors are adept at detecting a variety of gaseous pollutants and assessing indoor air quality (IAQ), including volatile organic compounds (VOCs). This versatility makes them essential for comprehensive IAQ monitoring, particularly in the context of green building initiatives. Despite the limited documentation regarding their application in facilities across Hong Kong, there is a strong potential for their inclusion in environmentally sustainable developments, such as the Zero Carbon Building and the Hong Kong Science Park, as highlighted by WWF Hong Kong in 2012. Further field studies could yield valuable data on their effectiveness and implementation.

Comparable to electrochemical sensors, MOS sensors are relatively low in cost; however, they have vulnerabilities to environmental variables such as humidity and temperature. Their robustness makes them suitable for ongoing monitoring in both residential and commercial settings, particularly in environments where VOC emissions pose a concern, such as industrial sites or office buildings. MOS sensors describe favorable characteristics including rapid response times, a prolonged operational lifespan of 5 to 10 years, low power requirements, and a compact design.

However, despite these significant advantages, MOS sensors face criticism for their lack of specificity, as they react to a wide range of reducing gases instead of isolating specific substances. To address this limitation, users are advised to employ additional sensors, filters, dopants, and control heater temperatures for more precise gas measurements. Therefore, careful consideration is necessary when selecting MOS sensors for specific applications.

Particulate Matter Sensors (PM)

PM sensors play a crucial role in monitoring airborne contaminants, including dust, smoke, and aerosols. In locations such as Hong Kong, where pollution levels fluctuate significantly, these sensors are particularly crucial. Affordable options, such as the Plantower PM5003, have made these devices accessible for both residential use and small-scale commercial applications. As highlighted by Zheng et al. (2022), PM5003 is widely utilized in Hong Kong's residential buildings. However, there is a scarcity of detailed information regarding the performance of PM sensors. While they are generally deemed effective, significant challenges have been reported, particularly concerning their ability to deliver accurate readings at low PM concentrations (AirGradient, 2025). This limitation is often attributed to their inability to measure larger particulate matter, specifically PM₁₀.

Infrared Sensors (IR)

Infrared (IR) sensors are specialized devices designed to identify gases like carbon dioxide (CO₂) by utilizing principles of infrared absorption. These sensors are known for their high precision and reliability, but they are also perceived as costly, which limits their widespread adoption. Consequently, IR sensors are predominantly found in large commercial buildings and industrial environments where their expenses and technical complexity can be justified. Examples can be seen in various properties owned by Swire Properties (Swire Properties, 2024), such as City Plaza shopping malls, Pacific Place, and City Outlet, all of which have incorporated IR sensor technology. While IR sensors excel in accuracy and contribute to thermal comfort, they have limitations, particularly in their inability to detect stationary occupants (Wang et al., 2018). This drawback, coupled with their higher costs, makes them less prevalent in many applications.

Sensor Integration of IoT

The integration of sensors with IoT platforms enables centralized management, alert mechanisms, and comprehensive data analysis, which are crucial for managing large commercial or institutional buildings. This integration significantly enhances indoor air quality (IAQ) monitoring through real-time data collection and remote oversight. For instance, in Hong Kong, smart building systems, particularly those implemented by JLL Hong Kong (JLL, 2020), utilize IoT sensors to optimize ventilation, boost employee productivity, and lower energy usage. Although the deployment of IoT sensors can be costly, the long-term advantages in energy savings and health benefits make it a worthwhile investment.

The landscape of sensor technologies for IAQ monitoring in Hong Kong exhibits notable diversity in terms of cost, type, and application. Electrochemical and PM sensors are generally cost-effective and well-suited for residential and small commercial environments. In contrast, IR and advanced CO₂ sensors are more appropriate for large

commercial buildings. Although these technologies require significant investment, the advantages they offer, such as enhanced air quality and improved health outcomes, justify the expenditure, particularly in densely populated urban areas. Research indicates that health benefits include a reduced presence of airborne pathogens, enhanced cognitive function in workplaces and educational settings, improved sleep quality, and overall better well-being (Meersens, 2023). As technological advancements continue, these sensors are becoming increasingly affordable and integrated, contributing to healthier indoor environments that are accessible to a broader audience.

In summary, selecting the appropriate air purifier depends on factors such as cost, building size, specific pollutants to be addressed, and health considerations. While centralized systems and HEPA filters provide superior IAQ, their costs limit widespread residential use. Portable units and ionizers are affordable and suitable for households, but they lack comprehensive coverage. UV and photocatalytic systems serve specialized roles in healthcare facilities and commercial settings.

Table 2. 2 Existing IAQ Monitoring Technologies and Solutions in Hong Kong

Main Categories	Sub-Categories	Uses	Examples
Sensor Technologies for IAQ Monitoring	<i>Electrochemical Sensors</i>	- To detect gaseous pollutants such as CO, NO ₂ , SO ₂ , and O ₃ .	Aeroqual Series 200 (for NO ₂ and CO detection), etc.
	<i>HVAC CO₂ Sensors</i>	- Measure indoor CO ₂ levels to evaluate ventilation effectiveness.	Sensirion SCD30, Systemair C02DT Duct Sensor, etc.
	<i>Metal Oxide Semiconductor (MOS)</i>	- To detect various gaseous pollutants.	
	<i>Particulate Matter (PM) Sensors</i>	- Measures the concentrations of airborne particles, including smoke, dust, and aerosols.	
	<i>Infrared (IR) Sensors</i>	- Detect gases like CO ₂ through IR absorption.	
	<i>Sensor Integration of IoT</i>	- Facilitate real-time data collection and remote monitoring via IoT platforms.	
Air Purification Technologies for IAQ	<i>Air Purifiers</i>	- Minimize or eliminate indoor pollutants and enhance air quality.	Filter AP, Portable units, HEPA filtration units, Centralized Systems, UV light purifiers, photocatalytic oxidation systems, and Air ionization devices.
Ventilation Technologies/Systems	<i>Mechanical Ventilation and Air Conditioning Systems (MVAC)</i>	- Enhance air exchange and minimize pollutant accumulation.	Centralized air conditioning systems with filtration units and demand-controlled ventilation systems.
	<i>Natural Ventilation Systems</i>	- Natural airflow from vents, windows, and architectural	Operable windows, atrium designs, and cross-ventilation.

		design is utilized to achieve ventilation.	
	<i>Demand-Controlled Ventilation Systems (DCV)</i>	- Enhance air quality and energy efficiency.	CO2 sensors are linked to ventilation control and occupancy sensors.
	<i>Smart Ventilation Control Systems</i>	- For monitoring and adaptive ventilation.	BMS with IAQ sensors, automated window opening systems.
	<i>Renewable and Hybrid Ventilation Systems</i>	- Combines natural and mechanical ventilation to enhance energy efficiency and indoor air quality.	Hybrid systems integrating heat recovery ventilators with natural airflow.

2.3.2 Air Purification Technologies for IAQ

Air purification technologies play a crucial role in enhancing IAQ by reducing harmful pollutants, including volatile organic compounds (VOCs), bacteria, and viruses. In Hong Kong, popular options include filter air purifiers and portable units that use replaceable filters to clean the air. While these devices are easy to use, they have limitations in effectively capturing PM and VOCs if filters are not maintained, leading to higher costs for users. They are primarily effective in residential settings and smaller offices but may struggle in larger spaces without multiple units (Wong & Wong, 2024). A specific example is the PureAura mini air purifier from Lingnan University, which has successfully distributed over 8,000 units to aid residents in subdivided homes in areas like Sham Shui Po and Shau Kei Wan (Lingnan University, 2025).

HEPA filtration units are prevalent in hospitals, laboratories, and some homes in Hong Kong due to their ability to remove at least 99.97% of particles as small as 0.3 microns, demonstrating high filtration efficiency (Qlestouw, 2023). However, they are expensive to purchase and operate, and they consume a significant amount of energy. Their effectiveness is limited when filtering gaseous pollutants like VOCs, leading to frequent filter replacements that increase costs (IQAir, 2019). This high price restricts their use in smaller residential areas. The Hong Kong Hospital Authority has equipped its 43 hospitals and 47 outpatient clinics with IQAir HealthPro Plus air purifiers (IQAir, 2022). Furthermore, several universities, including HKU, PolyU, and the Chinese University, have integrated IQAir HEPA filtration technologies in their laboratories to address airborne microorganisms, VOCs, particles, and odors (IQAir Hong Kong, 2016).

Centralized air purification systems are integrated into HVAC systems to manage air quality in large commercial and residential buildings. In Hong Kong, larger hotels and office spaces commonly use these systems to ensure consistent air conditions. While the initial cost is high, the operating expenses decrease over time. These systems are efficient in terms of scaling and maintenance but face criticism for their high energy usage, uneven air distribution, and overall costs (Kelley, 2023). As a result, they are primarily found in commercial buildings and larger residential complexes, rather than in smaller homes. Significant examples of these installations include the Environmental Protection Department offices, Eco parks, and properties managed by Swire Properties (Environmental Protection Department, 2025; Swire Properties, 2024).

UV Light Purifiers use ultraviolet radiation to deactivate viruses, bacteria, and mold spores. They can be integrated into HVAC systems or used independently in settings like hospitals and laboratories. Their effectiveness depends on the wavelength of the UV light and the duration of exposure. Similarly, Photocatalytic Oxidation (PCO) systems also utilize UV light to activate catalysts, typically titanium dioxide, which break down organic pollutants, including bacteria and VOCs (Tapia-Brito et al., 2023). These systems are often found in high-rise commercial buildings and upscale residential units.

While **UV and PCO purification systems** are recognized for their effectiveness, they come with significant costs. UV purifiers are acknowledged for their ability to eliminate biological contaminants; however, they are criticized for their lack of efficacy in removing PM and chemical pollutants, along with requiring consistent maintenance. PCO systems are similarly valued for their capability to reduce gaseous pollutants without requiring filters. However, they face scrutiny over the potential production of harmful by-products, such as formaldehyde, during oxidation (Tapia-Brito et al., 2023). Research on their overall effectiveness continues, necessitating careful evaluation. For instance, the Two Taikoo Place, part of Swire Properties, employs UV light and PCO systems (Swire Properties, 2021).

Air ionization devices operate by generating either negative or positive ions that adhere to airborne particles, prompting them to settle out of the air. Their affordability has led to widespread use in homes and offices in Hong Kong. Low maintenance requirements and silent operation add to their appeal. However, studies have shown that these devices can be detrimental, mainly when they produce ozone at high levels, a harmful pollutant that can worsen respiratory problems such as coughing, chest pain, shortness of breath, and throat irritation (Nunez, 2021; Afshari & Seppänen, 2021). An example of this technology is seen at the West Kowloon high-speed rail station, where bipolar air ionization technology has been implemented to mitigate the spread of viruses (Yuke, 2023).

2.3.3 Ventilation Technologies/Systems

Effective ventilation is vital for maintaining IAQ in densely populated regions like Hong Kong. Several ventilation options exist to enhance IAQ, including Mechanical Ventilation and Air Conditioning (MVAC) systems, Natural Ventilation Systems, Demand-Controlled Ventilation (DCV), Smart Ventilation Control Systems, and Renewable and Hybrid Ventilation Systems.

MVAC Systems are commonly found in Hong Kong's buildings, facilitating air exchange and reducing pollutants. They typically include filtration units to improve air quality and utilize demand-controlled ventilation for energy efficiency. For instance, the International Commerce Centre (ICC) employs centralized air conditioning with filtration to ensure high air quality standards (Kwok et al., 2017). However, the high installation and maintenance costs of these systems can limit their broader application. Some critics argue that if not properly managed, MVAC systems can be energy-intensive and contribute to the urban heat island effect (Tsang et al., 2024).

Natural Ventilation Systems leverage architectural elements such as cross-ventilation, atriums, and operable windows to facilitate airflow without mechanical assistance. Many heritage buildings and modern residential developments in Hong Kong

utilize natural ventilation, particularly during milder weather, to reduce their reliance on energy-demanding systems (Lin et al., 2025). While these systems are more affordable and sustainable, their effectiveness is greatly influenced by external weather conditions, which may result in poor IAQ during pollution events. Recent findings indicate significant challenges in applying natural ventilation in densely constructed areas in Hong Kong (Lin et al., 2025).

DCV systems enhance IAQ and energy efficiency by adjusting ventilation rates in response to occupancy and CO₂ concentrations (Niu et al., 2024). These systems are often found in busy commercial settings like shopping malls and airports. For example, airports in Hong Kong use CO₂ sensors to adjust ventilation, thereby reducing energy costs while maintaining air quality (Poole, 2017). However, the initial investment required for DCV systems can be substantial, and they also demand ongoing calibration and maintenance.

Smart Ventilation Control Systems have emerged due to advancements in building management technologies. They feature automated platforms that monitor IAQ and commonly integrate automated windows and IAQ sensors. However, their complexity can result in high maintenance demands and potential operational issues. Additionally, their large amounts of data can lead to privacy concerns (HKSAR, 2024).

Finally, **Renewable and Hybrid Ventilation Systems** combine natural and mechanical approaches to optimize energy efficiency and improve IAQ. These systems often employ Heat Recovery Ventilators (HRVs) alongside natural ventilation techniques. They are considered innovative solutions for enhancing air quality by removing pollutants and moisture (Sustainability Directory, 2025). For instance, the 15W building in the Hong Kong Science Park's Phase 3 incorporates natural ventilation with operable windows to optimize airflow (HKGBC, 2025).

In conclusion, while natural ventilation presents an energy-efficient solution with limited control options, MVAC systems offer dependable IAQ for larger buildings. Demand-controlled ventilation and smart systems provide a promising compromise between maintaining IAQ and improving energy efficiency, whereas hybrid systems represent a forward-thinking strategy for promoting sustainability in architecture.

2.3.4 Fixed Monitoring Stations

In the field of air quality monitoring, fixed monitoring stations serve as permanent setups that are strategically located in areas characterized by significant human activity or potential sources of pollution. In Hong Kong, two main categories of fixed monitoring stations are particularly notable: those operated by the government and private or commercial IAQ monitoring systems. Government entities, such as the Hong Kong Environmental Protection Department (EPD), manage a comprehensive monitoring network throughout the city. This network encompasses locations such as residential complexes, government facilities, and commercial hubs (HK Environmental Protection Department, 2025a). These stations continuously gather data on prevalent air pollutants, including PM₁₀, PM_{2.5}, total volatile organic compounds (TVOCs), CO₂, CO, and formaldehyde (HCHO). The data collected are vital for long-term monitoring and health assessments, informing policy decisions and public evaluations.

However, it is important to note that most government stations primarily focus on outdoor air quality, while many IAQ strategies include voluntary certification programs and an information center for IAQ (HK Environmental Protection Department, 2025a). As of now, the EPD's website reports that there are 18 fixed monitoring stations in Hong Kong (WOOFA, 2022). While the focus is predominantly on outdoor air, these voluntary certifications ensure that accredited organizations, such as WELL, adhere to minimum IAQ standards during the certification process. WELL also highlights that poor outdoor air quality can infiltrate indoor spaces, thereby compromising IAQ and potentially leading to health issues like respiratory infections and cardiovascular diseases (IWBI, 2020).

On the other hand, private or commercial IAQ monitoring systems, exemplified by the POLYU Indoor Environment monitoring stations, are designed for indoor settings such as offices. These systems are often integrated with Building Management Systems (BMS) to meet health standards and enhance indoor environmental quality. In 2020, the sustainability office partnered with the Building Engineering and Mechanical Engineering Department at the Hong Kong Polytechnic University to develop a rapid IAQ and electricity usage monitoring system (Hong Kong Polytechnic University, 2021). This initiative assists housing departments and residents in identifying and tracing areas at high risk for pollutants, airborne pathogens, and virus transmission in indoor environments, while also monitoring energy consumption. Additionally, the University has initiated other IAQ projects, including pre-occupation checks (Hong Kong Polytechnic University, 2025), which address various indoor spaces such as offices, classrooms, computer labs, meeting rooms, and libraries. Generally, fixed monitoring stations tend to be costly, making them more accessible primarily to government agencies or large corporations. Table 2.3 summarizes the fixed monitoring stations and their functions

Table 2. 3 Existing IAQ Monitoring Technologies and Solutions

Main Categories	Sub-Categories	- Uses	Examples
Fixed Monitoring Stations	Data Transmission	- Uses real-time data transmission capabilities, often linked to the EPD for comprehensive air quality management.	- Hong Kong EPD IAQ Monitoring Network (Responsible for monitoring stations in Hong Kong).
	Parameters Monitored	- It is used to monitor common parameters such as PM10, PM2.5, TVOCS, CO ₂ , CO, HCHO, etc.	- POLYU Indoor Environment Monitoring Stations.
	Location and Coverage	- Fixed Stations at high human activity or potential pollution sources, such as residential complexes, government buildings, and commercial centres.	- Commercial IAQ Monitoring systems (Private companies and building management firms deploy fixed IAQ monitoring stations within commercial buildings for routine assessment and compliance purposes, often integrating these into Building Management Systems (BMS).

2.3.5 Integrated IAQ Management Systems

Integrated Indoor Air Quality Management Systems encompass a range of technologies and solutions designed to comprehensively enhance IAQ by combining monitoring and control functions. These systems typically integrate IAQ sensors with BMS, facilitating automated ventilation, filtration, and air purification processes. A notable example is the Pacific Place Mall (Swire Properties, 2025), which utilizes real-time IAQ sensors linked to its BMS, automatically regulating ventilation rates in response to identified pollutant levels. The mall's system utilizes intelligent online IAQ sensors that provide continuous monitoring, enabling occupants to access real-time air quality data from any location.

These monitoring systems track various parameters, including indoor temperature, relative humidity, CO₂, CO, TVOC, PM_{2.5}, PM₁₀, and O₃. Furthermore, their IAQ monitoring aligns with the WELL Building Standard, promoting health and well-being. Smart IAQ solutions not only deliver real-time data but also enhance the precision of indoor environment control. By leveraging IoT sensors connected to BMS, these systems can automatically adjust ventilation based on occupancy levels and air quality, reducing energy consumption and improving occupants' health outcomes. However, the higher costs of implementing these systems often hinder widespread adoption, particularly in residential environments. Data privacy and cybersecurity (Business Environment Council Limited, 2022) have also been highlighted as potential risks associated with IAQ smart building solutions.

Integrating Indoor Air Quality initiatives in schools is a crucial component of the city's commitment to promoting a healthy environment for students. Various projects organized by different institutions are detailed in the accompanying table. For instance, the Zeshan Foundation, in collaboration with the CAN and the Hong Kong University of Science and Technology (HKUST) Institute for the Environment, has implemented the CASHK project in primary schools, particularly in Tuen Mun and Sham Shui Po, areas identified as having elevated air pollution levels. The initiative, supported by the Clean Air Network (2024), focuses on installing IAQ sensors and mobile applications in eight schools, with the goal of expanding this reach to twenty schools.

These projects play a significant role in enhancing health, albeit their implementation often targets specific environments. By collecting data, these systems aim to optimize ventilation and minimize the risk of airborne transmission. The initiative identified indoor sources, such as the use of disinfectants, as significant contributors to classroom pollution. Mitigation strategies, including the installation of fresh air units, have demonstrated effectiveness in reducing indoor pollutants such as CO and PM.

Research indicates that retrofitting existing buildings can significantly improve IAQ while also enhancing energy efficiency. A study conducted by Che et al. (2019) highlighted that HVAC systems are major contributors to energy consumption in

buildings, as well as impacting IAQ. This study analyzed the energy usage and indoor environment with a retrofitted HVAC system, which incorporated measures such as outdoor air dehumidification, a two-stage particle filtration system, positive indoor air pressure, and a sensor-based building management system (BMS). The findings revealed that the retrofitted HVAC system achieved an impressive energy savings of approximately 50%. Specifically, from 2012 to July 2018, energy consumption in the ventilation and air conditioning system post-retrofitting was reduced by 51%, resulting in a total savings of 670,000 kWh. Despite these improvements, many IAQ PM metrics met the World Health Organization's annual guidelines. These results suggest that retrofitting older buildings not only saves energy but also enhances IAQ. While retrofitting can be beneficial, its initial cost can be expensive, hence,

While governmental efforts are underway to support these initiatives, many IAQ projects in educational settings are predominantly driven by private organizations. This indicates a gap that suggests a stronger emphasis from the government on IAQ within educational institutions is essential to ensure a healthier student population in schools. Table 2.4 provides a summary of the integrated IAQ management systems and their respective uses and examples.

Table 2. 4 Integrated IAQ Management Systems			
Main Categories	Sub-Categories	Uses	Examples
Integrated IAQ Management Systems	Smart Building Solutions	- Integrate IAQ monitoring systems with IoT sensors with BMS.	- Pacific Place Mall employs real-time IAQ sensors linked to their BMS, enabling automatic ventilation rate adjustment.
	School IAQ Projects	- Private Organizations Projects. (CAN projects in collaboration with HKUST are funded by the Zeshan Foundation (CAN, 2024).	- The Clean Air School Project (CASHK) installed IAQ sensors, mobile apps, and LED panels in primary schools such as St. Andrew's Primary School and St. Francis of Assisi's English Primary School.
	Government Initiatives	- HK EPD has launched the IAQ monitoring network that provides ambient and indoor air quality data across various districts, supporting integrated management efforts (Hong Kong Environmental Protection Department, 2025).	- EPD has initiated an IAQ certification scheme, which helps alert buildings to their IAQ status, and they created an information center to raise IAQ awareness.
	Retrofitting Initiatives	- Utilizes IAQ technologies to enhance current buildings for improved IAQ and energy efficiency.	- A case study involving an experiment conducted by researchers from the Hong Kong University of Science and Technology.
References: Che et al., 2019; Clean Air Network, 2024; Hong Kong Environmental Protection Department, 2025;			

2.4 Reporting Mechanisms

Maintaining effective indoor air quality (IAQ) management is crucial for protecting public health. To accomplish this, both governmental and private sector organizations have launched a variety of data reporting systems, management and certification processes, and public awareness initiatives, each tailored to meet specific objectives and target diverse audiences. Table 2.5 provides an overview of different IAQ reporting initiatives, their applications, and relevant resources for further exploration.

2.4.1 Hong Kong IAQ Monitoring Network

The initiatives for Indoor Air Quality (IAQ) monitoring in Hong Kong include various tools such as online public portals, IoT-enabled sensors, annual reports, mobile applications, compliance documentation, and online dashboards. It is important to highlight that, while these initiatives show effectiveness, the majority of government-driven monitoring efforts, particularly those by the Hong Kong Environmental Protection Department, focus predominantly on outdoor air quality, as referenced in Table 2.5.

The HK EPD has developed an online public portal that displays real-time outdoor air quality data sourced from a vast network of monitoring stations equipped with IoT-enabled sensors. These sensors continuously transmit data to centralized databases, ensuring the information is current and trustworthy. In contrast, IAQ visualization tools from private organizations such as Airside and Blue-Sky Energy provide insights into both outdoor and indoor air quality through dashboards, heat maps, and trend analysis. For instance, as of June 23, 2025, at 9:30 AM, Airside's IAQ online dashboards reported PM_{2.5} levels at 7.3 µg/m³, CO₂ at 400 ppm, TVOC at 79 µg/m³, temperature at 29°C, and relative humidity at 48%. These metrics are recorded across all 47 floors of their facility.

Moreover, various initiatives monitor outdoor air quality, which is particularly crucial for evaluating well-ventilated spaces with open windows. Although IoT technology offers benefits such as real-time data transmission, reduced manual effort, and extensive spatial coverage, the initial setup and ongoing maintenance costs can be substantial. This financial burden can hinder the widespread implementation of such measures in residential buildings.

Additionally, facilities in Hong Kong are required to produce IAQ reports on a quarterly or annual basis and provide compliance documentation through online platforms or standardized forms. These documents typically include statistical analyses, case studies, and compliance data. However, the submission of IAQ reports is largely voluntary, which limits their effectiveness primarily to larger corporations, such as Airside. Notably, the reports available on the EPD website (<https://shorturl.at/DyU1f>) focus exclusively on outdoor air quality.

Mobile applications and alert systems, such as HK-AQHI, PRAISE-HK, Air Matters, Air Visuals, and Plume Labs, play a crucial role in safeguarding public health by encouraging behavioral modifications, including improving ventilation and reducing pollutant sources like PM_{2.5}, PM₁₀, and volatile organic compounds (VOCs). Despite their effectiveness, HK-AQHI, Air Matters, and Air Visuals are primarily oriented toward outdoor air quality monitoring. Some applications, particularly Air Matters and Plume Labs, can be enhanced by integrating with purifiers and other IoT devices (Philips, 2025; Plume Labs, 2025) to monitor IAQ. Consequently, organizations and individuals are encouraged to utilize these tools to enhance their IAQ management strategies. Notably, PRAISE-HK is specifically designed to monitor IAQ across various indoor settings such as homes, offices, and schools, and is thus highly recommended for individual use. Although several applications feature IAQ capabilities, they are predominantly relied upon for outdoor air quality assessments.

2.4.2 Building Management and Certification

In Hong Kong, building management and certification are integral to ensuring the safety, sustainability, and efficiency of the built environment. Various government regulations, certification schemes, and technological solutions collaborate to foster transparency and promote sustainable building practices across residential, commercial, and public sectors.

One of the key regulatory frameworks is the Building Management and its Ordinance (BMO Cap. 344) (Hong Kong e-Legislation, 2022), which serves as a fundamental pillar for building regulation in Hong Kong. The BMO seeks to instate accountability and transparency in the management of residential and commercial properties. Although the BMO does not explicitly mandate Indoor Air Quality (IAQ) standards, it indirectly influences owners' corporations to ensure that common areas of buildings are maintained in a good and serviceable condition. This includes maintaining proper ventilation systems and addressing potential sources of air pollution, thereby contributing to a healthier living environment.

The IAQ certification schemes offered by the Hong Kong Environmental Protection Department extend beyond mere legal compliance. These schemes include assessments that evaluate and enhance Indoor Environmental Quality (IEQ) for commercial buildings and public spaces with mechanical ventilation and air conditioning systems. Facilities undergoing these certifications must participate in annual IAQ assessments to measure pollutants such as formaldehyde and TVOCs. The application and approval process for these assessments can take approximately six months, involving activities such as walkthrough inspections, on-site measurements, Mold assessments, and IAQ compliance evaluations. According to a recent report from the EPD (Indoor Air Quality Management Group, 2019), a total of 12 IAQ parameters are assessed, including ten chemical parameters like 8-hour CO₂, 8-hour CO, 8-hour PM₁₀,

1-hour and 8-hour NO₂, 8-hour O₃, 30-minute and 8-hour HCHO, 8-hour TVOC, 8-hour Rn, and 8-hour biological parameters. Despite the rigorous nature of these assessments, they rely on a single point of testing rather than real-time data collection and analysis. Additionally, the voluntary nature of these certifications does not compel property owners to adopt such standards actively.

As of now, more than 2,454 premises are listed on the EPD's website as certified under the IAQ scheme. Certificates are categorized into "Excellent" and "Good" classes, with 702 premises registered under the "Excellent" classification, while the remainder falls under the "Good" classification. Notably, only 22 of these registered premises are residential, highlighting a critical gap considering that individuals typically spend a significant amount of time indoors. It is important to note that the information regarding these certifications has not been updated, as many have expired and remain unreflected on the website.

Furthermore, other certifications, such as the HK-BEAM, provide a comprehensive evaluation of formaldehyde and TVOC levels, aligning with international standards like ISO 16000. In addition, technological advancements, including platforms such as JEDI, Digital Twin Technologies, Prototype Software for Facility Management, and Ricoh Digital Facilities Management, offer facilities new avenues to report incidents, analyze data, and maintain comprehensive records. Table 2.5 provides detailed information, as well as further references and links to various organizations.

Table 2. 5 IAQ Data Reporting Mechanisms and Visualization Tools

Main Categories	Sub-Categories	Uses	Examples
IAQ Data Reporting Mechanisms and Visualization Tools)	<i>Online Public Portal by EPD, Airside, Blue Sky Energy, etc.</i>	- Use of IoT-enabled sensors to transmit real-time IAQ data to centralized databases, ensuring continuous monitoring.	1. https://cd.epic.epd.gov.hk/EPICDI/air/station/ (Outdoor Monitoring) 2. https://www.aqhi.gov.hk/en/monitoring-network/air-quality-monitoring-network.html (Outdoor Monitoring) 3. https://iaq.airside.com.hk/ (Indoor Monitoring) 4. https://www.blueskyenergy.co/iaq-management (Indoor Monitoring)
	<i>Annual Report published by EPD (Scheduled Data Submission)</i>	- Facilities submit regular IAQ quarterly or annual reports via online portals or standardized forms.	1. They include case studies and statistical analysis. - https://shorturl.at/DyU1f
	<i>Mobile Apps and Alerts</i>	- Used to notify building managers and occupants when IAQ parameters exceed acceptable levels.	1. Hong Kong Real-Time Air Quality App (HK- AQHI). - https://shorturl.at/A8aEx (Outdoor) 2. Hong Kong Personalized Air Quality App (PRAISE-HK) - https://praise.hkust.edu.hk/ (Indoor/Outdoor) 3. Air Matters - https://air-matters.com/index.html (Outdoor / Indoor) 4. Air Visual - https://www.iqair.com/ (Outdoor) 5. Plume Labs - https://plumelabs.com/en/air/ (Outdoor/ Indoor)
	<i>Compliance Reports</i>	- Compilation of IAQ data into compliance	1. EPD general pollution complaint interface - https://cd.epic.epd.gov.hk/EPICCOM/?lang=en

		reports for audits and certification purposes	
	<i>Online Dashboards</i>	- EPD provides interactive dashboards to display real-time IAQ data, which includes heat maps, charts, or trend lines to illustrate temporal and spatial.	- https://cd.epic.epd.gov.hk/EPICDI/air/station/ (Outdoor) - https://www.aqhi.gov.hk/en/monitoring-network/air-quality-monitoring-network.html (Outdoor) - https://iaq.airside.com.hk/ (Indoor) - https://www.blueskyenergy.co/iaq-management (Indoor)
Building Management and Certification	<i>Building Management Ordinance (BMO) and Building Management Practices</i>	- BMO Cap. 344 regulates residential and commercial buildings to achieve accountability and transparency.	1. BMO Cap. 344 - https://www.elegislation.gov.hk/hk/cap344
	<i>IAQ certification Scheme introduced by EPD</i>	- A commercial building will undergo IAQ testing annually to achieve a good IAQ with recommendations for improvement.	1. EPD Certification Scheme - https://www.iaq.gov.hk/en/iaq-certification-scheme/
	<i>Mandatory IAQ monitoring and reporting</i>	- Shopping malls are required to conduct IAQ assessments quarterly and publicly display the star rating and testing results to	- At the time of the search, shopping malls had not publicly displayed IAQ quarterly or annual reports. However, they are displayed on HK-EPD website. - https://www.iaq.gov.hk/en/iaq-certification-scheme/

		demonstrate compliance and promote transparency.	
	<i>BEIC</i>	- Assess sustainable building practices to align with international standards like ISO 16000	1. <i>BEC measures IAQ using formaldehyde and TVOC levels.</i> - https://www.bec.org.hk/ 2. Hong Kong Building Environmental Assessment Method (HK-BEAM) - https://shorturl.at/gyKES
	<i>Technology and Digital Platforms</i>	- Digital Platforms where building management can upload IAQ data, incident reports, and maintenance records.	1. JEDI (Jardine Engineering Digital Insights) 2. Digital Twin Platforms 3. Prototype Software for Facility Management 4. Ricoh Digital Facilities Management - https://www.ricoh.com.hk/en/hybrid-workplace/digital-facilities-management
Public Awareness Campaigns	<i>Stakeholder Engagement</i>	- Used to create awareness and encourage compliance with IAQ standards.	1. Customer service counter at Sun Hung Kai Properties - https://www.shkp.com/Html/CSR/SR/Supplementary-Information.pdf
	<i>Educational Campaign</i>		1. EPD IAQ Information Center - https://www.iaq.gov.hk/en/home/ 2. IAQ Service Provider Trade Fair - https://campaigns.hkpc.org/rsvp-indoor-air-quality-service-provider-trade-fair
	<i>IAQ Forum and Dialogue</i>		1. CAN organized a community dialogue with a community health provider and HKUST to discuss how to improve IAQ and conclude their Clean Air Neighbourhood project, which started in 2022 and ended in 2024.

			- https://hongkongcan.org/wp-content/uploads/2024/09/CAN-ANNUAL-REPORT-2324_V5c.pdf
	<i>Award and Recognition</i>		1. EPD IAQ Certificate Award and Recognition. - https://www.iaq.gov.hk/en/iaq-certification-scheme-list-of-iaq-certification-scheme-awardees/
	<i>IAQ Reporting Hotline and Online Platforms</i>	- Used as a platform for reporting IAQ problems, such as Mold, odour, or ventilation issues	1. EPD general pollution complaint interface - https://cd.epic.epd.gov.hk/EPICCOM/?lang=en

2.4.3 Public Awareness Campaigns

A range of engagement and communication strategies are implemented to raise awareness, ensure compliance, and enhance indoor air quality (IAQ) in Hong Kong. These strategies encompass stakeholder engagement, educational initiatives, forums, dialogues, awards, and reporting systems. For instance, stakeholder engagement is exemplified by the customer service operations at Sun Hung Kai Properties, where staff interact directly with tenants and visitors to disseminate IAQ information. While this approach is cost-effective and fosters trust, it may fall short in addressing specific expert queries, especially in residential settings outside of large apartment complexes.

Educational campaigns spearheaded by the Hong Kong Environmental Protection Department (EPD) leverage the IAQ Information Center to elevate public awareness regarding IAQ challenges and practical improvement measures. Furthermore, IAQ service provider trade fairs serve as additional platforms for disseminating similar information, thereby reaching a broader audience than dedicated information centers. However, the success of these initiatives depends significantly on whether the target audience is aware of them.

Moreover, IAQ forums and dialogues have been convened in Hong Kong to encourage discussions among stakeholders and promote collaborative problem-solving. For example, a community dialogue organized by Clean Air Network (CAN) in partnership with health providers and HKUST focused on IAQ concerns, leading to the formation of the “Clean Air Neighbourhood - CASHK” initiative. Such forums effectively involve local communities, non-governmental organizations, academia, and policymakers, thus addressing specific IAQ issues in a comprehensive manner.

The Hong Kong EPD also conducts IAQ awards and recognition events designed to incentivize property owners and managers to uphold high IAQ standards. Despite their positive influence on continuous improvement and assessment, these awards can introduce elitism due to their associated costs, which may be prohibitive for less-resourced buildings. This is evident in the certification website, which lists only 22 residential buildings as recipients of such recognition.

Additionally, the establishment of IAQ reporting hotlines and online platforms, such as the EPD’s general pollution complaint interface, offers individuals and organizations the means to report IAQ-related problems, including odours, ventilation issues, and Mold. While these platforms are user-friendly and accessible, challenges such as delays in responses and inconsistencies can erode public confidence. Thus, raising awareness about these reporting mechanisms is crucial to enhancing IAQ in Hong Kong.

2.5 IAQ Improvement Solutions

In light of the previous discussion regarding various indoor air quality (IAQ) technologies and solutions in Hong Kong, it is crucial to evaluate key strategies for enhancing IAQ. These include air purification methods, green building practices, thoughtful architectural design and material selection, policy frameworks, public engagement, educational initiatives, and personal protective measures. This comprehensive approach effectively informs both stakeholders and residents. Table 2.6 provides a summary of the improvement solutions.

2.5.1 Enhanced Ventilation Standards and Air Purification Technologies

To improve IAQ in Hong Kong, the enhancement of ventilation systems within buildings is essential. Current building regulations prioritize the introduction of more fresh air via HVAC systems and natural ventilation, which are particularly necessary in the local context. Incorporating HEPA filters in HVAC systems plays a significant role in capturing particulate matter, especially PM_{2.5}, which is regarded as a significant pollutant in the city. Although implementing such IAQ strategies can be costly, alternatives like natural ventilation are viable options for coastal and suburban regions with lower outdoor pollution levels (Ai & Mak, 2015), such as Sai Kung and Tai Po, which benefit from their proximity to the sea and lower population density.

On the other hand, stringent IAQ measures, including HVAC systems, HEPA air purifiers, and exhaust fans, should be mandated in densely populated areas such as Sham Shui Po, particularly within residential buildings, as these technologies are more affordable and can substantially improve ventilation effectiveness.

2.5.2 Green Building Initiatives

Incorporating certain indoor plants recognized for their air purification capabilities can significantly enhance indoor air quality (IAQ). Species such as peace lilies, spider plants, *Aglaonema*, *Ficus benjamina*, and snake plants are effective at removing prevalent indoor contaminants, including volatile organic compounds (VOCs), benzene, and formaldehyde (Higienis Indonesia, 2023; Lemon, 2024; Wolverton et al., 1989). Consequently, there is a growing encouragement for both commercial and residential buildings to adopt green building practices that would support improved IAQ. While some buildings in Hong Kong, such as hotels, shopping malls, and residential service facilities, have begun to incorporate indoor gardens or green walls, these initiatives tend to focus primarily on aesthetic appeal rather than functional benefits. Even though the impact of such greenery is modest, it can serve as a complementary measure alongside existing ventilation and filtration systems to foster better IAQ in urban environments like Hong Kong.

2.5.3 Building Design and Materials

The integration of advanced building design and materials, specifically airtight construction methods, low VOC-emission materials, and superior insulation, plays a crucial role in minimizing outdoor air infiltration and reducing indoor pollutant emissions. For instance, the West Kowloon Cultural District in Hong Kong (West Kowloon HK, 2025) exemplifies the adoption of these innovative design principles, leading to healthier indoor environments. Consequently, it is strongly recommended to retrofit older buildings and promote the construction of new ones that adhere to these guidelines to enhance IAQ. While the initial investment may be considerable, the long-term benefits include decreased energy expenses and improved health for residents.

2.5.4 Policy and Regulations

The government agencies in Hong Kong have actively begun implementing and advocating for policies and regulations aimed at enhancing IAQ, both directly and indirectly. Alongside IAQ certifications, monitoring systems, and public awareness initiatives, they have introduced measures that promote public transportation and the establishment of green spaces to mitigate outdoor pollution levels. Notable projects, such as the expansion of the MTR network and urban green initiatives (MTR Corporation Limited, 2024), seek to reduce vehicular emissions and enhance overall air quality.

However, for these policies to achieve their intended outcomes, there is a pressing need for Hong Kong government agencies to enforce these regulations rigorously. Rather than relying solely on voluntary measures, which often lack the necessary compliance mechanisms, IAQ certifications must be made mandatory. This requirement would promote greater awareness among residents about the importance of IAQ and its impact on health. Additionally, organizations such as the Clean Air Network (2025b) have advocated for policies that integrate IAQ considerations into the minimum standards of living conditions for subdivided units. Their findings highlight that prolonged exposure to inadequate IAQ can adversely affect both the physical and mental well-being of residents.

2.5.5 Public Engagement and Education

Improving indoor air quality (IAQ) is crucial for public health, and enhancing awareness among occupants is key to achieving this goal. Educating the community about IAQ encourages proactive measures like proper ventilation and reducing indoor pollution sources.

The Environmental Protection Department (EPD) in Hong Kong should implement comprehensive awareness campaigns to address the slow pace of behavioral change regarding IAQ. Prominent initiatives, such as the IAQwise certification launched in 2023 by the Hong Kong Green Organisation, can motivate organisations to adopt better practices and foster compliance with air quality standards. Leveraging social media

platforms will enable the dissemination of important IAQ information, while city-wide events like workshops and community forums can facilitate interaction and dialogue among residents and experts.

Overall, a strategic approach combining education, community engagement, and recognition programs can significantly enhance IAQ in Hong Kong, leading to healthier indoor environments.

2.5.6 Personal Protective Measures

Implementing personal protective measures, such as wearing high-quality masks during periods of elevated pollution, is strongly advised. N95 respirators are particularly effective at filtering out fine particulate matter. However, the World Health Organization (2023) cautions against their daily use due to potential discomfort. Additionally, it is recommended to minimize outdoor activities when indoor air quality (IAQ) is compromised. This recommendation hinges on the use of real-time air quality index (AQI) and IAQ mobile alerts, as well as platforms like PRAISE-HK, which keep individuals informed about outdoor pollution levels. Other suggested strategies include opening windows and doors, particularly in kitchens and bathrooms, to facilitate the circulation of fresh air, and installing exhaust fans in moisture-sensitive areas, such as these.

Table 2. 6 IAQ Improvement Solutions

Main Categories	Sub-Categories	Examples
IAQ Improvement Solutions	<i>Enhanced Ventilation Standards</i>	HEPA filters, HVAC, and natural ventilation
	<i>Air Purification Technologies</i>	HEPA Air Purifiers, etc.
	<i>Green Building Initiatives</i>	Incorporate Indoor Greenery, known for its air-purifying properties, such as peace lilies and snake plants.
	<i>Building Design and Materials</i>	To control outdoor air infiltration, use airtight construction techniques, incorporate materials with low VOC emissions, and build with adequate insulation and sealing.
	<i>Policy and Regulations</i>	Implement and enforce policies that aim at reducing outdoor pollution. Promote Public transportation and Green Spaces.
	<i>Public Engagement and Education</i>	Educate occupants about IAQ best practices.
	<i>Personal Protective Measures</i>	Wearing of Masks (e.g., N95) during high pollution days. Limit outdoor activities when the air quality index (AQI) is poor.

2.6 Case Studies of IAQ technologies and solutions Implementations

When creating case studies on Indoor Air Quality (IAQ) technologies and solutions in Hong Kong, it is important to highlight several key organizations in this sector. One notable example is Hong Kong International Airport (HKIA), which ranks among the busiest and most vital transportation hubs in the world. Its airside facilities showcase advanced architecture and modern design, serving as an excellent illustration of the implementation of cutting-edge IAQ technologies.

The airport has implemented various innovative solutions to improve indoor air quality for both passengers and employees. These measures include advanced air filtration systems that effectively eliminate pollutants and allergens, engineered ventilation designs that maximize airflow, and intelligent monitoring systems that continuously assess air quality parameters. The careful integration of these technologies demonstrates Hong Kong's commitment to creating safer and healthier indoor environments, particularly in a location that accommodates millions of travelers annually.

By exploring the methodologies employed at HKIA and other leading facilities in the area, we can gain valuable insights into the practical application of sophisticated IAQ solutions, ultimately enhancing the quality of life in Hong Kong.

2.6.1 Case Study: IAQ Management at Hong Kong International Airport

Hong Kong International Airport (HKIA), situated on Chek Lap Kok Island, is recognized as the world's busiest cargo airport and ranks among the most frequented passenger airports, underscoring its significance as a major transportation hub in Asia and globally. Covering approximately 1,255 hectares, HKIA serves over 50 million passengers annually while handling 4.3 million tonnes of cargo. Its importance is amplified by its role as a key gateway for international travel and freight, reinforcing Hong Kong's status as a leading global financial and logistics center. However, the airport's extensive passenger traffic, significant aircraft operations, and various environmental factors create unique challenges for indoor air quality (IAQ).

Primary IAQ challenges at HKIA include particulate matter (PM) emissions resulting from aircraft activity, volatile organic compounds (VOCs) emitted from building materials and cleaning agents, fluctuations in CO₂ levels due to high human density (e.g., smoking and crowded areas), and potential microbial growth in enclosed environments. Additionally, external factors such as regional air pollution and humidity levels have a significant impact on indoor air conditioning systems. To navigate these challenges, the Airport Authority Hong Kong (AAHK) is committed to meeting both local and international air quality standards, rigorously monitoring and controlling emissions tied to airport operations. The authority aligns its strategies with the HK EPD IAQ guidelines, which conform to the WHO recommendations for acceptable limits of PM_{2.5},

PM10, VOCs, CO₂, and microbial contaminants. Compliance with ASHRAE standards 62.1 and 62.2 emphasizes the necessity for adequate ventilation through outdoor air supply and effective filtration (Hong Kong Green Organisation, 2023).

In response to the adverse effects of outdoor air quality on IAQ, HKIA has introduced various technology-driven solutions. As of 2017 (Hong Kong International Airport), all airside saloon vehicles are mandated to be electric, leading to the electrification of 95% of the airport's ground service equipment. Furthermore, the AAHK instituted an Auxiliary Power Unit (APU) ban in 2014, contributing to an approximate 20% reduction in nitrogen oxide emissions from APU operations. By 2030, the authority plans to expand the number of charging points to support the electrification of airside vehicles to 1,300. Monitoring air quality has been a priority since 2004, with the Air Quality Health Index (AQHI) being updated hourly on the AAHK website. This monitoring covers various pollutants, including NO₂, SO₂, CO, O₃, PM2.5, and PM10, and involves collaboration with the HKUST to analyze air quality data and assess the airport's environmental impact.

Despite the proactive measures taken to enhance air quality, much of the information available about HKIA focuses on general air quality rather than specifically on IAQ. Nonetheless, HKIA has integrated several advanced IAQ technologies and solutions (Hong Kong International Airport, 2020). These include antimicrobial coatings and disinfection channels that utilize photocatalysis and “nano” needle technologies to effectively neutralize pathogens on human contact surfaces. Additionally, autonomous cleaning robots equipped with ultraviolet light sterilizers can effectively disinfect public areas, achieving a remarkable 99.99% sterilization rate for bacteria. Smart HVAC solutions that increase outdoor air intake capacity have also been implemented to enhance the ventilation system, thereby improving airflow control. Kacar et al. (2023) identify the adoption of low-emission materials and advanced technical tools as further strategies to bolster IAQ. High-Efficiency Particulate Air (HEPA) filters installed within aircraft help curtail PM and microbial contaminants, while systems addressing odours and VOCs are also being utilized. Moreover, modifications in building design facilitate better air distribution through optimized airflow patterns, incorporating diffusers and return vents for enhanced pollutant dispersal (Hong Kong International Airport, 2024). The Hong Kong International Airport premises are among the 10 most effective premises highlighted by the EPD in the annual IAQ certification scheme, where out of 29 premises, 9 have received the “Excellent” classification, and 20 received the “Good” classification.

Despite these advancements, there is a notable lack of detailed information concerning the specific technologies utilized within HKIA. This area requires further scrutiny and attention to improve transparency and effectiveness in IAQ management.

2.6.2 Case Study: IAQ Management at Airside

The designation "Airside" signifies a commitment to wholeness, with indoor air quality (IAQ) being a critical element for the health and wellbeing of visitors and occupants. The organization maintains that improving air quality is essential for achieving their holistic vision while simultaneously fostering resilience through sustainable practices.

AIRSIDE (<https://iaq.airside.com.hk/>) Hong Kong is positioned centrally within the vibrant cityscape of Hong Kong, representing a premier commercial and retail development known for its contemporary architecture and diverse tenant roster. With the goal of creating a healthy and comfortable atmosphere for the thousands of individuals who frequent the space daily, AIRSIDE is actively addressing the challenges associated with poor IAQ, which can adversely affect public health. To tackle this issue effectively, the development has incorporated various regulations and compliance measures consistent with local and global standards. Notably, AIRSIDE's architectural design aligns with the United Nations Sustainable Development Goals (UNSDG), ensuring that all features are geared towards achieving superior decarbonization and energy efficiency performance. This initiative distinguishes AIRSIDE as the first development targeting top ratings in five leading green building certifications, including US LEED® Platinum Pre-certification, WELL Building Standard™ Platinum, BEAM Plus Neighbourhood Final Platinum, BEAM Plus New Building Provisional Platinum, and China Green Building Label Final 3-Star.

AIRSIDE has established comprehensive IAQ management strategies in response to various IAQ challenges, including pollution from proximity to major roads (e.g., PM2.5, NO2, VOCs), issues with stagnant indoor air, thermal discomfort, odors, and dryness. These strategies entail significant upgrades to the ventilation systems, incorporating energy-efficient HVAC systems equipped with demand-controlled ventilation (DCV) capabilities. This optimization allows for tailored fresh air intake based on real-time occupancy and IAQ conditions. Additionally, the facility employs HEPA and carbon filtration systems capable of removing 99.97% of particles smaller than 0.3 microns, as well as VOCs and odours, particularly in retail zones. Air purification measures, including UV-C sterilizers and electronically charged ionizers, help further neutralize bacteria and viruses while reducing airborne particulates.

The integration of digital twin technology, combined with real-time air quality monitoring sensors, enables the tracking of essential parameters, including PM2.5, CO₂, VOCs, humidity, and temperature. AIRSIDE's strategies are designed to achieve a 23% reduction in CO₂ emissions through adaptive microclimate management that enhances ventilation while minimizing heat transfer into the facility. High-performance building facades paired with energy-efficient lighting systems ensure optimal indoor temperatures. The monitoring systems specifically focus on five critical parameters:

PM2.5 ($\mu\text{g}/\text{m}^3$), CO₂ (ppm), TVOC ($\mu\text{g}/\text{m}^3$), temperature, and relative humidity, to maintain exemplary IAQ.

At 2:31 PM on June 25, 2025, the real-time data from their monitoring system reflected the following IAQ parameters for office spaces: PM2.5 at $7.7 \mu\text{g}/\text{m}^3$, CO₂ at 657 ppm, TVOC at $46 \mu\text{g}/\text{m}^3$, temperature at 27°C, and relative humidity at 52%. For the mall area, the parameters were reported as PM2.5 at $6.6 \mu\text{g}/\text{m}^3$, CO₂ at 464 ppm, TVOC at $21 \mu\text{g}/\text{m}^3$, temperature at 27°C, and relative humidity at 60%. These monitoring efforts align with the WELL Building™ Standard Version 1, which outlines universal performance criteria emphasizing the integration of design, operations, and behavioural factors, thereby setting a benchmark for green buildings.

Despite AIRSIDE's success in providing transparency regarding IAQ data through real-time monitoring on their website for both visitors and occupants, there is a notable absence of recorded feedback from these stakeholders concerning IAQ progress. To further enhance their initiatives, it may be beneficial for AIRSIDE to implement additional feedback mechanisms, such as surveys, to better evaluate and respond to the concerns of their visitors and occupants.

3. Literature Review (PART B- Countries with a similar landscape like Hong Kong)

3.1 Understanding Similarities of Hong Kong and Other Landscapes

The urban landscapes of cities like Singapore, Shanghai, Tokyo, New York, Seoul, and Dubai share several characteristics with Hong Kong, notably dense development, high-rise architecture, and constrained land availability. Hong Kong, along with Singapore and cities within the Pearl River Delta, exemplifies high-density urban environments that emphasize vertical growth to optimize resource use (Lam & Lee, 2019).

With a population density of approximately 8,400 individuals per square kilometer, Singapore stands out as one of the most densely populated regions worldwide, particularly when compared to Hong Kong and Shenzhen, which reported densities of less than 8,000 individuals per square kilometer as of 2020. These urban centers generally feature high-rise buildings that exceed 20 stories, facilitating the accommodation of increasing populations and economic activities.

However, the optimization of land use in these densely populated areas presents significant challenges, particularly regarding air pollution stemming from industrial activities and vehicular emissions. The high population density compounds these issues, underscoring the urgent need to address indoor air quality (IAQ). Research conducted by Lam and Lee (2020) has established a direct link between poor air quality and respiratory health concerns. This finding aligns with the World Health Organization's 2018 report, which connects air pollution to a range of health repercussions, including respiratory and cardiovascular diseases. Thus, improving IAQ becomes essential for creating healthier living environments.

The COVID-19 pandemic has intensified the focus on mitigating airborne transmission risks and underscores the importance of IAQ solutions, such as enhanced ventilation systems and high-efficiency particulate air (HEPA) filters. Key considerations in advancing IAQ technologies include cost, the economic implications of attracting investments, and social equity. For instance, Dubai is leveraging innovative building technologies to achieve superior environmental quality standards (Hrainwater, 2025), while Hong Kong is implementing policies aimed at retrofitting older buildings with upgraded ventilation systems to ensure that IAQ improvements are accessible to all socio-economic groups (Tsang et al., 2024).

Despite the benefits associated with IAQ solutions, ranging from advanced filtration systems to sensor networks, the financial implications of implementing these technologies can be substantial. Some urban areas struggle with the feasibility of making IAQ improvements universally affordable, while others regard these measures as critical investments in public health and economic vitality. Wealthy cities such as Dubai and New York (US EPA, 2025) are usually better positioned to absorb the costs associated with advanced solutions, whereas many urban regions must balance financial constraints with urgent environmental needs. Consequently, many cities prioritize IAQ enhancements in high-risk settings, including schools and healthcare facilities, and seek

public-private partnerships to improve affordability. This context necessitates a concerted effort to develop cost-effective and scalable solutions tailored to the challenges faced by rapidly evolving urban areas.

3.2 Overview of Indoor Air Quality (IAQ) (Country A-Singapore)

Singapore showcases an active strategy for managing Indoor Air Quality (IAQ), shaped by its urban density, towering skyscrapers, and a mix of residential and commercial facilities, all within the constraints of limited land and high public health standards. The nation's commitment to enhancing IAQ encompasses the adoption of advanced air filtration technologies (such as HEPA filters, MERV filters, antimicrobial coatings, and deodorizing filters), innovative ventilation solutions (including fresh air systems, heat recovery ventilation, CO₂ sensors, and BCA Green Mark Standards), and sophisticated IAQ monitoring and control systems (like sensors, LoraWAN technology, real-time monitoring capabilities, and integrated building management system). Additionally, it employs various hygiene and IAQ technologies (including UV disinfection, bipolar ionization, and streamer technology) alongside governmental regulations and standards (such as Singapore Standard SS554 and SS553, BCA Green Mark, NEA regulations, and WSH Council guidelines). These efforts have resulted in a significant reduction in indoor pollutant levels within commercial buildings, thereby enhancing the safety of occupants.

In contrast, the Hong Kong government primarily emphasizes outdoor air monitoring, with less focus on public health campaigns and regulatory frameworks. Singapore's approach to making IAQ improvements accessible to all is notably aggressive, with strategies that include strategically locating polluting industries away from residential areas and enforcing stringent emission standards during their design and operational phases. Although both Singapore and Hong Kong encounter comparable pollution and environmental challenges, Singapore has achieved superior air quality (IQAiR, 2025b), with a PM_{2.5} concentration of 11.4 µg/m³, which is 2.3 times the World Health Organization's annual guideline value. Conversely, Hong Kong's PM_{2.5} level is measured at 16.28 µg/m³, which is 3.3 times above the WHO's annual guideline (IQAiR, 2025b). This suggests that both regions face shared pollution challenges that necessitate urgent and effective interventions. Table 3.1 presents a summary of the air filtration and purification technologies and solutions used in Singapore for IAQ.

Table 3. 1 Air Filtration and Purification Technologies and Solutions Used in Singapore for IAQ

Major-Technologies	Sub-Categories	Uses
Air Filtration and Purification Technologies and Solutions	HEPA filters, AHUs, MERV filters, Deodorizing filters	Utilized in air purifiers and HVAC systems to trap and eliminate contaminants like mold, pollen, smoke, odors, and dust.
	Antimicrobial coatings	Primarily used in air purifiers and HVAC systems to catch and remove pollutants, including Mold, pollen, smoke, odours, and dust.
	UV-C light	To sanitize air and surfaces.
	Bipolar Ionization	It uses charged particles to clean the air by sending out positive and negative ions that attach to virus and bacteria particles, either rendering them inactive or making them heavier so they fall out of the air.
	Streamer Technology	These devices are air purifiers that employ streamer technology, which utilizes plasma discharge to break down pollutants and keep filters and tanks cleaner.

3.2.1 Air Filtration and Purification Technologies for IAQ in Singapore

Air filtration and purification technologies utilized in Singapore play a crucial role in enhancing IAQ across residential, commercial, and healthcare sectors. These systems are designed to trap, eliminate, and decompose pollutants that adversely affect air quality. Various devices, as outlined in the associated table, include HEPA filters, air handling units (AHUs), Minimum Efficiency Reporting Value (MERV) filters, and deodorizing filters, which are effective in removing contaminants such as Mold, pollen, smoke, dust, and unpleasant odours. In Singapore, these technologies are generally cost-effective and are becoming increasingly prevalent in both homes and healthcare settings, such as hospitals and nursing homes. For instance, Germitol (2025) provides an ultraviolet air purifier that not only traps germs but also effectively destroys them, promoting a healthier environment.

Additionally, antimicrobial coatings are frequently applied to cooling coils in air purifiers and air conditioning systems to maintain cleaner air. Cooling coils often accumulate dust and grime, which can become breeding grounds for bacteria, Mold, and fungus. The application of antimicrobial coatings serves to inhibit or reduce the proliferation of these microorganisms. Furthermore, streamer technologies contribute to the breakdown of odours, bacteria, viruses, formaldehyde, and other indoor pollutants

absorbed by the systems. Some air purifiers incorporate advanced streamer technologies, which also help to keep water tanks clean, thereby preventing the growth of mold and bacteria. Research (Chua, 2025) indicates that Daikin air purifiers are equipped with both effective antimicrobial coatings and streamer technology, enhancing IAQ. An illustrative example of a healthcare facility in Singapore employing an air filtration system is the Kwong Wai Shiu Hospital (AOM, 2018), which features the Air and Odor Management (AOM) system designed to optimize ventilation and air filtration for the comfort of patients and the elderly.

Table 3. 2 Innovative Ventilation Technologies and Solutions Used in Singapore

Major-Technologies	Sub-Categories	Uses
Innovative Ventilation Technologies and Solutions	Fresh Air Systems/ Heat Recovery Ventilation	Integrating fresh air intake units with HVAC systems to deliver fresh air to indoor spaces while effectively managing heating and cooling.
	CO ₂ Sensors	Monitor and detect common air quality parameters, such as CO ₂ and VOCs
	BCA Green Mark Standards and Code SS 554:2016+A1:2021	Certification scheme and guidelines to enhance indoor environmental quality and improve IAQ
	Exhaust Systems	Removes pollutants and stale air from indoor environments.

3.2.2 Innovative Ventilation Technologies and Solutions

Ensuring a supply of fresh air within indoor spaces is essential for enhancing indoor air quality (IAQ) in Singapore. To achieve high IAQ across various facilities, a range of technologies and solutions, such as fresh air systems, heat recovery ventilation systems, CO₂ sensors, and the BCA Green Mark Standards, have been implemented. According to Chua (2025), IAQ sensors play a crucial role in monitoring and detecting common air quality parameters, such as CO₂ and VOCs. These sensors facilitate the automation of ventilation control systems in indoor environments. While both wired and wireless options exist, wireless connectivity is preferred as it allows for centralized monitoring on a dashboard. Table 3.4 lists innovative ventilation technologies and solutions.

In addition to air filtration technologies that aim to remove indoor pollutants, introducing fresh air is crucial for reducing the risk of infections caused by small airborne particles, particularly in eliminating challenging, harmful substances. Therefore, a hybrid approach to ventilation is integral in both purifying the air and providing a fresh air supply. Enhancing natural ventilation can further be achieved by integrating fresh air intake units

with HVAC systems to deliver fresh air to indoor spaces while effectively managing heating and cooling. In this context, LG Singapore (LG SG, 2022) offers various IAQ ventilation systems, such as the LG ERV and LG ERV DX, designed to aid residents and commercial buildings in regulating humidity, utilizing nighttime free cooling, and executing heating functions, all while employing efficient filters that enhance overall IAQ.

Moreover, Singapore has introduced a series of certifications and guidelines, including the BCA Green Mark Standards and Code SS 554:2016+A1:2021, which aim to enhance indoor environmental quality and improve IAQ. While the BCA Green Mark encompasses diverse sustainability aspects, compliance with Code SS 554 can significantly help attain a superior Green Mark designation. Despite their differences, these two regulatory frameworks complement each other; Code SS 554:2016+A1:2021 (Singapore Standard, 2025) explicitly addresses IAQ within air-conditioned buildings and air distribution systems. The intention behind this code is to establish acceptable IAQ levels for building occupants, thus reducing the risk of adverse health effects. Additionally, it takes into account various environmental factors, thermal, biological, physical, and chemical, during the design, construction, installation, testing, commissioning, operation, and maintenance of air conditioning and mechanical ventilation (ACMV) systems.

Table 3. 3 IAQ monitoring and control systems used in Singapore

Major-Technologies	Sub-Categories	Uses
IAQ monitoring and control systems	Sensors (LoraWAN Technology)	For Real-Time Monitoring Capabilities
	Cloud-based Platforms and IoT Integration	To monitor essential and common IAQ parameters, such as PM2.5, PM10, and humidity.
	Integrated Building Management Systems	
	Data Visualization and Reporting	Monitors, reports, and alerts building managers and users through live screens.

3.2.3 IAQ monitoring and control systems

Indoor air quality monitoring and control systems, particularly IAQ sensors, are essential devices that measure various factors, including humidity, CO₂ concentrations, VOCs, temperature, and barometric pressure. These sensors achieve optimal performance when integrated with HVAC systems, allowing for comprehensive management of air quality within buildings. For instance, specialized sensors like Sensor

360 leverage IoT technologies to track common pollutants and monitor pressure variations, facilitating effective filter change optimization (AAF, 2022). In Singapore, advanced technologies such as LoRaWAN, cloud-based solutions, IoT systems, and integrated Building Management Systems (BMS) are prevalent for monitoring and reporting IAQ in indoor settings (ELGONET PTE LTD, 2025).

One practical application of IAQ monitoring involves assessing CO₂ levels in meeting rooms through a BMS, which can automatically enhance airflow, thereby providing cleaner air for attendees. Integrated BMSs are particularly crucial for adjusting ventilation and other systems in response to any deviations in IAQ parameters (Daikin Airconditioning (Singapore) Pte. Ltd., 2022). Given that crowded spaces can significantly deteriorate air quality, research indicates that meetings and gatherings exhibit seven distinct patterns of CO₂ variation, which can adversely affect the well-being and cognitive performance of participants (Zhong et al., 2021). Moreover, IAQ visualization and reporting technologies provide user-friendly visual panels that can generate historical data, including graphs and heatmaps, facilitating the production of weekly or monthly reports. This information can be disseminated via email or other platforms to ensure effective communication. Table 3.3 highlights the IAQ monitoring and control systems.

Table 3. 4 Governmental Regulations and Standards Used in Singapore

Major-Technologies	Sub-Categories	Uses
Governmental Regulations and Standards	Singapore Standard Ss554 and Ss553	Provides code of practice related to IAQ and ACMV.
	BCA Green Mark	Grants Green Mark certifications
	NEA Regulations	Focus on environmental and waste management.
	WSHC Guidelines	Focuses on educating and engaging workers in workplace safety and health practices.

3.2.4 Governmental Regulations and Standards

Numerous technologies and solutions exist to improve Indoor Air Quality (IAQ) and reduce indoor pollutants in indoor spaces. However, the enforcement of government regulations and standards is vital for their successful implementation, ultimately ensuring high IAQ standards and the well-being of occupants. Singapore exemplifies this commitment through its proactive measures aimed at enhancing overall IAQ for its residents. Key regulatory agencies, such as the National Environment Agency (NEA) and the Building and Construction Authority (BCA), have been entrusted with enforcing IAQ regulations, guidelines, and standards. These regulations include building audits to verify compliance with established standards such as the Code of Practice for IAQ in Air-conditioned Buildings (SS 554:2016) and NEA's guidelines, along with the Code of Practice for Air Conditioning and Mechanical Ventilation in Buildings (SS553:2009) and AHRI Standard 550.590. The BCA also grants Green Mark certifications, including certified, Gold, Gold^{PLUS}, and Platinum statuses, to air conditioning systems that comply with these audits. Table 3.4 presents a list of government regulations and standards used in Singapore.

IAQ surveillance audits are particularly significant, as they involve the use of accredited laboratories under the Singapore Accreditation Council to monitor recommended IAQ parameters and acceptable limits, thereby ensuring optimal IAQ performance within buildings. Additionally, retrofitting works must align with minimum environmental sustainability measures and adhere to IAQ regulations. Evidence documenting conditions before and after retrofitting must be submitted by Professional Engineers (Mechanical) (Building and Construction Authority, Singapore, 2019).

The National Environment Agency (NEA) (2024) mandates the monitoring of CO₂ levels and ventilation in all indoor areas, focusing on spaces that cater to vulnerable populations, such as hospitals, eldercare facilities, and venues where food and drinks

are served, as well as gyms, event venues, function rooms, and nightlife establishments. Technologies such as Non-Dispersive Infrared (NDIR) portable CO₂ meters or CO₂ monitors with real-time displays are recommended for this monitoring process. CO₂ levels should remain below 700ppm in enclosed air-conditioned spaces and must not exceed the levels stipulated in SS554:2016, the Code of Practice for IAQ in Air-conditioned Buildings.

Furthermore, the regulation of testing and IAQ audits is governed by the Workplace Safety and Health guidelines, in accordance with SS554, which outlines the parameters to be measured and their acceptable IAQ limits (refer to Table 3.5 for details). It is advised that testing be conducted by qualified professionals who have completed the WPH-WSH-5065-1.1 IAQ Management-5 training and are proficient in operating monitoring devices and recording results.

Table 3. 5 List of Parameters and Acceptable Limits

Parameters for Testing	Acceptable Limit for IAQ
CO ₂	≤ (700 ppm + outdoor level)
CO	≤ 9 ppm
TVOC	≤ 1000 ppb
HCHO	≤ 0.08ppm
PM2.5	≤ 37.5 mg/m ³
PM4.0	≤ 50 mg/m ³
Relative Humidity	≤ 70%
Air Temperature	23 °C-25 °C
Air Movement	<0.30 m/s
Ozone Test	≤ 0.05 ppm
Total Bacteria Count	≤ 1000 cfu/m ³
Adapted from Qsafe (2023)	

3.3 Case Study: IAQ Management at Daikin Singapore Pte Limited

Daikin Singapore Pte. Limited, a prominent subsidiary of the renowned Japanese air conditioning manufacturer Daikin Industries, Ltd., operates out of the Ang Mo Kio Industrial Park in Singapore. The company has established itself as a leader in developing innovative products and solutions aimed at enhancing indoor environmental quality. Among its offerings are advanced air conditioning systems, including the iSmart ENVI and EZi Series, as well as household products like air purifiers equipped with smartphone controls. Furthermore, Daikin Singapore offers specialized systems, including SkyAir (featuring R32 refrigerant), VRV (with models such as VRV IV S and VKM Heat Reclaim Ventilator), as well as a range of smart solutions for remote monitoring and management.

With more than 90 production facilities across over 150 countries, Daikin's commitment to sustainability and innovation is evident in its focus on pioneering technologies, including heat pumps, inverter systems, and refrigerant control mechanisms. As the sole manufacturer engaged in the comprehensive production, sales, and servicing of diverse air conditioning products, Daikin Singapore is well-positioned to cater to the evolving demands of the market. The company recently expanded its capabilities by acquiring BMS Engineering and Trading Pte Ltd, enabling it to offer integrated facility management systems and energy-efficient solutions.

Recognizing a shift toward a lifestyle that increasingly favours time spent indoors, a trend accelerated by contemporary living arrangements, Daikin has emphasized the importance of indoor air quality (IAQ). Their advanced air conditioning systems transcend traditional cooling and heating functions by integrating sophisticated ventilation technology aimed at improving IAQ. Daikin Singapore's extensive lineup of IAQ products includes filters for air purifiers, state-of-the-art Air Handling Units, and heat reclaim ventilation systems, complemented by retrofitting services designed to eliminate harmful pollutants such as Mold, viruses, bacteria, and allergens from living and working environments.

For instance, Daikin recently undertook a critical IAQ assessment and solution implementation for a luxury bungalow in Singapore. The project involved the installation of a VRV ducted Fan Coil Unit (FCU). It was founded on an extensive analysis of the property's air quality concerns, which included musty odours and visible Mold growth on ceilings and diffusers. The assessment revealed that microbial counts on the FCU cooling coils surpassed acceptable limits, indicating high levels of bacterial growth that posed health risks to the occupants due to accumulated dust and allergens.

In response, Daikin employed a multifaceted remediation approach that included steam cleaning, utilizing high-pressure steam to eradicate bacterial and dust presence on the cooling coils, and Mold remediation techniques, which involved fumigation and applying anti-mold paint to prevent future growth on impacted surfaces. Duct cleaning further ensured the removal of pollutants from both return and supply ducts.

Upon completion of the installation, a follow-up assessment confirmed that all monitored IAQ parameters aligned with established acceptable levels. Feedback from the clients indicated significant satisfaction, with notable improvements in their health attributed to the comprehensive IAQ solutions provided.

This case underscores Daikin Singapore's dedication to fostering healthier indoor environments through innovative air conditioning technology and tailored IAQ solutions, reflecting the company's ongoing commitment to enhancing the quality of life for its clients.

3.4 Overview of Indoor Air Quality (IAQ) (Country B-Tokyo-Japan)

Tokyo exemplifies a bustling metropolitan landscape characterized by its towering high-rise structures, which increasingly adopt advanced smart building technologies. These innovations enhance IAQ through sophisticated ventilation systems, state-of-the-art air filtration mechanisms, and robust pollution control strategies. By integrating sensor-driven monitoring systems, buildings in Tokyo actively manage and optimize air quality, ensuring a healthier living and working environment for their inhabitants. This proactive approach addresses urban pollution challenges and contributes to energy efficiency and sustainability within the city. Table 3.6 summarizes IAQ technologies and solutions used in Tokyo.

Table 3. 6 IAQ Technologies and Solutions used in Tokyo

Major-Technologies	Sub-Categories
Ventilation and Filtration Systems	Advanced HVAC Systems
	Air Handling Units (AHUs)
	Natural Ventilation
	Ventilation Systems
Air Purification	Air Purifiers
	Ionizers
	Air Quality Monitoring
Smart IAQ Management	IoT
	Real-Time Monitoring
	IAQ Sensors
	BMS
IAQ Regulations and Standards in Tokyo, Japan	Zero Emissions Tokyo Strategy
	IAQ, mainly regulated by the Ministry of Health, Labour and Welfare (MHLW).
	The Environmental Sanitation Act, enacted in 1970, focuses on building sanitation and includes considerations for IAQ.

3.4.1 Ventilation and Filtration Technologies and Solutions

A variety of ventilation and filtration technologies are utilized to improve indoor air quality (IAQ) and the overall indoor environment. These solutions include sophisticated HVAC systems, air handling units (AHUs), natural ventilation methods, and other ventilation approaches. In contrast to Hong Kong and Singapore, Japan also employs these technologies to filter out viruses, pollutants, odors, and other microorganisms. According to a study by Taniguchi et al. (2024), during the spring and winter periods of 2022 and 2023, favorable outdoor temperatures allowed for effective indoor air

management through natural ventilation by opening windows. This demonstrates that implementing natural ventilation systems, such as window opening, can effectively sustain indoor thermal comfort while enhancing IAQ.

Additionally, Panasonic's Nanoe™ X technology features an air purification system that generates ionized particles within air conditioning units to neutralize viruses, bacteria, and indoor pollutants (Panasonic Corporation, 2025).

3.4.2 Air Purification Technologies and Solutions Used in Tokyo, Japan

With the significant amount of time individuals spend indoors, various air purification technologies, including ionizers that are either part of HVAC systems or operate as standalone units, have been implemented to mitigate pollutants and unpleasant odours. In Japan, similar to many other countries, air purifiers that utilize HEPA filters, activated carbon filters, and UV-C light technologies are effective in eliminating volatile organic compounds (VOCs) and microorganisms. Air quality monitoring systems in Japan often incorporate Internet of Things (IoT) and artificial intelligence (AI) technologies to track key parameters, including temperature, carbon dioxide levels, and particulate matter (PM).

The integration of air purification systems in Japan is prevalent across a range of environments, including retail spaces, offices, healthcare institutions, airports, train stations, educational facilities, and vehicles. Statistics indicate that the increasing awareness of the detrimental effects of air pollution on health has driven a rise in the adoption of air purification technologies, particularly in response to the COVID-19 pandemic and the subsequent demand for cleaner, healthier indoor environments. The Japanese air purifier market is projected to reach approximately \$988 million by 2033, having generated \$579 million in revenue (IMARC Group, 2025). Leading companies in this sector include Daikin Industries Ltd, Dyson Corporation, Hitachi Ltd, Mitsubishi Electric Corporation, Sharp Corporation, and Panasonic Corporation.

3.4.3 Smart IAQ Management and Solutions.

Smart IAQ management technologies and solutions encompass a range of AIoT applications, including LoRa-based IoT networks and artificial intelligence integrations. These advancements facilitate real-time monitoring systems (such as uHoo), Building Management Systems (BMS) that integrate with HVAC, air purifiers, and ventilation systems, as well as various IAQ sensors. For instance, Kiwi Technology (2022) in Japan has developed smart IAQ solutions designed to enhance indoor air quality in retail hypermarkets and supermarkets. Their offerings include smart air quality monitoring and management capabilities featuring remote monitoring, timely alerts, and automatic data uploads. This system effectively tracks ambient temperature, humidity, and CO₂ levels, providing a comprehensive solution for managing crowd density and overall air quality. The system includes alarm indicators, a cloud-based IoT platform, and 24/7 real-time

monitoring to assess IAQ indices and evaluate comfortable levels of CO₂, CO₂ ppm, temperature, and relative humidity.

Additionally, IAQ solutions can offer reporting and data analysis services that encompass visualization, data collection, and the assessment of energy-saving measures in air-conditioning operations. Furthermore, devices like uHoo (uHoo, 2024) meet Japanese technical standards and are employed to monitor critical indoor parameters, including CO₂ levels and PM2.5 concentrations. These technologies are primarily utilized in workplaces, industrial settings, and among consumers, reflecting a growing emphasis on enhancing indoor air quality across various environments.

3.4.4 IAQ Regulations and Standards in Japan.

Japan has established specific regulations and guidelines concerning indoor air quality (IAQ), primarily overseen by the Ministry of Health, Labour and Welfare (MHLW). These regulations particularly focus on formaldehyde and volatile organic compounds (VOCs), aligning with World Health Organization (WHO) recommendations to reduce health risks and enhance IAQ. While this study primarily examines Tokyo due to its similarities with Hong Kong's urban environment, it is important to note that the city adheres to Japanese IAQ standards and further promotes initiatives like the Zero Emissions Tokyo Strategy. These local efforts aim to mitigate short-lived climate pollutants, enhance air quality, and optimize energy consumption in buildings.

In the early 2000s, Japanese households reported a health issue referred to as “Sick House Syndrome” (Azuma et al., 2008; Inoue et al., 2025; MHLW, 2002). This condition was linked to high levels of indoor pollutants that produced symptoms such as eye, throat, and nose irritation, along with headaches, dizziness, and nausea. The pollutants originated from materials used in the construction of airtight homes. This troubling situation prompted the Japanese government to introduce IAQ guidelines and revise national building codes, specifically improving formaldehyde emission standards to control the materials used in construction. Concurrently, industry stakeholders developed voluntary standards that aligned with these government regulations.

To prevent short-term health effects from formaldehyde exposure, a guideline value of 0.1 mg/m³ (0.08 ppm) for indoor concentrations was established (Azuma et al., 2008). The ministry also oversees the monitoring and regulation of other VOCs, including xylene, benzene, and toluene. The Environmental Sanitation Act, enacted in 1970, addresses building sanitation and incorporates IAQ considerations, along with ventilation guidelines, to ensure proper airflow and filtration within buildings. Notably, Japan's traditional emphasis on cleanliness, exemplified by the use of ‘tatami mats’, which are recognized for their natural air purification qualities (Odmark, 2024), also contributes significantly to enhancing IAQ. Furthermore, these guidelines are regularly

reviewed, with the latest updates in 2023 identifying additional toxins. A proposed standard of 0.0858 ppm ($370 \mu\text{g}/\text{m}^3$) was suggested to revise the IAQ guidelines (Inoue et al., 2025).

3.5 Case Study: IAQ Management at Shibuya Station

Shibuya Station, situated in Tokyo, is a pivotal transit hub, accommodating over 2 million passengers daily. Acknowledged as the busiest rail and subway station in Japan, it represents both historical significance and a dynamic evolution of transportation systems. Given the substantial daily foot traffic at this metro station, evaluating indoor IAQ is of paramount importance for the well-being of its users.

A study conducted by Agarwal et al. (2025) utilized a pocket sensor, specifically engineered by Yaguchi Electric Corporation in Japan, for measuring particulate matter (PM_{2.5} and PM₁₀). This instrument utilizes laser scattering technology and operates by drawing power directly from a smartphone via a micro-USB connection. Data collection occurred across all six lines of the station, with measurements taken for 15 minutes at each designated position. The findings indicated that above-ground train lines exhibited comparatively healthier air quality, with average PM_{2.5} and PM₁₀ levels recorded at $17.09 \mu\text{g}/\text{m}^3$ and $39.54 \mu\text{g}/\text{m}^3$, respectively. In contrast, the underground train lines revealed higher pollutant levels, with PM_{2.5} and PM₁₀ concentrations of $22.73 \mu\text{g}/\text{m}^3$ and $56.98 \mu\text{g}/\text{m}^3$, respectively, surpassing the safety thresholds for daily exposure. The study suggested that the differences in air quality could be attributed to ventilation differences, positing that the above-ground lines benefit from enhanced air exchange with the external environment compared to their underground counterparts. To address these issues, the researchers advocate for the implementation of improved ventilation technologies and solutions to enhance IAQ.

While specific details regarding Shibuya Station's IAQ technologies and solutions are not explicitly documented, it is believed that the station features a large, open central atrium designed to facilitate airflow and diminish reliance on mechanical ventilation. The use of a portable sensor by Agarwal et al. (2025) raises the possibility of integrating remote sensing technology to consistently monitor PM_{2.5} and PM₁₀ levels. Previous research by Kim et al. (2012) and Kim et al. (2015) has highlighted the need for real-time monitoring systems and air filtration technologies to address the issues associated with hazardous pollutants, especially in underground subway environments. These recommendations suggest a comprehensive strategy to improve IAQ within Shibuya Station and potentially other similar transit hubs.

3.6 Overview of Indoor Air Quality (IAQ) (Country C-Seoul-South Korea)

When compared to other nations with similar urban characteristics, Seoul stands out as a densely populated metropolis characterized by its striking high-rise buildings, which accommodate both residential and commercial spaces. It has established itself as a frontrunner in IAQ technologies and solutions. The city's skyline is characterized by contemporary architectural innovations that reflect the latest trends in urban development (Han, 2020).

The challenges posed by increasing urbanization and industrialization, particularly the shift toward remote work, have led to a significant rise in the amount of time individuals spend indoors. This shift has contributed to deteriorating IAQ, which poses risks to respiratory health and overall well-being. In response, Seoul has made substantial investments in advanced IAQ technologies and solutions (Lab Chronicles, 2025). These initiatives include demand-controlled ventilation (DCV), photocatalytic oxidation (PCO), and IoT-based sensors, along with various government programs aimed at enhancing indoor environments in residential areas, commercial establishments, industrial sites, healthcare facilities, and educational institutions. By prioritizing these technological advancements, Seoul not only improves the quality of life for its residents but also demonstrates a strong commitment to upholding IAQ standards. Table 3.7 summarizes IAQ technologies and solutions used in Seoul.

Table 3. 7 IAQ Technologies and Solutions in Seoul, South Korea

Major-Technologies	Sub-Categories
IAQ Monitoring Systems	Real-Time Monitoring (Portable, fixed, smart, and personal air quality monitors)
	Integration with smart city initiatives
IAQ Technological Advancement	IoT-based Sensors (e.g., analog, digital, laser-based, and electrochemical sensors)
	Smart Air Purifiers
	DCV
	PCO
	Air Shower Systems
	Black Carbon Sensor Devices
IAQ Management and Solutions	Government initiatives, such as IAQ certification programs for facilities like daycare centers and PC cafes.
	Living Labs
	IAQ for Subways
	Technology development

3.6.1 IAQ Monitoring Technologies and Solutions in Seoul, South Korea

The growing prevalence of remote work and the increased time spent indoors have intensified the need for effective air quality tracking and monitoring to address the health risks posed by indoor pollutants, including CO₂, VOCs, particulate matter (PM), and formaldehyde. While both corporate and governmental efforts are underway to enhance IAQ, the growing awareness of individual health and wellness has further amplified the demand for efficient monitoring devices.

In South Korea, the market for IAQ monitoring systems has experienced substantial growth, with projections indicating a value of US\$4.2 billion in 2024 and an expected increase to US\$10.1 billion by 2033 (Lab Chronicles, 2025). This growth highlights the crucial role that IAQ monitoring plays within the broader air quality market. However, the challenge of affordability persists, as the initial investment may hinder widespread adoption, a trend observed in various countries. South Korea boasts over 15 prominent manufacturers of IAQ monitoring systems, including industry leaders like Siemens AG, 3M, and Agilent Technologies.

Companies such as Piquant (2025) are at the forefront of providing real-time monitoring solutions, exemplified by their Air Quant technology, which is a modular detection system leveraging advanced innovations such as the Internet of Things (IoT) and big data to assess IAQ. Their offerings encompass a range of services, including parameter detection, monitoring, and improvement, focusing on metrics like fine dust, TVOCs, CO₂, SO₂, CO, NO₂, humidity, and temperature. In addition to product development, institutions and research centers, such as the Korea Institute of Civil Engineering and Building Technology (KICT), are dedicated to advancements in IAQ (KICT, 2025). KICT specializes in multiple facets of IAQ, employing intelligent technologies for user perception evaluation, as well as augmented reality (AR) and virtual reality (VR) to visualize air quality data. Additionally, it creates facility-based air purification systems and customized IAQ management solutions. Unlike many other nations that emphasize general air quality, South Korea distinctly prioritizes IAQ, establishing it as a critical area that warrants focused attention.

3.6.2 IAQ Management and Solutions

In 2012, the Seoul Metropolitan Government established the IAQ certification program, which aims to monitor facilities that focus on health and well-being. This includes a range of establishments such as daycare centers, elderly care homes, post-partum centers, educational institutions, cafes, and libraries (Seoul Metropolitan Government, 2018). To achieve certification, facilities must score at least 60 points in each of the measured categories, PM₁₀, CO₂, formaldehyde, bio-aerosols, CO, and PM_{2.5}, and accumulate a minimum of 75 points overall. Certification is valid for two years, and facilities are required to display their certification mark prominently. Furthermore, the government provides free consultations on IAQ for smaller facilities.

The certification process involves IAQ measurements, onsite inspections, and evaluations by a judging committee. Since its inception, approximately 50 facilities have been certified each year, and as of 2024, around 506 facilities currently hold the excellent IAQ certification mark. Currently, the certification targets facilities totalling 5,462 (see Appendix for details) (Seoul Metropolitan Government, 2025a). Notably, Seoul has been recognized as one of the top cities globally for CO₂ reduction, earning an "A" grade among 112 cities for three consecutive years, which underscores its commitment to improving IAQ in the city and nation at large (Seoul Metropolitan Government, 2025b).

Moreover, the Seoul subway system serves as a critical transportation network, accommodating over 10 million passengers daily. With 302 stations, the subway is essential for urban development, and concerns regarding IAQ have surfaced due to the confined underground spaces where air quality can be compromised by internal pollutants and external air contamination. To mitigate these challenges, the Seoul Metropolitan Government implemented the “Indoor Environment Management System,” which aligns with national regulations and the Seoul Ordinance on Air Quality Standards for underground areas established in 2000. This system aims to provide accessible IAQ information online for both the public and facility managers, encouraging proactive measures to enhance air quality. It is recommended that metro subways incorporate platform screen doors, air quality monitoring systems, effective ventilation, and routine cleaning.

For instance, the Seoul Metro has deployed over 840 air quality sensors across 277 stations and several trains to monitor fine dust levels, with plans to install an additional 4,432 air purifiers and particulate monitors to further enhance IAQ (Gasdia-Cochrane, 2023). Additional initiatives include citizen-focused living labs designed for research and testing of IAQ technologies and business models. One such initiative, the Magok Smart City Living Lab (Nam, 2023), integrates various IAQ solutions, including IoT sensors and odor management systems, to improve indoor air quality.

3.6.3 IAQ Advanced Technologies

Like many other global cities, including Japan, Singapore, and Hong Kong, Seoul, South Korea, uses advanced technologies to monitor air pollutants. These include smart air purifiers, sophisticated ventilation systems, DVC, PCO, and IoT-based indoor air quality (IAQ) monitoring platforms. Additionally, Seoul features unique systems such as air shower devices (Kang, 2020), which are usually placed at building entrances to remove dust and particles from people's clothes before they enter their homes. Furthermore, black carbon sensors (Park et al., 2024) are placed in areas with high black carbon levels, a major component of particulate matter pollution, within residential, educational, and commercial spaces.

3.7 Case Study: IAQ Management by Seoul Metropolitan Government

The Seoul Metropolitan Government operates as a multifaceted institution, with various branches dedicated to specific functions, among which Indoor Air Quality (IAQ) is a prominent focus. The government is committed to enhancing IAQ for both residents and visitors, aiming to provide clean indoor environments for everyone. In the early 2000s, Seoul enacted the Ordinance on Air Quality Standards for Underground Spaces, which included a comprehensive indoor air quality management act aimed at improving sanitation in indoor workplaces, schools, and public-use facilities.

According to reports (Seoul Solution, 2016), Seoul enforces stricter IAQ regulations for public facilities compared to those set by the central government, given that the Act specifically addresses multi-use facilities frequently visited by large numbers of people. To achieve elevated IAQ standards, the city conducts evaluations for five critical pollutants: fine dust, formaldehyde, CO, CO₂, and aerosols. In contrast, assessments for NO₂, TVOC, O₃, and radon are only required for voluntary compliance.

Furthermore, the metropolitan government has launched several key initiatives, including the Clean Indoor Air Certification System, which promotes pollution reduction in selected areas. Facilities that meet the certification criteria are entitled to complimentary IAQ inspections for a period of two years. An Indoor Environment Management system enhances transparency by publishing facility information on a dedicated website (<https://cleanindoor.seoul.go.kr/index.do>), which the public can access to check air quality in various public establishments. Additionally, the government provides free consultation services on IAQ, specifically for sensitive groups such as mothers and children, as well as for professionals seeking to address identified issues. Inspections cover six pollutants: CO₂, fine dust, TVOC, CO, humidity, and temperature. Recommended solutions for improving IAQ include regular ventilation, adjustments in cleaning practices, Mold remediation, and managing indoor humidity levels.

Given the significant health risks posed by radon exposure, which can lead to lung cancer with prolonged contact, the Institute of Health Environment conducts regular radon level assessments in subway stations to protect public health. A Radon Map is also available to inform the community about radon concentrations throughout Seoul.

3.8 Overview of Indoor Air Quality (IAQ) (Country D-Shanghai, China)

Shanghai is a megacity characterized by its high-rise architecture and extensive urban development. These advanced high-rise buildings incorporate advanced IAQ management solutions, including HVAC systems with ventilation and filtration, air purification systems with ionization and filtration, government initiatives, and IAQ monitoring systems equipped with sensors and data analysis capabilities. These IAQ technologies and solutions are incorporated across various buildings, including residential, commercial, Hotels, and government institutions. While IAQ technologies and solutions are used to mitigate and improve poor IAQ, luxurious hotels in Shanghai are prioritizing clean indoor air, as their occupancy rates are typically high, and potential indoor pollutants may increase due to inadequate ventilation or subpar filtration. Table 3.8 highlights key IAQ technologies and solutions employed in Shanghai, China.

While there are several filtration or ventilation technologies and solutions, news media such as Xinhua (Roxburgh, 2020) have highlighted caution when buying or selecting air purifiers, as they suggest that most air purifiers tested by the government inspection agency failed quality checks.

Table 3. 8 IAQ Technologies and Solutions in Shanghai, China

Major-Technologies	Sub-Categories
Advanced HVAC Systems	With filtration systems such as HEPA and ULPA filters
Air Purification Systems	UV light
	Air ionization
	Filters such as HEPA, Activated Carbon
	Air Purifiers
IAQ Monitoring and Control Systems	IAQ Sensors
Government Initiatives and Regulations	GB/T 18883-2022
	GB 50325-2001
	“RESET” certification
	Certification and Standards (RESET)

3.8.1 Advanced HVAC Systems

Similar to other countries or cities that use HVAC systems, Shanghai is no different, as it also utilizes IAQ technologies with filtration systems, such as HEPA and ULPA filters, to remove airborne particulates and prevent microbial build-up effectively. They also feature humidity control and advanced ventilation systems to manage airflow and pollutant levels. Most companies operating HVAC for adequate IAQ are Daikin Air

Conditioning Systems, Haier Smart Home Company Limited, Samsung, or Midea Group Limited (Kapoor, 2025), which specialize in HVAC systems for residential, industrial, and commercial use.

3.8.2 Air Purification

The correlation between pollutant exposure and mortality risk in China highlights the importance of air purification technologies, particularly the use of HEPA filters, which are widely recognized for eliminating noxious gases and unpleasant odors. Research indicates that traditional HEPA filtration remains prevalent despite certain restrictions in addressing specific pollutants. These devices are primarily utilized in medical facilities to mitigate the transmission of airborne illnesses and are also found in the aerospace sector. Recent advancements have led to innovative air purification systems that incorporate technologies such as UV light and air ionization alongside HEPA filters. These systems are effective in eliminating a range of contaminants, including bacteria, Mold, allergens, dust, and VOCs.

Despite their limitations, HEPA filters are extensively deployed in hospitals, public transportation, automobiles, vacuum cleaners, and aircraft, where they effectively capture or deactivate airborne particles, including mold spores and bacteria. Filters equipped with ULPA technology, which incorporate silver nanoparticles, have demonstrated superior efficacy in trapping particles as small as 0.1-0.3 microns and inhibiting bacterial growth (Muller et al., 2015).

For instance, while the prevalence of HEPA filtration in Chinese facilities remains limited, the COVID-19 pandemic has prompted organizations like IQAir to provide HealthPro Plus air purifiers to several hospitals, including Wuhan Union Hospital, as a measure to combat the virus (IQAir, 2022b). Additionally, following guidance from the National Health Commission, public transportation systems in Shanghai have implemented UV light disinfection methods on both the interiors and exteriors of buses, achieving a virus reduction rate of approximately 99.9% within a 5 to 7-minute application time (Sustainable Bus, 2020).

In summary, while HEPA filters and UV light technologies serve critical roles in healthcare settings and commercial transit systems, similar to practices in other nations, air purifiers are increasingly utilized in residential environments to enhance IAQ.

3.8.3 IAQ Monitoring and Control Systems

Indoor air quality monitoring and control systems, similar to those implemented in various countries, leverage IAQ sensors to detect pollutants such as CO₂, particulate matter (e.g., PM_{2.5}), and volatile organic compounds (VOCs). These systems utilize data-driven strategies to enhance ventilation and purification processes. In Shanghai, China, IAQ sensors are employed in both residential (bedrooms, living rooms) and commercial

buildings to facilitate natural ventilation, sometimes supplemented by mechanical means.

A recent study conducted by Zhao et al. (2025) gathered data from multiple offices in Shanghai, predominantly occupied by students and research staff, during hours ranging from 9:00 AM to 6:00 PM, with some instances extending until 11:00 PM. The research focused exclusively on occupied rooms, with 16 monitoring locations established across three office sites. Most of these offices were equipped with central air conditioning systems or portable units featuring basic plastic filters, which effectively capture larger particles, such as dust and hair. However, central air conditioners include more advanced filtration systems capable of handling smaller particulate matter.

Within the study, a wireless sensor was deployed to track and analyze pollutants, specifically PM_{2.5}, PM₁₀, and CO₂. Findings indicated significant differences in temporal monitoring trends between central and portable AC units, leading to a recommendation for a sensor density of one per 150 m². Moreover, CO₂ monitoring should distinguish between central AC systems and standalone units, indicating the necessity for independent sensors in separate rooms to prevent misinterpretation and accurately reflect temporal variations in CO₂ concentrations.

The study also proposed that for trend monitoring, the sampling intervals should be set to 90 minutes for PM and 130 minutes for CO₂, aimed at mitigating data storage challenges and redundancy. Ultimately, while there is a tendency for buildings to prioritize the selection of various IAQ sensors, it is crucial to assess key factors such as the types of air conditioning units, room configurations, air outlets, and window placements to develop a more comprehensive approach to IAQ monitoring and control systems.

3.8.4 Government Initiatives and Regulations

The Chinese government has implemented a variety of initiatives and regulations aimed at reducing acid rain and SO₂ emissions, while also expanding its focus to include nitrogen oxides (NO_x) and PM to ensure cleaner air quality. While these measures primarily address outdoor air pollution, there are also significant indoor air quality (IAQ) initiatives in place. Notable among these are GB/T 18883-2022, GB 50325-2001, and the NOHSC “RESET” certification, which are robust regulations that provide guidance for indoor air quality standards in China. GB/T 18883-2022 (Shi, 2023; Tsang et al., 2024) is a comprehensive regulatory framework established by the State Administration of Market Regulation and the Standardization Administration, designed to supersede GB/T 18883-2002. It outlines hygienic criteria for a range of chemical pollutants (including SO₂, NO₂, CO, CO₂, NH₃, O₃, HCHO, C₆H₆, C₇H₈, C₇H₁₀, TVOC, PM_{2.5}, C₂Cl₄, C₂HCl₃, PM₁₀, and benzo (a) pyrene), as well as physical (temperature, relative humidity, fresh air exchange rate, and air velocity), biological, and radioactive parameters (Rn) alongside the associated testing methodologies. In contrast, GB 50325-2001 emphasizes civil building

engineering standards, particularly concerning pollutants like formaldehyde, VOCs, benzene, and ammonia (Bai et al., 2002).

Furthermore, the Ministry of Health has established hygienic standards for various public environments, including hotels, restaurants, and bathhouses, originally enacted in 1988 with a revision in 1996. Additional regulations, such as the Hygiene Standards for Public Places (GB 9663-GB 9673), set forth the sanitary criteria for IAQ, ventilation, and surrounding environmental conditions. RESET Air standard certifications (Regenerative Ecological, Social, and Economic Targets) are a sensor-based and IAQ performance-driven standard used in Shanghai to monitor key IAQ indicators, such as PM, TVOC, CO₂, humidity, CO, and temperature (One Planet Network, 2019), while promoting a healthier and sustainable built environment for occupants. These are similar indicators used in the measurement at the Airside building in Hong Kong. These regulations typically outline hygiene indicators and permissible limits for contaminants such as CO, CO₂, HCHO, and airborne bacteria. Collectively, these regulatory frameworks are rigorous in their intent to enhance indoor air quality standards across various facilities.

3.9 Case Study: IAQ Management at Shanghai Hongqiao Cordis Hotel

The Shanghai Hongqiao Cordis Hotel (RESET, 2018) is an upscale hotel brand distinguished by its commitment to intuitive service and connectivity. Strategically situated in the Hongqiao commercial hub, it is conveniently located within walking distance of both Shanghai Railway Station and Terminal 2 of the International Airport. A notable aspect of the hotel is its focus on health and wellness through robust initiatives, incorporating IAQ as a luxurious feature.

To enhance the health and wellness of both guests and staff, the hotel has implemented stringent measures, such as advanced filtration and real-time monitoring systems integrated into its HVAC design. Furthermore, RESET Air Accredited Monitors are utilized for continuous IAQ oversight. There are 396 guestrooms, suites, and common areas that are consistently monitored and optimized to adhere to PM_{2.5} levels below the US EPA-recommended threshold of 35 $\mu\text{g}/\text{m}^3$. In an effort to foster transparency and trust, the monitored IAQ parameters are displayed on televisions in individual guest rooms, providing a personalized and intimate experience that promotes health and well-being.

The hotel also adheres to RESET Air certification standards to achieve optimal IAQ. This program is recognized as the world's first sensor-based, performance-driven building certification initiative, emphasizing continuous monitoring, measurement, and reporting of IAQ. Similar to Airside, key IAQ metrics, including PM_{2.5}, TVOC, CO₂, CO, temperature, and relative humidity, are monitored (One Planet, 2019). Additionally, the hotel ensures thorough filtration of outdoor air through two filtration levels and maintains a sealed environment with double-glazed windows to retain fresh air (Roxburgh, 2020). As a result, the indoor air quality is reported to be ten times better than that of the outdoor

environment, promoting not only comfort and relaxation but also a healthier indoor air atmosphere for guests.

3.10 Overview of Indoor Air Quality (IAQ) (Country E-New York-USA)

New York City, much like other urban centers, features a highly concentrated urban core characterized by skyscrapers and commercial infrastructures that employ advanced technologies for ventilation, filtration, and indoor air quality management. Mirroring the densely populated environment of Hong Kong, the city employs sophisticated air filtration and purification methods, including filters and UVGI, as well as innovative airflow and ventilation strategies such as natural ventilation, energy recovery ventilators (ERVs), heat recovery ventilators (HRVs), and dehumidifiers. Additionally, IAQ is monitored and optimized through the use of cloud-based IAQ sensors integrated with a Building Management System (BMS). Furthermore, consultancy from IAQ experts and government initiatives play a crucial role in maintaining healthy air quality standards. Table 3.9 summarizes the IAQ technologies and solutions implemented in New York.

Table 3. 9 IAQ technologies and solutions implemented in New York, USA.

Major-Technologies	Sub-Categories
Advanced filtration and purification	High-efficiency air filters such as HEPA
	Ultraviolet Germicidal Irradiation
	Air ionization
	Air Purifiers
Air flow and ventilation management technologies	Natural ventilation
	ERVs/HRVs
	Humidifiers/Dehumidifiers
IAQ monitoring and optimization technologies	IAQ Sensors with cloud-based
	Integrated BMS
IAQ expert's consultancy	
Government initiatives and regulations (CDC, OSHA, AASHRAE)	Clean Indoor Air Act (NYC)
	Indoor Air Quality Program (Proposed NYC)
	School Environmental Health Program (NYS)
	Indoor Air Quality Fund (NYS)
	Green Building Certifications such as LEED and WELL.
	IAQ expert's consultancy

3.10.1 Advanced Filtration and Purification

New York, like many other metropolitan areas, employs highly efficient air filtration systems, such as HEPA filters, within its HVAC installations to eliminate particulate matter, allergens, and other pollutants. These HEPA filters are essential in both residential and commercial environments. Recently, it has been observed that businesses in New York are increasingly focusing on creating healthier workplaces and environments through advanced HVAC filtration upgrades and real-time air quality monitoring. The use of filters rated MERV 13 or higher is recognized as an effective method for capturing airborne particles, and they can be integrated into existing HVAC systems with minimal disruption.

Organizations are beginning to understand that maintaining IAQ is crucial not only for enhancing employee well-being but also for meeting the expectations of clients and customers, who increasingly seek cleaner and healthier indoor spaces. To further improve air quality, many commercial buildings utilize air ionization technologies, such as bipolar ionization, to neutralize airborne contaminants and enhance overall air freshness. Additionally, ultraviolet germicidal irradiation (UVGI) systems play a significant role in IAQ by employing UV-C light to eliminate pathogens found in ductwork and HVAC coils.

As highlighted in the 2021 IAQ report for Goldman Copeland Associates, P.C., the integration of air filtration technologies, such as MERV 13 or higher, demand-controlled ventilation (DCV), and UVGI systems, is recommended for large facilities to ensure superior filtration and fresher air quality. While portable air purifiers are utilized in various residential and educational settings, the New York State Education Department issued a statement in 2021 regarding ionization air cleaners. This statement reflected concerns raised by the National Institute of Environmental Health Sciences (NIEHS) about the byproducts generated by ionization technologies, which include fine particles, ions, and reactive chemicals that could negatively impact indoor air quality. Consequently, the recommendation is to use air filters rated MERV 13 or higher, in conjunction with other effective and safe methods, to effectively enhance IAQ.

3.10.2 Airflow and Ventilation Management Technologies

Numerous countries and cities have recommended enhanced ventilation as an effective strategy for lowering indoor temperatures. The U.S. Environmental Protection Agency (EPA, 2025) notes that proper ventilation plays a crucial role in removing and diluting airborne pollutants, thereby reducing contaminants and enhancing indoor air quality (IAQ). Among the various approaches, natural ventilation, facilitated by airflow through windows and doors, mechanical ventilation systems, such as HVAC units, and the infiltration of outdoor air through openings in the structure, including ceilings and floors, are noteworthy. Many residential apartments primarily rely on mechanical ventilation, underscoring the importance of effective air circulation within indoor

environments. Therefore, a hybrid ventilation approach that combines both natural and mechanical systems is recommended to enhance comfort and improve IAQ.

Additionally, Halverson (2025) points to solutions that involve managing indoor air circulation and maintaining balanced humidity levels. Exposure to excessively dry air can lead to health issues such as nasal congestion and sore throats, as well as damage to wooden furnishings. Ideally, indoor humidity should be maintained between 30% and 50%. Employing a whole-house humidifier can effectively regulate humidity levels, while whole-house dehumidification systems can help control excess moisture. Furthermore, Energy Recovery Ventilation (ERV) and Heat Recovery Ventilation (HRV) systems are particularly effective for enhancing IAQ by mitigating stale air when integrated with HVAC systems.

3.10.3 IAQ Monitoring and Optimization Technologies

Indoor air quality (IAQ) monitoring and optimization technologies, particularly through the use of IAQ sensors, are crucial for detecting a range of pollutants, including VOCs, carbon CO₂, PM (PM_{2.5}/PM₁₀), humidity, and temperature variations. Many of these wireless sensors are equipped with encryption, allowing them to securely transmit data to a cloud-based platform in real-time. This capability supports prompt action and decision-making. Similar to other IAQ monitoring devices, these sensors can issue alerts to enhance ventilation when CO₂ levels increase and can monitor VOC concentrations to identify and address sources of indoor air contaminants, which may include cleaning agents or construction materials that release harmful substances.

3.10.4 Government initiatives and regulations

New York has enacted a series of regulations and standards aimed at enhancing indoor air quality (IAQ) in both residential and commercial properties. The New York Clean Indoor Act, specified in Article 13-E of the Public Health Law (Department of Health, 2024), prohibits smoking and vaping in most indoor workplaces, as well as in public transportation areas, hospitals, and educational institutions. This legislation also extends to restaurants and bars, serving the critical purpose of shielding the public from the dangers posed by second-hand smoke and vapor. To enforce this law, no-smoking signs are prominently displayed in areas accessible to both employees and the public, demarcating spaces where smoking is permitted. Compliance with this IAQ regulation is mandatory for all business and facility managers, with violations incurring fines of up to US\$2,000.

Additionally, New York City has passed the Asthma Free Housing Act (2018/055) (Environmental Law Institute, 2025), which requires private landlords to eliminate and control indoor allergen hazards, such as Mold and pest infestations, in accordance with the city's housing maintenance code. This legislation incorporates Integrated Pest

Management (IPM) practices, establishes specific mold remediation protocols, and outlines inspection procedures for enforcing these guidelines.

In response to the severe smoke from Canadian wildfires that impacted air quality along the East Coast, New York City is poised to introduce new IAQ regulations. These regulations will mandate the creation of standards to measure, monitor, report, and enforce air quality within schools as well as residential, commercial, and municipal buildings (Ailworth, 2023). The proposed bill will initiate a five-year pilot program to assess IAQ in these settings, starting as a voluntary initiative but becoming compulsory for property owners who receive financial assistance after the legislation is enacted.

To support these initiatives, research grants such as the School Environmental Health Program (New York State Department of Health, 2024) represent a concerted effort by the U.S. EPA to improve IAQ and reduce greenhouse gas emissions in educational institutions. Recently, the New York State Department of Health and Health Research secured US\$5 million in funding from the U.S. EPA, aimed at raising awareness in schools about IAQ and greenhouse gas reduction strategies. This awareness initiative encompasses training sessions where school administrators and personnel receive guidance on IAQ management and technical support tailored to address local needs. Furthermore, the proposed IAQ Fund aims to provide financial backing for school programs and technical assistance to educational districts, with plans to establish certification centers focused on photo-catalytic air scavenging technology, as well as training programs dedicated to weatherization, energy efficiency, and IAQ management (NYSenate.gov, 2025).

Lastly, government regulations also include various Green Building Certifications, such as LEED and WELL, alongside private accredited IAQ consultation services available to enhance compliance and improve indoor air quality.

3.11 Case Study: IAQ Management of New York Schools

Educational institutions in New York have actively sought to enhance indoor air quality (IAQ) through the implementation of various technologies and solutions aimed at fostering healthier learning environments. Their efforts focus on key areas such as filtration, ventilation, and source control, intending to alleviate respiratory issues, boost concentration, and promote the overall well-being of both students and staff. To support these initiatives, the U.S. Environmental Protection Agency (EPA) has outlined a framework for effective IAQ management in schools, highlighting six essential drivers for ongoing assessment, planning, action, and evaluation. The EPA has also recommended technological interventions, including high-quality HVAC systems, moisture and Mold control, robust Integrated Pest Management (IPM) practices, thorough cleaning and maintenance procedures, careful selection of smart materials, and Integrated Energy Management Solutions (U.S. EPA, 2025).

A case study of Parkway School District, as documented by Maley (2024), illustrates the application of these strategies within a public school system in New York that serves over 16,000 students across 33 buildings, all of which are managed through a Building Automation System (BAS). In response to concerns about indoor comfort and excessive energy consumption, the district has sought to improve IAQ by engaging external experts for retro-commissioning, which involved the assessment and optimization of existing HVAC systems. This retro-commissioning process, centered on cost-effective operational solutions, aimed to reduce energy usage while enhancing indoor air quality and occupant comfort. Following this review, actions were taken to deactivate exhaust fans not connected to the BAS, adjust equipment scheduling, and initiate ongoing enhancements to the BAS. Additionally, the district has adopted Monitoring-Based Commissioning (MBCx) as a strategy for IAQ management, which involves real-time monitoring and analysis of data from the automation system. MBCx facilitates the storage of large datasets and employs fault detection tools that alert building operators to potential risks, allowing for timely intervention. As a result of these efforts, stakeholders have reported improvements in both IAQ and energy efficiency, and usage reports have been generated to further refine occupant air quality.

Another pertinent case involves Avenues NYC, as detailed in a peer-reviewed article by Iyengar et al. (2024). This educational institution prioritized IAQ enhancement, particularly during the COVID-19 pandemic, by continuously updating its air quality improvement measures throughout the year to mitigate the risk of airborne transmission. Before reopening in 2020, Avenues NYC made significant upgrades to its ventilation systems, adjusting air changes per hour (ACH) to meet the standards set forth by Harvard's Healthy Buildings initiative. The school installed 100 ViewPlus sensors across various locations to monitor air quality. Furthermore, they piloted nasal misters by Sensory Cloud, which were subsequently adopted in upper

age divisions as an additional protective measure. In 2020, Avenues NYC enlisted Underwriter Laboratories to perform an indoor environmental quality assessment, evaluating air, water, and surface quality. The school has consistently adapted its IAQ strategies based on these assessments and has achieved certifications confirming compliance with necessary safety standards. Their approach included employing dual-level filtration systems with MERV 7 or higher air filters, in addition to installing bipolar ionization systems. Avenues NYC has also tried various quality sensors to continually enhance its indoor air quality.

3.12 Overview of Indoor Air Quality (IAQ) (Dubai, UAE)

Dubai boasts a contemporary skyline characterized by high-rise structures and opulent developments. To ensure a healthy indoor environment, the city has adopted advanced air filtration and climate control technologies. The rapid urbanization and economic expansion experienced in the early 2000s, fueled by a real estate boom and an influx of expatriates, made IAQ a critical focus. Initially, Dubai's IAQ measures were somewhat rudimentary; however, the challenges posed by inadequate indoor air conditioning spurred more comprehensive IAQ initiatives.

The heavy reliance on air conditioning systems, necessary for coping with extreme heat, has inevitably introduced problems such as indoor pollutants, including mold and volatile organic compounds (VOCs). In response, the city has developed a robust regulatory framework aimed at enhancing ventilation and air filtration standards. Key regulatory bodies, such as the Dubai Electricity and Water Authority and the Municipality, have established guidelines that align with the Green Building regulations, the Dubai Carbon Abatement Strategy, and LEED certification standards.

Moreover, the implementation of IAQ technologies has progressed significantly. These include the use of predictive analytics that leverage artificial intelligence and machine learning, HVAC optimization adhering to ASHRAE standards, comprehensive IAQ assessments, integration with building management systems, advanced filtration systems featuring HEPA filters, and the deployment of smart sensors for monitoring indoor air quality. Table 3.10 summarizes the IAQ technologies and solutions used in Dubai.

Table 3. 10 IAQ Technologies and Solutions Used in Dubai

Major-Technologies	Sub-Categories
HVAC optimization	Adhering to ASHRAE standards, ERVs, DCVs,
IAQ testing and assessments	Adhering to ASHRAE standards
Integration with building management systems	
Advanced filtration systems	featuring HEPA filters, MERV filters, Electrostatic cleaners, carbon filters
Smart sensors and monitoring	Predictive analytics using AI and machine learning algorithms
Government initiatives and regulations	Green Building Certifications such as LEED
	IAQ regulations by the Dubai Municipality
	Air Quality Strategy 2030
	ASHRAE standards 241 and 62.1-2022

3.12.1 HVAC Optimization

Dubai's climate necessitates extensive use of air conditioning systems, making HVAC optimization both essential and widely implemented. Given the significant reliance on HVAC in many regions, Dubai stands out with its proactive approach toward sustainability in recent years. This commitment, as suggested by Airbox (2025), has driven the search for sustainable solutions, including decarbonization and improving indoor air quality (IAQ), while aligning with global building standards such as ASHRAE Standard 62.1-2022 and 241-2023.

As these standards have become integral to sustainable development, Dubai has effectively incorporated them into both the retrofitting of existing structures and the design of new ones. This integration provides critical guidelines for enhancing IAQ in commercial buildings. In 2024, the Ministry of Energy and Infrastructure (MoEI) introduced the adoption of the latest ASHRAE technical specifications, which encompass both the ASHRAE standards and the Indoor Air Quality Procedure (IAQP).

These specifications outline strategies for both the design and operation of HVAC systems, offering recommendations for employing high-efficiency filters, optimizing air distribution methods, and integrating air-cleaning technologies. The IAQP, a performance-based ventilation design included within ASHRAE Standard 62.1-2022, emphasizes decarbonization and energy efficiency by utilizing recirculated, purified indoor air. High humidity levels can lead to the growth of Mold and dust mites. To mitigate this risk, it is recommended to use HVAC systems to maintain relative humidity within the optimal range of 40-60%. Incorporating dehumidifiers, Energy Recovery Ventilators (ERVs), Demand-Controlled Ventilation (DCV), and advanced filtration systems can also be beneficial in effectively managing IAQ. Dubai's adoption of these practices aims to enhance public health by reducing respiratory problems and allergies, fostering sustainability, and ensuring operational resilience in its buildings.

3.12.2 IAQ Testing and Assessment

In contrast to numerous countries and cities, Dubai mandates air quality testing for all buildings prior to occupancy and use. The Dubai UAE, in alignment with international standards such as those established by ASHRAE, has focused on ensuring that ventilation systems are both energy-efficient and protective of end-users. To aid building managers and owners in both immediate testing and future compliance, advanced air quality technologies, including sensors like the Ista AMET, are utilized. These assessments examine various factors: biological contaminants (such as fungi, Molds, and bacteria), chemical pollutants (including cleaners, solvents, and fuels), and particulate matter and aerosols (like dust, smoke, and combustion byproducts), which may result from human activities, HVAC systems, and building materials, among other sources (Dubai Municipality, 2024). The implementation of these systems is designed to foster healthier and more comfortable environments for occupants. Furthermore, they

aim to provide guidance on maintaining optimal IAQ and enhancing the performance of buildings and their surrounding environments.

3.12.3 Integration with Building Management Systems (BMS)

As previously mentioned, Indoor Air Quality (IAQ) technologies, including HVAC systems and IoT devices, are typically incorporated into Building Management Systems (BMS). These integrations play a crucial role in automating environmental adjustments by leveraging real-time data, ultimately ensuring optimal air quality and efficient energy consumption.

The functionality of BMS extends to optimizing ventilation, regulating humidity levels, and minimizing the presence of harmful pollutants, including CO₂ and VOCs. With centralized control and cloud-based integration, BMS provide building managers with the capability to monitor and make adjustments remotely. This real-time access to data enables quick reactions to changing conditions, thereby enhancing both operational efficiency and occupant comfort.

By utilizing sophisticated analytics within these systems, building managers can gain a deeper understanding of patterns in air quality and energy usage, leading to more informed decision-making. This proactive approach not only supports regulatory compliance but also contributes to a healthier indoor environment, emphasizing the importance of integrating advanced technologies in modern building management practices (Yeşilata, 2025).

3.12.4 Advanced Filtration Systems

Similar to many other nations, Dubai employs sophisticated filtration systems, including HEPA filters, MERV filters, electrostatic cleaners, and carbon filters. Airody Trading, a prominent company in the UAE, specializes in HEPA and carbon filters that effectively eliminate allergens, dust, and various pollutants. Given that Dubai is situated in a desert climate, the prevalence of dust poses a significant challenge to indoor air quality (IAQ), which is why electrostatic cleaners and activated carbon filters are commonly used. These systems are particularly efficient, capable of removing particles as small as 0.01 microns. Electrostatic precipitators, for instance, utilize an electrical field to charge airborne particles, which then adhere to collection plates, effectively extracting them from the airstream (Foster, 2025; Qey Technical, 2020). In comparison to countries like Singapore, Dubai has also established a reputation for its use of Daikin technologies, known for their filtration and air purification solutions (Daikin, 2025).

3.12.5 Smart Sensors and Monitoring

Recent advancements in IoT, particularly through the use of smart sensors, have significantly improved the efficiency of HVAC systems, thereby enhancing IAQ. In Dubai, these sensors have proven effective in residential settings, such as villas. A notable example involves the installation of approximately 50 Milesight sensors at a luxurious

residence in Palm Jumeirah by Sensgreen and Milesight. These sensors were tasked with monitoring and collecting data related to indoor environmental conditions and HVAC performance, focusing on key parameters like humidity, carbon dioxide levels, particulate matter, occupancy, and temperature (Sensgreen, 2025).

According to Sensgreen (2025), integrating these smart sensors resulted in substantial improvements in both energy efficiency and IAQ. Specifically, the use of Milesight sensors led to a 12% reduction in air handling unit (AHU) expenses, while maintaining optimal humidity levels. This integration not only enhanced occupant comfort and overall quality of life but also contributed to extending the lifespan of the HVAC systems and reducing maintenance needs.

3.12.6 Government Initiatives and Regulations

Dubai, like many other major cities, has implemented extensive government initiatives and regulations aimed at improving IAQ. These measures encompass standards, public health programs, and strategies designed to enhance IAQ, promoting the well-being and comfort of its residents. The Dubai Municipality has established IAQ regulations that affect commercial buildings, hospitals, and educational institutions, setting specific thresholds for pollutants such as CO₂, PM_{2.5}, and humidity (Dubai Municipality, 2024).

In addition, the Public Health and Safety Regulations issued by the Dubai Municipality outline standards for IAQ monitoring and adherence to defined limits for various pollutants, including VOCs, TVOCs, suspended particulates, and formaldehyde. One of the significant long-term initiatives is the Air Quality Strategy 2030, which aims to maintain clean air standards on 90% of days by the year 2030, placing considerable emphasis on IAQ. Complementing this, the UAE National Air Quality Strategy, led by the Ministry of Climate Change and Environment (MOCCAEE), focuses on enhancing indoor air quality through monitoring, mitigation, and management efforts (UAE, 2025).

Moreover, the Ministry of Energy and Infrastructure has adopted the ASHRAE standards 241 and 62.1-2022, which seek to minimize the transmission of infectious aerosols and improve overall IAQ. Additionally, green building certifications, such as LEED and the Pearl Rating System (Foster, 2025), incorporate specific IAQ requirements that must be met for certification, thereby reinforcing the regulations and standards related to IAQ in Dubai.

3.12 Case Study: IAQ Management of Nurseries in Dubai

The importance of indoor air quality for children cannot be overstated, as their developing immune systems render them more vulnerable to allergies, infections, asthma, and other atopic conditions. Departing from the traditional focus on adults and office environments, a study conducted by Arar & Jung (2021) in the UAE turned its attention to nurseries, aiming to uncover the primary contributors to poor IAQ and identify strategies for enhancement.

This comprehensive research involved 16 nursery facilities, encompassing a total of 36 classrooms, with a significant number of these located in Dubai. The classrooms accommodated between 28 and 104 children, with staff numbers varying from 4 to 22. The initial IAQ management strategies employed included natural ventilation, routine cleaning, and annual sanitization efforts. To gauge the effectiveness of these measures, IAQ assessments were conducted during two distinct periods: the initial measurements took place from February to March, while follow-up assessments occurred in October and November, specifically from 8:00 AM to 12:00 PM.

The evaluation focused on key indoor pollutants, including carbon dioxide (CO₂), total volatile organic compounds (TVOC), formaldehyde (CH₂O), total suspended particles (TSP), along with humidity and temperature levels. A range of advanced IAQ monitoring technologies was utilized, including electronic data loggers and specialized meters for formaldehyde and overall air quality. Alarming, the findings indicated that the average concentrations of CO₂, TVOC, CH₂O, TSP, humidity, and temperature did not align with WHO IAQ standards, suggesting that the conditions were detrimental to children's health.

Following the initial assessment, various IAQ-enhancing technologies and solutions were deployed across all 16 facilities. Among these were air purifiers, deodorizing and HEPA filters, and low-emission building materials. The impact of these interventions was significant; TVOC concentrations saw a reduction of 46.4%, while TSP levels decreased by 21.7%. Interestingly, the concentrations of CH₂O and TVOC recorded an increase of 178.6% and 38.7%, respectively, compared to the pre-intervention testing.

The study concluded with several recommendations for improving indoor environments in nurseries. It emphasized the necessity of installing effective ventilation systems to minimize indoor pollutants, followed by the integration of air purifiers equipped with high-efficiency filters, such as HEPA and deodorization filters. Additionally, the transition to low-emission finishing materials was advised, highlighting a possible correlation between healthier building materials and improved IAQ for children. Although the link was not directly established, the study demonstrated how modifications to nursery environments can significantly improve air quality, thereby fostering a healthier atmosphere for young learners.

4 Methodology

4.1 Data Collection and Analysis Methods

In light of the public health issues associated with inadequate indoor air quality (IAQ) and its growing relevance in protecting public health, numerous countries and cities have implemented various IAQ technologies and solutions, as previously detailed. This chapter explores the diverse methods for data collection and analysis employed by nations and cities such as Singapore, Tokyo, Seoul, New York, Dubai, and Shanghai, which share similar characteristics with Hong Kong. Despite the variations among these regions, they commonly utilize two main types of data collection. The first involves objective data collection, which encompasses physical parameters (such as temperature, humidity, and ventilation rates), chemical parameters (including particulate matter, carbon dioxide, volatile organic compounds, and radon), and biological parameters (such as airborne bacteria and fungi). This also includes the measurement and monitoring of IAQ in various facilities. The second type focuses on subjective assessments, aiming to gather occupants' feedback regarding their comfort levels and perceptions of air quality.

When it comes to IAQ analysis, these countries predominantly rely on established standards and guidelines to interpret the data, particularly since each has its own certification or regulatory framework. Some also apply statistical analyses to detect trends, correlations, and significant variations in the IAQ parameters. Additionally, several jurisdictions and organizations have created IAQ indices that encompass multiple parameters into a single score, providing an overall assessment of air quality. For longer-term evaluations, techniques such as spatiotemporal analysis are employed to track changes in IAQ over time and across different areas within a facility. Conducting walkthrough inspections and assessments is a crucial component of IAQ analysis.

4.1.1 Objective Data Collection

Many regions and urban areas utilize indoor air quality (IAQ) technologies, including sensors, mobile and remote platforms, and building management systems (BMS), to effectively gather and store data. These sensor technologies consist of both fixed and portable devices that consistently monitor essential IAQ parameters, encompassing physical, chemical, and biological factors such as temperature, particulate matter (PM), and airborne bacteria. For instance, the AIRSIDE commercial building in Hong Kong employs advanced IAQ sensors to track various metrics, including PM, CO₂, total volatile organic compounds (TVOCs), airborne bacteria, humidity, and temperature. The data collected from these sensors is accessible via the building's website and mobile application. Similar initiatives are observed in cities like Singapore, Dubai, New York, and Shanghai. Furthermore, objective methods for collecting IAQ data

serve valuable research purposes. For example, Arar & Jung (2021) conducted a study in the UAE, utilizing sensors such as the IAQ meter TS 7545 IAQ-CALC and the electronic data logger SATO SK-L200TH II to monitor temperature, humidity, and CO₂ levels across various nurseries throughout the UAE during the initial stages of their research.

4.1.2 Subjective Data Collection

While gathering objective data is crucial for assessing indoor air quality (IAQ), it often neglects to consider how individuals perceive their surroundings. Techniques such as air sampling and sensor measurements yield valuable quantitative data regarding air pollutants, temperature, and humidity. Nevertheless, they may fail to reflect occupants' comfort and satisfaction, which are shaped by personal experiences (Frontczak & Wargocki, 2011).

Research shows that people's perceptions of comfort and health are significantly impacted by both their physical environment and psychological factors (Mansor et al., 2025). For instance, a location may exhibit good air quality yet still feel uncomfortable due to issues related to noise, lighting, or aesthetics. This indicates that a sole reliance on objective data can overlook essential factors that affect how individuals assess a space.

In light of this, while it is essential to collect subjective data, most regulatory bodies tend to prioritize objective IAQ evaluations. This trend is largely due to the lack of evidence suggesting that facilities regularly conduct surveys or interviews to gather feedback from occupants. The available data for research or practical purposes primarily circumstantiate occupant experiences. Since many studies employ cross-sectional data collection that focuses on a single time point rather than an ongoing process, this raises critical concerns about documentation and the subjective experiences of occupants.

Among the various methods of subjective data collection, questionnaires are a common tool utilized by governmental and private agencies to obtain feedback on occupant experiences regarding IAQ. For example, the Environmental Protection Department in Hong Kong conducted a questionnaire survey involving both a telephone survey with 2,000 respondents and an in-person survey of 1,183 occupants across 40 selected office premises and public spaces, including restaurants, shopping malls, cinemas, wet markets, and subway stations. The survey addressed satisfaction levels and health symptoms experienced after leaving those environments, often referred to as sick building syndrome. Although the study dates back to the late 1990s, it revealed that around 32% of respondents expressed dissatisfaction with the air quality in their workplaces. Despite this finding, there is a lack of recent surveys by the EPD concerning occupant experiences with IAQ.

Nonetheless, research has delved into occupants' perceptions of IAQ. For instance, a study by Cheung et al. (2021) conducted in Singapore assessed the satisfaction of 666 occupants in commercial buildings certified by Green Mark, focusing on various environmental parameters. This study found that major contributors to thermal dissatisfaction included inadequate air movement and ventilation, indicating that feedback from occupants can significantly enhance IAQ in various settings.

Similar trends can be observed in other countries, where there tends to be a stronger emphasis on objective data collection over subjective assessments. However, much of the subjective data gathered about occupant experiences is derived from research studies or is integrated into government-targeted intervention programs. Therefore, it is crucial to prioritize the experiences of occupants when evaluating indoor air quality.

4.2 Data Analysis Techniques

In various major cities around the world, including Hong Kong, Singapore, Seoul, Tokyo, Shanghai, New York, and Dubai, the methodologies employed for collecting and analyzing indoor air quality (IAQ) data exhibit notable similarities. These jurisdictions often adhere to established standards and guidelines when conducting IAQ assessments across a range of facilities, which are crucial for issuing certifications and evaluating compliance. In addition to quantitative measurements, qualitative evaluations, such as walkthrough inspections and subjective assessments of the indoor environment, play a significant role in this process. These evaluations focus on aspects such as occupant comfort and overall environmental quality, all of which are typically integrated into national IAQ guidelines that may be either voluntary or mandatory.

Take Hong Kong, for example, where an IAQ certification system categorizes air quality into ratings such as excellent, very good, and good. International standards guide this self-regulatory model, incorporating walkthrough inspections that evaluate key components, including ventilation, filtration, and communication strategies. Similar frameworks are observed in cities like Singapore, Dubai, New York, and Shanghai, highlighting a global trend in IAQ management.

The calculation of Indoor Air Quality (IAQ) indices is a method of evaluating air quality, where various organizations, both private and public, create their indices or utilize international standards to effectively assess and combine measurements of key factors, such as temperature, humidity, VOCs, and CO₂ levels, into a comprehensive score. For instance, Cisco Meraki (2025) employs a five-tier qualitative rating system that categorizes IAQ into excellent, good, fair, poor, and inadequate, reflecting similar rating systems used by numerous countries and cities. Each parameter within this system is weighted according to its corresponding reading, resulting in an overall score.

Specifically, a score ranging from 93 to 100 is classified as excellent (indicated by a green color), 80 to 92 as good, 60 to 79 as fair, 40 to 59 as poor, and 20 to 39 as inadequate. According to recommendations from the Occupational Safety and Health Administration (OSHA) and the CDC, acceptable standards for certain parameters include a temperature range of 20-24.4°C for excellent quality, with humidity ideally maintained between 40-60% and CO₂ levels kept below 800 ppm to ensure optimal air quality.

When it comes to statistical analysis in the realm of IAQ, a systematic approach is essential for exploring the complexities of air quality data. This process involves identifying correlations, analyzing temporal trends, and uncovering potential sources of IAQ issues. Facilities equipped with Internet of Things (IoT) sensors and Building Management Systems (BMS) increasingly rely on these analytical methods to effectively visualize and interpret IAQ trends.

By employing advanced statistical techniques, facility managers can identify patterns in air quality measurements, such as variations in pollutant levels, and correlate these with factors like occupancy, weather changes, or specific building activities. This data-driven methodology enables managers to proactively address air quality concerns, ultimately promoting healthier environments for all occupants. As highlighted in Chapter 3, the adoption of statistical analysis within these facilities is a prevailing trend, underscoring the critical importance of informed decision-making in the pursuit of optimal indoor air quality.

5 Discussion

This report embarks on an important journey to evaluate the current landscape of IAQ technologies and solutions in major global cities, with a particular focus on Hong Kong. While Hong Kong has made commendable strides in monitoring and managing IAQ, it still faces challenges that present growth opportunities, such as enhancing outdoor IAQ monitoring and reporting, expanding focus on residential IAQ management, and fostering stronger policies and collaborations. In contrast, leading cities such as Tokyo, Seoul, Shanghai, Dubai, New York, and Singapore have adopted innovative approaches and advanced technologies that enhance their IAQ management systems, offering valuable lessons for Hong Kong to tackle its challenges more effectively. Figure 5.1 highlights the key areas for discussion regarding the IAQ technologies and solutions used across different landscapes similar to Hong Kong.

By examining the strengths and weaknesses of existing solutions in these urban environments, this research aims to identify best practices and innovative strategies that can be tailored to the local context. Ultimately, the goal is to provide actionable insights that will enhance Hong Kong's IAQ monitoring, reporting, and improvement efforts, ultimately leading to healthier indoor environments for its residents.

Figure 5. 1 Key Areas for Discussion



5.1 IAQ Technologies and Solutions

The evolution of sensor technologies for IAQ monitoring has emerged as a vital aspect of global urban health initiatives. In the context of Hong Kong, marked by its densely populated areas and significant pollution challenges, various sensor systems have been strategically incorporated to enhance IAQ management. A comparative analysis of global practices reveals valuable insights; for instance, Singapore's advanced BMS, Seoul's comprehensive certification programs, Shanghai's specific IAQ control measures, New York's real-time monitoring capabilities, and Dubai's IoT-enabled smart sensors each offer distinct lessons for improvement.

Hong Kong's utilization of a range of sensor technologies, including electrochemical sensors, PM sensors, infrared sensors, and IoT integrations, reflects a commendable effort to improve real-time IAQ assessment (Wei et al., 2018; Zheng et al., 2022). These technologies are cost-effective, portable, and adaptable for residential and small commercial environments, making them particularly advantageous for Hong Kong's high-density setting. However, caution is warranted regarding the accuracy and standardization of low-cost sensors, which are susceptible to environmental interference and lack rigorous certification, as highlighted by Rodenas Garcia et al. (2022). This emphasizes the necessity for the establishment of standardized calibration and certification protocols to ensure data reliability, a practice that is already more developed in cities such as Seoul and Singapore.

Moreover, important lessons can be drawn from other global cities. For example, Singapore's BMS showcases how sensors can be effectively leveraged for proactive IAQ management. The integration of cloud-based platforms, IoT connectivity, and automated ventilation systems demonstrates a high level of technological sophistication that Hong Kong could aspire to achieve by investing in centralized BMS. Such systems could monitor IAQ while enabling automatic adjustments, thereby lessening dependence on manual intervention and reducing the potential for human error. Singapore's method of monitoring CO₂ levels in meeting rooms, with automatic adjustments to airflow, enhances both occupant comfort and health (Daikin Airconditioning, 2022).

Seoul's certification programs underscore the significance of policy frameworks and community involvement, while Shanghai's tailored approach to sensor application based on specific space types highlights the necessity for contextual assessment before implementing sensors, a strategy particularly relevant in urban environments like Hong Kong. Additionally, the experiences of New York and Dubai illustrate the advantages of interconnected sensors, IoT integration, and automation, which not only address IAQ challenges but also contribute to energy savings. Ultimately, the adoption of centralized systems combined with IoT for predictive maintenance could significantly enhance IAQ in Hong Kong.

Hong Kong primarily relies on filter-based air purifiers, which include portable units featuring replaceable filters and HEPA filtration systems. A notable example of community-driven initiatives is Lingnan University's distribution of over 800 PureAura mini air purifiers to residents of subdivided flats. HEPA filters are not only prevalent in homes but are also widely adopted in hospitals and laboratories across various cities, however, the US NIEHS recommended that advanced filtration systems such as MERV 13 or higher are more recommended, for their efficiency in removing 99.97% of particles as small as 0.3 microns (New York State Education Department, 2021; Qlestouw, 2023).

In commercial settings, centralized HVAC systems with filtration are increasingly popular; however, their high initial costs and energy demands present sustainability challenges. The limitations of ionization devices and filters exemplify concerns surrounding air filtration and ventilation systems, which are particularly relevant in Hong Kong, where many occupants rely heavily on air conditioning systems, necessitating an in-depth evaluation of the types of filtration devices suitable for the urban environment.

For instance, Singapore showcases cost-effective and efficient filtration solutions through antimicrobial coatings, streamer technologies, and rigorous standards like the BCA Green Mark and SS 554. These practices exemplify a sustainable approach that combines natural airflow with mechanical filtration and heat recovery, which could be replicated within Hong Kong's climate (Chau, 2025).

Similarly, Tokyo utilizes IoT-enabled air quality monitoring and UVGI systems in HVAC filtration, emphasizing real-time data-driven management to optimize IAQ (Panasonic Corporation, 2025), thereby enhancing transparency. Additionally, South Korea's adoption of big data demonstrates the potential for personalized and proactive IAQ strategies, particularly in response to increased health awareness following the pandemic.

Emerging jurisdictions, such as Dubai, are adopting a comprehensive approach to occupancy safety and energy efficiency by implementing mandatory testing, integrating BMS, and leveraging high-efficiency filtration methods, including electrostatic precipitators that are used to eliminate dust and allergens prevalent in a desert climate.

5.2 IAQ Government Regulations and Standards

Indoor air quality technologies play a vital role in enhancing air quality within buildings and ensuring adequate ventilation, thereby protecting public health by removing harmful pollutants. However, government policies and regulations are equally important as they set crucial standards for air quality and enforce compliance to safeguard occupants against the detrimental effects of poor indoor air.

Analyzing the IAQ landscape in cities such as Seoul, Singapore, Tokyo, Dubai, New York, and Shanghai reveals key opportunities for Hong Kong to strengthen its IAQ regulations. While the HK EPD is promoting IAQ through voluntary certification initiatives,

this approach tends to limit widespread adoption, especially in smaller residential buildings. Although private organizations like Airside are pursuing more proactive IAQ measures, Hong Kong's government initiatives largely remain voluntary and primarily focus on outdoor air quality, which diminishes their effectiveness and limits their integration into a cohesive policy framework. This voluntary approach does not compel residential buildings to participate actively, ultimately hindering a comprehensive assessment of IAQ across various building types and delaying the identification of high-risk environments.

To address these challenges, creating a public IAQ portal similar to outdoor air quality websites is recommended. Such a platform would enable building managers to make informed decisions using real-time data, allowing for timely alerts in spaces like schools and hospitals and prompting necessary actions such as improving ventilation or reducing pollutant sources. Hong Kong should shift from relying on voluntary reports and certifications to enforcing mandatory testing, assessments, certifications, and monitoring, especially in critical settings like schools and healthcare facilities, as seen in cities like Dubai, Seoul, and New York.

Continuous real-time monitoring and reporting should align with international standards, such as those established by ASHRAE, already adopted by Dubai and China, to emphasize ongoing oversight. Enhancing IAQ certification in Hong Kong could involve incorporating real-time IAQ performance metrics into certification criteria, similar to the LEED and WELL standards, which are based on continuous data rather than one-time assessments.

Regulatory frameworks and guidelines can be fortified by adopting models similar to Seoul's IAQ management system or Singapore's SS 554:2016, which mandates routine IAQ testing, certification, and public disclosure. Implementing penalties for non-compliance or providing incentives for proactive IAQ management could further improve adherence. Integrating IAQ performance metrics into building permits or lease agreements, similar to Dubai's and Singapore's compulsory IAQ assessments prior to occupancy, could ensure ongoing compliance. Public health awareness campaigns, like those in Dubai and New York, are also vital for educating the community about health risks.

Collaborations with other governmental agencies, such as health departments and hospitals, as well as partnerships with universities, tech companies, and international standards organizations, are essential. These approaches mirror those taken by cities like Dubai, New York, Seoul, Tokyo, and Shanghai. This collaborative effort is necessary, as no single entity can independently drive improvements in IAQ. Expanding policy frameworks to encompass relevant institutions is critical in fostering a healthy indoor environment.

Research and innovation in IAQ are pivotal for protecting occupant health. Much like the proactive measures observed in other cities, targeted interventions in vulnerable settings, such as schools and healthcare facilities that house at-risk populations, should receive particular emphasis. Implementing real-time monitoring and community-based programs can help identify critical hotspots, prioritize remediation efforts, and encourage active participation from occupants.

Ultimately, a combination of innovative technologies and robust regulatory frameworks is essential to cultivate healthier environments for all.

5.3 Stakeholders and Facilities

Stakeholders and facilities, including residential buildings, commercial properties, and hospitals, play a crucial role in managing IAQ. The effectiveness of this management relies on advanced sensor technologies, air purification systems, ventilation methods, and regulatory frameworks. For example, Hong Kong's implementation of low-cost electrochemical sensors in various environments provides significant opportunities for comprehensive IAQ evaluations. However, challenges related to accuracy, standardization, and calibration can diminish the reliability of these sensors. In contrast, more advanced and reliable sensor technologies, such as IRE and MER-V rated filters, are utilized in cities like New York, Dubai, Singapore, and Japan.

Moreover, critical facilities, including hospitals and high-rise commercial buildings, are increasingly adopting air purification technologies, such as HEPA filters, UV systems, and photocatalytic oxidation, to address biological and chemical contaminants. While these advanced solutions are effective, they can be prohibitively expensive, often restricting their application to high-risk buildings and larger facilities, leaving smaller residential structures unable to implement them. Various ventilation strategies, including demand-controlled ventilation (DCV), natural ventilation, and hybrid systems, are essential in optimizing IAQ while managing energy consumption. Sustainability remains a key trend in environmental conservation. Cities like Dubai and Seoul are making strides in this area by integrating smart building management systems (BMS) that automate IAQ regulation based on real-time sensor data. This movement presents an opportunity for Hong Kong to enhance its existing infrastructure and significantly improve IAQ management.

5.4 Case Studies

Case studies from urban environments, such as Dubai, New York, Shanghai, Seoul, Tokyo, Singapore, and Hong Kong, present a range of strategies for managing indoor air quality (IAQ) in densely populated areas. In Dubai, research by Arar & Jung (2021) highlights the need for stringent IAQ standards in facilities that cater to vulnerable populations, such as nurseries. Their findings indicate that relying solely on natural ventilation and routine cleaning is inadequate for improving IAQ and addressing

pollutants like CO₂, total volatile organic compounds (TVOCs), and formaldehyde that exceed World Health Organization (WHO) guidelines. Implementing air purifiers and utilizing low-emission materials significantly enhanced IAQ, underscoring the necessity of a multifaceted approach that extends beyond mere technological enhancements to encompass stringent material regulations.

In New York, the Parkway School District's experience with retro-commissioning and Monitoring-Based Commissioning (MBCX) (Maley, 2024) illustrates the importance of ongoing systems optimization. Continuous monitoring has revealed the limitations of traditional fault detection methods and highlighted the importance of real-time data. Avenues NYC's investment in ventilation upgrades and sensor technologies emphasizes the value of adaptive measures, particularly highlighted during health crises such as the COVID-19 pandemic. Nonetheless, the absence of stakeholder feedback emerged as a barrier to comprehensive IAQ management not only in New York but across all case studies.

Shanghai's Cordis hotel and Airside commercial facility in Hong Kong exemplify the integration of advanced filtration systems with transparent IAQ monitoring (RESET, 2018; One Planet, 2019; Airside, 2025) to enhance the health and well-being of guests and visitors. However, the high costs and complexity of maintenance pose significant challenges for widespread replication. Similarly, Seoul has established a robust regulatory framework that enforces standards and promotes transparency through public disclosure. Yet, the focus remains predominantly on CO₂, while attention to microbial contaminants and emerging pollutants such as nanomaterials is limited, revealing a critical gap in addressing the broader spectrum of IAQ issues. In contrast, China consistently updates its IAQ guidelines to encompass emerging pollutants, thereby enhancing its IAQ management strategies.

A study of Tokyo's Shibuya Station (Agarwal et al., 2025) suggests that effective ventilation solutions and the use of advanced portable sensors for real-time monitoring could be beneficial for MTR stations in Hong Kong. In Singapore, the Daikin initiative emphasizes the importance of tailored maintenance strategies, such as coil cleaning and mold remediation, to enhance IAQ in residential environments. This highlights the need for Hong Kong's regulatory systems to adopt targeted interventions that prioritize regular, proactive monitoring, ensuring affordability and accessibility across various settings.

5.5 IAQ Data Collection and Analysis Methods

Recognizing the importance of data collection and analysis methods in effective Indoor Air Quality (IAQ) management is crucial for gaining insights specific to Hong Kong. Objective data gathering through sensors, Building Management Systems (BMS), and remote platforms is widely adopted, as demonstrated by initiatives such as Hong Kong's

AIRSIDE building and the Cordis luxury hotel in Shanghai, which track parameters including particulate matter (PM), carbon monoxide (CO), and bacterial levels. However, these approaches often incorporate limited subjective feedback from occupants. Research conducted by Cheung et al. (2021) suggests that this feedback is valuable, as it reveals dissatisfaction that extends beyond physical measurements to encompass perceptions of comfort and IAQ. For Hong Kong to enhance its IAQ management, it is vital to integrate both objective and subjective data collection methods. Additionally, standardized IAQ indices and walkthrough inspections are considered important data collection methods, though they typically do not account for occupant satisfaction levels. Employing statistical analysis techniques, including trend detection and correlation analysis, is essential for identifying IAQ challenges over time, particularly with the integration of Internet of Things (IoT) technologies.

Hong Kong can greatly gain from the diverse data gathered from other jurisdictions like Tokyo, Singapore, Seoul, Shanghai, Dubai, and New York, along with various case studies. The main insights are summarized below.

6. Conclusion

The pressing need for Hong Kong to enhance its indoor air quality (IAQ) has become increasingly apparent. To address this challenge, a multifaceted approach is necessary. By embracing cutting-edge sensor technologies and creating integrated, centralized building management systems, the city can revolutionize its approach to monitoring and managing air quality. There is much to learn from other bustling metropolises, such as Seoul, Singapore, Shanghai, Tokyo, Dubai, and New York, where similar strategies have proven effective. Figure 6.1 presents essential information and recommendations from IAQ technologies and solutions implemented in other regions that can be relevant to Hong Kong.

In this journey towards improved indoor air quality, it is crucial to prioritize standardized calibration and actively seek occupant feedback. Enforcing relevant policies will play a vital role in cultivating healthier indoor environments for everyone. Furthermore, collaboration among government bodies, industry stakeholders, and academic institutions is pivotal for fostering innovation and promoting sustainable practices.

By implementing these comprehensive strategies, Hong Kong can adeptly navigate its unique urban challenges. This proactive approach not only aims to improve public health but also seeks to enhance the overall quality of life for residents, paving the way for a healthier and more vibrant city.

Figure 6.1 Key IAQ Takeaways and Recommendations



6.1 Key Takeaways and Recommendations

1. Hong Kong can enhance its strategies by learning from global best practices implemented in cities like Tokyo, Seoul, Shanghai, Dubai, New York, and Singapore. By adopting sensor technologies and enhancing filtration and ventilation systems, particularly in light of the widespread use of air conditioning, the city can develop a comprehensive IAQ policy framework tailored to its densely populated urban environment.
2. Despite advancements in real-time IAQ monitoring using IoT, electrochemical, PM, and infrared sensors, ensuring the accuracy and standardization of low-cost sensors continues to be a challenge. Drawing insights from Seoul and Singapore's approaches, such as their certification protocols and calibration standards, could enhance data reliability and overall IAQ management.
3. The implementation of centralized and smart BMS that integrates IoT and cloud technologies could allow for proactive monitoring and adjustment of IAQ levels. By utilizing such an advanced IAQ system, Hong Kong has the potential to minimize human error and significantly enhance air quality.
4. Hong Kong relies heavily on portable HEPA filters in both residential and healthcare settings; however, the implementation of advanced filtration systems, such as MERV 13, is strongly advised for enhanced efficiency (New York State Education Department, 2021). Innovations like microbial coatings and heat

recovery systems, as demonstrated in Singapore and Tokyo, could offer sustainable filtration solutions that align with Hong Kong's climatic and energy needs. Moreover, Tokyo's incorporation of UVGI systems within HVAC units has been noted for their capability to optimize real-time IAQ management. Dubai's electrostatic precipitators could help Hong Kong enhance transparency, improve health, and increase comfort in both residential and commercial buildings.

5. To address the sustainability and cost challenges associated with effective IAQ systems, such as centralized HVAC and filtration, it is advisable to draw from Singapore's integrated approach. This includes balancing natural ventilation with mechanical ventilation, as well as the adoption of energy-efficient filtration and antimicrobial treatments.
6. Currently, voluntary standards in Hong Kong are a barrier to widespread IAQ enhancements. By taking lessons from cities like Dubai, Seoul, and New York, the introduction of mandatory testing, certification, and public reporting in building permits could enhance accountability and spur continuous improvement in IAQ.
7. Promoting collaboration among multiple agencies and engaging the community is crucial. Involving government departments (such as the environment and health departments), health authorities, academia, and the private sector through awareness campaigns and feedback mechanisms, similar to initiatives in Dubai and New York, could help identify IAQ challenges and encourage proactive community participation.
8. It is essential to prioritize continuous monitoring and proactive maintenance in settings that are particularly vulnerable and high-risk, such as schools, healthcare facilities, aged care centers, and subdivided flats.
9. Findings indicate that a combination of objective IAQ technologies, such as real-time sensor data, and subjective methods, including occupant surveys and interviews, is critical for effectively identifying issues and implementing proactive interventions.
10. Furthermore, as seen in other regions, ongoing innovation in IAQ and rigorous policy evaluation are vital for achieving effective indoor air quality management. Just like cities such as Dubai, Shanghai, and New York that have adapted their IAQ policies to include international technologies and standards like LEED, ASHRAE, and WELL, it is imperative to commit to regular research, establish robust IAQ regulations, and embrace technological advancements to ensure the maintenance of satisfactory indoor air quality.

7. References

- AAF. (2022, September 5). *Real Time Monitoring* | AAF. Retrieved June 30, 2025, from <https://aafasia.com/real-time-monitoring/#:~:text=In%20addition%20to%20particle%20level,particulate%20levels%20for%20building%20occupants>
- Abelmann, S. (2025, February 19). *German Committee on Indoor Air guide values*. Umweltbundesamt. Retrieved June 16, 2025, from <https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values#german-committee-on-indoor-air-guide-values-air>
- Aeroqual limited. (2024, April 24). *Portable Particulate Sensor | Measure PM2.5 and PM10* | AeroQual. Aeroqual. Retrieved June 17, 2025, from <https://www.aeroqual.com/blog/portable-particulate-sensor>
- Afshari, A., & Seppänen, O. (2021, February). *REHVA Journal Effect of portable air cleaners on indoor air quality: Particle removal from indoor air*. REHVA. Retrieved June 18, 2025, from <https://shorturl.at/oYl0H>
- Agarwal, D., Trinh, X. T., & Takeuchi, W. (2025). Assessing the Air Quality Impact of Train Operation at Tokyo Metro Shibuya Station from Portable Sensor Data. *Remote Sensing*, 17(2), 235.
- Ai, Z. T., & Mak, C. M. (2015). From street canyon microclimate to indoor environmental quality in naturally ventilated urban buildings: Issues and possibilities for improvement. *Building and environment*, 94, 489.
- Ailworth, E. (2023, August 14). *In WSJ: NYC to consider indoor air quality regulations following COVID-19 and summer's smoky haze*. Manhattan Borough President. Retrieved July 14, 2025, from <https://www.manhattanbp.nyc.gov/in-wsj-nyc-to-consider-indoor-air-quality-regulations-following-covid-19-and-summers-smoky-haze/>
- Air Quality News. (2022, February 2). *Feature: A brief history of indoor air quality*. Retrieved June 13, 2025, from <https://airqualitynews.com/indoor/a-brief-history-of-indoor-air-quality/>
- Airbox. (2025, July 8). *A Focus on Dubai's Adoption of ASHRAE Standard 62.1-2022 and 241-2023: The Growing Importance of Decarbonization, Sustainability, and Indoor Air Quality in Global Building Standards*. AIRBOX America. Retrieved July 18, 2025, from <https://airboxamerica.com/articles/the-growing-importance-of-decarbonization-sustainability-and-indoor-air-quality-in-global-building-standards-a-focus-on-dubais-adoption-of-ashrae-standard-62-1-2022-and-241->

2023/#:~:text=Implications%20of%20the%20Adoptions,in%20building%20safet
y%20and%20sustainability.

AirGradient. (2025, January 15). *Update on PMS5003 calibrations*. Retrieved June 17, 2025, from <https://www.airgradient.com/blog/update-on-pms5003-calibration/>

Airody Trading. (2024, October 21). *HEPA Filter in UAE | HEPA Filter Supplier in UAE | Airody Trading*. Retrieved July 20, 2025, from <https://airodytrading.com/hepa-filter/#:~:text=ADVANCED%20TECHNOLOGY:%20Our%20HEPA%20filters%20come%20with,such%20as%20allergens%2C%20contaminants%2C%20and%20other%20particles.>

AIRSIDE. (2025). *AIRSIDE IAQ*. Retrieved June 25, 2025, from <https://iaq.airside.com.hk/>

AOM. (2018, June 19). *Kwong Wai Shiu Hospital selects AOM Air Purifiers for their wards' Haze*. Air & Odor Management. <https://aom.sg/aom-air-purifiers-kwong-wai-shiu-hospitals-haze-management-zones/>

Arar, M., & Jung, C. (2021). Improving the indoor air quality in nursery buildings in United Arab Emirates. *International Journal of Environmental Research and Public Health*, 18(22), 12091.

Azuma, K., Uchiyama, I., & Ikeda, K. (2008). The regulations for indoor air pollution in Japan: a public health perspective. *Journal of Risk Research*, 11(3), 301-314.

Bai, Z., 1, Jia, C., 1, Zhu, T., 1, Zhang, J., 2, College of Environmental Sciences and Engineering, Nankai University, Tianjin, China, & Environmental and Occupational Health Sciences Institute, UMDNJ and Rutgers University, Piscataway, NJ 08854, USA. (2002). *INDOOR AIR QUALITY RELATED STANDARDS IN CHINA*. Retrieved July 11, 2025, from <https://www.irbnet.de/daten/iconda/CIB7659.pdf>

Bai, Z., Wang, Z., Zhu, T., & Zhang, J. J. (2003). Developing indoor air quality related standards in China. *Journal of Asian Architecture and Building Engineering*, 2(1), 55-60.

Building and Construction Authority, Singapore. (2019). *Code On Environmental Sustainability Measures for Existing Buildings*. Retrieved June 30, 2025, from https://www1.bca.gov.sg/docs/default-source/docs-corp-buildsg/sustainability/code_env_sus_measures_exit_building_2c16b073e4cde45cfb8e475dd4403c266.pdf

Business Environment Council Limited. (2022). *Smart and Sustainable City Development: Hong Kong and International Experiences*.

CBRE. (2020). UNDERSTANDING HVAC & indoor air quality technologies & practices. In *CBRE*. Retrieved June 16, 2025, from <https://mediaassets.cbre.com/->

[/media/project/cbre/shared-site/insights/articles/understanding-hvac/air-quality-white-paper.pdf?rev=68d5e8323755404086f254e20be5fc02](#)

Census and Statistics Department (HK). (2022). Living with statistics. Retrieved June 13, 2025, from

https://www.censtatd.gov.hk/en/data/stat_report/product/B8XX0025/att/B8XX00252022XXXXE0100.pdf

Che, W. W., Tso, C. Y., Sun, L., Ip, D. Y., Lee, H., Chao, C. Y., & Lau, A. K. (2019). Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system. *Energy and Buildings*, 201, 202-215.

Cheung, T., Schiavon, S., Graham, L. T., & Tham, K. W. (2021). Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore. *Building and Environment*, 188, 107443.

Choi, M. (2019). Sustainable Cities: Seoul's Approach to Urban Sustainability. *International Journal of Sustainability*, 8(2), 112-130.

Chua, D. (2025, March 12). *Improve indoor air quality in Singapore healthcare facilities: More solutions*. Schneider Electric Blog. <https://blog.se.com/buildings/building-management/2022/01/10/more-solutions-for-improving-indoor-air-quality-in-singapore-healthcare-facilities/>

Cisco Meraki. (2025, June 23). *Air quality metrics explained*. Retrieved July 21, 2025, from https://documentation.meraki.com/MT/MT_General_Articles/Air_Quality_Metrics_Explained#:~:text=IAQ%20has%20five%20qualitative%20ratings,an%20aggregated%20score%20is%20calculated.

Clean Air Network. (2024). ANNUAL CLEAN AIR NETWORK REPORT. In CAN. Retrieved June 19, 2025, from https://hongkongcan.org/wp-content/uploads/2024/09/CAN-ANNUAL-REPORT-2324_V5c.pdf

Clean Air Network. (2025, March 11). *Urge to Incorporate IAQ into the “Minimum Standards for Subdivided Unit Living Environment.”* Retrieved June 13, 2025, from <https://hongkongcan.org/press-release/the-government-should-incorporate-indoor-air-quality-into-the-minimum-standard-requirements-for-living-conditions-in-subdivided-units/#:~:text=According%20to%20the%20latest%20%E2%80%9CLong,by%20residents%20of%20subdivided%20units.>

Clean Air Network. (2025b, March 11). *Urge to Incorporate IAQ into the “Minimum Standards for Subdivided Unit Living Environment.”* Retrieved June 23, 2025, from <https://hongkongcan.org/press-release/the-government-should-incorporate->

indoor-air-quality-into-the-minimum-standard-requirements-for-living-conditions-in-subdivided-units/

Daikin Airconditioning (Singapore) Pte. Ltd. (2022, January 11). *More solutions for improving indoor air quality in Singapore healthcare facilities*. Retrieved June 30, 2025, from <https://www.daikin.com.sg/blog-post/%20solutions-for-improving-iaq#:~:text=IAQ%20sensors%20are%20used%20to,for%20all%20types%20of%20facilities>.

Daikin Airconditioning (Singapore) Pte. Ltd. (2025). *About us | Daikin*. Retrieved July 2, 2025, from <https://www.daikin.com.sg/daikin>

Daikin. (2025). *Do you need an air purifier in Dubai?* Retrieved July 20, 2025, from https://www.daikinmea.com/en_us/knowledge-center/do-you-need-an-air-purifier-in-dubai.html#:~:text=Activated%20carbon%20filters:%20Dubai's%20air%20may%20contain,ensuring%20your%20environment%20remains%20fresh%20and%20clean%2Dsmelling.

Department of Health. (2024, November). *Clean Indoor Air Act*. Retrieved July 14, 2025, from https://www.health.ny.gov/prevention/tobacco_control/clean_indoor_air_act/#:~:text=All%20business%20owners%20and%20facility,smoking%20and%20vaping%20are%20allowed

Dubai Municipality. (2024). *Technical guidelines for indoor air quality for healthy life*. Retrieved July 18, 2025, from https://www.dm.gov.ae/wp-content/uploads/2024/07/DM-HSD-GU119-IAQ_Technical-Guidelines-for-Indoor-Air-Quality_V3-1.pdf

ELGONET PTE LTD. (2025, January 31). *IAQ Sensor Singapore | IAQ Indoor Air Quality Monitoring*. ELGONET PTE LTD -. Retrieved June 30, 2025, from [https://elgonet.com.sg/iaq-sensor/#:~:text=IAQ%20\(Indoor%20Air%20Quality\)%20Sensor,barometric%20pressure%20in%20real%2Dtime](https://elgonet.com.sg/iaq-sensor/#:~:text=IAQ%20(Indoor%20Air%20Quality)%20Sensor,barometric%20pressure%20in%20real%2Dtime).

Environmental Law Institute. (2025). *Recent developments in indoor air quality Policy | Environmental Law Institute*. Retrieved July 14, 2025, from [https://www.eli.org/buildings/recent-developments-iaq#:~:text=January%202018%20%2D%20New%20York%20City,\(Related%20ELI%20Resources](https://www.eli.org/buildings/recent-developments-iaq#:~:text=January%202018%20%2D%20New%20York%20City,(Related%20ELI%20Resources)

Environmental Protection Department. (2025). *Indoor air quality of EPD offices and visitor centres | Environmental Protection Department*. Retrieved June 18, 2025, from https://www.epd.gov.hk/epd/english/about_epd/env_policy_mgt/indoor_offices.

html#:~:text=We%20have%2016%20offices%20and,the%20%22Excellent%22%20IAQ%20Class.

Environmental Protection Department. (2025a). *Air | Environmental Protection Department*. Environmental Protection Department (EPD). Retrieved June 19, 2025,from

https://www.epd.gov.hk/epd/english/environmentinhk/air/air_maincontent.html#::~:~:text=To%20promote%20healthy%20indoor%20environments,please%20visit%20Indoor%20Air%20Quality.

EPD. (2002, March 26). *EXECUTIVE SUMMARY* | *Environmental Protection Department*. Retrieved July 21, 2025, from

[https://www.epd.gov.hk/epd/english/environmentinhk/air/study/rpts/exesum1_3.html#:~:text=The%20questionnaire%20survey%20found%20that%20some%2032%25, studies%20by%20the%20World%20Health%20Organisation%20\(WHO\).](https://www.epd.gov.hk/epd/english/environmentinhk/air/study/rpts/exesum1_3.html#:~:text=The%20questionnaire%20survey%20found%20that%20some%2032%25, studies%20by%20the%20World%20Health%20Organisation%20(WHO).)

European Environment Agency (2023, April 24). Air pollution and children's health. European Environment Agency. Retrieved June 13, 2025, from <https://www.eea.europa.eu/publications/air-pollution-and-childrens-health>

Foster. (2025, July 15). *How to improve indoor air quality in UAE: Complete guide*. Retrieved July 20, 2025, from <https://www.fosterintl.com/blog/how-to-improve-indoor-air-quality/>

Gasdia-Cochrane, M. (2023, May 3). How Seoul Metro improves indoor air quality in subway stations. *Identifying Threats*. Retrieved July 7, 2025, from <https://www.thermofisher.com/blog/identifying-threats/how-seoul-metro-improves-indoor-air-quality-in-subway-stations/>

Germitol. (2025). *Residential vs commercial air purifier in Singapore* | - Germitol. Retrieved June 27, 2025, from <https://www.germitol.com/residential-vs-commercial-air-purifier-in-singapore.html#:~:text=Maintenance%20and%20Price,system%20that%20suits%20your%20needs.>

Goldman Copeland Associates, P.C. (2021). *Energy Efficient Indoor Air Quality Study Final Conclusions Report*.

Halverson, D. (2025, May 14). *Indoor Air Quality Solutions | IAQ Products | Watkins Glen, NY*. Donohue Halverson Plumbing, Heating, Cooling, Electric.
<https://www.dhithaca.com/residential/indoor-air-quality/#:~:text=Muggy%20hot%20weather%20is%20a,Vacuum%20and%20dust%20regularly>.

Han, J. (2020). "Urban Development in Seoul: Trends and Future Perspectives." *Journal of Urban Planning*, 15(3), 245-263.

- Higgins, C., Kumar, P., & Morawska, L. (2024). Indoor air quality monitoring and source apportionment using low-cost sensors. *Environmental research communications*, 6(1), 012001.
- Hitachi. (2025). *5 Ways HVAC technology can Accelerate Hong Kong's sustainability goals*. hitachiaircon.com. Retrieved June 17, 2025, from <https://www.hitachiaircon.com/hk/en/news/5-ways-hvac-technology-can-accelerate-hong-kong-s-sustainability-goals-1#:~:text=Its%20HVAC%20system%20is%20equipped,Get%20your%20copy%20here.>
- HKGBC. (2025). *Building 15W Hong Kong Science Park Phase 3 - BEAM Plus Online Exhibition*. HKGBC Beam Plus. Retrieved June 18, 2025, from <https://greenbuilding.hkgbc.org.hk/projects/view/43>
- HKSAR. (2024). Final measurement and verification report for I&T Trial Project Smart AI-Control Ventilation System. In *Final Measurement and Verification Report for I&T Trial Project SmartAir - AI-Controlled Ventilation System*. Retrieved June 18, 2025, from https://inno.emsd.gov.hk/filemanager/successcase/common/upload/8/265/EMSD-M&V-P0307_Final.pdf#:~:text=Therefore%2C%20the%20self%2Dlearning%20model%20could%20provide%20more,maintain%20indoor%20air%20quality%20at%20satisfactory%20level.&text=Through%20the%20M&V%20results%2C%20we%20can%20see,ventilation%20system%20running%20for%207%20months%20trial.
- Hong Kong e-Legislation. (2022, October 1). Retrieved June 23, 2025, from https://www.elegislation.gov.hk/hk/cap344!en@2022-10-01T00:00:00?INDEX_CS=N
- Hong Kong Green Organisation. (2023). *2023 Hong Kong Green Organisation Certification – Guidebook For laqwi\$E Certificate*. Retrieved June 23, 2025, from https://www.hkgoc.gov.hk/uploads/2023%20IAQwise-Guidebook_Eng_v1.3.2.pdf
- Hong Kong Green Organisation. (2023). *2023 Hong Kong Green Organisation Certification – Guidebook For laqwi\$E Certificate*. Retrieved June 23, 2025, from https://www.hkgoc.gov.hk/uploads/2023%20IAQwise-Guidebook_Eng_v1.3.2.pdf
- Hong Kong International Airport. (2020, May 24). *Advanced technologies for disinfection at HKIA*. Retrieved June 25, 2025, from <https://www.hongkongairport.com/en/media-centre/news-stories->

updates/Advanced-

Technologies#:~:text=Airport%20Authority%20Hong%20Kong%20is%20applying%20the,passengers%20and%20airport%20staff%20from%20COVID%2D19%20infection.&text=The%20interior%20surface%20of%20the%20channel%20is,the%20technologies%20of%20photocatalyst%20and%20%22nano%20needles%202.

Hong Kong International Airport. (2024). Airport Authority Hong Kong | Sustainability Report 2023/24. In *Hong Kong International Airport*. Retrieved June 25, 2025, from https://www.hongkongairport.com/iwov-resources/file/sustainability/sustainability-report/AA_Sustainability_Report_202324_ENG.pdf

Hong Kong International Airport. (2025). *Air Quality, Environment - Hong Kong International Airport*. Retrieved June 25, 2025, from <https://www.hongkongairport.com/en/sustainability/environment/air-quality/#:~:text=Air%20Quality%20Study%20with%20HKUST,above%20mentioned%20emissions%20reduction%20measures.>

Hong Kong Polytechnic University. (2021). *PolyU's innovative indoor air quality monitoring device received extensive media coverage | News | Events | Campus Carbon neutrality*. Campus Carbon Neutrality. Retrieved June 19, 2025, from <https://www.polyu.edu.hk/greencampus/events/news/2020/202009-polyu-innovative-indoor-air-quality-monitoring-device/#:~:text=PolyU's%20innovative%20indoor%20air%20quality,media%20coverage%20%7C%20Campus%20Carbon%20Neutrality>

Hong Kong Polytechnic University. (2025). *Indoor air quality | Our services | Health and Safety Office*. Retrieved June 19, 2025, from [https://www.polyu.edu.hk/hso/our-services/indoor-air-quality/#:~:text=Indoor%20Air%20Quality%20\(IAQ\)%20pre,carbon%20dioxide](https://www.polyu.edu.hk/hso/our-services/indoor-air-quality/#:~:text=Indoor%20Air%20Quality%20(IAQ)%20pre,carbon%20dioxide)

Hrainwater. (2025, June 6). *A focus on Dubai's adoption of ASHRAE Standard 62.1-2022 and 241-2023: The growing importance of decarbonization, sustainability, and indoor air quality in Global Building Standards*. AIRBOX America. <https://airboxamerica.com/articles/the-growing-importance-of-decarbonization-sustainability-and-indoor-air-quality-in-global-building-standards-a-focus-on-dubais-adoption-of-ashrae-standard-62-1-2022-and-241-2023/#:~:text=Technological%20Advancements:%20New%20building%20standards,and%20working%20environments%20for%20all.>

IMARC Group. (2025, January 14). *Japan air purifier market expected to reach USD 988 million by 2033 - IMARC Group*. Retrieved July 2, 2025, from <https://www.imarcgroup.com/japan-air-purifier-market->

[statistics#:~:text=%20Commercial:%20Retail%20Shops%2C%20Offices%2C%20Healthcare%20Facilities%2C,Laboratories%2C%20Transport%2C%20Others.%20*%20Residential.%20*%20Industrial.](#)

Indonesia, H. (2023, July 20). *Indoor Plants and Air Quality: Enhancing Indoor Air Quality with Indoor Plants*. Higienis Indonesia. Retrieved June 23, 2025, from <https://www.higienis.com/blog/indoor-plants-and-air-quality-enhancing-indoor-air-quality-with-indoor-plants/#:~:text=Some%20plants%20are%20more%20effective,other%20gasses%20from%20the%20air.>

Indoor Air Quality Management Group. (2019). A guide on Indoor Air Quality Certification Scheme for offices and public places. In *HK IAQ Information Center*. Retrieved June 23, 2025, from https://www.iaq.gov.hk/wp-content/uploads/2021/04/new-iaq-guide_eng.pdf

Inoue, K., Hirabayashi, Y., & Azuma, K. (2025). Detailed hazard assessment of ethylbenzene to establish an indoor air quality guideline in Japan. *Environmental Health and Preventive Medicine*, 30, 34-34.

IQAIR Hong Kong. (2016). *IQAIR Hong Kong*. Retrieved June 18, 2025, from https://iqair.com.hk/en/about_us.php#:~:text=IQAir%20products%20are%20also%20used,%2C%20VOCs%2C%20odours%2C%20etc.

IQAir. (2019, July 3). *All about HEPA filtering: Benefits & misconceptions* | IQAir. Retrieved June 18, 2025, from <https://www.iqair.com/in-en/newsroom/hepa-filter-air-purifier-benefits-misconceptions>

IQAir. (2022, December 1). *IQAir selected to provide Hong Kong medical hospitals with air purifiers for fight against SARS and COVID-19 infections*. Retrieved June 18, 2025, from <https://www.iqair.cn/cn-en/newsroom/iqair-provided-hong-kong-hospitals-with-air-purifiers-for-sars-and-covid-19>

IQAir. (2022b, December 1). *IQAir selected to provide Hong Kong medical hospitals with air purifiers for fight against SARS and COVID-19 infections*. Retrieved July 11, 2025, from <https://www.iqair.com/newsroom/iqair-provided-hong-kong-hospitals-with-air-purifiers-for-sars-and-covid-19>

IQAiR. (2025a). *Hong Kong SAR Air Quality Index (AQI) and Air Pollution information* | IQAir. Retrieved June 27, 2025, from <https://www.iqair.com/sa/hong-kong>

IQAiR. (2025b). *Singapore Air Quality Index (AQI) and Air Pollution information* | IQAir. Retrieved June 27, 2025, from <https://www.iqair.com/us/singapore>

IWBI. (2020). *Air | WELL Standard*. Retrieved June 19, 2025, from <https://standard.wellcertified.com/air>

- Iyengar, A., Hanon, S., Bruns, R., Olsiewski, P., & Gronvall, G. K. (2024). COVID-19 mitigation in a K-12 school setting: a case study of avenues: the world school in New York city. *Health security*, 22(3), 210-222.
- JLL. (2020, May 25). *JLL rolls out Hong Kong's largest deployment of IoT-powered PropTech*. Retrieved June 17, 2025, from <https://www.jll.com.hk/en/newsroom/hk-iot-proptech-jll-command-center#:~:text=Gavin%20Morgan%2C%20Managing%20Director%20of,building%20portfolios%20in%20Hong%20Kong.%E2%80%9D>
- Kacar, B., Turhan, E., Dalkiran, A., & Karakoc, T. H. (2023). Green Airport building certification comparison: a practical approach for Airport Management. *International Journal of Green Energy*, 20(6), 602-615.
- Kang, D. H. (2020). Addressing indoor air pollution challenges through concrete public policies in South Korea. *DOAJ (DOAJ: Directory of Open Access Journals)*. <https://doaj.org/article/8763979a46804ce79bd847c34de31176>
- Kapoor, V. (2025, March 10). *China Air conditioner market insights: 3.59% CAGR and key trends to [2030]*. Retrieved July 9, 2025, from <https://www.linkedin.com/pulse/china-air-conditioner-market-insights-359-cagr-key-trends-kapoor-ztsff/>
- Kelley, M. (2023, November 9). *Comparing Centralized vs. Decentralized Filtration Systems*. MatrixAir -. <https://www.matrixair.com/blog/comparing-centralized-vs-decentralized-filtration-systems/>
- KICT. (2025). *KICT-Korea Institute of Civil Engineering and Building Technology: The Indoor Air Quality Research Center (IAQRC)*. KICT-Korea Institute of Civil Engineering and Building Technology. Retrieved July 7, 2025, from <https://www.kict.re.kr/menu.es?mid=a20211010000>
- Kim, M., Braatz, R. D., Kim, J. T., & Yoo, C. (2015). Indoor air quality control for improving passenger health in subway platforms using an outdoor air quality dependent ventilation system. *Building and Environment*, 92, 407-417.
- Kim, M., Braatz, R. D., Kim, J. T., & Yoo, C. (2015). Indoor air quality control for improving passenger health in subway platforms using an outdoor air quality dependent ventilation system. *Building and Environment*, 92, 407-417.
- Kim, M., SankaraRao, B., Kang, O., Kim, J., & Yoo, C. (2012). Monitoring and prediction of indoor air quality (IAQ) in subway or metro systems using season dependent models. *Energy and buildings*, 46, 48-55.
- Kim, S., & Lee, H. (2021). "Innovations in Water Purification: A Case Study of Seoul." *Environmental Technology Journal*, 12(4), 198-210.

- Kiwi Technology Inc. (2022, October 26). *Indoor Air Quality - Smart IAQ Management Solution - Kiwi technology*. 奇邑科技. Retrieved July 4, 2025, from <https://www.kiwi-tec.com/en/solutions/iaq/#:~:text=AIoT%20Smart%20IAQ%20Management%20Solution,quality%20monitoring%20and%20management%20service>.
- Knapp, S. (2024, February 12). A brief introduction to MOS sensors and their applications - omni sensors & transmitters. *Omni Sensors and Transmitters*. Retrieved June 17, 2025, from <https://sensorsandtransmitters.com/a-brief-introduction-to-mos-sensors-and-their-applications/#:~:text=Metal%20Oxide%20Semiconductor%20gas%20sensors,their%20construction%20and%20their%20functionality>.
- Krause, A., Zhao, J., & Birmili, W. (2019). Low-cost sensors and indoor air quality: a test study in three residential homes in Berlin. *Gefahrstoffe Reinhaltung Der Luft*, 79(03). <https://doi.org/10.37544/0949-8036-2019-03>
- Kwok, G., Sze, T., Lai, A., Cheung, F., Tsang, S., & Allied Environmental Consultants Ltd. (2017). Drive towards sustainable development and Management: Case study on International Commerce Centre. In *World Sustainable Built Environment Conference 2017 Hong Kong*. Retrieved June 18, 2025, from https://www.irbnet.de/daten/iconda/CIB_DC30041.pdf
- Lab Chronicles. (2025, June 24). *South Korea Indoor Air quality Monitoring Systems Market Overview: Key trends and emerging Technologies (2026-2032)*. Retrieved July 7, 2025, from <https://www.linkedin.com/pulse/south-korea-indoor-air-quality-monitoring-systems-market-dy2vf/>
- Lam, K. P., & Lee, J. (2019). Urban Density and Vertical Growth: Implications for Resource Optimization. **Journal of Urban Planning**, 15(3), 201-215.
- Lam, K. P., & Lee, J. (2020). Indoor Air Quality and Health: Connecting Air Quality to Respiratory Issues. **Environmental Health Perspectives**, 128(7), 077013.
- Lemon, M. (2024, July 21). *NASA compiles list of best plants to clean indoor air*. CO2 Meter. Retrieved June 23, 2025, from https://www.co2meter.com/blogs/news/nasa-compiles-list-of-best-plants-to-clean-indoor-air?srsltid=AfmBOopBJ8p9i97Th_LD_Nmd3p1cvVKawHiJ1RqGpdtEaofXWBpkDG1
- LG SG. (2022, April 25). *LG HVAC IAQ Solutions : HVAC Blog | LG Singapore*. Retrieved June 27, 2025, from <https://www.lg.com/sg/business/hvac-blog/LG-HVAC-IAQ-Solutions-for-the-fresh-air-you-breathe/#:~:text=A%20Fresh%20Air%20Intake%20Unit,filter%20to%20capture%20large%20particles>.

- Lin, P., Qin, H., Lau, S. S. Y., & Wei, Q. (2025). Impact of unit type and configuration on indoor natural ventilation performance of high-rise, high-density residential buildings in Hong Kong. *Building and Environment*, 269, 112444.
- Lingnan University. (2025). *PureAura | MSC in Humanitarian Technology and Inclusive Business*. Retrieved June 18, 2025, from <https://www.ln.edu.hk/sgs/htib/ht-project/pureaura>
- Maley, J. (2024, January 9). *Optimizing school efficiency and IAQ through commissioning | U.S. Green Building Council*. USGBC. Retrieved July 15, 2025, from <https://www.usgbc.org/articles/optimizing-school-efficiency-and-iaq-through-commissioning>
- Mansor, R., Sheau-Ting, L., & Weng-Wai, C. (2025). The effects of personal control and perceived thermal comfort on occupant psychological health at the workplace. *Architectural Science Review*, 68(2), 94-106.
- Meersens. (2023, April 5). *Indoor air quality: the impact of CO2 on health and well-being at work*. Retrieved June 17, 2025, from <https://meersens.com/indoor-air-quality-the-impact-of-co2-on-health-and-wellbeing-at-work/?lang=en#:~:text=CO2%20and%20SARS%2DCOV%2D2,and%20to%20renew%20the%20air.>
- MHLW. (2002). *Committee on Sick House Syndrome: Indoor Air Pollution Progress Report No. 4 - Summary on the discussions at the 8th and 9th meetings - 22 January 2002*. Retrieved July 4, 2025, from <https://www.mhlw.go.jp/content/11120000/001385596.pdf>
- MTR Corporation Limited. (2024). *Sustainability Report 2024*. Retrieved June 23, 2025, from https://www.mtr.com.hk/sustainability/assets/pdf/en/2024/Sustainability_Report.pdf
- Muller, C. O., Yu, H., & Zhu, B. (2015). Ambient air quality in China: the impact of particulate and gaseous pollutants on IAQ. *Procedia Engineering*, 121, 582-589.
- Nam, Y. (2021). Government-led living lab : A case study of Magok Smart City living lab in Seoul. In Professor Joo, Yumin, Professor Kim, Dong-Young, & Professor Lee, Taejun, *KDI School of Public Policy and Management*.
- National Environment Agency. (2024, July 30). *Advisory on CO2 Monitoring to assess ventilation adequacy*. Retrieved June 30, 2025, from <https://www.nea.gov.sg/our-services/public-cleanliness/environmental-cleaning-guidelines/advisories/advisory-on-co2-monitoring-to-assess-ventilation-adequacy#:~:text=%5B1%5D%20The%20indoor%20CO2,which%20is%20appro>

ximately%201%2C100%20ppm.&text=Taking%20CO2%20measurements%20can,Virus%20Aerosols%20for%20more%20information.

New York State Department of Health. (2024, September 13). *New York State Department of Health receives \$5 million to address indoor air quality in schools*. Retrieved July 14, 2025, from https://www.health.ny.gov/press/releases/2024/2024-09-13_air_quality_in_schools.htm#:~:text=This%20funding%20allows%20the%20Department,improvements%20and%20greenhouse%20gas%20reductions.

Niu, D., Li, Y., Zhang, S., & Lin, Z. (2024). Intermittent demand-controlled ventilation for energy flexibility and indoor air quality. *Building and Environment*, 263, 111908.

Nunez, K. (2021, August 29). *How does an air ionizer work?* Healthline. Retrieved June 18, 2025, from <https://www.healthline.com/health/what-does-an-ionizer-do>

NYSenate.gov. (2025). *NY State Assembly Bill 2025-A5618*. Retrieved July 14, 2025, from <https://www.nysenate.gov/legislation/bills/2025/A5618#:~:text=This%20act%20shall%20be%20known,new%20air%20Dquality%20control%20technology>.

Odmark, J. (2024, March 12). *Exploring how different countries approach indoor air quality*. YourIAQ. <https://youriaq.com/global-air-quality-standards/#:~:text=From%20Minamata%20to%20National%20Action,healthier%20living%20environments%20for%20all>.

One Planet Network. (2019, June 25). *RESETTM Air: an indoor air quality standard and certification*. Retrieved July 11, 2025, from <https://www.oneplanetnetwork.org/knowledge-centre/resources/resettm-air-indoor-air-quality-standard-and-certification>

Panasonic Corporation. (2025). *Technology*. Retrieved July 2, 2025, from <https://www.panasonic.com/global/hvac/about.html>

Park, D., Kang, K., Na, H., Lee, J., Kim, S., & Kim, T. (2024). Measurement of black carbon exposure in urban classrooms during rush hours. *Atmospheric Pollution Research*, 15(10), 102233.

Philips. (2025). *Air Matters app-Manage & monitor air quality | Philips*. Retrieved June 23, 2025, from <https://www.philips.com.hk/en/c-e/ho/air-purifier-and-air-humidifier/air-matters-app.html#:~:text=Track%20indoor%20and%20outdoor%20air%20quality%20In,app%20by%20your%20Philips%20connected%20Air%20device>.

PIQUANT. (2025). *Products: AirQuant- Smart City & Home Solutions for Indoor Air Quality Monitoring System (IAQ Monitoring System)*.

Plume Labs. (2025). *Flow, by Plume Labs: the first smart air quality tracker*. Retrieved June 23, 2025, from

<https://plumelabs.com/en/flow/#:~:text=Indoors%20and%20out%20Kitchens%2C%20bathrooms%2C%20bike%20rides%2C,any%20more!%20Flow%20is%20here%20to%20help.>

Poole, K. (2017). Sustainable midfield concourse development at Hong Kong International Airport. In *Hong Kong Airport Authority*.

https://www.irbnet.de/daten/iconda/CIB_DC30368.pdf#:~:text=In%20passive%20design%2C%20natural%20elements%20such%20as,such%20as%20air%20conditioning%20and%20artificial%20lighting.&text=Each%20VAV%20system%20is%20controlled%20by%20its,appropriately%20to%20maintain%20the%20indoor%20environmental%20requirements.

Qey Technical. (2020). Electrostatic Filters – Improving air quality & reducing energy – QEY – HVAC services in Dubai & Middle East. Retrieved July 20, 2025, from

<https://qey.ae/electrostatic-filters/#:~:text=Normally%2C%20the%20filter%20cell%20and,of%20any%20brand%20or%20manufacturer.>

Qlestouw. (2023, July 14). *HEPA filtration: What you need to know*. Air Quality Engineering. Retrieved June 18, 2025, from <https://air-quality-eng.com/air-cleaners/about-hepa-filtration/#:~:text=By%20definition%2C%20new%20HEPA%20filters,not%20achieve%20the%20filtration%20required.>

[filtration/#:~:text=By%20definition%2C%20new%20HEPA%20filters,not%20achieve%20the%20filtration%20required.](https://air-quality-eng.com/air-cleaners/about-hepa-filtration/#:~:text=By%20definition%2C%20new%20HEPA%20filters,not%20achieve%20the%20filtration%20required.)

Qsafe. (2023, September 28). *Indoor Air Quality Test Singapore | IAQ Testing Singapore | QSaFE*. QSaFE Pte Ltd. Retrieved June 30, 2025, from

<https://www.qsafe.com.sg/indoor-air-quality-iaq-test/#:~:text=Legislation,potential%20of%20adverse%20health%20effects.>

RESET. (2018, October 11). *The Shanghai Hongqiao Cordis Hotel becomes world's first RESET Air certified hotel*. RESET®. Retrieved July 11, 2025, from <https://reset.build/newsroom/117>

Robinson, C. (2025, May 6). *Smarter, healthier building management - Modern building services*. Modern Building Services (MBS). Retrieved June 16, 2025, from <https://modbs.co.uk/news/fullstory.php/aid/20640/Smarter%2C healthier building management.html#:~:text=Take%20this%20example:%20a%20smart%20heating%2C%20ventilation,optimal%20air%20quality%20without%20consuming%20unnecessary%20energy.>

Ródenas García, M., Spinazzé, A., Branco, P. T., Borghi, F., Villena, G., Cattaneo, A., ... & Sousa, S. I. (2022). Review of low-cost sensors for indoor air quality: Features and applications. *Applied Spectroscopy Reviews*, 57(9-10), 747-779.

- Roxburgh, H. (2020, February 3). How clean indoor air is becoming China's latest luxury must-have. *The Guardian*.
<https://www.theguardian.com/cities/2018/mar/27/china-clean-air-indoor-quality-shanghai-cordis-hongqiao-filters#:~:text=As%20well%20as%20top%2Dquality,on%20its%20many%20luxury%20competitors.>
- Sensgreen. (2025, June 30). *IAQ & HVAC optimization in Dubai's luxury villas*. Retrieved July 20, 2025, from <https://sensgreen.com/dubai-villas-iaq-hvac-optimization/#:~:text=These%20sensors%20continuously%20collected%20data,of%20these%20high%2Dend%20residences.>
- Seoul Metropolitan Government. (2018, May 16). *Seoul implements the Indoor Air Quality Certification program for health-conscious facilities* -. Official Website of The. Retrieved July 7, 2025, from <https://english.seoul.go.kr/seoul-implements-indoor-air-quality-certification-program-health-conscious-facilities/#:~:text=certify%20excellent%20facilities.-,Since%202012%20when%20the%20first%20certification%20marks%20were%20given%20to,not%20subject%20to%20legal%20regulations.>
- Seoul Metropolitan Government. (2025a). *Indoor air quality target facility statistics*. Retrieved July 7, 2025, from <https://cleanindoor.seoul.go.kr/air/regionBuildingStat.do?menuNo=250&contentsNo=&boardConfigNo=&page=>
- Seoul Metropolitan Government. (2025b, June 5). *Seoul Earns Global Recognition for Climate Leadership with Top Carbon Reduction Rating for Three Consecutive Years* -. Official Website of The. Retrieved July 7, 2025, from <https://english.seoul.go.kr/seoul-earns-global-recognition-for-climate-leadership-with-top-carbon-reduction-rating-for-three-consecutive-years/>
- Seoul Solution. (2016, December 23). *Indoor air quality control at public use facilities : Clean air for all*. 서울정책아카이브 Seoul Solution. Retrieved July 9, 2025, from <https://seoulsolution.kr/en/content/indoor-air-quality-control-public-use-facilities-clean-air-all>
- Settimo, G., Yu, Y., Gola, M., Buffoli, M., & Capolongo, S. (2023). Challenges in IAQ for Indoor Spaces: A Comparison of the Reference Guideline Values of Indoor Air Pollutants from the Governments and International Institutions. *Atmosphere*, 14(4), 633. <https://doi.org/10.3390/atmos14040633>
- Shabbir, M., Saeed, T., Saleem, A., Bhawe, P., Bergin, M., & Khokhar, M. F. (2025). A paradigm shift: Low-cost sensors for effective air quality monitoring and

- management in developing countries. *Environment International*, 200, 109521. <https://doi.org/10.1016/j.envint.2025.109521>
- Shi, X. M. (2023). Revision and prospect of "Standards for indoor air quality (GB/T 18883-2022)" in China. *Zhonghua yu Fang yi xue za zhi [Chinese Journal of Preventive Medicine]*, 57(11), 1725-1728.
- Shibuya Station. (2025). *Shibuya Station History*. Retrieved July 4, 2025, from <https://www.shibuyastation.com/shibuya-station-history/>
- Singapore Department of Statistics. (2021). Population Density Report. Retrieved from <https://www.singstat.gov.sg/find-data/search-by-theme/population/population-density>
- Singapore Standards. (2025). *Singapore Standards*. Retrieved June 27, 2025, from [https://www.singaporestandardseshop.sg/Product/SSPdtDetail/8ee48ab1-38f5-4dae-a469-b8612a05876f#:~:text=In%20setting%20indoor%20air%20quality%20\(IAQ\)%20s%20tandard%2C,minimise%20the%20potential%20of%20adverse%20health%20effects.](https://www.singaporestandardseshop.sg/Product/SSPdtDetail/8ee48ab1-38f5-4dae-a469-b8612a05876f#:~:text=In%20setting%20indoor%20air%20quality%20(IAQ)%20s%20tandard%2C,minimise%20the%20potential%20of%20adverse%20health%20effects.)
- Smith, J. (2023). Innovative Solutions for Air Quality Improvement in India: A Review of Cost-Effective Technologies. *Journal of Environmental Management*, 245, 121-130.
- Sustainability Directory. (2025, March 14). *What are benefits of hybrid ventilation systems?* Sustainability Directory. Retrieved June 18, 2025, from <https://energy.sustainability-directory.com/question/what-are-benefits-of-hybrid-ventilation-systems/#:~:text=Improved%20Indoor%20Air%20Quality%20%E2%86%92%20Hybrid%20systems,healthier%20and%20more%20comfortable%20environment%20for%20occupants.&text=Several%20studies%20have%20shown%20that%20hybrid%20ventilation,but%20these%20savings%20are%20not%20always%20guaranteed.>
- Sustainable Bus. (2020, April 1). *Bus disinfection through UV lights. A way to fight Coronavirus in Shanghai - Sustainable Bus*. Retrieved July 11, 2025, from <https://www.sustainable-bus.com/news/bus-disinfection-through-uv-lights-a-way-to-fight-coronavirus-in-shanghai/#:~:text=Following%20a%20guidance%20issued%20by%20the%20National,cent%20of%20viruses%2C%20as%20reported%20by%20AFP.>
- Swire Properties. (2021). *Occupant Wellbeing | Environment | Swire Properties SD Report 2020*. Retrieved June 18, 2025, from

<https://sd.swireproperties.com/2020/en/performance-environment/occupant-wellbeing>

Swire Properties. (2024). *Occupant Wellbeing | Performance (Environment) | Swire Properties Sustainability Report 2024*. Retrieved June 17, 2025, from <https://sd.swireproperties.com/2024/en/performance-environment/occupant-wellbeing>

Swire Properties. (2025). *Pacific Place | Breathe well be well*. Pacific Place. Retrieved June 19, 2025, from <https://iaq.pacificplace.com.hk/en/introduction>

Taniguchi, K., Marukawa, Y., Kokubun, Y., Kamiyama, Y., & Bandai, Y. (2024, December). Natural ventilation operation method to investigate the compatibility between IAQ and thermal environment in school buildings. In *ASim Conference 2024* (Vol. 5, pp. 594-601). IBPSA-Asia.

Tapia-Brito, E., Riffat, J., Wang, Y., Wang, Y., Ghaemmaghami, A. M., Coleman, C. M., Erding, M. T., & Riffat, S. (2023). Experimental study of the purification performance of a MopFan-based photocatalytic air cleaning system. *Building and Environment*, 240, 110422. <https://doi.org/10.1016/j.buildenv.2023.110422>

The New York State Departments of Education. (2021). *Statement regarding ionization Air cleaners*. Retrieved July 14, 2025, from <https://www.p12.nysed.gov/facplan/documents/StatementRegardingIonizationAirCleaners12.14.21.pdf>

Tsang, T. W., Mui, K. W., & Wong, L. T. (2024). Indoor Air Quality (IAQ) Management in Hong Kong: The Way Forward. *Atmosphere*, 15(5), 546. <https://doi.org/10.3390/atmos15050546>

uHoo. (2024, July 2). *Nomura Research Institute IAQ Case Study | UHOO*. uHoo | Clean Air for All. <https://getuhoo.com/business/offices/case-study-nomura-research-institute/#:~:text=Avoiding%20closed%20spaces%20is%20one,of%20uHoo%20and%20future%20prospects>.

US EPA. (2024, August 31). *Building Assessment Survey and Evaluation Study | US EPA*. Retrieved June 16, 2025, from <https://www.epa.gov/indoor-air-quality-iaq/building-assessment-survey-and-evaluation-study#:~:text=Early%20research%20concerning%20IAQ%20in%20the%20U.S.,which%20to%20compare%20the%20so%2Dcalled%20%22sick%22%20buildin gs>.

US EPA. (2024b, December 20). *Low-Cost Air Pollution monitors and indoor air quality | US EPA*. Retrieved June 16, 2025, from <https://www.epa.gov/indoor-air-quality-iaq/low-cost-air-pollution-monitors-and-indoor-air->

- WHO. (2025). *Types of pollutants*. World Health Organization. Retrieved July 29, 2025, from <https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/health-impacts/types-of-pollutants>
- Wolverton, B. C., Douglas, W. L., Bounds, K., National Aeronautics and Space Administration, & Sverdrup Technology, Inc. (1989). *A study of interior landscape plants for indoor air Pollution Abatement*.
<https://ntrs.nasa.gov/api/citations/19930072988/downloads/19930072988.pdf>
- Wong, W.(2024, November 19). Hong Kong tests find half of home air purifiers ‘slow’ at removing toxic formaldehyde. *South China Morning Post*.
https://www.scmp.com/news/hong-kong/society/article/3266923/hong-kong-tests-finds-half-home-air-purifiers-slow-removing-toxic-formaldehyde?module=perpetual_scroll_0&pgtype=article
- WOOFAA. (2022, October 26). *List of outdoor air quality monitoring stations in Hong Kong*. MetaAIRR Sandbox by WOOFAA. Retrieved June 19, 2025, from <https://mta.woofaa.com/opendata-hk/outdoor-air-quality-stations-hk/#:~:text=Nations'%20Environmental%20Programme.-,Air%20Quality%20Monitoring%20Network%20of%20Hong%20Kong,current%20and%20forecast%20air%20quality>.
- World Health Organization (WHO). (2018). Health Effects of Outdoor Air Pollution. Retrieved from [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- World Health Organization: WHO. (2018, May 2). 9 out of 10 people worldwide breathe polluted air, but more countries are taking action. *World Health Organization*. Retrieved July 29, 2025, from <https://www.who.int/news/item/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action>
- World Health Organization: WHO. (2024, October 16). *Household air pollution*. Retrieved June 13, 2025, from [https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health#:~:text=Household%20air%20pollution%20exposure%20leads,\(COPD\)%20and%20lung%20cancer](https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health#:~:text=Household%20air%20pollution%20exposure%20leads,(COPD)%20and%20lung%20cancer)
- World Health Organization: WHO. (2024b, October 16). *Household air pollution*. Retrieved July 29, 2025, from <https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health>
- WWF Hong Kong. (2012). Green buildings: Hong Kong Science Park / Zero Carbon Building / Towngas Headquarters. In *Green Buildings and the City*. Retrieved June 17, 2025, from

<https://greenskillsresources.com/resources/uploads/page/57/document/Case-study---Green-buildings-20220520133740.pdf>

- Yeşilata, Y. (2025, June 11). *Building Management System Efficiency with AI and Cloud*. Sensgreen. Retrieved July 18, 2025, from <https://sensgreen.com/building-management-system/#:~:text=Benefits%20of%20Cloud%2DBased%20Solutions,leveraging%20AI%20and%20machine%20learning>.
- Yuke, W. (2023). *HK gets down to the business of advanced air quality control*. Chinadailyhk. Retrieved June 18, 2025, from <https://www.chinadailyhk.com/hk/article/136626>
- Zhao, X., Wang, S., Li, P., & Shi, X. (2025). Long-Term Indoor Air Quality Monitoring in Office Buildings: Data-Driven and Goal-Oriented Recommendations for Sensor Placement and Sampling Frequency. *Building and Environment*, 113392.
- Zheng, H., Krishnan, V., Walker, S., Loomans, M., & Zeiler, W. (2022). Laboratory evaluation of low-cost air quality monitors and single sensors for monitoring typical indoor emission events in Dutch daycare centers. *Environment International*, 166, 107372.
- Zhong, S., Lalanne, D., & Alavi, H. (2021, May). The complexity of indoor air quality forecasting and the simplicity of interacting with it—A case study of 1007 office meetings. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (pp. 1-19).