GLOBAL OPEN INDOOR AIR QUALITY STANDARDS

A UNIFIED FRAMEWORK

NOVEMBER 2025 | VERSION 1.0

GO AQS

GLOBAL OPEN AIR QUALITY STANDARDS

About GO AQS

Founded as a non-profit in September 2024, at GO AQS (Global Open Air Quality Standards), we brought together over 160 industry professionals, researchers, and community representatives from more than 32 countries on a mission to establish and promote open, transparent, and scientifically grounded air quality standards. Through our inclusive and collaborative air quality development frameworks, we are committed to ensuring that everyone has access to healthy environments. Our principles of Equality, Equity, Science, and Universality guide every aspect of our work, driving accountability, innovation, and lasting impact in air quality management.

Declaration of non-competing interest

The preparation, analysis, and publication of the *Global Open Indoor Air Quality Standards: A Unified Framework*, was conducted entirely by the contributing committee and advisory experts on a voluntary, pro bono basis. This work received no external financial funding, sponsorship or financial support in connection with the preparation, compilation, or publication of this White Paper.

The authors hold no employment contracts, paid consultancies, stock holdings, patents, or other financial or non-financial relationships with any organisation or entity that could be perceived to have influenced, or be perceived to influence, the objectivity or conclusions of this work; ensuring that the integrity of the standards remains dedicated solely to the pursuit of open science, public health imperatives, and the universal mandate for clean air.

Global Open Indoor Air Quality Standards: A Unified Framework | November 2025, Version 1.0
Global Open Air Quality Standards (GO AQS)
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Manuscript completed in November 2025. Current Version 1.0.0.5

How to Cite

Global Open Air Quality Standards (GO AQS), 2025, *Global Open Indoor Air Quality Standards: A Unified Framework, November 2025, Version 1.0*; ISBN: 9798274916158.

"WE SHARE THE SAME AIR; LET'S SHARE THE SAME AIR QUALITY STANDARDS"

Foreword

Clean air is humanity's most fundamental shared resource. It sustains every cell in our bodies, every community, and every generation that will follow. Yet the air we breathe remains profoundly unequal.

The Global Open Air Quality Standards (GO AQS) initiative was founded on a simple but transformative principle: "*If we all share the same air, we deserve the same protection*".

Stemming from this, and through the efforts of a truly international consensus, in this white paper, we present a unified, science-backed framework to address one of the most pressing public health challenges of our time. We brought together research expert committees, industry representatives, and leading organisations from over 32 countries to forge an open, interoperable, and accessible set of standards. The output of this collaborative work establishes a new global benchmark for indoor air quality, providing governments, institutions, integrators, and individuals with the necessary tools to take action.

The mission is ambitious yet achievable: to define clear, practical targets that safeguard human health, empower public understanding, and inspire technological and policy innovation. By harmonising how indoor air quality is measured, communicated, and improved, GO AQS seeks not merely incremental progress, but a new paradigm, one where healthy air becomes a universal right, not a privilege.

I am deeply grateful to everyone who has shared their knowledge in this publication. Your contributions help ensure that the barriers standing in the way of clean air as a universal right, can be meaningfully challenged.

This document is a call to action. Together, we can create a world where everyone, everywhere, breathes safe and clean air.

Sotirios Papathanasiou, Founder of GO AQS

Executive Summary

Indoor air quality (IAQ) is a global public health issue that affects people regardless of age, geography, or socioeconomic status. As individuals spend up to 90% of their time indoors, pollutant exposure within buildings has a profound impact on respiratory health, cognitive performance, cardiovascular risk, and overall well-being. Yet today, no single cohesive global IAQ standard exists; current guidelines vary widely, leaving governments, integrators, building owners, and the public without consistent, actionable benchmarks.

Our White Paper addresses this critical gap by introducing the **Global Open Indoor Air Quality Standards (GO IAQS)**, a transparent, science-based framework that harmonises pollutant thresholds, strengthens policy direction, and simplifies communication through the GO IAQS Score.

These standards are structured into two tiers:

- **GO IAQS Starter**: Accessible baseline guidelines focused on PM$_{2.5}$ and CO$_2$, enabling immediate global adoption using widely available low-cost sensors.
- **GO IAQS Ultimate**: Advanced, health-protective thresholds covering PM$_{2.5}$, CO$_2$, O$_3$, CO, CH$_2$O, NO$_2$, and radon, aligned with leading global research and regulatory bodies.

Complementing these standards is the GO IAQS Score, which operates as an inclusive, colour-blind, friendly air quality index, enabling intuitive public communication and empowering individuals to make informed decisions in real-time.

The publication also introduces a comprehensive policy roadmap that identifies essential actions for governments, institutions, and practitioners.
These include coordination frameworks, incentives, monitoring strategies, sector-specific requirements, and public transparency measures.

GO AQS provides a unified vision to elevate global health, guide policy transformation, empower communities, and future-proof buildings in an increasingly polluted world.

Key Findings

1. **Indoor air pollution is a universal and urgent health threat.** People are equally vulnerable to airborne pollutants, with impacts ranging from respiratory disease and cardiovascular stress to cognitive decline and developmental harm. Indoor concentrations often exceed outdoor levels, and exposure varies dramatically due to inconsistent standards and building performance.

2. **There is no globally unified standard for indoor air quality.** Existing IAQ regulations focus largely on ventilation rates rather than pollutant concentrations, leaving the public without clear, comprehensible benchmarks. WHO guidelines are essential but not sufficiently adopted or adapted for real-world indoor environments.

3. **Indoor environments require stricter and more specific standards than outdoor settings.** Unique indoor sources, such as building materials, combustion appliances, occupant activity, and ventilation systems, demand pollutant-specific thresholds that account for intermittent occupancy, peak exposure, and vulnerable populations.

4. **Lack of communication raises mortality cases.** Countries have chosen to ignore or limit the knowledge around the dangers of poor air quality. In addition, current air quality indices (AQIs) vary internationally and rely on colour schemes that are not accessible to all users. Combinely, this results in confusing messaging, the fragmentation of knowledge, and ultimately inaction that costs lives.

5. **Effective IAQ improvement requires strong governance and coordinated policy frameworks.** Key barriers include fragmented oversight, limited funding, lack of technical expertise, and insufficient enforcement mechanisms. Clear leadership, transparency, monitoring, and support for disadvantaged communities are indispensable

6. **Vulnerable populations and high-priority sectors need targeted interventions.** Children, the elderly, and individuals with pre-existing conditions face disproportionate risks. Schools, long-term care facilities, workplaces, and homes require tailored standards, monitoring, and resources.

Key Recommendations

1. **Establish national leadership and coordination frameworks.** Governments should designate IAQ coordinators or task forces to harmonise efforts across health, housing, education, and energy sectors.

2. **Adopt and enforce health-based IAQ standards.** National and regional authorities should formally adopt GO IAQS or equivalent pollutant-based standards, integrate them into building codes, and ensure enforcement across both new and existing buildings.

3. **Prioritise high-risk and high-impact sectors.** Implement stringent requirements in:
   - Schools (IAQ plans, monitoring, data transparency, support for under-resourced districts).
   - Long-term care facilities (healthcare-level ventilation and pollutant limits).
   - Workplaces (monitoring, automation systems, public-sector leadership).
   - Residential buildings (healthy housing standards, source control, radon mitigation).

4. **Mandate continuous IAQ monitoring and public transparency.** Real-time monitoring for key pollutants, with data accessible to occupants, should become standard practice. This builds accountability, awareness, and trust.

5. **Two-tier GO IAQS guidelines meet diverse global needs.** Starter Tier provides achievable targets using low-cost sensors ($PM_{2.5}$ and CO_2). Ultimate Tier covers seven critical pollutants with stricter, health-based limits aligned with WHO, ASHRAE, scientific consensus, and global regulations.

6. **Provide financial and technical support to accelerate upgrades.** Governments should deploy grants, subsidies, tax incentives, and pilot programmes for ventilation improvements, filtration upgrades (MERV 13+), and portable air cleaners, especially in disadvantaged communities.

7. **Promote open standards and interoperable technologies.** Integrators and manufacturers should adopt GO IAQS to ensure harmonised data, reduce vendor lock-in, improve system longevity, and foster global innovation..

8. **Launch public awareness and education initiatives.** Effective IAQ improvement requires informed decision-makers and empowered communities. Communication should emphasise pollutant sources, health impacts, and practical mitigation steps.

9. **Strengthen enforcement and inspection frameworks.** Periodic IAQ audits, ventilation assessments, and verified compliance mechanisms are critical to ensuring real-world performance, not just paper compliance.

10. **Clear communication is essential for public understanding.** Current AQIs vary internationally and rely on colour schemes that are not accessible to all users. The GO IAQS Score introduces a simplified 10–0 scale, a three-breakpoint system, and colour-blind–safe palette.

Content

Abbreviations

GO AQS	Global Open Air Quality Standards
GO IAQS	Global Open Indoor Air Quality Standards
GO AAQS	Global Open Ambient Air Quality Standards
IAQ	Indoor Air Quality
AQI	Air Quality Index (or Air quality indices)
WHO	World Health Organisation
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
HVAC	Heating, Ventilation, and Air Conditioning (Systems)
HEPA	High Efficiency Particulate Air
MERV	Minimum Efficiency Reporting Value (Filter rating)
LTCF	Long-Term Care Facilities
BACS	Building Automation and Control Systems
VOC	Volatile Organic Compound
TVOC	Total Volatile Organic Compound
IEQ	Indoor Environmental Quality
STC34	Scientific and Technical Committee 34
API	Application Programming Interface
LCM	Low-cost monitors
LCS	Low-cost sensors
TWA	Time-weighted average
ppb	Parts per billion
ppm	Parts per million
$PM_{2.5}$	Fine Particulate Matter (particles 2.5 microns or less in aerodynamic diameter)
CO_2	Carbon Dioxide
O_3	Ozone
CO	Carbon Monoxide
CH_2O	Formaldehyde
NO_2	Nitrogen Dioxide
Rn	Radon

Introduction

Regardless of age, ethnicity, socioeconomic status, or any other external factor, every human being is equally vulnerable to the negative effects of air pollution. Although everyone breathes the same air, and everyone's body requires clean air to function properly, factors like body size, age, and pre-existing health conditions make people even more susceptible to negative health symptoms. This shared vulnerability emphasizes the importance of protecting air quality for the entire population worldwide.

People breathe oxygen in the air to keep their cells alive and exhale carbon dioxide (CO_2) as a waste product. Polluted air contains harmful components like particulate matter (PM), gases, and toxins that can interfere with this vital process. Breathing polluted air can lead to a variety of health problems, including:

- Respiratory diseases like asthma, bronchitis, and lung cancer.
- Cardiovascular diseases like heart attack and stroke.
- Damage to the nervous system and brain development.
- Increased risk of cancer and other chronic diseases.

Air pollution is not confined to specific regions or countries. It travels across borders and continents, affecting everyone on the planet. Whether you live in a bustling city or a remote village, you are exposed to pollutants originating from various sources like industrial activity, transportation, heating, and agricultural practices. This interconnectedness reinforces the need for collective action and global cooperation to address air pollution challenges.

Ensuring access to clean air is a fundamental human right recognised by international law (United Nations). Access to clean air is critical for a healthy and dignified life, and everyone deserves to breathe freely without fearing the detrimental consequences of air pollution. Denying clean air to any individual or group violates this basic right and raises ethical concerns about environmental justice and equitable distribution of resources.

For these reasons we need to develop and adopt global and open indoor and outdoor air quality standards and air quality indices (aka air quality scores) that will help people understand their exposure regardless where they located in the world.

The need for clean air is universal and transcends individual differences. It is a matter of human survival, well-being, and ethical responsibility. Recognising this shared need is crucial for driving collective action towards cleaner air and a healthier planet for everyone with equal rights.

Indoor Air Quality Policies

Poor indoor air quality (IAQ) poses a significant public health risk, as people spend up to 90% of their time indoors where pollutant levels can be dangerously high. Comprehensive IAQ policies are therefore essential to protect and ensure healthy, productive environments.

To support widespread adoption of improved indoor air quality (IAQ) and uptake of the standards proposed here, policies will be required at the local, state, or national level. The Global Open IAQ Standards (GO AQS) provide a recommendation and template for the global community to follow; however, translating these standards into practice is essential. Translation and adoption of these standards will require: 1) government recognition of the importance of IAQ; 2) government leaders or policymakers that will champion new policies, programmes, incentives, or regulations; 3) specific policy recommendations and templates for standards (WHO, GO AQS) adoption, and 4) a strong practitioner community to provide implementation frameworks and on-the-ground execution.

Non-governmental and independent organisations (e.g., academic institutions) will also play a crucial role in advising governments on adopting and implementing standards. Policies will require a multi-layered, evidence-based approach that is adaptable to different indoor environments such as schools, offices, and homes, among others. Such policies must address coordination, set clear standards, provide implementation support, and prioritize vulnerable populations and high-priority sectors. Here, we outline core principles for IAQ policies.

Core Principles for IAQ Policies

A comprehensive IAQ policy framework should be built on three foundational pillars: 1) strengthen coordination, 2) accelerate improvements through standards and incentives, and 3) target high-priority sectors (outlined below). The primary goal is to ensure buildings provide a healthy indoor climate. Health of building occupants should not be sacrificed for the sake of meeting building energy performance targets - buildings are built for people, and healthy air should be a non-negotiable foundation of sustainable buildings.

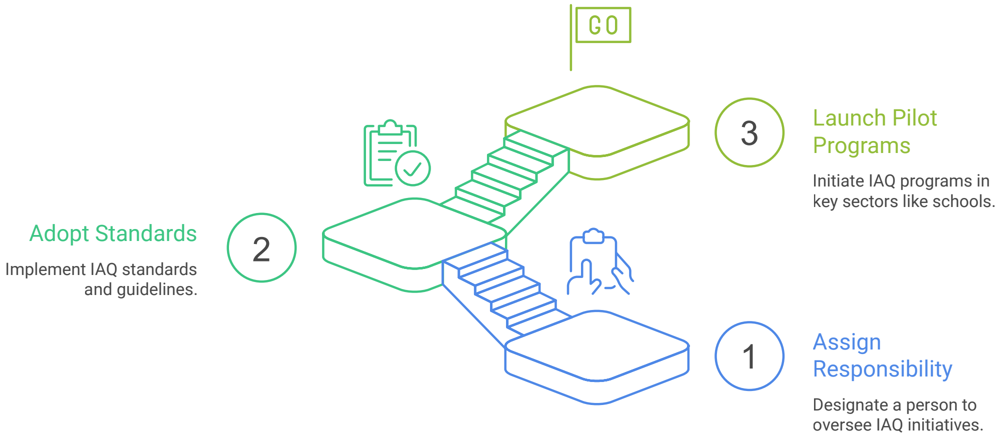

Figure 1. Priority Actions for Policymakers.This figure illustrates the three priority actions that policymakers must undertake to effectively address indoor air quality: assign responsibility for coordination and implementation, adopt standards to ensure consistency and quality, and launch pilot programmes to test and refine approaches before widespread deployment.

I. Strengthen Coordination and Capacity

a. **Appoint Leadership**: At a national or subnational level, designate an Indoor Air Coordinator or a dedicated IAQ program to ensure IAQ is a priority across government agencies (e.g., health, energy, education, housing). Some countries have created interagency task forces or advisory councils with external experts to guide policy.

b. **Set Clear Targets**: There are currently no widely adopted national or global targets for IAQ. In the absence of a unified framework, state and local authorities should set clear, evidence-based targets for key pollutants and ventilation rates. These targets can be based on reputable sources like the World Health Organisation (WHO), Global Open Air Quality Standards, and expert groups.

c. **Publish Guidance**: Public health authorities should publish clear, accessible guidance for different sectors (schools, homes, workplaces, and public buildings) and for high-risk events like wildfire smoke, dust storms, or respiratory disease outbreaks. This helps building owners, facility managers, and the general public understand how to improve IAQ.

II. Accelerate IAQ Improvements

a. **Adopt and Enforce Building Codes**: Building codes are a powerful tool for improving IAQ in new construction and major renovations. Governments should adopt and enforce the most recent versions of mechanical ventilation standards, such as ASHRAE Standards 62.1 (commercial), 62.2 (residential) in the US, EN 16798 (residential and non-residential buildings) in the European Union, and others. However, it is crucial to recognize that newer codes do not apply to existing buildings, and often operations and maintenance components are left out of code adoption. Steps should be taken to ensure routine ventilation maintenance requirements (as found in ASHRAE 62.1) are adopted fully by building code councils.

b. **Lead by Example in Public Buildings**: Governments can demonstrate immediate progress by implementing health-based IAQ requirements in buildings they own, operate, or fund. This includes requiring healthy building certifications or any nationally or internationally recognized certification, conducting regular HVAC assessments, and monitoring IAQ in state and municipal buildings to potentially meet standards such as GO IAQS.

c. **Provide Incentives and Support**: Financial incentives like tax credits or grants can motivate building owners to invest in IAQ upgrades, such as better filters (MERV 13 or higher), HVAC system retrofits, or portable air cleaners when it is not possible to implement mechanical ventilation with filtration, and additionally compensating with other measures to prevent excessive concentrations of CO2 or toxic gases like radon. Pilot programmes are also effective for testing interventions in sectors like schools or public housing.

III. Target High-Priority Sectors

Different indoor environments require tailored policies due to their unique occupancy patterns, vulnerabilities, and emission sources. Priority sectors should include schools and elderly care facilities, which are occupied by vulnerable populations. Furthermore, workplaces and homes host occupants for many hours each day and should also be prioritized. Experts have also called for advancing clean indoor air in all public spaces, which would include government buildings, transportation, and other public spaces (Morawska et al., 2024).

All High-Priority Sectors (Schools, LTCF, Workplaces, Homes) should adhere to the following universal policy components to ensure a foundation of healthy indoor air:

1. Set and Integrate Health-Based Standards: Designate rigorous, health-based standards and targets, such as GO IAQS, for indoor air quality, and ensure the latest building ventilation codes are adopted for all new construction and major renovation projects.

2. Continuous Monitoring and Enhanced Transparency: Implement continuous IAQ monitoring programmes for key pollutants and ventilation performance, and ensure that relevant data is made accessible to facility occupants and stakeholders to promote accountability.

3. Required Ventilation and IAQ Assessments: Mandate regular, qualified ventilation system assessments and general indoor air quality audits to identify performance gaps in existing buildings.

4. Financial and Technical Support for Upgrades: Establish programmes, grants, or tax incentives to support the deployment of clean air technologies, such as MERV 13 filters, HVAC retrofits, and supplemental portable air cleaners, especially for disadvantaged or vulnerable communities.

SECTOR-SPECIFIC POLICIES

A) Schools: Why it is a priority: Children are particularly vulnerable to air pollution because their respiratory system, immune system, and brain are still developing. Clean air in schools improves student health, reduces absenteeism (e.g., due to asthma and influenza), and boosts learning outcomes and test scores.

Recommended actions:

1. **Require IAQ Management Plans**: Mandate that school districts develop and implement written IAQ management plans, designating an IAQ Coordinator to oversee them.

2. **Make Data Visible to Families**: Require that monitored IAQ data is made visible to staff, students, and their families to build confidence and ensure accountability for maintaining a healthy indoor environment.

3. **Prioritize Support for Under-resourced Districts**: Offer targeted grants and specialized technical assistance to under-resourced districts to help with HVAC upgrades and the purchase of portable air cleaners.

B) Long-Term Care Facilities (LTCF): **Why it is a priority**: LTCF house residents who are elderly or have pre-existing health conditions that make them highly susceptible to the negative effects of poor indoor air. The close living quarters facilitate the transmission of airborne pathogens.

Recommended actions:

1. **Compliance with Health Care Standards**: Require LTCFs to comply with rigorous, health-based ventilation standards designed for healthcare environments, such as ANSI/ASHRAE/ASHE Standard 170 and ASHRAE Standard 241 (Control of Infectious Aerosols).

2. **Stricter Pollutant Targets**: Health departments should set stricter health-based targets for key indoor air pollutants (e.g., fine particulate matter, CO2, radon) that go beyond occupational exposure limits, which are inadequate for sensitive populations.

3. **Integrate IAQ into Infection Control**: Mandate the integration of portable air cleaners, higher filter upgrades, and increased ventilation into existing Infection Prevention and Control Practices, especially during times of high respiratory disease transmission.

C) Offices and Workplaces (Non-residential Buildings): **Why it's a priority:** Improved IAQ boosts employee performance and productivity, reduces sick days, and can deliver significant financial benefits. Many workplaces, however, lack enforceable IAQ requirements beyond outdated occupational exposure limits.

Office-specific Policies:

1. **Promote Monitoring and Control**: Require the installation of Building Automation and Control Systems (BACS) in larger non-residential buildings to continuously monitor and actively regulate IAQ and energy use, ensuring systems optimize for both.

2. **Public Sector Leadership**: Public sector workplaces should adhere to the highest IAQ standards to demonstrate feasibility, test implementation strategies, and protect public employees.

D) Homes (Residential Buildings): **Why it's a priority:** People spend most of their time at home, where they can be exposed to a wide range of pollutants from cooking, cleaning products, and building materials. Vulnerable groups are disproportionately affected by poor housing conditions.

Right Policies:

1. **Establish Healthy Housing Standards and Maintenance Codes**: Adopt and enforce statewide property maintenance codes that include clear IAQ requirements for ventilation, mould remediation (referencing standards like ANSI/IICRC S520), and radon control.

2. **Protect Tenants**: Implement proactive rental inspection programmes to identify hazards without relying on tenant complaints, and ensure legislative protections are in place so that renovations do not lead to unfair evictions or rent hikes.

3. **Promote Source Control**: Encourage the switch from gas appliances to electric ones and the use of low/free-VOC materials and cleaning products through public awareness campaigns and product labeling.

4. **Public Awareness Campaign**: Fund widespread dissemination campaigns to explain the problem of indoor pollution, communicate recommended limit values, and detail practical, low-cost recommendations for abatement that respect private residences.

Barriers to Effective IAQ Implementation

While the above policy framework provides a clear roadmap, several high-level systemic barriers impede the effective implementation of IAQ standards globally:

Lack of Coordination and Collaboration: IAQ nis inherently cross-sectoral, involving health, energy, housing, and education agencies. A lack of high-level coordination and clear designation of responsibility (as addressed in Section I) leads to siloed efforts, policy gaps, and fragmented funding streams.

Funding-Constrained Political Environment: Moving IAQ from a best-practice recommendation to a mandated standard requires significant capital investment, especially for retrofitting existing, older building stock. In a constrained political environment, securing the necessary grants, tax incentives, and dedicated public funding to accelerate improvements (as outlined in Section II) remains a continuous challenge.

Lack of Technical Capacity and Workforce: A widespread lack of qualified professionals—from building operators trained in modern ventilation maintenance to inspectors knowledgeable about IAQ metrics—hampers the ability to assess, install, and maintain the necessary infrastructure, particularly in decentralised or under-resourced jurisdictions.

Lack of Enforcement and Oversight Mechanisms: The current policy landscape often includes regulations without corresponding, mandatory mechanisms for verification. This can result in reported compliance that does not reflect real-world, occupied conditions, demonstrating a systemic failure in effective oversight and validation.

Lack of Accountability and Transparency: While monitoring is essential, the absence of standardized, publicly accessible reporting requirements limits the ability of citizens, advocates, and regulatory bodies to hold building owners and policymakers accountable for continuous IAQ performance.

What People Need to Know: The Role of Open Information (like GO AQS)

For global IAQ policies to be effective, the public, advocates, and decision-makers need access to clear, reliable, and open information. Initiatives like the Global Open Air Quality Standards (GO AQS), which aim to centralise this information, are critical for several reasons:

1. **Understanding What to Aim For**: Since there are no universal IAQ standards, people need a single place to find evidence-based targets and guidelines from trusted sources like the GO AQS, WHO, or various national health agencies. This helps communities understand what "clean air" means in measurable terms.

2. **Empowering Advocacy**: Citizens and advocates can use centralised, open data and policy examples to push for practical changes in their local communities, schools, and workplaces. Access to information on best practices and successful case studies from other regions provides a powerful tool for demanding action.

3. **Informing Personal Choices**: Accessible information helps individuals understand the sources of indoor pollution and the concrete steps they can take to protect themselves, such as improving ventilation, using portable air cleaners, wearing a mask, or choosing low-emission products.

4. **Driving Market and Policy Change**: When information on IAQ becomes transparent and widely available, it can influence the real estate market, with consumers potentially choosing hotels or renting apartments based on verified IAQ performance. This, in turn, creates a business case for building owners to invest in healthier buildings, reinforcing the need for clear standards and policies.

The right global IAQ policies are comprehensive, sector-specific, and rooted in strong coordination and public guidance. Openly available resources are the cornerstone of this effort, empowering everyone from individuals to policymakers to make informed decisions that protect public health.

Global Open Indoor Air Quality Standards (GO IAQS)

Did you know there is no single, global standard for clean indoor air? Indoor air quality (IAQ) regulations vary widely across countries, leaving many breathing in a confusion as, in most cases, they focus on ventilation rates and not the pollutants.

Introducing GO IAQS

The World Health Organisation (WHO) has developed air quality guidelines (updated in September 2021). Unfortunately, they are rarely adopted into air quality monitors [1] which are the devices everyday people and scientists use to determine how good or bad is the air quality.

Several integrators have developed their own air quality indices [2] but that initiative creates even more confusion to the public as in many cases multiple instruments from multiple brands are owned by individuals. Air quality indices, while helpful, often present accessibility challenges. The design of these indices can be culturally specific, making them less intuitive for people from other countries. Additionally, the colour-coding used to represent air quality levels may not be inclusive for individuals with colour vision deficiencies. Furthermore, the wording used to describe air quality conditions can sometimes be complex, hindering understanding for those with lower literacy levels or even language barriers. These factors can limit the effectiveness of air quality indices in conveying critical information to a diverse population.

While outdoor air quality standards from many countries serve as a valuable baseline, they are not always directly applicable to indoor environments. This is because indoor spaces have unique factors influencing air quality, such as building materials, ventilation systems, and occupant activities. These factors can significantly contribute pollutants indoors or introduce new ones not commonly found outdoors. Therefore, stricter or more specific IAQ standards are often necessary to ensure a healthy and comfortable environment.

Taking into account most of the available IAQ standards, thanks to the Scientific and Technical Committee 34 (STC34) IEQ guidelines, we were able to develop new standards that are easy to understand as the language behind them is universal and simple to comprehend.

For integrators, adopting open standards in their devices unlocks a multitude of benefits that enhance project success, future-proof, and improve overall client satisfaction. Here are some key reasons why integrator adoption of the GO IAQS is crucial:

1. Seamless Interoperability and Data Exchange:

Imagine the frustration of trying to understand new air quality indices from different brands. Open standards eliminate these headaches by ensuring devices from different manufacturers can communicate the same information and exchange data seamlessly (e.g. harmonised metrics). Furthermore the adherence to IAQ standards promotes the integration of different air quality data obtained from many and different low-cost sensors.

2. Increased Choice and Flexibility:

Open standards break the vendor lock-in, empowering users to choose the best-fit equipment for each project, not just those made by the same company. This opens up a vast pool of innovative solutions and allows you to tailor systems to specific client needs and budgets without compromising on quality.

3. Future-proofing:

Closed, proprietary systems become obsolete quickly. Open standards, constantly evolving through community collaboration, guarantee longer lifespans for your clients' systems. Upgrades and expansions of air quality monitoring systems become easier, as new devices from any compliant vendor can seamlessly integrate with existing infrastructure. This translates to reduced long-term costs and increased client satisfaction with a system that stays relevant.

4. Lower Costs and Faster Time-to-Market:

Open standards are typically royalty-free, eliminating expensive licensing fees. Additionally, the plug-and-play nature of interoperable Application Programming Interface (API) that uses the GO IAQS reduces integration time and complexity. This leads to significant cost savings and faster project completion times, increasing your competitiveness and profitability.

5. Fosters Innovation and Collaboration:

Open standards create a dynamic ecosystem where researchers, developers, and manufacturers can collaboratively innovate, leading to advancements in technologies and functionalities.

Note: It's important to understand that GO IAQS, while valuable for assessing indoor air quality in general, is not designed or intended for the specific purpose of ensuring occupational safety. Organisations like OSHA (Occupational Safety and Health Administration), EU-OSHA (European Agency for Safety and Health at Work), and NIOSH (National Institute for Occupational Safety and Health), to name a few, are the authoritative bodies that provide guidelines, regulations, and recommendations specifically aimed at protecting worker health and safety through the management of workplace air quality. Their focus includes permissible exposure limits (PELs), threshold limit values (TLVs), and other critical factors relevant to occupational environments.

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1. An Air Quality monitor is a device that measures and reports on the levels of various pollutants in the air.
2. An Air Quality Index (AQI) is a number used to communicate how polluted the air currently is or how polluted it is forecast to become. It's a simple way to quickly understand how the air quality might affect your health.

GO IAQS Guidelines

Air quality guidelines are set to define safe levels of various pollutants in the air we breathe. These limits are crucial for protecting public health, as exceeding them can cause respiratory problems and other health issues. There are two main types of limits: short-term and long-term. Short-term limits focus on daily or hourly concentrations of pollutants, while long-term limits target annual averages. These limits based on scientific studies and are constantly reviewed as new information emerges.

A significant development in building safety is the introduction of IAQ guidelines. These guidelines consider exposure duration or maximum values.

The World Health Organisation (WHO) has established guidelines for both indoor and outdoor air quality. The basis for developing these health guidelines is health information, particularly the exposure-response relationship. Based on available data, recommendations were developed for 24-hour and annual concentrations. For these specific averaging periods, the same recommendations apply whether the exposure occurs indoors or outdoors, as there are no differences in the exposure-response relationship identified for these durations.

Applying these guidelines to specific indoor environments with intermittent occupancy, such as public spaces, presents challenges. While the WHO provides recommendations for 24-hour and annual averages based on available epidemiological data, they do not offer recommendations for shorter durations like 1-hour due to a lack of sufficient exposure-response data for such periods. This data gap means the guidelines do not directly address potential peak exposures during periods of high occupancy, which annual or 24-hour averages may obscure. Furthermore, the WHO 2021 Air Quality Guidelines do not provide recommendations for all specific exposure scenarios, such as occupied buildings, offices, or schools, as this is not the primary focus of the document.

Finally, GO IAQS' guidelines are categorised into two tiers: "Starter" and "Ultimate." This distinction caters to different needs, potentially offering achievable goals for beginners in air quality management while providing stricter guidelines for those seeking optimal indoor environments based on the latest research.

GO IAQS Starter

A starter guideline is a great first step for those who lack the resources for stricter protocols. It offers a basic compliance framework requiring minimal investment. Think of it as a stepping stone - you cannot climb a mountain without taking the first step, and a starter standard gets you on the path towards achieving more rigorous goals.

The first tier GO IAQS Starter only pays attention to two basic indoor pollutants that can be monitored with the existing low-cost monitors (LCM) technology in an accurate manner. Fine particulate matter – particles that are 2.5 microns or less in aerodynamic diameter ($PM_{2.5}$) – and carbon dioxide (CO_2) LCS are widely available worldwide and affordable by most dwellers.

Particulate Matter ($PM_{2.5}$)

GO IAQS's adoption of the WHO 2021 Air Quality Guidelines interim target 4 of 25 µg/m^3 for 24-hour $PM_{2.5}$ exposure demonstrates a strong commitment to public health, aligning its standards with the latest scientific understanding of harmful particulate matter. This proactive step not only mirrors the WHO's recommendations for progressively improving air quality but also reflects a convergence with various indoor air quality guidelines and regulations established by governments worldwide. By embracing this target, GO IAQS positions itself at the forefront of efforts to create healthier indoor environments, acknowledging the global consensus on the importance of minimizing exposure to airborne pollutants.

Carbon Dioxide (CO_2)

CO_2 can act as a helpful indicator for potential problems with IAQ and the spread of airborne diseases. Since humans are the primary source of CO_2 indoors, its rising levels often signal inadequate ventilation. This stagnant air can then trap other pollutants emitted from building materials, cleaning products, or even people themselves.

While CO_2 itself is not directly harmful at low concentrations, its presence suggests a higher likelihood of these other irritants and pathogens being present, prompting the need for improved ventilation to reduce the risk of health problems and the spread of airborne illnesses.

Given a baseline outdoor CO_2 concentration of 450 ppm, we recommend setting an indoor CO_2 limit of 1000 ppm. This recommendation is grounded in the widespread adoption of this value by numerous countries and green building organisations, reflecting a consensus on a practical and achievable target for maintaining acceptable indoor air quality. This standardized limit serves as a balance between ensuring adequate ventilation and minimizing energy consumption associated with excessive air exchange.

Note: While the WHO 2021 Air Quality Guidelines provide crucial benchmarks for both indoor and outdoor air quality, their annual average concentration target, while valuable for assessing outdoor air pollution, is less informative for indoor air quality in intermittently occupied public spaces. Averaging pollutant concentrations across both occupied and unoccupied periods in such buildings can obscure the potentially higher and more relevant exposure levels experienced during occupancy, which is the critical period from a public health standpoint. This contrasts with outdoor air quality, where continuous exposure necessitates the use of annual averages to gauge long-term health impacts.

GO IAQS Starter Guidelines	$PM_{2.5}$	CO_2
24-hour	25 µg/m^3	
Threshold		1000 ppm (1)

GO IAQS Starter Guidelines

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1. Given a baseline outdoor CO_2 concentration of 450 ppm.

GO IAQS Ultimate

The second tier GO IAQS Ultimate was developed for buildings that want to offer ever higher performance and health protection to occupants.

GO IAQS's Ultimate guidelines represent a significant advancement in the pursuit of healthy indoor air quality. These guidelines are designed to be encompass a wider array of pollutants such as Particulate Matter ($PM_{2.5}$), Carbon Dioxide (CO_2), Ozone (O_3), Carbon Monoxide (CO), Formaldehyde (CH_2O), Nitrogen Dioxide (NO_2) and Radon (Rn) that emerging research has identified as critical to human health. Furthermore, the limits set within these guidelines are demonstrably stricter than the GO IAQS Starter and many existing regulations, reflecting the latest scientific understanding of the adverse health effects associated with even low levels of certain pollutants. By adopting these more stringent limits, GO IAQS aims to create indoor environments that offer a higher level of protection, aligning with and often exceeding the recommendations put forth by leading health organisations and progressive government bodies worldwide. This commitment to incorporating the most up-to-date research and regulatory standards underscores a proactive approach to safeguarding public health within indoor spaces.

Particulate Matter ($PM_{2.5}$)

The GO IAQS Ultimate tier incorporates the influential research of Morawska et al., 2024, adopting a 15 µg/m^3 1-hour averaging time limit for $PM_{2.5}$ exposure. This 1-hour limit represents a carefully considered balance between acknowledging the practical realities of occupancy and exposure patterns in public spaces and upholding the scientific rigor required for a health-based standard. By focusing on a shorter averaging period, this approach avoids the underestimation of exposure that can occur with longer averages in intermittently occupied spaces. While a 1-hour exposure assessment adopts a conservative perspective, essentially treating each environment as a space of continuous occupancy, it ensures a robust level of health protection that aligns with the need for stringent air quality in public settings.

Carbon Dioxide (CO_2)

The GO IAQS Ultimate tier recognizes once more the significant findings of Morawska et al., 2024, by adopting a CO_2 threshold of 800 ppm. This level is particularly relevant when considering spaces ventilated with 100% outdoor air, assuming a typical outdoor CO_2 concentration of 450 ppm. Maintaining indoor CO_2 levels below this threshold in such scenarios indicates effective ventilation, ensuring that occupants are primarily breathing fresh, outdoor air and that the buildup of internally generated pollutants is minimized. This focus on CO_2 as a proxy for ventilation effectiveness underscores the GO IAQS Ultimate tier's commitment to creating healthy indoor environments through optimal air exchange and directly addressing a key factor in the spread of respiratory infections.

Ozone is a highly reactive gas that can be harmful to human health when inhaled. While it plays a crucial role in protecting the Earth from harmful UV radiation in the stratosphere, it becomes a pollutant when present in high concentrations at ground level. O_3 can enter homes and buildings from outdoor air, but it can also be generated indoors by various sources like photocopiers and printers, some air purifiers, gas stoves, and certain cleaning products.

Ozone (O_3)

The ozone limit adopted by GO IAQS aligns with the WHO 2021 Air Quality Guidelines, setting an 8-hour average of 51 ppb, a value that reflects a growing international consensus on acceptable exposure levels. This standard is not only supported by the WHO's expert recommendations but also mirrors the governmental guidelines and regulations established in various countries, including Poland, Singapore, Malaysia, the United Kingdom, and Slovenia. The convergence of these diverse regulatory bodies on a similar O_3 limit underscores a shared understanding of the potential health risks associated with O_3 exposure and highlights a global effort to establish protective air quality standards.

Formaldehyde (CH_2O)

Formaldehyde as a specific measurement provides a more targeted assessment of potential health risks. Formaldehyde is commonly found in building materials, furniture, and other household products, making it a crucial factor to monitor for IAQ. By focusing on CH_2O levels, individuals can take more informed steps to mitigate potential health hazards.

The CH_2O limit within GO IAQS is directly adopted from ASHRAE Standard 189.1-2020, the Standard for the Design of High-Performance Green Buildings, which recommends a maximum concentration of 27 ppb for this significant indoor air quality pollutant. ASHRAE's comprehensive approach to sustainable building design identifies CH_2O as a key concern due to its potential health impacts, and this specific limit reflects a balance between achieving high-performance building standards and ensuring occupant health and well-being. By aligning with this recognized industry benchmark, GO IAQS underscores its commitment to incorporating established best practices in indoor air quality management.

Carbon Monoxide (CO)

While acute exposure to CO can lead to immediate symptoms like headache, dizziness, nausea, or even death, the long-term effects of low-level exposure remain a significant concern. Preliminary research suggests chronic CO exposure and neurological disorders. The scientific community must invest in further investigations to elucidate the mechanisms through which low-level carbon monoxide exposure can mimic the symptoms of neurological conditions such as Parkinson's disease. By establishing clear target thresholds, we can safeguard public health and mitigate the potential long-term consequences of CO exposure.

The carbon monoxide limits adopted by GO IAQS draw upon established guidelines from both the WHO 2010 and the latest research by Morawska et al., 2024, setting an 8-hour average of 9 ppm and a more stringent 1-hour limit of 31 ppm. The 8-hour average of 9 ppm represents a widely accepted standard internationally, shared by countries such as United Kingdom, Singapore, Australia, Nigeria, and the United Arab Emirates, reflecting a global consensus on managing longer-term exposure to this colourless and odorless gas. The inclusion of a stricter 1-hour limit based on contemporary research further emphasizes GO IAQS's commitment to addressing potential acute exposure risks and ensuring a higher level of protection for occupants.

Nitrogen Dioxide (NO_2)

Nitrogen dioxide is a respiratory irritant that can exacerbate asthma, bronchitis, and other respiratory conditions. It can also lead to inflammation of the lungs and reduced lung function. The primary sources of indoor NO_2 are combustion appliances like gas stoves, gas heaters, and wood-burning fireplaces. Outdoor NO_2, primarily from vehicle emissions and industrial activities, can enter homes and buildings through open windows, doors, and ventilation systems. It's crucial to be aware of these sources and take steps to reduce NO_2 emissions to maintain healthy indoor air quality.

The NO_2 limits within GO IAQS are derived from the WHO 2010 guidelines, establishing a 1-hour average of 106 ppb, a value consistent with government regulations in France and the United Kingdom. Additionally, GO IAQS adopts an 8-hour average limit of 21 ppb for NO_2, which aligns with the regulatory standards and guidelines set forth by countries such as Nigeria, Hong Kong, and Singapore. This dual approach, incorporating both a short-term and a longer-term exposure limit based on established international and national standards, reflects a comprehensive strategy to mitigate the potential health impacts associated with NO_2 pollution in indoor environments.

Radon (Rn)

Radon is a naturally occurring radioactive gas that seeps into homes from the ground. While it's invisible and odorless, it poses a significant health risk. Radon is the second leading cause of lung cancer in the United States, and the leading cause among non-smokers. Prolonged exposure to high radon levels significantly increases the risk of developing this deadly disease.

The radon reference level adopted by GO IAQS is set at 100 Bq/m^3, aligning with the recommendations from the WHO 2010 guidelines. It is crucial to understand that this value is a reference level, not a safety threshold. This designation implies that there is no level of radon exposure below which the risk of adverse health effects, particularly lung cancer, is entirely eliminated. The 100 Bq/m^3 reference level serves as a point above which interventions to reduce radon concentrations are strongly encouraged to minimize potential health risks.

Disclosures:

$PCN_{0.3}$ and $PCN_{0.5}$

At GO IAQS, the initial aspiration was to incorporate limits for $PCN_{0.3}$ and $PCN_{0.5}$ within the guidelines. However, following extensive discussions among the Particulate Matter working group, it was determined that the current lack of sufficient data and research necessitates excluding these sub-micron particle counts from the first version of the guidelines. Despite this omission, we strongly encourage the scientific community to prioritize investigations into the health impacts of $PCN_{0.3}$, $PCN_{0.5}$ or even ultra fine particles (UFP). Furthermore, sensor manufacturers are urged to expand their capabilities beyond $PM_{2.5}$ measurements, focusing on the development and calibration of sensors that can accurately quantify particle count numbers for these crucial sub-micron fractions.

Mass concentration ($PM_{2.5}$), while useful for larger particles, falls short for sub-micron particles. Since these tiny particles are incredibly light, their mass is negligible and can be misleading. Instead, particle count provides a more accurate picture of potential health risks. By counting the individual particles, we can understand how many could be infiltrating our lungs, regardless of their minute weight.

While GO AQS won't be establishing formal limits for $PCN_{0.3}$ and $PCN_{0.5}$ for the reasons we've discussed, our internally gathered anecdotal data suggests some practical benchmarks for these submicron particles. Within a HEPA-controlled office setting, maintaining levels below 10 particles/cm^3 for $PCN_{0.3}$ and below 3 particles/cm^3 for $PCN_{0.5}$ (8-hour mean) appears to correlate with good air quality. In contrast, for general ambient air, a reasonable target for low levels might be below 50 particles/cm^3 for $PCN_{0.3}$ and below 20 particles/cm^3 for $PCN_{0.5}$ (8-hour mean). It's important to remember these are not official standards but rather observations from our data that can serve as a helpful guide.

Total Volatile Organic Compound (TVOC)

It is crucial to acknowledge the absence and limitations of TVOC. These values often lack specificity, providing a general measurement of various volatile organic compounds present in the air. Due to this lack of specificity and the wide range of VOCs with varying health impacts, the GO AQS currently does not include a specific limit for TVOC (Salthammer, 2022). If a TVOC sensor indicates elevated levels indoors, further investigation is strongly recommended. This may involve professional assessment by experts utilizing laboratory-grade methods to identify and quantify specific VOCs present in the environment. As initiatives like VDI/VDE 3518 work towards a standardized definition of TVOC sensing technology through collaboration with sensor manufacturers, the GO AQS will eagerly incorporate a TVOC limit once the industry adopts this refined definition.

Units of Measurement

GO AQS prioritizes reporting gas pollutant concentrations, such as O_3, NO_2, CO, and CH_2O, in parts per million (ppm) or parts per billion (ppb), aligning with the direct output of instruments. While conversion to mass units (e.g., µg/m^3) is feasible, it necessitates accurate absolute temperature and atmospheric pressure data, which some instruments lack. Even when these sensors are present, some may default to standard conditions (25°C, 1 atm) for conversion, compromising accuracy. In such cases, GO AQS recommends clear disclosure of the conversion method. In contrast, the WHO primarily utilizes mass concentrations for these pollutants. To bridge this gap and facilitate clear communication, GO AQS will provide a conversion table, enabling users to easily translate between volume and mass units, Appendix B.

Finally, becquerels per cubic meter (Bq/m^3) is the most commonly used unit of measurement for radon worldwide. It is the preferred unit in the International System of Units (SI) and is widely adopted by scientific and regulatory bodies.

GO IAQS Ultimate Guidelines	$PM_{2.5}$	CO_2	O_3	CH_2O	CO	NO_2	Radon
1-hour	15 µg/m^3				31 ppm	106 ppb	
8-hour			51 ppb		9 ppm	21 ppb	
Threshold		800 ppm (1)		27 ppb (2)			100 Bq/m^3 (3)

GO IAQS Ultimate Guidelines

1. Given a baseline outdoor CO_2 concentration of 450 ppm.
2. Maximum concentration of formaldehyde relevant to IAQ.
3. The designation of reference level, not a safety threshold implies that there is no level of radon exposure below which the risk of adverse health effects.

GO IAQS Score

The GO IAQS Score, aka Air Quality Index (AQI), is a measurement system that translates complex air pollution data into a user-friendly score. It considers pollutants like gases and particulate matter, condensing them into a single value from 10 to 0.

Simplicity

The scientific community emphasizes the need for air quality indices (AQIs) that are both simple and comprehensive to effectively communicate air quality information to the public and policymakers (Kanchan et al., 2015; K & Kumar, 2022; Gayer et al., 2018; Guttikunda, 2024)

This easy-to-understand number corresponds to a colour-coded health risk category, allowing people to quickly grasp how safe the air is to breathe. However, with different countries and organisations using slightly varying AQI scales, confusion can arise. A single, unified AQI would eliminate this ambiguity, offering a universally understood picture of air quality. This would empower people to make informed decisions about their health and well-being, while also providing a more comprehensive global perspective on air pollution.

While some agencies and companies try to tackle complexity with custom AQI, their numerous breakpoints can be confusing. Many AQIs use colour coding, but with too many ranges, similar colours become difficult to differentiate.

Therefore, GO IAQS proposes a 3-breakpoint AQI that combines the strengths of the, US EPA, South Korean CAI, and the EU EAQI, offering a more realistic and user-friendly colour scheme (see proposed GO IAQS Score below). This streamlined approach would be easier to understand and remember.

Many countries use a combination of grades (letters) and numbers as a score system at schools. For example, a school might use A, B, C, etc. for grades, but also have a numerical scale from 1 to 10. Ten (10) is the highest achievable score and reflects outstanding performance. GO IAQS adapts the same logic.

Having the categories colour-coded, numerical ordered 10 (Highest Score) - 0 (Lowest Score) and alphabetically named A/B/Z, GO IAQS makes sure it easy to understand and share the information with others, for example, users could easily mention "*The air indoors is rated **B** now*" or "*The air is **Moderate** in the classroom, now*". The localization of the words and letters A/B/Z in air quality communication is crucial for encompassing diverse languages and fostering better understanding.

To align with a more health-centric approach, these breakpoints will be categorised as **Good, Moderate, and Unhealthy**. While the "Good" category may not signify a completely pollution-free environment, it represents air quality conditions that generally pose minimal risk to public health. It's important to note that even low levels of certain pollutants can have potential health implications, especially for vulnerable populations. The "Moderate" category indicates air quality that may cause minor health concerns especially for sensitive individuals, such as those with respiratory or pre-existing health conditions. The "Unhealthy" category signifies air quality that could adversely affect the health of all population.

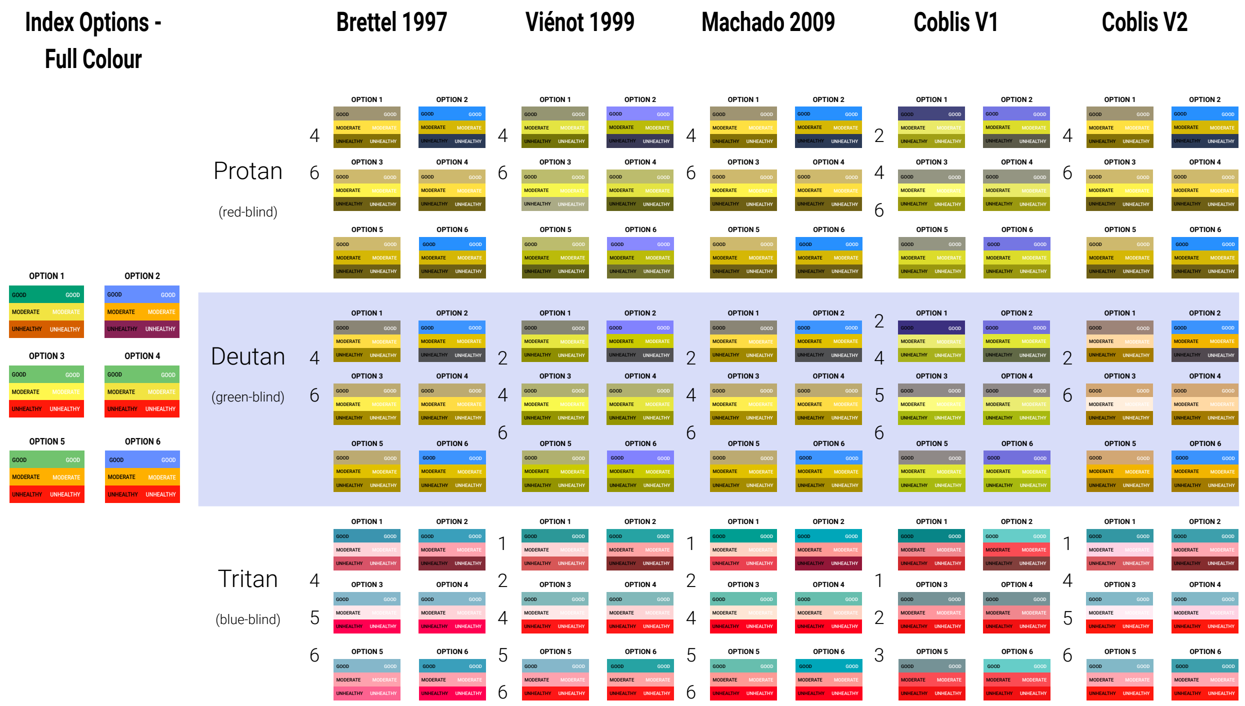
Score Colours

To enhance our understanding of colour vision deficiency, we simulated various index colour options using different simulation profiles and we created a matrix, which we called CVD AQI Matrix. We assessed the readability of black and white text against diverse background colours and the distinguishability of different score levels. Here it worths mentioning that deuteranomaly, the most common form of red-green colour vision deficiency, distorts certain shades of green, making them appear more red. This condition, often congenital, affects approximately 8% of males and 0.5% of females (National Eye Institute, n.d.).

After analyzing all colour variations in the CVD AQI Matrix simulation, we concluded that Option 6 is the most suitable choice for the GO IAQS Score.

GO IAQS Score HEX Colour Code:

- **Good #648eff**
- **Moderate #ffb000**
- **Unhealthy #ff190c**



CVD AQI Matrix

Description	Number Score	I_{high} - I_{low}	Letter Score	Health advice
Good	10 - 8	2 - 0	A	Ideal air quality - Enjoy activities
Moderate	7 - 4	6 - 3	B	Reduce sources of pollution. Cut back or reschedule strenuous activities indoors. Ventilate and/or filtrate.
Unhealthy	3 - 0	10 - 7	Z	Leave the room. Avoid all physical activities indoors. Wear N95/FFP3 masks and use personal or central air filtration systems in case of particle pollution or high carbon dioxide levels. Ventilate.

GO IAQS Score

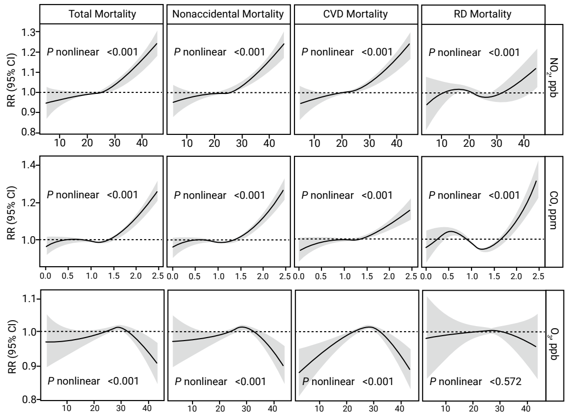
Air Pollutant	Good (C_{low} - C_{high})	Moderate (C_{low} - C_{high})	Unhealthy (C_{low} - C_{high})
$PM_{2.5}$ ($\mu g/m^3$)	0 - 10	11 - 25	26 - 100
CO_2 (ppm)	400 - 800	801 - 1400	1401 - 5000
CO (ppm)	0 - 1.7	1.8 - 9.0	9.1 - 31
CH_2O (ppb)	0 - 27	28 - 100	101 - 500
O_3 (ppb)	0 - 25	26 - 100	101 - 300
NO_2 (ppb)	0 - 21	22 - 100	101 - 250
Radon (Bq/m^3)	0 - 100	101 - 150	150 - 300

Score Breakpoints (based on pollutant concentrations)

Weighting Factors

An initial internal GO AQS survey revealed varying opinions on the appropriate weighting of different pollutants in the GO IAQS Score. While the original proposed system assigns equal weight to all pollutants, many experts suggested adjustments. Specifically, there was an agreement that $PM_{2.5}$ should have a greater weight due to its significant impact on human health. Conversely, CO_2 was deemed less critical and should therefore contribute less to the index value. Other pollutants, including particle number ($PCN_{0.3/0.5}$), O_3, CH_2O, CO, NO_2, and radon, were generally considered to require increased weighting to accurately reflect their potential health risks. These insights highlight the need for a refinement approach to pollutant weighting and synergistic effects of multiple pollutants, ensuring that the index effectively prioritizes the most harmful substances and provides accurate information to the public.

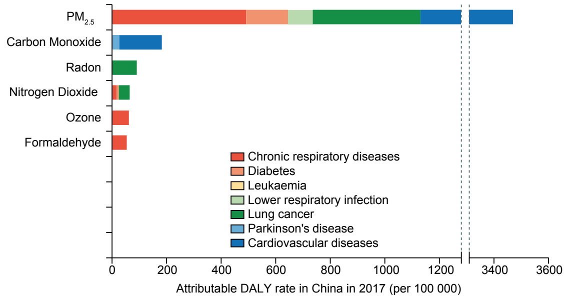
The scientific literature emphasize the significant impact of long-term exposure to gaseous air pollutants, particularly NO_2 and CO, on mortality risk. These pollutants are causally linked to increased rates of total, non-accidental, and cardiovascular deaths. While O_3 did not show a significant association overall, it was linked to increased mortality risk in individuals aged 65-74. The study reveals that the risk of mortality increases more sharply at higher exposure levels for NO_2 and CO. Younger individuals, specifically those aged ≤64 years, exhibit greater vulnerability to the harmful effects of CO. Researchers strongly suggest that targeted policies are needed to mitigate these risks, with NO_2 being a primary concern (Yu et al., 2024).



Estimated exposure–response curves for the associations of gaseous pollutant concentrations with total, non-accidental, cardiovascular, and respiratory mortality.

A large-scale international study on short-term CO exposure and mortality has revealed a significant and concerning association between ambient CO levels and increased daily mortality rates, even at concentrations below current air quality guidelines. Specifically, a 1 mg/m^3 increase in the average CO concentration of the previous day was linked to a 0.91% increase in daily total mortality. The study highlights that there appears to be no safe threshold for CO exposure, with even low levels posing potential health risks. Notably, the risk associated with CO exposure is particularly pronounced at lower concentrations, underscoring the importance of controlling emissions even when levels seem relatively low (Chen et al., 2021).

Liu et al. (2023) examined the burden of disease attributable to indoor air pollutants in China from 2000 to 2017. The researchers found that while there has been a 20% decrease in disability-adjusted life years (DALYs) attributed to indoor air pollutants (IAPs) over this period, IAPs still ranked as the third leading risk factor in China in 2017, after tobacco and high blood pressure. This indicates the significant impact these pollutants continue to have on human health. The study identified ten specific IAPs with the greatest impact: $PM_{2.5}$ was the most significant contributor to the burden of disease, accounting for 88.5% of total DALYs. The health effects of $PM_{2.5}$ are well-documented and include respiratory and cardiovascular diseases. CO, also a major contributor, is known to reduce oxygen-carrying capacity in the blood, leading to various health problems. Radon, a radioactive gas, increases the risk of lung cancer. NO_2 is associated with respiratory illnesses. CH_2O is linked to respiratory problems and eye irritation.



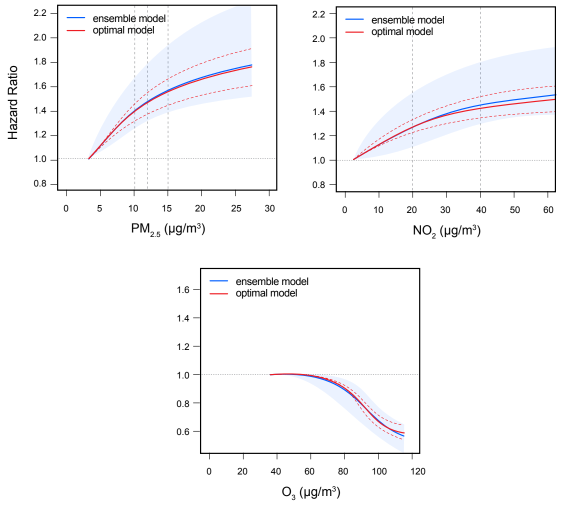
National-level DALY rates (per 100 000) attributable to ten targeted indoor air pollutants in China in 2017

Wang et al. (2021b) demonstrated that short-term exposure to ambient CO, even at levels below the current Chinese Ambient Air Quality Standards, was significantly associated with increased daily years of life lost (YLL) from various causes, including non-accidental, cardiovascular, and respiratory diseases. Certain subgroups, including females, elderly individuals, people with lower educational attainment, and residents of southern Chinese cities, were found to be more vulnerable to the adverse effects of CO exposure. However, the study also found that cities with higher urbanization rates, greater GDP and GDP per capita, and more robust healthcare infrastructure experienced attenuated harmful effects of CO on YLL, suggesting that socioeconomic development and improved healthcare access may offer some protection against the negative health consequences of CO pollution. Notably, the study estimated that reducing daily CO concentration to 1 mg/m^3 could result in a gain of 0.081 years of life per deceased person, highlighting the potential public health benefits of implementing policies and interventions to reduce CO emissions.

Holnicki et al. (2017) emphasizes that $PM_{2.5}$ is the most significant contributor to air pollution-related health risks in Warsaw. While other pollutants, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and heavy metals, were also considered in the study, their contributions to the overall health burden were considerably smaller compared to $PM_{2.5}$. The researchers found that $PM_{2.5}$ was responsible for nearly all (91%) of the attributable deaths caused by air pollution in the city. When considering both mortality and morbidity, $PM_{2.5}$ accounted for about 71% of the total DALYs lost due to air pollution.

The literature highlights how the composition of pollutants, particularly particulate matter, can significantly influence their toxicity. For example, Gavett et al. (2003) and Schaumann et al. (2004) studies found that PM with a higher content of heavy metals caused more severe inflammatory responses than PM with lower metal content. Other pollutants discussed in the literature, such as O_3 and NO_2, also pose health risks, primarily to the respiratory system. However, their impact might be less pronounced compared to $PM_{2.5}$, and they might also act as precursors to the formation of secondary pollutants like $PM_{2.5}$ (Weisenberg et al., 2020).

A major report looked into long-term exposure to low levels of ambient air pollution, particularly $PM_{2.5}$, NO_2, and O_3. $PM_{2.5}$ and NO_2 exhibit consistent positive associations with various causes of death, including all-cause, cardiovascular, respiratory, and diabetes mortality. These associations were observed even at low concentrations, specifically below 12 µg/m^3 for $PM_{2.5}$ and 40 µg/m^3 for NO_2. Notably, the shape of the concentration-response function for these pollutants tends to be linear to supra-linear, indicating a steeper risk increase at lower concentrations. This suggests that even small reductions in these pollutants could yield substantial public health benefits. O_3, unlike the other pollutants, generally shows inverse associations with mortality. This means that higher ozone concentrations are linked to lower mortality rates. However, one study indicates potential increased risks at O_3 exposures above 85 µg/m³. Similar to mortality, $PM_{2.5}$ and NO_2 are associated with increased risks of several morbidity outcomes, including stroke, asthma, and COPD. Additionally, NO_2 is linked to acute coronary heart disease, and $PM_{2.5}$ to lung cancer incidence. These findings were consistent across both pooled and administrative cohorts (Health Effects Institute, 2023).

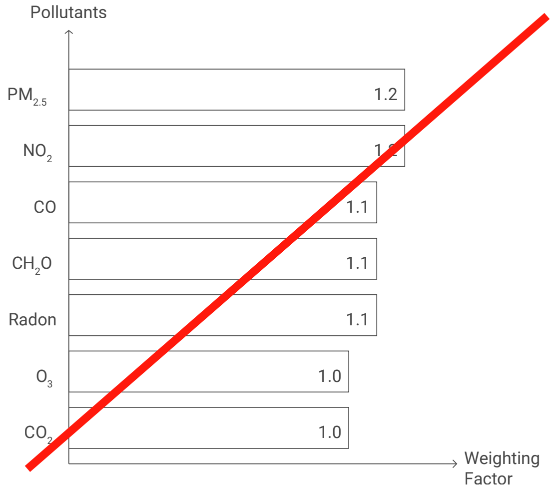


Associations between air pollution exposure and natural-cause mortality.

$PM_{2.5}$ stands out as the pollutant most strongly associated with both mortality and morbidity. The literature consistently demonstrate $PM_{2.5}$'s link to increased risks of premature death from cardiovascular and respiratory diseases, as well as a range of morbidity outcomes like asthma, COPD, and lung cancer. This strong association with adverse health outcomes is reflected in the development of air quality indices (AQI), where $PM_{2.5}$ typically receives a high weighting factor, indicating its significant contribution to overall air quality and health risks. While specific weighting methodologies vary between countries and regions, the underlying principle is to prioritize pollutants with the greatest potential for harm. For example, the US Environmental Protection Agency's AQI assigns a higher weighting factor to $PM_{2.5}$ compared to other pollutants like ozone and carbon monoxide, emphasizing its greater impact on public health. In addition to $PM_{2.5}$, other pollutants like NO_2 and O_3 also contribute to mortality and morbidity and are considered in AQI development, although with generally lower weighting factors compared to $PM_{2.5}$.

This weighting approach reflects the relative severity of health risks posed by different pollutants, ensuring that the AQI effectively communicates the overall health risks associated with air quality.

The GO IAQS Score will no longer use weight factors for pollutants. Instead, it will directly incorporate the measured concentrations of each pollutant. This simplified approach reflects a decision to remove weighting factors from the score. Previously, the score had assigned multipliers to different pollutants. For context, $PM_{2.5}$, were slated to receive the highest weight of 1.2, reflecting their significant health impacts. NO_2 was also assigned a weight of 1.2 due to its respiratory and cardiovascular risks. CO, CH_2O, and Radon were to receive a weight of 1.1, acknowledging their potential health effects. O_3 and CO_2 were assigned a weight of 1.0, with CO_2 intended as a surrogate for air renovation, as high concentrations can potentially indicate the accumulation of other indoor air pollutants and pathogens. However, these weightings will not be used in the revised GO IAQS Score.



Weighting Factors for Pollutants

Synergistic Effects of Pollutants

The scientific literature criticizes single-pollutant AQIs, which report only the highest pollutant value, for underestimating the actual air quality status and potentially providing a false sense of security by neglecting the combined effects of multiple pollutants (K & Kumar, 2022; Cromar et al., 2020; Kanchan et al., 2015).

We considered the AQHI (Stieb et al., 2008) and GAQHI (Tan et al., 2020) indexes as potential frameworks for a multiple-contaminant approach to indoor air quality. While these indexes offer a valuable framework, we identified two key limitations: Firstly, the data and weight factors used in these indexes primarily represent a specific geographical region (Canada), potentially limiting their applicability to other regions with distinct pollutant profiles and exposure patterns. Secondly, there is a notable lack of comprehensive scientific research on the impact of multiple indoor contaminants on human health, particularly in the context of indoor environments. This knowledge gap hinders the direct application of the AQHI and GAQHI methodologies to the development of GO IAQS. For instance, the transformation of ozone into secondary pollutants upon entering indoor environments, as highlighted by Quarcoo et al. (2019), underscores the complexity of indoor air chemistry and the need for further research to accurately assess indoor air quality.

In fact, the solution to the single-pollutant AQIs conundrum could be what the Dutch Air Quality Index suggests which calculates a total index by considering the individual indices of multiple pollutants, assigning a lower overall score when multiple pollutants reach similar levels, but when all pollutant indices available have the same value for the moderate and unhealthy breakpoints, then the total score is equal to the next lower value. (Air Quality, Energy and Health (AQE), 2023). GO IAQS adopts the same logic for the overall calculation of the score.

GO IAQS Score

Existing studies and country-specific indices investigate the health effects of pollutants, yet their established limits are predicated on time-weighted average (TWA) exposure concentrations. We intend to harness real-time pollution measurement capabilities (sampling at one-second intervals) to provide instantaneous alerts to occupants regarding indoor air quality risks.

For this reason, the GO IAQS Score is based on continuous measurements, otherwise it moves to the next available time frame. It is important to proof the AQI from possible issues and inconsistencies. For this reason, we have created the GO IAQS Score Playground, and you can find it in Appendix A.

The GO IAQS Score will clearly indicate the dominant pollutant(s) to assist with evaluation and mitigation. Additionally, the use of integer numbers for the Score simplifies communication and understanding for the general public. By presenting the AQI as a single, easily comprehensible integer, individuals can quickly grasp the current air quality conditions.

Please refer to Appendix D for a comprehensive comparison of the indoor and outdoor indices, where various colour schemes, values, and the numbers of breakpoints are meticulously analysed.

Commonly, a piecewise linear function is used to convert the pollutant to AQI and the equation is:

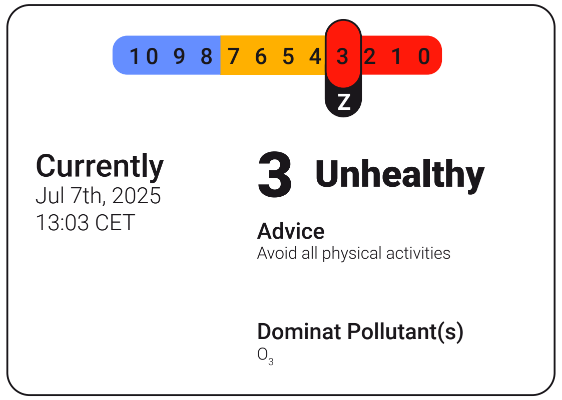
Formula

$$I = 10 - \left(\frac{Ihigh - Ilow}{Chigh - Clow}(C - Clow) + Ilow\right)$$

I = Air Quality Index
C = Pollutant concentration
C*low* = Low concentration breakpoint
C*high* = Hight concentration breakpoint
I*low* = Score breakpoint corresponding to C*low*
I*high* = Score breakpoint corresponding to C*high*

Note: *While the GO IAQS Score is primarily a real-time indicator designed for proactive user action, some data sources provide averaged time values instead. In these instances, we recommend maintaining the standard breakpoints and colours for consistency, provided that users are clearly notified that the data is not real-time.*

Examples: Example one, if $PM_{2.5}$, NO_2, CO, and O_3 have individual scores of 5, 5, 5, and 3, respectively, then the final score will be 3 (worst). E.g. two, if for $PM_{2.5}$, NO_2, CO, and O_3 have individual scores of 7, 7, 7, and 7, respectively, then the final score will be 6. E.g. three, unhealthy air quality in Greek language. E.g. four, good air quality in Hindi language. E.g. five provides a generic score representation designed to offer everyday people an at-a-glance understanding of their indoor air quality.



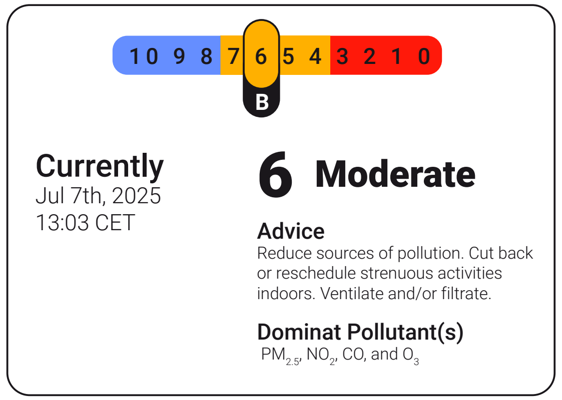
Currently
Jul 7th, 2025
13:03 CET

3 Unhealthy

Advice
Avoid all physical activities

Dominat Pollutant(s)
O_3

E.g. One: Detailed representation (Unhealthy IAQ)



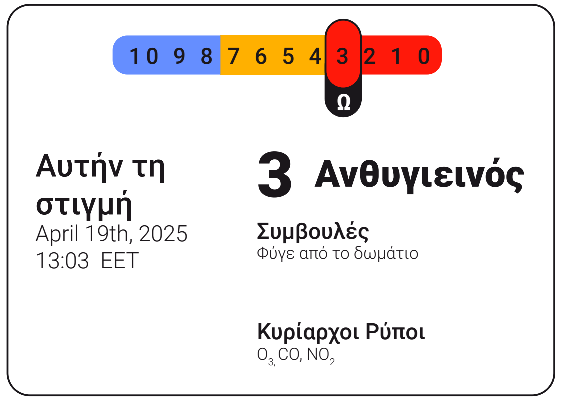
Currently
Jul 7th, 2025
13:03 CET

6 Moderate

Advice
Reduce sources of pollution. Cut back or reschedule strenuous activities indoors. Ventilate and/or filtrate.

Dominat Pollutant(s)
$PM_{2.5}$, NO_2, CO, and O_3

E.g. Two: Detailed representation (Moderate IAQ)



Αυτήν τη στιγμή
April 19th, 2025
13:03 EET

3 Ανθυγιεινός

Συμβουλές
Φύγε από το δωμάτιο

Κυρίαρχοι Ρύποι
O_3, CO, NO_2

E.g. Three: Detailed representation (Unhealthy IAQ in Greek)

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8 Good

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$PM_{2.5}$

E.g. Four: Detailed representation (Good IAQ in Hindi)

E.g. Generic representation of the score.

$PM_{2.5}$ Breakpoints Analysis

Multiply studies explore the health effects of $PM_{2.5}$ exposure at various concentrations.

- Respiratory issues like coughing, wheezing, shortness of breath, and aggravated asthma.
- Cardiovascular problems like heart attack, stroke, and irregular heartbeat.
- Increased risk of lung cancer and dementia.

Concentration and Health Effects:

- Low Concentration Levels (Below 5 µg/m³): This is the WHO guideline for annual average $PM_{2.5}$ concentration. However, even at these levels, some health risks may exist, particularly for sensitive individuals.
- Moderate Concentration Levels (12 - 35 µg/m³): Studies suggest an increased risk of respiratory problems and cardiovascular issues compared to lower levels.
- High Concentration Levels (Above 35 µg/m³): Significant health risks are observed, with a sharp rise in respiratory and cardiovascular problems, and potentially even increased mortality rates.

Initially, the GO IAQS Score for $PM_{2.5}$ was developed with the intention of converting the World Health Organisation's 2021 Air Quality Guidelines (AQGs) annual concentration of 5 µg/m³ as the upper limit for the "Good" breakpoint. However, following extensive deliberation among the team members, it was collectively decided to align with the TAIL scheme for indoor environmental rating concerning this specific pollutant. Consequently, the upper limit for the "Good" breakpoint for $PM_{2.5}$ in the GO IAQS Score has been set at 10 µg/m³, consistent with the TAIL scheme's guidelines (Wargocki et al., 2021).

A research on indoor $PM_{2.5}$ concentrations and personal exposure determined not only by the concentration of $PM_{2.5}$ in a specific location, but also by the amount of time spent in that environment and individual activity levels. This means someone could be exposed to high levels of $PM_{2.5}$ in their kitchen while cooking, but if they spend little time in that space, their overall exposure might be lower than someone who spends extended periods in a room with moderate $PM_{2.5}$ levels (Liu et al., 2022). Factors such as time-activity patterns, variations in indoor and outdoor sources, building characteristics, and individual behaviors are critical.

Indoor $PM_{2.5}$ exposure is also associated with cognitive performance. Zhou et al. (2023) found that office workers demonstrated significantly better performance in 9 out of 16 cognitive skills when exposed to lower $PM_{2.5}$ concentrations (3.7 µg/m³) compared to higher concentrations (18.0 µg/m³). This improvement was particularly consistent in memory-related tasks.

Personal behaviors might play a significant role in reducing actual indoor $PM_{2.5}$ exposure per Song et al. (2023). The study consistently found that indoor and personal $PM_{2.5}$ concentrations were lower than outdoor levels across different seasons and study areas (urban, industrial, and rural). Revealed how indoor $PM_{2.5}$ levels compared to outdoor levels (Indoor/Outdoor Ratio), with seasonal medians ranging from 0.30 to 0.51 in fall, winter, and spring, and 0.70 in summer. Overall outdoor $PM_{2.5}$ was 16.3 (9.1–29.4) µg/m³. The median seasonal range for indoor $PM_{2.5}$ was 5.9–7.5 µg/m³.

While personal exposure to $PM_{2.5}$ is higher than suggested by fixed-site monitoring data, using unadjusted exposure-response coefficients (like those from the American Cancer Society (ACS) cohort study) to assess the health impacts of indoor $PM_{2.5}$ from outdoor sources is generally appropriate. The study found that personal exposure to $PM_{2.5}$ is about 30-50% greater than what the ACS coefficient indicates. This is because people are exposed to $PM_{2.5}$ in various micro-environments, not just at the fixed monitoring sites according to Milner et al. (2017). Moreover, while personal exposure needs adjusting, the required adjustment for indoor exposure to outdoor-generated $PM_{2.5}$ is relatively minor. This is because indoor $PM_{2.5}$ from outdoor sources makes up only a portion of the total $PM_{2.5}$ exposure.

Most research underscores that indoor activities are not insignificant when it comes to $PM_{2.5}$ exposure. Even activities like candle burning, often perceived as harmless, can lead to elevated indoor $PM_{2.5}$ concentrations, particularly in airtight buildings with low air exchange rates. The researchers found that candle burning in such environments could result in 7 to 11 $\mu DALY/h_{activity}$ (4 to 11 $minutes_{lost}/h_{activity}$) (Bhoonah et al. 2023). Moreover, the paper acknowledges that outdoor $PM_{2.5}$ levels play a role in determining indoor concentrations, particularly through infiltration and ventilation. Even without indoor sources, outdoor air pollution can penetrate indoors, establishing a baseline level of $PM_{2.5}$.

Thangavel et al. (2022) suggest that while molecular epidemiological research is growing, current studies are limited in scope, focusing on specific localities with high pollution levels. This makes it difficult to generalise findings to other parts of the world and hinders a comprehensive understanding of air pollutants' impact on global health.

According to the evidence presented by Yang et al. (2022), long-term exposure to $PM_{2.5}$ has been consistently linked to an increased risk of several adverse health outcomes, including all-cause/non-accidental and cardiovascular mortality, cardiovascular diseases, type 2 diabetes, kidney diseases, and chronic obstructive pulmonary disease (COPD). These findings underscore the urgent need for concerted efforts to mitigate the health risks associated with air pollution.

The findings of this study Kannan et al. (2009) demonstrate that communities situated in close proximity to $PM_{2.5}$ emission sources experience heightened pulse pressure (PP) and systolic blood pressure (SBP) responses to $PM_{2.5}$ exposure, and that this effect is exacerbated by obesity. Furthermore, the study underscores that residents of disadvantaged communities are often exposed to a confluence of factors, including obesity, and socioeconomic disadvantages, all of which contribute to an increased risk of cardiovascular disease (CVD).

Exposure to air pollutants, especially $PM_{2.5}$, is linked to greater atrophy of the medial temporal lobe (MTL), a brain region crucial for memory. This atrophy is similar to the neurodegeneration seen in Alzheimer's disease. The study found that higher $PM_{2.5}$ exposure was associated with a greater increase in AD-PS, a measure of Alzheimer's disease-related neurodegeneration, which in turn partially explained the MTL atrophy. For every interquartile range (IQR) increase in $PM_{2.5}$ (3.17 $\mu g/m^3$), there was a -0.29 standard deviation change in MTL volume. This indicates that higher $PM_{2.5}$ levels are associated with greater MTL atrophy (Petkus et al., 2023).

Yang et al. (2019) also conclude that arrived at a conclusion that there is association with an increased risk of type 2 diabetes (T2D) and $PM_{2.5}$ exposure after reviewing 86 studies on air pollution and diabetes, and conducting meta-analyses on 29 of them focusing on PM. The study found that for each 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration, there was an 8% increase in the odds of having T2D (prevalence). In a similar study researchers found that for every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration, the risk of developing T2D increases by approximately 11% (Park and Wang, 2014).

Grande et al. (2021) found that the relationship between $PM_{2.5}$ exposure and cognitive decline was not strictly linear. Instead, they observed an inverted U-shaped association. This means that the risk of accelerated cognitive decline increased as $PM_{2.5}$ levels rose from low to mean concentrations. However, above a certain threshold (around the mean $PM_{2.5}$ level of 8.6 $\mu g/m^3$ in this study), the risk plateaued and did not continue to increase with higher exposures.

Despite the absence of a definitive "safe" level, all sources emphasize that minimising $PM_{2.5}$ exposure is crucial for public health (Air Quality, Energy and Health (AQE), 2021).

CO_2 Breakpoints Analysis

While CO_2 itself is not considered a direct pollutant at typical indoor concentrations, it serves as a valuable proxy or indicator of ventilation adequacy in classrooms and other indoor spaces. Due to its effectiveness and affordability, CO_2 is widely used to assess indoor conditions. Consequently, it is imperative to establish target thresholds for CO_2 levels to ensure adequate ventilation and air quality.

Here is a breakdown of CO_2's effects on human health at various concentrations, with a focus on indoor environments:

General Effects:

- Low Concentration Levels (Up to 800 ppm): At these concentrations, CO_2 itself is not posing any risk, neither for indications of poor ventilation nor for pathogen transmission.

- Moderate-to-High Concentration Levels (850 - 5000 ppm): These levels can indicate poor ventilation, which can lead to build-up of other indoor air pollutants and can impair decision-making.

- Very High Concentration Levels (Above 5000 ppm): At these concentrations, CO_2 becomes a direct health hazard, potentially leading to nausea, vomiting, disorientation, and even unconsciousness.

The GO IAQS Score establishes the upper limit for the "Good" breakpoint for CO_2 based on the stringent criteria defined within the GO IAQS Ultimate tier. This specific limit, set at 800 ppm, was established by Morawska et al. (2024), and notably, it aligns with the recommendations found in the European standard EN13779, which provides guidelines for ventilation in non-residential buildings. Furthermore, this 800 ppm threshold for CO_2 is widely adopted by numerous countries as a critical trigger for implementing indoor mitigation measures, specifically to safeguard occupants against the transmission of airborne pathogens.

Inadequate ventilation, often indicated by high CO_2 levels, is linked to increased respiratory symptoms, asthma attacks, and reduced cognitive function in students according to Oluyemi et al. (2023) and Moonie et al. (2008). Studies recommend maintaining specific ventilation rates to mitigate these issues as insufficient classroom ventilation to be associated with absenteeism, with a 100 ppm increase in classroom CO_2 being related to missing a half day of school per year by Gaihre et al. (2014).

In another study, Kuramochi et al. (2023) the source reference ASHRAE Standard 62.1, which suggests that CO_2 concentrations exceeding 700 ppm above outdoor levels (generally around 1000 ppm total) may indicate insufficient ventilation for effectively removing human bio-effluents. It is essential to recognise that this standard primarily targets odor control and occupant comfort rather than directly addressing potential health or cognitive impacts.

According to Guo et al. (2023) exposure to a high CO_2 concentration (2500 ppm) for one hour led to poorer performance on a specific reasoning test (Rotations) compared to exposure to a lower CO_2 concentration (500 ppm). This suggests that high CO_2 levels, even for relatively short periods, can negatively affect certain aspects of cognitive function.

The researchers found that increasing CO_2 concentrations from a mean of 690 ppm to 2909 ppm led to a roughly 5% decrease in students' "Power of Attention." This factor reflects the intensity of concentration, with faster responses indicating higher levels of focus. Interestingly, the study notes that the magnitude of the observed attention decrement caused by high CO_2 is similar to that was noticed in students who skip breakfast. This comparison highlights the potential significance of CO_2 as a factor influencing cognitive function in the classroom (Coley et al., 2007).

The study by Allen et al. (2015) showed a significant decrease in cognitive function scores with increasing CO_2 levels, even when controlling for other environmental factors like ventilation rate and VOCs. This suggests a direct and independent effect of CO_2 on cognitive performance, rather than an indirect effect mediated by other pollutants. Controlling for individual participant factors, a 400 ppm increase in CO_2 levels was linked to a 21% decline in cognitive performance across all domains. Conversely, increasing outdoor air ventilation by 20 cubic feet per minute per person resulted in an 18% improvement in cognitive scores.
In a resent paper Morawska et al. (2024), researchers suggest a CO_2 level of 800 ppm as a recommended threshold for public spaces. This recommendation stems from a specific scenario analysis of a classroom setting with one infected student. The researchers used a model to determine the ventilation rate needed to keep the virus's reproduction number (R0) below 1, meaning the virus would not spread effectively. The logic is that human respiration releases both CO_2 and potentially infectious particles. Therefore, effectively removing CO_2 through ventilation suggests that other respiratory emissions are also being adequately diluted.

Finally, the researchers demonstrate that even a moderate increase in ambient CO_2 concentration (e.g., from 500 ppm to 800 ppm) significantly enhances the aerostability of SARS-CoV-2. This effect becomes more pronounced over time, with significantly more infectious viral particles remaining viable in the aerosol phase at elevated CO_2 levels compared to well-ventilated conditions Haddrell et al. (2024).

CO Breakpoints Analysis

The carbon monoxide (CO) breakpoints are established at lower concentration than the General Concentration and Effects due to the highly toxic nature of CO and its potential to cause significant health risks, even at low concentrations. The WHO guidelines for IAQ suggests that for every 1.2 mg/m^3 increase in CO concentration, absence increased by 3.79% (95% CI 1.04–6.55). Furthermore, long-term exposure to CO has been associated with an increased risk of speech disturbances, anxiety, depression, and Parkinsonism, highlighting the importance of maintaining low CO levels in indoor environments to safeguard public health.

WHO highlights health risks were only seen when the median was 1.15 mg/m^3 or greater, which is about 1 ppm. The effects were mostly seen in studies with higher CO concentrations, with an effect estimate of RR =1.019 [95% CI: 1.011-1.027] in studies with a median carbon monoxide level exceeding 1.15 mg/m^3 compared with RR = 1.00 [95% CI: 0.998-1.003] in the rest of the studies.

General Concentration and Health Effects:

- Low Concentrations Levels (Up to 2.0 ppm): Mild symptoms: Headaches, fatigue, nausea, and difficulty concentrating.
- Moderate Concentrations Levels (2.1 - 9 ppm): Severe symptoms: Dizziness, confusion, shortness of breath, and loss of coordination.
- High Concentrations Levels (Above 10 ppm) Rapid onset of symptoms: Severe headache, nausea, vomiting, and disorientation. Loss of consciousness: Can lead to unconsciousness and death within a short period.

The GO IAQS Score establishes the upper limit for the "Good" breakpoint for carbon monoxide at 1.7 ppm. While an initial proposal considered 5 ppm for this threshold, further evaluation concluded that this level was significantly too high for an index designed to provide immediate warnings based on current pollutant concentrations. This decision is underpinned by extensive environmental epidemiology, with over a hundred studies reporting statistically significant increases in same-day morbidity or mortality from CO increases as marginal as 1 ppm in an 8-hour rolling average. Crucially, a thorough review found no evidence supporting safe exposure for non-smokers to CO in the 2 to 5 ppm range, averaged over 8 or 24 hours, without a significant rise in adverse health outcomes. Consequently, to ensure robust protection, the GO IAQS score adopted the "Excellent Class" benchmark of 1.7 ppm as defined by the Government of the Hong Kong Special Administrative Region's Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places (The Government of the Hong Kong Special Administrative Region, 2019).

Clinical studies demonstrate that acute exposure to carbon monoxide at levels producing blood COHb levels between 2.4% and 5.9% aggravates cardiovascular disease in patients with pre-existing conditions. Healthy individuals can tolerate even higher COHb levels (3–20%) without experiencing adverse cardiovascular effects. Typical COHb levels in non-smokers are below 2% but symptoms of acute CO poisoning can manifest at COHb levels ranging from 3% to 24% while exposures resulting in COHb levels exceeding 50% are often fatal (Wilbur et al., 2012). Moreover, endogenous CO production is estimated at 1.1–2.2 mg/m^3, which is close to national average ambient air CO concentrations in the United States (approximately 0.57 mg/m^3).

An interesting pilot study lead by Gładyszewska-Fiedoruk and Wiater (2022) measured CO levels under various scenarios, including the presence of smokers who had recently smoked cigarettes outside. The baseline indoor room had averaged 0.34 mg/m^3 of CO. The maximum CO concentration observed in the room was 1.6 mg/m^3 , which occurred when individuals who had smoked cigarettes immediately before entering the room occupied 15% of the space. The authors extrapolated that if all occupants entered the room after smoking, the instantaneous CO concentration might reach 10 mg/m^3, which is still below the recommended limits set by various authorities. Finally, when 13 smokers were allowed to smoke inside the room, the CO concentration peaked at 10.48 mg/m^3.

WHO sets safe indoor CO exposure levels based on averaging time. For 15 and 60 minutes, a maximum of 100 and 35 mg/m^3 respectively is recommended for light exercise. For 8 hours, the arithmetic mean should be 10 mg/m^3 (light to moderate exercise), while for 24 hours, it should be 7 mg/m^3 (awake and alert without exercise). Exceeding these limits should be infrequent and ideally limited to once per day. WHO emphasizes that these guidelines are based on a comprehensive review of scientific evidence, considering various factors like exercise capacity, cardiovascular health, and the potential for chronic exposure effects. Safe levels of CO exposure vary depending on the averaging time.

The paper, "Ambient Carbon Monoxide and Daily Mortality: a global time-series study in 337 cities", focuses on analyzing the association between ambient CO exposure and daily mortality across a large dataset of cities worldwide. All 337 cities included in the analysis exhibited relatively low annual mean CO concentrations, with all values below 2.3 mg/m^3. Only 28 out of the 337 cities had an average of 0.2% of days with CO levels exceeding 7 mg/m^3, and 24 of these cities were in the USA. K. Chen et al. (2021) noted that even when CO concentrations were restricted to less than 4 mg/m^3, a significant association with mortality was still observed. Growing body of evidence suggesting that even relatively small increases in ambient CO can have detrimental health effects.

CO exposure is associated with severe health risks, specifically the cardiovascular and neurological systems, potentially leading to death (Dimitroulopoulou et al, 2023). The authors also highlight the risk to unborn children. The primary sources of CO indoors are identified as incomplete combustion from appliances using carbon-based fuels, such as gas boilers, kerosene heaters, and wood stoves. The researchers emphasize the importance of proper installation, maintenance, and ventilation to minimize CO risks. The paper references the WHO guidelines for indoor CO exposure limits at 10 mg/m^3 for 8-hour average. The paper compares WHO guidelines with national guidelines for CO from 34 countries, using data from the ISIAQ STC34 IEQ database. It notes that the most common 8-hour average guideline value across these countries is also 10 mg/m^3, aligning with the WHO recommendation. However, variations exist in other averaging times.

The study conducted by Chuang et al. (2023) found that long-term exposure to CO was significantly associated with a heightened risk of all-cause mortality within one year after hip fracture surgery. Specifically, they determined that for each 1 SD increment in average CO exposure levels over a decade, the risk of mortality increased by a substantial 49%.

An extensive paper reported that out of 384 occupied buildings studied, 224 (58.3%) had indoor carbon monoxide concentrations above the permissible limit for a 15-minute exposure, which is 100 mg/m^3 according to the 2010 European air quality guidelines. The remaining 160 (41.7%) buildings had CO levels within the permissible limit. The minimum CO concentration measured was 1.7 mg/m^3, and the maximum concentration was 126 mg/m^3 (Gizaw and Teka, 2020). It is important to note that the study used the European guideline for comparison because no local guidelines for CO exist in the study and similar areas.

A study examined the connection between long-term exposure to carbon monoxide and its impact on health. The study quantified this association by calculating the relative risk (RR) of mortality associated with an increase in CO exposure. It reported that for every interquartile range (IQR) increase in CO exposure, the RR for total mortality was 1.028 (95% confidence interval: 1.017–

1.038). This means that individuals exposed to higher levels of CO had an approximately 2.8% greater risk of dying from any cause compared to those with lower CO exposure. J-Shaped Exposure-Response Curve: The study further investigated the relationship between the level of CO exposure and the corresponding mortality risk. It identified an approximately J-shaped curve, indicating that the risk of mortality rises more steeply at higher levels of CO exposure. This suggests that while even moderate levels of CO exposure can be harmful, the danger escalates considerably with greater exposure (Yu et al., 2024).

CH_2O Breakpoints Analysis

Formaldehyde (CH_2O) exposure can have various health effects depending on the concentration and duration of exposure. Here is a breakdown with studies for reference:

General Effects:

Formaldehyde is a known irritant that can affect the eyes, nose, throat, and skin. Symptoms include:

Eye irritation (watering, burning), respiratory irritation (coughing, wheezing), and skin irritation (rash, burning)

Concentration and Effects:

- Low Levels (Below 30 ppb): These levels may cause some irritation in sensitive individuals, but most people won't experience any problems.

- Moderate Levels (31 - 100 ppb): These concentrations can cause eye, nose, throat, and skin irritation in most people.

- High Levels (Above 101 ppb): At these levels, significant irritation and respiratory problems can occur.

The GO IAQS Score sets the upper limit for the "Good" breakpoint for CH_2O at 27 ppb, a threshold derived directly from the highly stringent criteria of the GO IAQS Ultimate tier. This specific limit is consistent with the established guidelines in ASHRAE Standard 189.1-2020, which provides environmental performance requirements for high-performance green buildings. Furthermore, this value closely aligns with the TAIL scheme for indoor environmental rating, which sets a very similar upper limit of 24.4 ppb for this particular pollutant, underscoring a strong consensus among leading standards for healthy indoor environments.

As per Cammalleri et al. (2021) found that the settings with the highest levels of airborne formaldehyde were gross anatomy and pathology laboratories, hairdressing salons, and some specific productive settings such as wooden furniture factories, dairy facilities, and fish hatcheries. In hairdressing salons, the levels of formaldehyde ranged from less than the limit of detection to more than 3.26 ppm. The results of personal monitoring are generally higher than environmental ones but the authors recommend both personal monitoring and environmental monitoring should be performed to define risk levels and elaborate a risk assessment document.

The researchers Mazurkiewicz et al. (2024) have found numerous occupational groups face high levels of formaldehyde exposure in their workplaces, including healthcare workers, firefighters, construction workers, and those in the beauty industry. Average indoor formaldehyde concentrations in residential buildings in European countries, the USA, Canada, and Japan generally range from 16 to 33 ppb. Some studies indicate a broader range of 8–65 ppb. In China, the average indoor formaldehyde concentration in residences is significantly higher, reaching 196 ppb. Formaldehyde concentrations in office and public buildings tend to be much lower than those found in residential buildings. A previous paper by Liang et al. (2022) found a significant difference in formaldehyde concentrations between winter and summer. Although all homes met the safety standard of 80 ppb in winter, 28.3% exceeded this limit in summer, with the highest concentration reaching 85 ppb.

According to Lam et al. (2021) there was "sufficient evidence of toxicity" to support the association between exposure to formaldehyde and both asthma diagnoses and asthma symptoms in both children and adults. The paper standardise the measurements to determine the change in asthma outcomes per 8.15 ppb increase in exposure or per 1 ppb decrease in exposure. They found that a 8.15 ppb increase in formaldehyde exposure was associated with a 20% increased odds of being diagnosed with asthma (OR=1.20, 95% CI: [1.02, 1.41]).

Exposure to formaldehyde may cause myeloid leukemia, in humans. However, the authors Hauptmann et al. (2003) caution that results from other investigations are mixed, suggesting caution in drawing definitive conclusions. The study found that relative risks for myeloid leukemia, increased with formaldehyde exposure. For example, Myeloid Leukemia and Peak Formaldehyde Exposure: Compared with workers exposed to low peak levels of formaldehyde (100–1900 ppb), the relative risk for myeloid leukemia was 2.43 for workers exposed to peak levels of 1.96–3.83 ppm and 3.46 for workers exposed to peak levels of ≥ 3.99 ppm. Myeloid Leukemia and Average Exposure Intensity: Compared to workers exposed to low average exposure intensities of formaldehyde (0.10–0.40 ppm), the relative risk for myeloid leukemia was 1.15 for workers exposed to 0.50 – 0.90 ppm and 2.49 for workers exposed to ≥ 0.98 ppm.

The Hauptmann et al. (2004) found that relative risks for nasopharyngeal cancer (NPC) cancer increased with average exposure intensity, cumulative exposure, highest peak exposure, and duration of exposure to formaldehyde. Cumulative Exposure: Workers with 1.50–<5.50 ppm–years of cumulative exposure had a relative risk of 1.19 for nasopharyngeal cancer, while workers with ≥5.50 ppm–years of cumulative exposure had a relative risk of 4.14. The authors acknowledge that their analysis of the relationship between cancer and formaldehyde exposure was limited by a small sample size (n=9).

Researchers found that mortality from myeloid leukemia increased statistically significantly with both increasing number of years of embalming and increasing peak formaldehyde exposure Hauptmann et al. (2009). The study found that embalmers whose estimated cumulative formaldehyde exposure exceeded 11363 mg/m^3–hours had a statistically significantly increased risk for mortality from myeloid leukemia compared to those with lower levels of exposure.

The health effects of formaldehyde exposure in residential and public buildings suggests that formaldehyde exposure in civil buildings is significantly associated with asthma in adults and children in eastern and western countries. For asthma in children, the pooled odds ratios (ORs) were 1.27 (95% CI: 1.20–1.35) in eastern countries and 1.03 (95% CI: 1.02–1.04) in western countries per 8.15 ppb increase in formaldehyde concentration. For asthma in adults, the pooled OR was 1.09 (95% CI: 1.03–1.15) per 8.15 ppb increase in formaldehyde concentration (Liu et al., 2023).

Finally, the study conducted by Khoshakhlagh et al. (2024) concluded that while formaldehyde concentrations in most indoor environments were below recommended limits, unacceptable carcinogenic risk values were reported for residents and employees in most of the investigated studies. Formaldehyde concentrations ranged from 0.01 to 1319.75 ppb in various indoor environments, with the highest concentrations reported in water pipe cafes and the lowest concentrations in residential environments. In over 90% of the studies, an unacceptable carcinogenic risk due to formaldehyde inhalation exposure was reported. This means that the risk of carcinogenesis was higher than 1.00×10^{-6} in over 90% of the studies, indicating either an uncertain risk ($1.00 \times 10^{-6} < CR < 1.00 \times 10^{-4}$) or an actionable risk ($CR > 1.00 \times 10^{-4}$). The meta-analysis also revealed that the highest carcinogenic risk values were in high-income countries.

A recent toxicological report on formaldehyde (IRIS Toxicological Review of Formaldehyde (Inhalation) (Final Report, 2024) | IRIS | US EPA, n.d.) focuses on sensory irritation, pulmonary function, immune system effects, respiratory tract pathology, nervous system effects, reproductive and developmental toxicity, and cancer. Formaldehyde is found to be carcinogenic to humans by the inhalation route of exposure. The noncancer reference concentration (RfC) is 0.007 mg/m^3, and the cancer inhalation unit risk (IUR) is 1.1 × 10–5 per µg/m^3. Inhaled formaldehyde can cause respiratory effects in humans, and children and those with respiratory diseases may be most susceptible. These assessments provide a scientific basis for decisions to protect public health.

O_3 Breakpoints Analysis

The breakpoints for ozone on the AQI are not directly based on ozone depletion, but rather on the health effects of ozone levels at different concentrations.

There is a wealth of research on the health effects of O_3 exposure at various concentrations. Here are some key points and resources to explore further:

- O_3 exposure can irritate the respiratory system, causing coughing, chest tightness, and shortness of breath.
- It can worsen existing respiratory conditions like asthma, leading to increased medication use and hospital admissions.
- Long-term exposure may contribute to the development of asthma, especially in children.

Concentration and Health Effects:

- Low Concentration Levels (Below 50 ppb): Studies suggest some negative health effects might occur at even these seemingly low levels, though the evidence is less clear-cut.
- Moderate Concentration Levels (51 - 100 ppb): This is the range where the US EPA sets its primary national ozone standard. Exposure here can cause respiratory irritation, particularly in sensitive individuals.
- High Concentration Levels (Above 101 ppb): Definite health risks are observed, including increased respiratory problems, reduced lung function, and even increased mortality rates.

The GO IAQS Score establishes the upper limit for the "Good" breakpoint for ozone at 25 ppb, a decision reached after extensive internal discussions and comprehensive surveys. This conservative threshold stems from the understanding that ozone's high reactivity leads to the formation of numerous byproducts, many of which can pose significant additional risks to human health. Furthermore, this limit is reinforced by the principle that no indoor devices should be permitted to generate or emit ozone. Adopting a precautionary principle, and recognizing that the GO IAQS score represents a continuous safe exposure level in contrast to the World Health Organisation's 2021 guidelines which set an 8-hour limit of 51 ppb, it was determined that the index's upper limit for continuous exposure should be substantially lower, approximately two-thirds to three-fourths less than the TWA limit, to ensure optimal indoor air quality and occupant well-being.

As a reference measurements in approximately 2000 indoor environments from Asia, Europe, and North America indicate the median indoor ozone concentrations are also comparable across building types: 12 μg/m^3 in residences, 12 μg/m^3 in schools, and 8 μg/m^3 in offices. The median indoor/outdoor concentration ratios are similar for residences (0.25) and schools (0.28) (Nazaroff and Weschler, 2021). Similar findings are observed by Weschler (2006) where indoor ozone levels are typically 10-50% of outdoor values with median indoor/outdoor ozone concentration ratios of around 0.25 for residences and 0.28 for schools.

Researchers imply that focusing solely on outdoor ozone levels is insufficient for protecting public health. Indoor ozone levels need to be addressed as well, especially, the formation and potential toxicity of various ozone reaction products generated indoors (Weschler, 2006).. Even when analyzing data restricted to days with average ozone levels below 30 μg/m^3. This finding suggests that even relatively low levels of ozone can have detrimental health consequences. A papewr by Brenner (2023) indicates that far-UVC light generates ozone at levels less than 20 μg/m^3 in real-world settings. This amount is significantly lower than the 70-100 μg/m^3 threshold where most epidemiological studies start to show increased health risks from ozone exposure.

Zhang et al. (2019) highlights that emerging evidence suggests that there may not be a safe threshold for ozone exposure, and even low levels can have adverse health effects. The WHO Air Quality Guidelines recommend an 8-hour daily maximum ozone concentration of 100 μg/m^3. While the US National Ambient Air Quality Standards (NAAQS) for ozone include a 1-hour standard of 236 μg/m^3 and an 8-hour standard of 137 μg/m^3.

Bell et al. (2005) concludes that there is evidence of a short-term association between ozone exposure and increased mortality, particularly for cardiovascular and respiratory causes. A 20 μg/m^3 increase in daily ozone was associated with a 0.87% increase in total mortality in the meta-analysis, compared to a 0.25% increase in National Morbidity, Mortality, and Air Pollution Study. Meta-analysis results indicated larger effect estimates for the elderly (64+ years) with a 1.45% increase in total mortality for a 20 μg/m^3 ozone increase.

Short-term exposure to ozone at levels above 80 μg/m^3 significantly increases the risk of asthma attacks in children according to Huang et al. (2022). This conclusion is based on a case-crossover study conducted in Xiamen, China, involving 3,475 children diagnosed with asthma attacks between 2016 and 2019. Moreover, for every 10 μg/m^3 increase in ozone above 100 μg/m^3, the risk of an asthma attack increased by approximately 6-7%. The study also observed a negative correlation between ozone levels and asthma attacks when ozone concentrations were below 80 μg/m^3. The authors suggest that this finding could be related to the dual role of reactive oxygen species (ROS) produced by ozone.

A paper that looked into the tropospheric ozone formation and its impact on indoor environments, specifically schools and offices found that the median concentration of ozone was 8.50 μg/m^3 in schools ranged from 0.8 μg/m^3 to 114 μg/m^3 and 9.04 μg/m^3 in offices ranged from 0 to 96.8 μg/m^3. These levels, while generally below the WHO's 8-hour guideline of 100 μg/m^3, can sometimes exceed the recommended limits. Ozone infiltration is the primary source of indoor ozone, with median I/O ratios of 0.21 and 0.29 in school and office environments, respectively. However, indoor sources like printers, photocopiers, and some air-cleaning devices can also contribute to elevated ozone levels (Salonen et al., 2018).

Based on available data from the REVIHAAP Project, (2013) the findings suggest that if a threshold exists for short-term exposure, it likely lies below 90 μg/m^3 for the maximum 1-hour average. The report recommends using a linear concentration-response relationship and cut-off points of 20 μg/m^3 and 70 μg/m^3 for daily maximum 8-hour ozone in health impact assessments.

The study lead by Xue et al. (2023) revealed a statistically significant positive association between long-term ozone exposure and under-5 mortality. Specifically, a 20 μg/m^3 increase in life-course average peak-season ozone concentration was linked to a 6.4% (95% CI 2.4–10.7) higher risk of death before the age of 5. The research identified a non-linear relationship between ozone exposure and under-5 mortality, characterized by a threshold below which the effects of ozone were not statistically significant. This threshold was found to be near the WHO's IT1 level 100 μg/m^3.

NO_2 Breakpoints Analysis

Nitrogen dioxide (NO_2) is a harmful air pollutant that can have significant negative impacts on human health, particularly for individuals with respiratory conditions.

General Concentration and Health Effects:

- Low concentrations (Up to 29 ppb) Typically considered safe for most people.

- Moderate concentrations (30 - 100 ppb): May cause irritation to the eyes, nose, and throat, especially in sensitive individuals.

- High and very high concentrations (Above 101 ppb): Can lead to more severe respiratory problems, such as bronchitis, pneumonia, and increased susceptibility to respiratory infections. In very high concentrations can be life-threatening, especially for individuals with existing heart or lung conditions.

The GO IAQS Score's upper limit for the "Good" breakpoint for nitrogen dioxide at 21 ppb was established following extensive internal discussions and comprehensive surveys. This specific threshold is derived by converting the World Health Organisation's (WHO) 8-hour time-weighted average guideline, reflecting a robust health-protective foundation. Furthermore, by adopting a precautionary principle approach and aligning with the "Excellent Class" NO_2 limit of 21 ppb as outlined in the Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places by the Government of the Hong Kong Special Administrative Region, we ensure a comprehensive and highly protective score mechanism for indoor air quality (The Government of the Hong Kong Special Administrative Region, 2019).

Adamkiewicz et al. (2011) and Baxter et al. (2006) note that low-income households in multifamily buildings tend to have elevated NO_2 concentrations because of smaller unit sizes, higher source strengths, and often inadequate ventilation. According to the paper, gas stoves used for cooking are the most significant indoor source of NO_2, and using gas stoves for supplemental heating can substantially increase indoor NO_2 levels. The simulation model estimated 24-hour average indoor NO_2 concentrations across 162 scenarios in CONTAM. These scenarios varied factors that are known to be socioeconomically patterned, such as gas stove use, smoking rate, house leakiness, outdoor air pollution, and apartment size. In the highest quartile of simulated NO_2 concentrations, 61% of the exposure was from indoor sources.

The study conducted by Algar et al. (2004) found that homes in Barcelona had much higher NO_2 concentrations (median: 45.65 μg/m³) than Ashford (median: 11.07 μg/m³) or Menorca (median: 11.59 μg/m³), which the authors attribute to higher background levels of outdoor NO_2 pollution in Barcelona. While outdoor NO_2 levels contributed to indoor concentrations, indoor sources were still the primary drivers of high NO_2 levels. The use of gas appliances, particularly gas cookers, was a major determinant of indoor NO_2 levels across all three locations. Homes with gas cookers had 2.13 times higher NO_2 concentrations on average than homes with electric cookers.

Belanger et al. (2013b) found a threshold for health effects around 11 μg/m^3 and noted that every 5-fold increase in NO_2 exposure above this threshold was linked to increased risks of higher asthma severity scores and increased asthma morbidity. The authors highlight the public health implications of their findings, emphasizing that indoor NO_2 exposure, often stemming from gas appliances like stoves, poses a significant risk to children with asthma.

In a similar papers Hansel et al. (2008) observed a substantial impact of indoor NO_2 on respiratory symptoms. For instance, a child would experience 10% more days of cough symptoms or 15% more days with limited speech due to wheeze with each 38-μg/m³ increase in NO_2 exposure. Measured indoor NO_2 levels in participants' homes were with a mean concentration of 56 μg/m³, ranging from 5 to 741 μg/m³. Seasonally, summer had the lowest levels at 30 μg/m³, while the other seasons averaged around 56 μg/m³ or higher.

The Canadian Residential Indoor Air Quality Guideline (Health Canada, 2015) concludes that long-term exposure to NO_2 in homes, particularly for asthmatic children, can pose a significant risk to respiratory health. While the ideal long-term Residential Indoor Air Quality Guideline (RIAQG) is set at 10 μg/m³ to prevent adverse health effects, the paper acknowledges that achieving this level in most homes with gas stoves is challenging, even with proper ventilation. Consequently, a more practical long-term RIAQG of 20 μg/m³ is proposed, considering the feasibility of achieving this level with available risk management measures.

The research done by Jarvis et al. (2010) presented in the sources concludes that exposure to NO_2, even at levels below regulatory standards, can negatively impact respiratory health, especially for those with asthma. Controlled human studies show that short-term exposure to 380–560 μg/m³ of NO_2 for an hour or more can cause lung inflammation and weaken immune defenses, particularly in asthmatics. Some studies even suggest that lower exposures (188–360 μg/m³) can increase airway reactivity in asthmatics. Epidemiological studies, using both direct NO_2 measurements and gas appliances as exposure indicators, consistently link indoor NO_2 exposure to respiratory symptoms like cough, wheeze, and shortness of breath in children and adults.

These studies indicate that these health effects occur at NO_2 levels common in homes with gas stoves, even below the 40 μg/m³ outdoor air quality guideline. A key meta-analysis, which influenced the WHO's outdoor NO_2 guideline, concluded that a 28 μg/m³ increase above a 15 μg/m³ background level was associated with a 20% higher risk of lower respiratory illness in children. The research emphasizes that susceptibility to NO_2 varies, with children and asthmatics being most vulnerable, and that exposure levels depend on factors like gas appliance usage, ventilation, and proximity to the source. The sources recommend a long-term indoor NO_2 guideline of 20 μg/m³ and suggest measures like ventilating combustion appliances and using back burners on gas stoves to reduce exposure.

Radon Breakpoints Analysis

Radon is found in many countries worldwide, and its levels can vary significantly depending on the geology of the region. Areas with high radon concentrations are often found in regions with granite or crystalline rocks. Radon is a major contributor to lung cancer cases worldwide. While specific data on the global burden of radon-induced lung cancer may vary, it is estimated to be a substantial cause of lung cancer deaths.

The risk of developing lung cancer from radon exposure is a matter of chance as any radon level poses some health risk, with higher concentrations and longer exposure times increasing the odds.

General Concentration and Health Effects:

- Low Levels (Up to 100 Bq/m³): Even at low levels, radon exposure can increase the risk of lung cancer, especially in individuals who smoke.
- Moderate Levels (100 - 150 Bq/m³): The risk of lung cancer increases as radon levels rise.
- High Levels (Above 150 Bq/m³): Exposure to high levels of radon can significantly increase the risk of developing lung cancer.

The GO IAQS Score's upper limit for the "Good" breakpoint for radon is set at 100 Bq/m³, a threshold meticulously established for our GO IAQS Ultimate tier. This specific value is deliberately chosen to align with the recommendations put forth in the World Health Organisation's (WHO) 2010 guidelines on radon, ensuring that our indoor air quality standards are consistent with leading international health advisories and provide a robust level of protection.

The global average indoor radon concentration is roughly 39 Bq/m^3, and a 10% increase in lung cancer risk is associated with every 100 Bq/m^3 rise in measured radon levels. Most exposure occurs indoors. However, due to radon concentration fluctuations, this estimate might be underestimated, potentially leading to a risk closer to 20% per 100 Bq/m^3 increase in long-term average radon exposure. While the relative increase in lung cancer risk is similar for smokers and non-smokers, the absolute risk is significantly higher for smokers due to their increased baseline risk. According to the World Health Organisation (2009b), radon is estimated to contribute between 3% and 14% of all lung cancers, depending on the country's average radon levels and the calculation method.

A cross-Canada radon survey by Chen et al. (2012) concluded that 16% of lung cancer deaths in Canada are attributable to indoor radon exposure. This revised estimate, based on a recent national radon survey, is significantly higher than the previous estimate of 10% derived from a survey conducted in the late 1970s. Using long-term measurement techniques, revealed that more Canadians are exposed to higher radon concentrations than previously estimated. The survey found a geometric mean radon concentration of 41.9 Bq/m^3, compared to 11.2 Bq/m^3 from the earlier survey.

The Italian study by Antignani et al. (2020), conducted over a decade, included 84 dwellings with long-term average radon concentrations ranging from 28 to 636 Bq/m^3. The paper reviews other studies on year-to-year radon variability, noting that average radon concentration levels in these studies ranged from 69 Bq/m^3 (median value in a study in Grand Junction, USA) to 790 Bq/m^3 (geometric mean in a Czech study). Uncertainty in long-term radon exposure, including year-to-year variability, can significantly bias lung cancer risk estimates in epidemiological studies. Ignoring this uncertainty can underestimate the risk, as seen in the European pooled analysis, where correcting for year-to-year variability led to a 100% increase in risk estimates.

The paper from Garzillo et al. (2017), which is a meta-analysis of 25 case-control studies, concludes that exposure to indoor radon is likely associated with an elevated risk of developing lung cancer. The researchers found a relative risk (RR) of 1.19 (95% CI, 1.02–1.39), showing a statistically significant link between radon exposure and lung cancer incidence. Importantly, the study revealed a possible relationship between geographic location, specifically absolute latitude, and lung cancer risk from radon. They observed a higher risk of lung cancer associated with radon exposure at higher latitudes, with RR of 1.09 (95% CI, 0.92–1.31) at 40 degrees, 1.26 (95% CI, 1.08–1.48) at 50 degrees, and 1.46 (95% CI, 1.12–1.91) at 60 degrees. These findings suggest that factors related to geography, such as building materials and ventilation rates, might influence the impact of radon on lung cancer development.

A systematic review and meta-analysis by Ngoc et al. (2022) examined the connection between residential radon exposure and the occurrence of lung cancer and childhood leukemia. The analysis, encompassing 55 case-control studies, found that exposure to residential radon significantly elevates the risk of both lung cancer and childhood leukemia. Specifically, they reported a pooled odds ratio (OR) of 1.38 [1.19; 1.60] for lung cancer and 1.43 [1.19; 1.72] for childhood leukemia. Further subgroup analyses, performed to mitigate heterogeneity, indicated a particularly strong association between radon exposure and lung cancer in studies conducted in Europe and those focused on areas with high radon levels (≥100 Bq/m^3). A similar trend emerged for childhood leukemia, with a significant association observed in European studies and those examining areas with radon levels ≥200 Bq/m^3. The study concluded that that inhaling radon in indoor environments is strongly linked to the development of lung cancer and childhood leukemia, especially in Europe and areas with elevated radon levels.

Establishing precise thresholds for radon exposure is challenging due to the complex relationship between exposure levels, duration, and individual susceptibility. Unlike other pollutants with clear dose-response curves, the risk of lung cancer from radon appears to increase linearly with dose, suggesting that there might be no truly "safe" level. Instead of rigid thresholds, many health organisations advocate for a more flexible approach using "action levels".

Ventilation & Filtration

Ventilation and filtration are fundamental aspects of indoor air quality (IAQ), and while GO AQS will not offer specific guidelines, it's crucial to understand their importance for a holistic approach to IAQ. Effective ventilation, whether natural or mechanical, is essential for diluting and removing airborne pollutants, including gas pollutants, particulate matter, and biological contaminants. Coupled with appropriate filtration systems, such as those utilizing MERV-rated filters or HEPA filters, ventilation can significantly reduce the concentration of these harmful substances. It is important to remember that proper maintenance of those systems is also very important, to ensure that they are working as intended. A well balanced approach of both good ventilation, and proper filtration, will have the best outcome for IAQ.

Based on the comprehensive discussions within the Filtration and Ventilation Working Groups of the GO AQS, several key conclusions emerge regarding achieving optimal IAQ while considering energy efficiency and safety:

Prioritization of IAQ: There is a strong consensus on the paramount importance of IAQ, particularly in sensitive environments like schools and hospitals. While energy conservation remains a significant consideration, there's a general willingness to prioritize IAQ, especially when health and well-being are primary concerns. The balance between IAQ and energy efficiency is context-dependent, varying by building type (e.g., commercial vs. residential vs. retail).

Trusted Core Technologies: Mechanical filtration (HEPA, MERV filters) and absorbent filtration (activated carbon for gases, with noted limitations) are generally trusted due to proven performance according to specifications. Similarly, established ventilation strategies like controlled ventilation, Energy Recovery Ventilation (ERV)/Heat Recovery, and Demand Control Ventilation (DCV) based on sensors (like CO_2) are recognized as effective ways to manage air exchange and conserve energy.

Significant Concerns Regarding Byproducts: A major shared concern across both groups involves advanced air cleaning technologies, particularly electronic methods (hard ionizers, plasma, etc.) and Photocatalytic Oxidation (PCO). There is considerable skepticism about their effectiveness and significant worry about the potential generation of harmful byproducts like ozone, hydroxyl radicals, and other oxygen radicals. The lack of standardized testing for all potential byproducts and misleading marketing claims are critical issues.

Crucial Need for Validation and Standardization: Both groups repeatedly stressed the absolute necessity for rigorous, independent, third-party testing and certification to verify both the efficacy and safety (i.e., absence of harmful byproducts) of air filtration and purification technologies before widespread adoption. There's a call for standardized classification of technologies based on their physical/chemical principles, moving beyond marketing terms, potentially mirroring regulatory approaches like Belgium's restrictive stance on certain technologies.

Integrated Approach: Effective IAQ management requires an integrated approach. This includes:

- **Source Control**: Removing or minimizing indoor pollutants at their source is fundamental.
- **Ventilation**: Providing adequate fresh air exchange (dilution), optimized through controls (DCV) and energy recovery (ERV). Paid standards such as ASHRAE 62.1/62.2 are widely followed, the newer ASHRAE Standard 241 for Control of Infectious Aerosols, and finally, the European EN 16798-1 specifies input parameters for building design and energy calculations, while EN 171340 deals with validation and qualification of atmosphere-controlled rooms in hospitals.
- **Filtration/Purification**: Cleaning the air (incoming or recirculated) using appropriately selected and validated technologies. Indoor purification via portable air purifiers can potentially reduce the required outdoor air ventilation rates, saving energy, but only if proven safe and effective.
- **System Design & Maintenance**: Ensuring HVAC systems are correctly designed (e.g., minimizing pressure drop for energy efficiency), properly maintained, and use appropriate filters (e.g., MERV 13 where applicable).

Data Gaps and Future Directions: There's a recognized need for more robust data and refined metrics, particularly concerning sub-micron particle filtration and the impact of specific pollutants like VOCs. Standards need to evolve to potentially incorporate these finer metrics and address challenges posed by extreme outdoor pollution events (e.g., wildfires). Continued research and data collection are essential to support evidence-based recommendations.

Latest Research: In schools, the recommended ventilation rate is 14 liters/s per person or 8.7 air changes per hour (ACH) for the specific size of the given classroom. This recommendation is based on a risk assessment model that considered a classroom scenario with one infected student, aiming to keep the reproduction number (Re) below 1 even for highly transmissible respiratory pathogens like SARS-CoV-2 Delta and Omicron variants, and measles. This scenario assumed susceptible individuals were in the classroom microenvironment for the same duration (1 hour) as the infected student, in a 150 m³ (5297 ft³) classroom with 25 students and 1 teacher, where the infected student's infectious particle emission occurred through 80% oral respiration and 20% phonation. The research highlights that this recommended rate is higher than the WHO's minimum ventilation rate for nonresidential settings (10 liters/s per person) and the highest category (I) ventilation rate in ISO 17772-1, but aligns with recommendations from an experimental study on schoolchildren. Finally, in case of a more infectious variants, a higher ventilation rate might be needed, or additional measures like local air cleaners could be used (Morawska et al., 2024).

In essence, while established methods like mechanical filtration and controlled ventilation with heat recovery form a reliable foundation, the path forward involves cautious evaluation of newer purification technologies, demanding stringent proof of safety and effectiveness. Optimizing IAQ is a complex balance requiring tailored strategies based on building use, pollutant types, energy considerations, and validated technology performance.

Infiltration

A recent study indicates that wildfire smoke had the most significant impact on indoor $PM_{2.5}$ concentrations compared to inversion and dust events. The average infiltration factor (Fin) during wildfire smoke events was 4-5 times larger than during dust and inversion events. Furthermore, HVAC systems equipped with air-side economizers (HVAC-1) showed higher $PM_{2.5}$ infiltration factors than systems without economizers but with the same filter efficiency (HVAC-2) across all pollution events. Specifically, the average Fin for HVAC-1 was three times larger for inversion and wildfire smoke events and 28 times larger for dust events compared to HVAC-2. Overall, indoor $PM_{2.5}$ concentrations remained below the 24-hour mean of 15 $\mu g/m^3$. These findings highlight the crucial role of both the type of pollution event and the HVAC system in determining indoor air quality (Mangin et al., 2025).

Portable Air Filtration Market and Usage Trends

In a 2021 memorandum report air filtration methods are primarily dominated by HEPA and carbon filtration, often found in combination, with HEPA filtration being particularly prevalent across various brands. Consumers are most strongly motivated to purchase air purifiers to combat allergies and specific allergens like dust and pollen. While reducing smoke is a less common overall motivator, it's significantly more important for some residents. Interestingly, lower-income respondents were more likely to cite COVID-19 as a very or extremely important purchasing factor.

Regarding usage patterns, seasonal variation isn't strong for about half the sample, though there's a slight increase in usage during summer months and a dip in winter. Bedrooms are the most common location for purifiers, with most units running in a single room. Usage time varies, with roughly half of users operating purifiers for less than six hours daily, but nearly a quarter running them all day long. A clear trend emerges with household size: households with one or two members are significantly more likely (37%) to run their purifiers all day compared to larger households 14% for three to four members, and 13% for five to six members (Evergreen Economics, 2021).

Good IAQ Practices

Indoor Air Quality (IAQ) extends far beyond mere measurements and adherence to guideline limits; it is fundamentally a dynamic interplay of good practices and occupant behavior. While sensors and standards provide a crucial baseline, sustaining healthy indoor environments relies heavily on the collective understanding and actions of those inhabiting the space. Ultimately, empowering occupants with knowledge about these practices transforms IAQ from a technical compliance issue into a shared responsibility for well-being.

1. Source Reduction & Elimination

Controlling the sources of indoor air pollution is arguably the most effective and proactive strategy for maintaining a healthy indoor environment. Rather than solely relying on ventilation or air purification to dilute and remove pollutants after they've been emitted, eliminating or minimizing their release at the source prevents their accumulation in the first place. This approach requires a conscious effort in daily habits and product choices.

For instance, cooking can be a significant source of particulate matter, volatile organic compounds (VOCs), nitrogen dioxide, and carbon monoxide, especially with gas stoves or high-heat methods like frying. To mitigate this, always use a range hood that vents outdoors, preferably on higher settings, and turn it on before you start cooking and keep it on for a few minutes after you finish. Cooking on back burners (lower temperatures) can also improve the effectiveness of the hood. Covering pots and pans with lids helps contain steam and reduce emissions, and choosing cooking oils with higher smoke points can minimize the release of harmful fumes.

Smoking indoors is perhaps the most egregious source of indoor air pollution, releasing a cocktail of carcinogens and toxic compounds that linger in the air and on surfaces. The only truly effective way to control this source is to prohibit smoking entirely indoors. Ventilation and air purifiers can only minimally reduce, not eliminate, the dangers of secondhand smoke.

Perfumes and other strongly scented products, including air fresheners, can release numerous VOCs into the air, contributing to poor IAQ and potentially triggering respiratory issues or headaches in sensitive individuals. Opting for fragrance-free personal care products and cleaning supplies, or using natural alternatives and with good ventilation, can significantly reduce this source of pollution.

When it comes to cleaning with non-harmful chemicals, the impact is profound. Many conventional cleaning products contain harsh chemicals that off-gas VOCs, phthalates, and other respiratory irritants. Switching to natural cleaning alternatives like vinegar, baking soda, and plant-based cleaners dramatically reduces chemical exposure and improves indoor air quality. Look for products certified as "*green*" or "*low-VOC*".

Vacuuming and dusting, while essential for cleanliness, can paradoxically stir up settled dust, allergens, and other particles, temporarily worsening air quality. To control this, use a vacuum cleaner with a High-Efficiency Particulate Air (HEPA) filter and seal system to trap fine particles. Damp dusting with microfiber cloths prevents dust from becoming airborne, and regular cleaning schedules can keep accumulation at bay. Consider removing shoes at the door to prevent tracking in outdoor pollutants.

The selection of building materials is critical, especially in new construction or renovations. Many conventional building materials, furniture, and finishes can continuously off-gas harmful chemicals like formaldehyde, benzene, and other VOCs for years. Prioritize materials that are low-VOC or zero-VOC certified, such as solid wood over pressed wood products (like particleboard or MDF), low-VOC paints and adhesives, natural insulation like wool or cotton, and stone, ceramic, or glass. Checking for certifications like GREENGUARD, Green Label Plus, or Green Seal can guide healthier material choices and significantly reduce long-term chemical emissions in your building.

An often-overlooked source of indoor air pollution with significant health implications is the burning of mosquito coils. According to the paper "Mosquito coil emissions and health implications" published in Environmental Health Perspectives, the smoke generated by burning these coils can contain pollutants that far exceed health-based air quality guidelines. For instance, burning just one mosquito coil can release the same amount of fine particulate matter ($PM_{2.5}$) as burning 75-137 cigarettes, and its formaldehyde emissions can be equivalent to those from 51 cigarettes (Liu et al., 2003). The smoke also contains a large suite of other volatile organic compounds, including polycyclic aromatic hydrocarbons (PAHs). This highlights the importance of choosing alternative mosquito control methods, such as screens, or fans, to avoid introducing harmful pollutants into the indoor environment.

By taking proactive steps to control these sources, we can create truly healthier and more breathable indoor environments.

2. **Mitigating Building Air Pollution During External Events**

When air quality is compromised by events outside of our control—such as wildfires, dust storms, or volcanic eruptions—implementing good practices is crucial to protect building occupants from harmful pollutants like fine particulate matter ($PM_{2.5}$) and gases. The primary goal is to prevent outdoor contaminants from entering the building and to mitigate any pollutants that do infiltrate.

Effective response hinges on real-time data. It is crucial to monitor both outdoor and indoor air quality (AQ) throughout the event. Monitoring outdoor AQ provides necessary context and informs the decision to switch HVAC systems to recirculation mode. Monitoring indoor AQ confirms the effectiveness of protection measures, particularly tracking $PM_{2.5}$ levels, and ensuring that pollutants are not being inadvertently generated or infiltrating the space. The operational goal is to maintain indoor $PM_{2.5}$ significantly below outdoor readings, aiming for levels below 25 μg/m^3 (micrograms per cubic meter) or less.

Effective protection starts with managing the interface between the interior and exterior environment—the building envelope and the mechanical ventilation system.

Sealing and Infiltration Control: The foundational step is to minimize outside air intrusion by sealing the building envelope. This involves checking and sealing all noticeable leaks around windows, doors, utility penetrations, and any cracks in the structure. A well-sealed building is the first defense against external pollution.

HVAC Operational Adjustments: During severe air quality events, the HVAC system must be temporarily optimized for filtration and recirculation. The most critical action is to disable or significantly minimize the intake of outdoor air, switching the system to a recirculation-only mode to condition the air already inside the building. Simultaneously, air filtration must be dramatically increased. This is achieved by upgrading the filters to a high MERV rating, ideally MERV 13 or higher, which effectively captures fine particulate matter. Ensure the HVAC system can safely handle the chosen high-efficiency filter without excessive pressure drop. To maximize the air cleaning cycle, the fans should be operated continuously (24/7).

Occupants play a vital role in maintaining clean indoor air through awareness and action.

Communication and Restriction: It is vital to clearly communicate the air quality situation and the required protective measures to all occupants. Advise occupants to remain indoors with all windows and exterior doors securely closed. Occupants should also limit strenuous physical activity, as increased breathing rates lead not only to higher pollutant intake but also contribute to increased cases of airborne pathogen transmission due to the resulting buildup of indoor stale air (CO_2 levels).

Supplemental Air Cleaning: Encourage the deployment of portable HEPA (High Efficiency Particulate Air) air cleaners within occupied spaces, such as offices and residences. These devices provide localized, high-level filtration, offering significant protection against $PM_{2.5}$ in immediate living and working areas.

Controlling Indoor Pollutants: Occupants must be mindful of not introducing new pollutants. They should avoid activities that generate indoor air pollution, including smoking indoors, burning candles or incense, using unvented gas or wood-burning appliances, and vacuuming without a HEPA-filtered vacuum, which can stir up settled particles.

Outdoor Protection: If an occupant must venture outside, they should be advised to wear appropriate respirators, such as an N95 or P100 mask, which are designed to filter fine particles. Simple cloth or surgical masks offer insufficient protection against the particulates found in smoke or dust.

Enhance Ventilation & Air Filtration

Enhanced or improved ventilation stands as a cornerstone of good IAQ, serving as a primary mechanism to dilute and remove indoor air pollutants. Effective ventilation strategies ensure a continuous exchange of stale, pollutant-laden indoor air with fresh outdoor air, thereby reducing the concentration of contaminants such as formaldehyde, carbon dioxide, allergens, and even airborne pathogens. Examples of enhanced ventilation include opening windows and doors when outdoor air quality permits, utilizing exhaust fans in kitchens and bathrooms to remove moisture and pollutants at their source, and critically, ensuring that mechanical ventilation systems like HVAC (Heating, Ventilation, and Air Conditioning) operate optimally with sufficient outdoor air intake and proper filtration. Demand-controlled ventilation, which adjusts airflow based on occupancy or CO_2 levels, is another advanced method for optimizing ventilation efficiency.

However, a crucial challenge arises from the varying stringency of legislation and guidelines regarding ventilation rates across different regions and building types. Some existing standards may be more permissive than others, potentially leading to indoor environments that, while technically compliant, may not provide optimal air quality for occupant health and comfort. This disparity necessitates a proactive approach where building owners, managers, and occupants do not take minimum requirements for granted. Instead, there's a strong imperative to "*go a step further*" by implementing ventilation strategies that exceed baseline mandates, especially in spaces with high occupancy, specific pollutant sources, or vulnerable populations. For instance, while a standard might specify a certain air changes per hour (ACH) for an office, a truly health-focused approach might aim for higher ACH, or incorporate advanced filtration and air purification technologies to achieve superior IAQ. GO AQS, as previously discussed in earlier chapters, has already emphasized the importance of this proactive stance by recommending specific, often higher, ventilation rates and advanced filtration technologies, such as MERV (Minimum Efficiency Reporting Value) 13 or higher filters, and potentially even HEPA filtration, to effectively capture a wider range of airborne pollutants, underscoring that optimal IAQ often demands exceeding mere regulatory compliance.

3. Measure IAQ

Continuous monitoring of IAQ is absolutely critical, given its inherently dynamic nature and susceptibility to a multitude of influencing factors. Unlike fixed parameters, IAQ is constantly in flux, responding to variables that can shift dramatically throughout the day or even minute-by-minute. External conditions, such as outdoor air pollution levels (e.g., from traffic, industrial activity, or pollen counts), temperature, and humidity, directly impact the quality of air drawn into buildings. Internally, occupancy levels play a significant role; a room that is sparsely used will have different CO_2 and particulate levels than one packed with people. Human activities further compound this variability: cooking generates specific pollutants, cleaning introduces chemicals, even simply walking around can stir up dust and allergens. Without continuous monitoring, these fluctuations go unnoticed, leaving occupants potentially exposed to suboptimal or even harmful conditions without their knowledge.

The ability to constantly measure IAQ parameters like CO_2, $PM_{2.5}$, radon, and other gases, allows for real-time insights into the indoor environment. This real-time data is invaluable for several reasons. Firstly, it enables immediate identification of potential issues, such as a sudden spike in VOCs indicating a cleaning product being used improperly, or rising CO_2 levels signaling insufficient ventilation. Secondly, it facilitates timely intervention, allowing building management systems to adjust ventilation rates automatically or alerting occupants to take corrective actions, such as opening a window or ctivating an exhaust fan. Thirdly, continuous data collection provides a comprehensive historical record, enabling long-term analysis of IAQ trends, identification of persistent problems, and verification of the effectiveness of implemented solutions. This constant feedback loop transforms IAQ management from a reactive, periodic assessment into a proactive, adaptive process. It is precisely for these reasons that GO AQS has developed tools like the GO IAQS Score. This score serves as an intuitive and efficient communication mechanism, distilling complex IAQ data into an easily understandable metric. By presenting IAQ information in a clear and actionable format, the GO IAQS Score empowers occupants and building managers to understand the current state of their indoor environment and respond effectively and precisely to maintain optimal air quality for health and well-being.

Finally, Building Automation Systems (BAS) represent a significant beneficiary of continuous indoor air quality (IAQ) measurements, transforming the management of building environments from static to dynamic and responsive. By integrating real-time IAQ data from sensors monitoring parameters like CO_2 levels, particulate matter, and VOCs, BAS can intelligently and automatically adjust ventilation rates. For example, when CO_2 levels rise due to increased occupancy, the BAS can trigger an increase in the fresh air supply to dilute pollutants. Conversely, during periods of low occupancy or when outdoor air quality is poor, the system can reduce outdoor air intake, minimizing the introduction of external pollutants and conserving energy. This granular control not only ensures optimal indoor air quality for occupants by continuously responding to changing conditions but also translates directly into substantial energy reductions and operational cost savings, making continuous IAQ monitoring an indispensable tool for modern, sustainable building management.

4. Air Quality Metadata

At GO AQS, we fundamentally believe that the true value of air quality data is unlocked through the rigorous inclusion of metadata. Metadata is not merely an optional addition; it is the critical contextual layer that transforms raw air pollutant measurements into actionable, reliable information. Without robust metadata, air quality measurements —such as concentrations of $PM_{2.5}$— are essentially meaningless numbers, as their reliability, relevance, and origin cannot be confirmed. Metadata transforms a simple numerical value into an understandable, scientific observation, enabling proper interpretation, validation, and reuse by scientists, policymakers, and the public.

We encourage the inclusion of several key types of metadata to ensure data utility. This includes spatial data (the precise location, such as latitude and longitude, of the monitoring station if possible) and temporal data (the exact date, time, and the averaging period over which the measurement was taken). Furthermore, instrumentation details are vital, covering the specific model, serial number, and measurement principle of the analyser, along with its recent calibration history. Crucially, data quality flags must be included to indicate known issues, the current data validation status, and the associated uncertainty of the measurement. This comprehensive information guarantees data comparability across different monitoring networks and facilitates accurate regulatory reporting, air quality modeling, and scientific research.

Metadata become even more important when air quality measurements are taken using non-reference methods —approaches that are faster or more cost-effective but may not directly align with primary regulatory standards. For example, while the gold standard for $PM_{2.5}$ is often the Federal Reference Method (FRM) based on gravimetric analysis, many widely used lower-cost sensors or monitors employ light scattering. In these cases, including metadata with vital information about conversion factors and statistical estimations is essential. This information explains how the non-reference measurement was converted or adjusted to relate to a reference standard, detailing the model, algorithm, or statistical relationship used. This transparency strengthens the air quality data, providing users with the necessary information to evaluate its precision and its appropriate use (Watne et al., 2021; Santana et al., 2016).

5. Date/Time & Air Quality Data

To fully embrace good data practices in the crucial domain of Indoor Air Quality (IAQ), air quality monitoring solutions and manufacturers must extend their commitment beyond adopting the core GO AQS framework by implementing the ISO 8601 timestamp standard for their data output. This international standard defines an internationally recognized format for date and time representation, typically looking like this: **YYYY-MM-DDThh:mm:ssZ** (e.g., 2025-09-16T12:27:09Z), and its clear, unambiguous format is vital for interoperability and data integration. The final Z is critical as it denotes Zulu time (UTC), the international standard for coordinated universal time, which eliminates ambiguity in time zones and ensures a measurement's time is always correctly understood regardless of the sensor's local time zone. For instance, a measurement taken in Spain at 15:30:00 on September 16, 2025, would be timestamped as 2025-09-16T15:30:00+01:00 (local time with UTC+1 offset) or, more consistently, as 2025-11-07T14:30:00Z (Zulu/UTC time). This consistent, globally accessible timestamp is the bedrock for accurate data analysis and visualization, allowing for seamless data exchange between diverse monitoring devices, BAS, and analytics platforms, while dramatically reducing data conversion issues and enabling precise trend identification and event correlation essential for diagnosing air quality fluctuations. Beyond this crucial data formatting, GO AQS achieves interoperability by promoting a universal Indoor Air Quality Score with the same health-based limits and breakpoints for pollutants across the board, ensuring a pollutant reading is converted to the same index score corresponding to the same health implications, which drives global efforts to improve air quality based on unified, actionable thresholds.

6. Decarbonization & IAQ

The relationship between IAQ and decarbonization is not one of competing goals but a deeply synergistic one, creating a powerful, positive feedback loop. Although this profound interconnectedness is often overlooked, strategies for one objective can directly and impact the other, creating essential co-benefits for public health, climate, and the economy. This holistic approach is crucial for driving a global transition towards buildings that are simultaneously healthy for occupants and carbon-neutral.

Improving IAQ is a catalyst for decarbonization, primarily by drastically reducing a building's operational carbon emissions. This efficiency is achieved through the "*Clean First*" framework, which advocates for cleaning indoor air using advanced filtration and air cleaning technologies rather than relying on solely energy-intensive dilution with large volumes of outside air. By optimizing ventilation and reducing reliance on outside air for dilution, this approach can significantly lower the energy needed for HVAC systems. Combining sorbent air cleaning and high-efficiency energy recovery (ERV) with optimized ventilation can reduce annual ventilation energy by 73–86% (Aamidor et al., 2022). ERVs are key technologies because they recover energy from exhaust air to precondition incoming fresh air, allowing for adequate ventilation to manage indoor contaminants and maintain good IAQ without the significant energy penalty of conditioning un-tempered outside air. This substantial energy reduction supports the transition to all-electric systems, such as heat pumps, by reducing the cooling or heating load they must handle, which can help enable retrofits without requiring costly electrical capacity upgrades. Furthermore, the focus on minimizing indoor pollutant sources encourages the use of low-VOC and low-embodied-carbon materials, which simultaneously creates healthier indoor environments and accelerates a holistic, whole-life carbon approach to building design and operation.

Conversely, core decarbonization strategies inherently produce substantial enhancements to IAQ, making decarbonization a public health imperative. The central strategy of building electrification involves replacing appliances that burn fossil fuels (like natural gas or oil) with high-efficiency electric alternatives. This process eliminates on-site combustion, which is a major source of harmful indoor air pollutants like carbon monoxide and particulate matter. By removing these pollution sources, switching to all-electric directly reduces health risks such as asthma and CO poisoning. Additionally, the "*fabric-first*" approach to decarbonization emphasizes enhancing the building envelope through better insulation and air sealing. A well-sealed building minimizes the infiltration of outdoor pollutants like $PM_{2.5}$ from traffic or wildfire smoke, creating a more controlled and resilient indoor environment. Decarbonization retrofits also commonly upgrade to modernized ventilation systems that include higher-efficiency filters (MERV 13) and ERV.

Committee

Establishing air quality target limits is a democratic process involving a committee and expert advisors with equal voting power.

The GO AQS Committee comprises a diverse group of scientists, public health professionals, and air quality experts, classified into a main committee, advisory expert groups, and ambassadors. The primary distinction between the two main committee and advisory expert groups lies in the time commitment members are able to dedicate. While the main committee holds a more substantial role, both groups are equally valued and members can shift between them as their availability changes. This flexible structure respects individual commitments while ensuring a robust pool of expertise to inform air quality standards.

All members from the main committee and advisory expert groups must participate in the voting process to maintain project vitality. Proposed limits are subjected to a voting round, requiring a minimum of 60% approval to be enacted. This system ensures broad consensus and accountability, fostering a collaborative approach to safeguarding public health and environmental well-being.

Fianlly, GO AQG ambassador group members play a pivotal role in fostering community engagement and promoting the organisation's mission. Their responsibilities often encompass representing GO AQG at events, networking with key stakeholders, and providing valuable feedback on programmes and initiatives. Ambassadors serve as enthusiastic advocates, sharing their passion for the organisation's work with the public and inspiring others to get involved. Additionally, they may contribute to social media campaigns, volunteer for special projects, and participate in mentorship programmes, ultimately strengthening GO AQG's impact and reach.

Members of Committee, Advisory Experts, and Ambassadors

Main Committee

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References

A

Adamkiewicz, G., Zota, A. R., Fabian, M. P., Chahine, T., Julien, R., Spengler, J. D., & Levy, J. I. (2011). Moving Environmental Justice indoors: Understanding structural influences on residential exposure Patterns in Low-Income Communities. American Journal of Public Health, 101(S1), S238–S245. https://doi.org/10.2105/ajph.2011.300119

Air Quality, Energy and Health (AQE). (2021, September 22). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. https://www.who.int/publications/i/item/9789240034228

Air Quality, Energy and Health (AQE). (2023, February 17). Risk communication of ambient air pollution in the WHO European Region: review of air quality indexes and lessons learned. https://www.who.int/publications/i/item/WHO-EURO-2023-6885-46651-67825

Algar, O. G., Pichini, S., Basagana, X., Puig, C., Vall, O., Torrent, M., Harris, J., Sunyer, J., & Cullinan, P. (2004). Concentrations and determinants of NO2 in homes of Ashford, UK and Barcelona and Menorca, Spain. Indoor Air, 14(4), 298–304. https://doi.org/10.1111/j.1600-0668.2004.00256.x

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2015). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environmental Health Perspectives, 124(6), 805–812. https://doi.org/10.1289/ehp.1510037

Antignani, S., Venoso, G., Ampollini, M., Caprio, M., Carpentieri, C., Di Carlo, C., Caccia, B., Hunter, N., & Bochicchio, F. (2020). A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates. The Science of the Total Environment, 762, 144150. https://doi.org/10.1016/j.scitotenv.2020.144150

B

Baxter, L. K., Clougherty, J. E., Laden, F., & Levy, J. I. (2006). Predictors of concentrations of nitrogen dioxide, fine particulate matter, and particle constituents inside of lower socioeconomic status urban homes. Journal of Exposure Science & Environmental Epidemiology, 17(5), 433–444. https://doi.org/10.1038/sj.jes.7500532

Belanger, K., Holford, T. R., Gent, J. F., Hill, M. E., Kezik, J. M., & Leaderer, B. P. (2013b). Household levels of nitrogen dioxide and pediatric asthma severity. Epidemiology, 24(2), 320–330. https://doi.org/10.1097/ede.0b013e318280e2ac

Bell, M. L., Dominici, F., & Samet, J. M. (2005). A Meta-Analysis of Time-Series studies of ozone and mortality with comparison to the national Morbidity, Mortality, and Air Pollution Study. Epidemiology, 16(4), 436–445. https://doi.org/10.1097/01.ede.0000165817.40152.85

Bhoonah R, Maury-Micolier A, Jolliet O, Fantke P. Fine Particulate Matter Exposure and Health Impacts from Indoor Activities. Indoor Air. 2023;2023:1-12. doi:10.1155/2023/8857446

Brenner, D. J. (2023). The public-health significance of far-UVC-induced indoor ozone and its associated secondary chemistry. Photochemistry and Photobiology. https://doi.org/10.1111/php.13892

C

Carbon Monoxide Safety & Awareness | NCOAA. (n.d.). NCOAA. https://www.ncoaa.us/

Cassee, F., Muijser, H., Duistermaat, E., Freijer, J., Geerse, K., Marijnissen, J., & Arts, J. (2002). Particle size-dependent total mass deposition in lungs determines inhalation toxicity of cadmium chloride aerosols in rats. Application of a multiple path dosimetry model. Archives of Toxicology, 76(5–6), 277–286. https://doi.org/10.1007/s00204-002-0344-8

Chen, J., Moir, D., & Whyte, J. (2012). Canadian population risk of radon induced lung cancer: a re-assessment based on the recent cross-Canada radon survey. Radiation Protection Dosimetry, 152(1–3), 9–13. https://doi.org/10.1093/rpd/ncs147

Chen, K., Breitner, S., Wolf, K., Stafoggia, M., Sera, F., Vicedo-Cabrera, A. M., Guo, Y., Tong, S., Lavigne, E., Matus, P., Valdés, N., Kan, H., Jaakkola, J. J. K., Ryti, N. R. I., Huber, V., Scortichini, M., Hashizume, M., Honda, Y., Nunes, B., . . . Schneider, A. (2021). Ambient carbon monoxide and daily mortality: a global time-series study in 337 cities. The Lancet Planetary Health, 5(4), e191–e199. https://doi.org/10.1016/s2542-5196(21)00026-7

Chen, K., Breitner, S., Wolf, K., Stafoggia, M., Sera, F., Vicedo-Cabrera, A. M., Guo, Y., Tong, S., Lavigne, E., Matus, P., Valdés, N., Kan, H., Jaakkola, J. J. K., Ryti, N. R. I., Huber, V., Scortichini, M., Hashizume, M., Honda, Y., Nunes, B., . . . Schneider, A. (2021). Ambient carbon monoxide and daily mortality: a global time-series study in 337 cities. The Lancet Planetary Health, 5(4), e191–e199. https://doi.org/10.1016/s2542-5196(21)00026-7

Choi, S., & Oh, S. (2015). Acute carbon monoxide poisoning and delayed neurological sequelae: a potential neuroprotection bundle therapy. Neural Regeneration Research, 10(1), 36. https://doi.org/10.4103/1673-5374.150644

Chuang, S., Kuo, Y., Huang, S., Zhang, H., Peng, H., & Chen, Y. (2023). Association between Long-Term Exposure to Air Pollution and the Rate of Mortality After Hip Fracture Surgery in Patients over 60 Years Old: A Nationwide Cohort Study in Taiwan (Preprint). JMIR Public Health and Surveillance. https://doi.org/10.2196/46591

Cocârţă, D. M., Prodana, M., Demetrescu, I., Lungu, P. E. M., & Didilescu, A. C. (2021). Indoor Air Pollution with Fine Particles and Implications for Workers' Health in Dental Offices: A Brief Review. Sustainability, 13(2), 599. https://doi.org/10.3390/su13020599

Coley, D. A., Greeves, R., & Saxby, B. K. (2007). The effect of low ventilation rates on the cognitive function of a primary school class. International Journal of Ventilation, 6(2), 107–112. https://doi.org/10.1080/14733315.2007.11683770

Cromar, K. R., Ghazipura, M., Gladson, L. A., & Perlmutt, L. (2020). Evaluating the U.S. Air Quality Index as a risk communication tool: Comparing associations of index values with respiratory morbidity among adults in California. PLoS ONE, 15(11), e0242031. https://doi.org/10.1371/journal.pone.0242031

D

Dimitroulopoulou, S., Dudzińska, M. R., Gunnarsen, L., Hägerhed, L., Maula, H., Singh, R., Toyinbo, O., & Haverinen-Shaughnessy, U. (2023). Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort. Environment International, 178, 108127. https://doi.org/10.1016/j.envint.2023.108127

E

Evergreen Economics. (2021). Air purifier study results (EERE-2021-BT-TP-0036-0010). https://downloads.regulations.gov/EERE-2021-BT-TP-0036-0010/attachment_2.pdf

F

Frischer, T., Studnicka, M., Gartner, C., Tauber, E., Horak, F., Veiter, A., Spengler, J., Kühr, J., & Urbanek, R. (1999). Lung function growth and ambient ozone. American Journal of Respiratory and Critical Care Medicine, 160(2), 390–396. https://doi.org/10.1164/ajrccm.160.2.9809075

G

Gaihre, S., Semple, S., Miller, J., Fielding, S., & Turner, S. (2014). Classroom carbon dioxide concentration, school attendance, and educational attainment. Journal of School Health, 84(9), 569–574. https://doi.org/10.1111/josh.12183

Garzillo, C., Pugliese, M., Loffredo, F., & Quarto, M. (2017). Indoor radon exposure and lung cancer risk: a meta-analysis of case-control studies. Translational Cancer Research, 6(S5), S934–S943. https://doi.org/10.21037/tcr.2017.05.42

Gavett, S. H., Haykal-Coates, N., Copeland, L. B., Heinrich, J., & Gilmour, M. I. (2003). Metal composition of ambient PM2.5 influences severity of allergic airways disease in mice. Environmental Health Perspectives, 111(12), 1471–1477. https://doi.org/10.1289/ehp.6300

Gayer, A., Adamkiewicz, Ł., Mucha, D., & Badyda, A. (2018). Air quality health indices - review. MATEC Web of Conferences, 247, 00002. https://doi.org/10.1051/matecconf/201824700002

Gizaw, Z., & Teka, Z. (2020). Correlates of indoor concentration of carbon monoxide in residential buildings in Gondar Town, northwest Ethiopia. Environmental Health Insights, 14, 117863022097823. https://doi.org/10.1177/1178630220978234

Gładyszewska-Fiedoruk, K., & Wiater, J. (2022). Indoor Air Quality with Particular Reference to Carbon Monoxide in the Room – A Pilot Study. Journal of Ecological Engineering, 23(6), 286–293. https://doi.org/10.12911/22998993/149284

Grande, G., Wu, J., Ljungman, P. L., Stafoggia, M., Bellander, T., & Rizzuto, D. (2021). Long-Term exposure to PM2.5 and Cognitive Decline: a Longitudinal Population-Based study. Journal of Alzheimer S Disease, 80(2), 591–599. https://doi.org/10.3233/jad-200852

Guo, M., Yu, W., Sun, Y., Wang, L., Zhou, H., & Zhang, Y. (2023). Effects of increasing indoor negative air ions on cognitive performance and health of high pure CO2 Level-Exposed college students. Indoor Air, 2023, 1–11. https://doi.org/10.1155/2023/8298339

Guttikunda, S. K. (2024). Why Communicating air quality information in the simplest form gets more people to understand and get involved in the fight against air pollution. EGUsphere. https://doi.org/10.5194/egusphere-2024-1712

H

Haddrell, A., Oswin, H., Otero-Fernandez, M., Robinson, J. F., Cogan, T., Alexander, R., Mann, J. F. S., Hill, D., Finn, A., Davidson, A. D., & Reid, J. P. (2024). Ambient carbon dioxide concentration correlates with SARS-CoV-2 aerostability and infection risk. Nature Communications, 15(1). https://doi.org/10.1038/s41467-024-47777-5

Hansel, N. N., Breysse, P. N., McCormack, M. C., Matsui, E. C., Curtin-Brosnan, J., Williams, D. L., Moore, J. L., Cuhran, J. L., & Diette, G. B. (2008). A Longitudinal Study of Indoor Nitrogen Dioxide Levels and Respiratory Symptoms in Inner-City Children with Asthma. Environmental Health Perspectives, 116(10), 1428–1432. https://doi.org/10.1289/ehp.11349

Hauptmann, M., Lubin, J. H., Stewart, P. A., Hayes, R. B., & Blair, A. (2003). Mortality from lymphohematopoietic malignancies among workers in formaldehyde industries. JNCI Journal of the National Cancer Institute, 95(21), 1615–1623. https://doi.org/10.1093/jnci/djg083

Hauptmann, M., Lubin, J. H., Stewart, P. A., Hayes, R. B., & Blair, A. (2004). Mortality from Solid Cancers among Workers in Formaldehyde Industries. American Journal of Epidemiology, 159(12), 1117–1130. https://doi.org/10.1093/aje/kwh174

Hauptmann, M., Stewart, P. A., Lubin, J. H., Freeman, LEB., Hornung, R. W., Herrick, R. F., Hoover, R. N., Fraumeni, J. F., Blair, A., & Hayes, R. B. (2009). Mortality from lymphohematopoietic malignancies and brain cancer among embalmers exposed to formaldehyde. JNCI Journal of the National Cancer Institute, 101(24), 1696–1708. https://doi.org/10.1093/jnci/djp416

Health Canada. (2015, November 26). Residential indoor air quality Guideline: Nitrogen dioxide. Canada.ca. https://www.canada.ca/en/health-canada/services/publications/healthy-living/residential-indoor-air-quality-guideline-nitrogen-dioxide.html

Health Effects Institute. (2023, July 17). Assessing adverse health effects of Long-Term exposure to low levels. https://www.healtheffects.org/publication/assessing-adverse-health-effects-long-term-exposure-low-levels-ambient-air-pollution

Holnicki, P., Tainio, M., Kałuszko, A., & Nahorski, Z. (2017). Burden of mortality and disease attributable to multiple air pollutants in Warsaw, Poland. International Journal of Environmental Research and Public Health, 14(11), 1359. https://doi.org/10.3390/ijerph14111359

Huang, W., Wu, J., & Lin, X. (2022). Ozone exposure and asthma attack in children. Frontiers in Pediatrics, 10. https://doi.org/10.3389/fped.2022.830897

I

IRIS Toxicological Review of Formaldehyde (Inhalation) (Final Report, 2024) | IRIS | US EPA. (n.d.). https://iris.epa.gov/document/&deid=361799

J

Jarvis, D. J., Adamkiewicz, G., Heroux, M., Rapp, R., & Kelly, F. J. (2010). Nitrogen dioxide. WHO Guidelines for Indoor Air Quality: Selected Pollutants - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK138707/

Joseph Aamidor, Barry Abramson, Dr. William Bahnfleth, Phoebe Beierle, James Dice, Tim Dorman, Cory Duggin, David Ellowitz, Anthony M. Montalto, Larissa Oaks, Dr. Amanda Rischbieth, Jared Rodriguez, Jay Stein, Brice Watson, and Marwa Zaatari. (2022). How to achieve Sustainable Indoor Air quality: A roadmap tosimultaneously improving indoor air quality & meeting building decarbonization and climate resiliency goals.. https://enverid.com/wp-content/uploads/2022/08/enVerid-Sustainable-IAQ-Whitepaper-f10.pdf

K

K, P., & Kumar, P. (2022c). A critical evaluation of air quality index models (1960–2021). Environmental Monitoring and Assessment, 194(5). https://doi.org/10.1007/s10661-022-09896-8

Kanchan, N., Gorai, A. K., & Goyal, P. (2015). A review on air quality Indexing system. Asian Journal of Atmospheric Environment, 9(2), 101–113. https://doi.org/10.5572/ajae.2015.9.2.101

Kannan, S., Dvonch, J. T., Schulz, A. J., Israel, B. A., Mentz, G., House, J., Max, P., & Reyes, A. G. (2009). Exposure to fine particulate matter and acute effects on blood pressure: effect modification by measures of obesity and location. Journal of Epidemiology & Community Health, 64(01), 68–74. https://doi.org/10.1136/jech.2008.081836

Khoshakhlagh, A. H., Mohammadzadeh, M., Ghobakhloo, S., Cheng, H., Gruszecka-Kosowska, A., & Knight, J. (2024). Health risk assessment from inhalation exposure to indoor formaldehyde: a systematic review and meta-analysis. Journal of Hazardous Materials, 471, 134307. https://doi.org/10.1016/j.jhazmat.2024.134307

Kuramochi, H., Tsurumi, R., & Ishibashi, Y. (2023). Meta-Analysis of the effect of ventilation on intellectual productivity. International Journal of Environmental Research and Public Health, 20(8), 5576. https://doi.org/10.3390/ijerph20085576

L

Lam, J., Koustas, E., Sutton, P., Padula, A. M., Cabana, M. D., Vesterinen, H., Griffiths, C., Dickie, M., Daniels, N., Whitaker, E., & Woodruff, T. J. (2021). Exposure to formaldehyde and asthma outcomes: A systematic review, meta-analysis, and economic assessment. PLoS ONE, 16(3), e0248258. https://doi.org/10.1371/journal.pone.0248258

Liang, X., Zhang, B., Wang, K., Ji, X., Geng, Z., & Chen, C. (2022). Indoor formaldehyde pollution and its influencing factors of newly decorated residential buildings in Kunshan city, Jiangsu province. Current Urban Studies, 10(02), 263–274. https://doi.org/10.4236/cus.2022.102016

Liu, N., Fang, L., Liu, W., Kan, H., Zhao, Z., Deng, F., Huang, C., Zhao, B., Zeng, X., Sun, Y., Qian, H., Mo, J., Sun, C., Guo, J., Zheng, X., Bu, Z., Weschler, L. B., & Zhang, Y. (2023). Health effects of exposure to indoor formaldehyde in civil buildings: A systematic review and meta-analysis on the literature in the past 40 years. Building and Environment, 233, 110080. https://doi.org/10.1016/j.buildenv.2023.110080

Liu, N., Liu, W., Deng, F., Liu, Y., Gao, X., Fang, L., Chen, Z., Tang, H., Hong, S., Pan, M., Liu, W., Huo, X., Guo, K., Ruan, F., Zhang, W., Zhao, B., Mo, J., Huang, C., Su, C., . . . Zhang, Y. (2023). The burden of disease attributable to indoor air pollutants in China from 2000 to 2017. The Lancet Planetary Health, 7(11), e900–e911. https://doi.org/10.1016/s2542-5196(23)00215-2

Liu, Y., Ma, H., Zhang, N., & Li, Q. (2022). A systematic literature review on indoor PM2.5 concentrations and personal exposure in urban residential buildings. Heliyon, 8(8), e10174. https://doi.org/10.1016/j.heliyon.2022.e10174

Liu, W., Zhang, J., Hashim, J. H., Jalaludin, J., Hashim, Z., & Goldstein, B. D. (2003). Mosquito coil emissions and health implications. Environmental Health Perspectives, 111(12), 1454–1460. https://doi.org/10.1289/ehp.6286

M

Mangin, T., Barrett, Z., Palmer, Z., Tang, D., Nielson, S., Sleeth, D., & Kelly, K. (2025). Understanding the effect of outdoor pollution episodes and HVAC type on indoor air quality. Building and Environment, 112978. 10.1016/j.buildenv.2025.112978

Milner, J., Armstrong, B., Davies, M., Ridley, I., Chalabi, Z., Shrubsole, C., Vardoulakis, S., & Wilkinson, P. (2017). An Exposure-Mortality Relationship for Residential Indoor PM2.5 Exposure from Outdoor Sources. Climate, 5(3), 66. https://doi.org/10.3390/cli5030066

Moonie, S., Sterling, D. A., Figgs, L. W., & Castro, M. (2008). The relationship between school absence, academic performance, and asthma status. Journal of School Health, 78(3), 140–148. https://doi.org/10.1111/j.1746-1561.2007.00276.x

Morawska, L., Allen, J., Bahnfleth, W., Bennett, B., Bluyssen, P. M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S. J., Floto, A., Franchimon, F., Greenhalgh, T., Haworth, C., Hogeling, J., Isaxon, C., Jimenez, J. L., Kennedy, A., Kumar, P., Kurnitski, J., . . . Yao, M. (2024). Mandating indoor air quality for public buildings. Science, 383(6690), 1418–1420. https://doi.org/10.1126/science.adl0677

N

National Eye Institute. (2024, April 15). Color blindness | National Eye Institute. https://www.nei.nih.gov/learn-about-eye-health/eye-conditions-and-diseases/color-blindness

National Eye Institute. (n.d.). Types of Color Vision Deficiency | National Eye Institute. https://www.nei.nih.gov/learn-about-eye-health/eye-conditions-and-diseases/color-blindness/types-color-vision-deficiency#:~:text=The%20most%20common%20type%20of,of%20green%20look%20more%20red.

Nazaroff, W. W., & Weschler, C. J. (2021). Indoor ozone: Concentrations and influencing factors. Indoor Air, 32(1). https://doi.org/10.1111/ina.12942

Ngoc, L. T. N., Park, D., & Lee, Y. (2022). Human Health Impacts of Residential radon Exposure: Updated Systematic Review and Meta-Analysis of Case–Control Studies. International Journal of Environmental Research and Public Health, 20(1), 97. https://doi.org/10.3390/ijerph20010097

P

Park, S. K., & Wang, W. (2014). Ambient Air Pollution and Type 2 Diabetes Mellitus: A Systematic Review of Epidemiologic research. Current Environmental Health Reports, 1(3), 275–286. https://doi.org/10.1007/s40572-014-0017-9

Pepe, G., Castelli, M., Nazerian, P., Vanni, S., Del Panta, M., Gambassi, F., Botti, P., Missanelli, A., & Grifoni, S. (2011). Delayed neuropsychological sequelae after carbon monoxide poisoning: predictive risk factors in the Emergency Department. A retrospective study. Scandinavian Journal of Trauma Resuscitation and Emergency Medicine, 19(1). https://doi.org/10.1186/1757-7241-19-16

Petkus, A. J., Salminen, L. E., Wang, X., Driscoll, I., Millstein, J., Beavers, D. P., Espeland, M. A., Braskie, M. N., Thompson, P. M., Casanova, R., Gatz, M., Chui, H. C., Resnick, S. M., Kaufman, J. D., Rapp, S. R., Shumaker, S., Younan, D., & Chen, J. (2023). Alzheimer's related neurodegeneration mediates air pollution effects on medial temporal lobe atrophy. medRxiv (Cold Spring Harbor Laboratory). https://doi.org/10.1101/2023.11.29.23299144

Q

Quarcoo, M. A., Strickland, P. O., & Shendell, D. G. (2019). Indoor ozone estimation from outdoor ozone and LBNL relocatable classroom study data. Atmospheric Environment, 213, 491–498. https://doi.org/10.1016/j.atmosenv.2019.06.036

R

Rastogi, S., & Mathur, N. (2007). Respiratory effects due to occupational exposure to formaldehyde: Systematic review with meta-analysis. Indian Journal of Occupational and Environmental Medicine, 11(1), 26. https://doi.org/10.4103/0019-5278.32461

S

Salthammer, T. (2022). TVOC - revisited. Environment International, 167, 107440. https://doi.org/10.1016/j.envint.2022.107440

Salonen, H., Salthammer, T., & Morawska, L. (2018). Human exposure to ozone in school and office indoor environments. Environment International, 119, 503–514. https://doi.org/10.1016/j.envint.2018.07.012

Santana, M. a. A., Guimarães, P. L. O., Almêida, E. S., & Eklin, T. (2016). The importance of metrological metadata in the environmental monitoring. Journal of Physics Conference Series, 733, 012033. https://doi.org/10.1088/1742-6596/733/1/012033

Schaumann, F., Borm, P. J. A., Herbrich, A., Knoch, J., Pitz, M., Schins, R. P. F., Luettig, B., Hohlfeld, J. M., Heinrich, J., & Krug, N. (2004). Metal-rich ambient particles (Particulate matter2.5) cause airway inflammation in healthy subjects. American Journal of Respiratory and Critical Care Medicine, 170(8), 898–903. https://doi.org/10.1164/rccm.200403-423oc

Schraufnagel, D. E. (2020). The health effects of ultrafine particles. Experimental & Molecular Medicine, 52(3), 311–317. https://doi.org/10.1038/s12276-020-0403-3

Shi, H., Magaye, R., Castranova, V., & Zhao, J. (2013). Titanium dioxide nanoparticles: a review of current toxicological data. Particle and Fibre Toxicology, 10(1). https://doi.org/10.1186/1743-8977-10-15

Song, C., Lim, C. C., Gurmu, B. L., Kim, M., Lee, S., Park, J., & Kim, S. (2023). Comparison of personal or indoor PM2.5 exposure level to that of outdoor: over four seasons in selected urban, industrial, and rural areas of South Korea: (K-IOP Study). International Journal of Environmental Research and Public Health, 20(17), 6684. https://doi.org/10.3390/ijerph20176684

Sönmez, B. M., İşcanlı, M. D., Parlak, S., Doğan, Y., Ulubay, H. G., & Temel, E. (2018). Delayed neurologic sequelae of carbon monoxide intoxication. Turkish Journal of Emergency Medicine, 18(4), 167–169. https://doi.org/10.1016/j.tjem.2018.04.002

Stieb, D. M., Burnett, R. T., Smith-Doiron, M., Brion, O., Shin, H. H., & Economou, V. (2008). A new multipollutant, No-Threshold air quality health index based on Short-Term associations observed in daily Time-Series analyses. Journal of the Air & Waste Management Association, 58(3), 435–450. https://doi.org/10.3155/1047-3289.58.3.435

T

Tan, X., Han, L., Zhang, X., Zhou, W., Li, W., & Qian, Y. (2020). A review of current air quality indexes and improvements under the multi-contaminant air pollution exposure. Journal of Environmental Management, 279, 111681. https://doi.org/10.1016/j.jenvman.2020.111681

Thangavel, P., Park, D., & Lee, Y. (2022). Recent Insights into Particulate Matter (PM2.5)-Mediated Toxicity in Humans: An Overview. International Journal of Environmental Research and Public Health, 19(12), 7511. https://doi.org/10.3390/ijerph19127511

The Government of the Hong Kong Special Administrative Region. (2019). Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places. https://www.iaq.gov.hk/wp-content/uploads/2021/04/gn_officeandpublicplace_eng-2019.pdf

W

Wargocki, P., Wei, W., Bendžalová, J., Espigares-Correa, C., Gerard, C., Greslou, O., Rivallain, M., Sesana, M. M., Olesen, B. W., Zirngibl, J., & Mandin, C. (2021). TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project). Energy and Buildings, 244, 111029. https://doi.org/10.1016/j.enbuild.2021.111029

Wang, Y., Li, J., Wang, L., Lin, Y., Zhou, M., Yin, P., & Yao, S. (2021b). The impact of carbon monoxide on years of life lost and modified effect by individual- and city-level characteristics: Evidence from a nationwide time-series study in China. Ecotoxicology and Environmental Safety, 210, 111884. https://doi.org/10.1016/j.ecoenv.2020.111884

Watne, Å. K., Linden, J., Willhelmsson, J., Fridén, H., Gustafsson, M., & Castell, N. (2021). Tackling data quality when using Low-Cost air quality sensors in citizen science projects. Frontiers in Environmental Science, 9. https://doi.org/10.3389/fenvs.2021.733634

Weisenberg, H., Zhao, T., & Heinrich, J. (2020). Combinations of Epidemiological and Experimental Studies in Air Pollution Research: A Narrative review. International Journal of Environmental Research and Public Health, 17(2), 385. https://doi.org/10.3390/ijerph17020385

Weschler, C. J. (2006). Ozone's Impact on Public Health: Contributions from Indoor Exposures to Ozone and Products of Ozone-Initiated Chemistry. Environmental Health Perspectives, 114(10), 1489–1496. https://doi.org/10.1289/ehp.9256

WHO Regional Office for Europe. (2013b). Health effects of ozone. Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK361809/

Wilbur, S., Williams, M., Williams, R., Scinicariello, F., Klotzbach, J. M., Diamond, G. L., & Citra, M. (2012, June 1). HEALTH EFFECTS. Toxicological Profile for Carbon Monoxide - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK153687/

World Health Organisation. (2009b). Health effects of radon. WHO Handbook on Indoor Radon - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK143219/

Xing, Z., Yang, T., Shi, S., Meng, X., Chai, D., Liu, W., Tong, Y., Wang, Y., Ma, Y., Pan, M., Cui, J., Long, H., Sun, T., Chen, R., & Guo, Y. (2023). Combined effect of ozone and household air pollution on COPD in people aged less than 50 years old. Thorax, 79(1), 35–42. https://doi.org/10.1136/thorax-2022-219691

Xue, T., Wang, R., Tong, M., Kelly, F. J., Liu, H., Li, J., Li, P., Qiu, X., Gong, J., Shang, J., & Zhu, T. (2023). Estimating the exposure–response function between long-term ozone exposure and under-5 mortality in 55 low-income and middle-income countries: a retrospective, multicentre, epidemiological study. The Lancet Planetary Health, 7(9), e736–e746. https://doi.org/10.1016/s2542-5196(23)00165-1

Y

Yang, B., Fan, S., Thiering, E., Seissler, J., Nowak, D., Dong, G., & Heinrich, J. (2019). Ambient air pollution and diabetes: A systematic review and meta-analysis. Environmental Research, 180, 108817. https://doi.org/10.1016/j.envres.2019.108817

Yang, Z., Mahendran, R., Yu, P., Xu, R., Yu, W., Godellawattage, S., Li, S., & Guo, Y. (2022). Health Effects of Long-Term Exposure to Ambient PM2.5 in Asia-Pacific: a Systematic Review of Cohort Studies. Current Environmental Health Reports, 9(2), 130–151. https://doi.org/10.1007/s40572-022-00344-w

Yu, Y., Tang, Z., Huang, Y., Zhang, J., Wang, Y., Zhang, Y., & Wang, Q. (2024). Assessing long-term effects of gaseous air pollution exposure on mortality in the United States using a variant of difference-in-differences analysis. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-66951-9

Yu, Y., Tang, Z., Huang, Y., Zhang, J., Wang, Y., Zhang, Y., & Wang, Q. (2024c). Assessing long-term effects of gaseous air pollution exposure on mortality in the United States using a variant of difference-in-differences analysis. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-66951-9

Z

Zhang, J., Wei, Y., & Fang, Z. (2019). Ozone pollution: a major health hazard worldwide. Frontiers in Immunology, 10. https://doi.org/10.3389/fimmu.2019.02518

Zhou, J., Wang, H., Huebner, G., Zeng, Y., Pei, Z., & Ucci, M. (2023). Short-term exposure to indoor PM2.5 in office buildings and cognitive performance in adults: An intervention study. Building and Environment, 233, 110078. https://doi.org/10.1016/j.buildenv.2023.110078

Imagine a World Where People Breathe Equally the Same Clean Air

GO AQS

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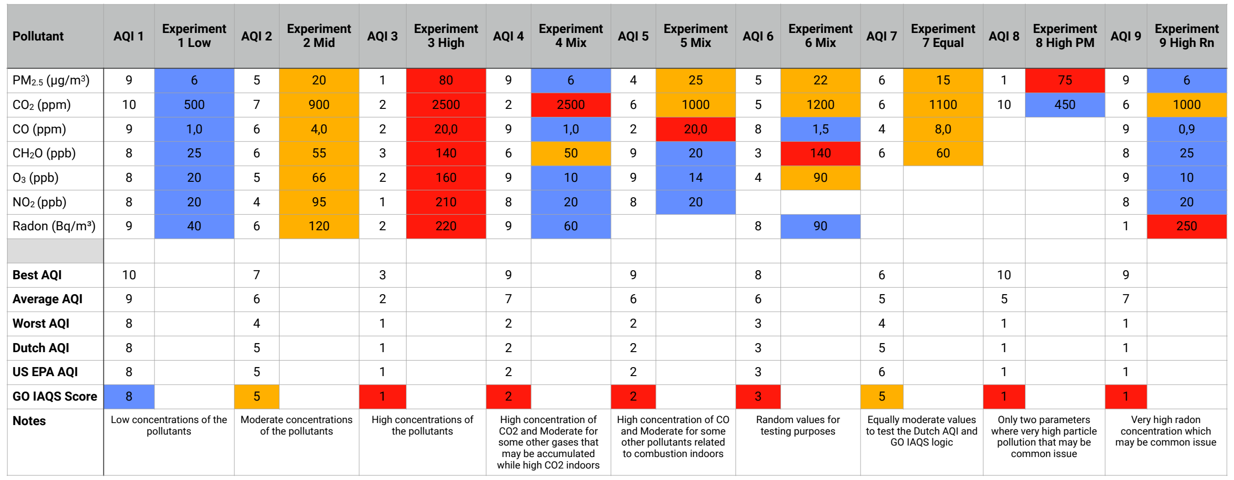
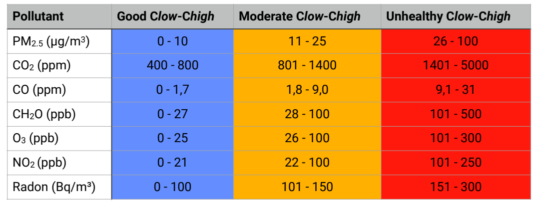
Appendix A

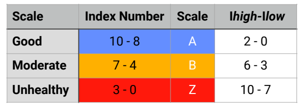
The GO IAQ Score Playground is a simulation tool designed to test and refine Air Quality Index (AQI) calculations. By allowing users to manipulate and combine various air pollutant levels, such as particulate matter (PM$_{2.5}$), ozone (O$_3$), nitrogen dioxide (NO$_2$), carbon dioxide (CO$_2$), carbon monoxide (CO), Radon (Rn), and formaldehyde (CH$_2$O) the playground facilitates the creation of diverse real-world and hypothetical air quality scenarios. This enables a detailed analysis of how different pollutant concentrations impact the resulting AQI, ensuring the index's accuracy and robustness across a wide range of pollution conditions.



Pollutant	AQI 1	Experiment 1 Low	AQI 2	Experiment 2 Mid	AQI 3	Experiment 3 High	AQI 4	Experiment 4 Mix	AQI 5	Experiment 5 Mix	AQI 6	Experiment 6 Mix	AQI 7	Experiment 7 Equal	AQI 8	Experiment 8 High PM	AQI 9	Experiment 9 High Rn
PM$_{2.5}$ (µg/m^3)	9	6	5	20	1	80	9	6	4	25	5	22	6	15	1	75	9	6
CO$_2$ (ppm)	10	500	7	900	2	2500	2	2500	6	1000	5	1200	6	1100	10	450	6	1000
CO (ppm)	9	1,0	6	4,0	2	20,0	9	1,0	2	20,0	8	1,5	4	8,0			9	0,9
CH$_2$O (ppb)	8	25	6	55	3	140	6	50	9	20	3	140	6	60			8	25
O$_3$ (ppb)	8	20	5	66	2	160	9	10	9	14	4	90					9	10
NO$_2$ (ppb)	8	20	4	95	1	210	8	20	8	20							8	20
Radon (Bq/m^3)	9	40	6	120	2	220	9	60			8	90					1	250
Best AQI	10		7		3		9		9		8		6		10		9	
Average AQI	9		6		2		7		6		6		5		5		7	
Worst AQI	8		4		1		2		2		3		4		1		1	
Dutch AQI	8		5		1		2		2		3		5		1		1	
US EPA AQI	8		5		1		2		2		3		6		1		1	
GO IAQS Score	8		5		1		2		2		3		5		1		1	
Notes	Low concentrations of the pollutants		Moderate concentrations of the pollutants		High concentrations of the pollutants		High concentration of CO2 and Moderate for some other gases that may be accumulated while high CO2 indoors		High concentration of CO and Moderate for some other pollutants related to combustion indoors		Random values for testing purposes		Equally moderate values to test the Dutch AQI and GO IAQS logic		Only two parameters where very high particle pollution that may be common issue		Very high radon concentration which may be common issue	



Pollutant	Good *Clow-Chigh*	Moderate *Clow-Chigh*	Unhealthy *Clow-Chigh*
PM$_{2.5}$ (µg/m^3)	0 - 10	11 - 25	26 - 100
CO$_2$ (ppm)	400 - 800	801 - 1400	1401 - 5000
CO (ppm)	0 - 1,7	1,8 - 9,0	9,1 - 31
CH$_2$O (ppb)	0 - 27	28 - 100	101 - 500
O$_3$ (ppb)	0 - 25	26 - 100	101 - 300
NO$_2$ (ppb)	0 - 21	22 - 100	101 - 250
Radon (Bq/m^3)	0 - 100	101 - 150	151 - 300



Scale	Index Number	Scale	*Ihigh-Ilow*
Good	10 - 8	A	2 - 0
Moderate	7 - 4	B	6 - 3
Unhealthy	3 - 0	Z	10 - 7

$$I = 10 - (\frac{Ihigh - Ilow}{Chigh - Clow}(C - Clow) + Ilow)$$

Appendix B

Concentrations of gaseous pollutants is sometimes given in units of mass per volume, and at other times in ppb or ppm. Conversion Factors Between ppb and µg/m^3 and ppm and mg/m^3.

Conversion factors are listed in the table below for GO IAQS pollutants. The conversion assumes an ambient pressure of 1 atmosphere (1.01325 bars) and a temperature of 25 °C degrees Celsius.

The general equation is µg/m^3 = (ppb)*(12.187)*(M) / (273.15 + 25) where M is the molecular weight of the gaseous pollutant.

Disclaimer: Across various literary works and through comparisons with established scientific and regulatory standards, a consistent tendency emerges to present numerical data concerning concentrations in parts per billion (ppb), parts per million (ppm), or micrograms per cubic meter (µg/m^3) as rounded values.

Pollutant	Conversion	WHO 2021 AQGs	Equivalent in ppm/ppb
NO$_2$	1 ppb = 1.88 µg/m^3	10 µg/m^3 (1-year)	5 ppb 1-year
		25 µg/m^3 (24-hour)	13 ppb (24-hour)
O$_3$	1 ppb = 2.00 µg/m^3	100 µg/m^3 (8-hour)	51 ppb (8-hour)
		60 µg/m^3 (season peak)	25 ppb (season peak)
CO	1 ppb = 1.145 µg/m^3	4 mg/m^3 (24-hour)	3 ppm (24-hour)
CH$_2$0	1 ppb = 1.23 µg/m^3	0.1 mg/m^3 (30-min)	81 ppb (30-min)

Appendix C

Appendix C diligently compiles a summary of the air quality guidelines and regulations that our research has uncovered for various pollutants. This section serves as a concise reference point, bringing together disparate information into one accessible location. By outlining the established limits and recommendations for each identified pollutant, Appendix C aims to provide a clear overview of the regulatory landscape relevant to our analysis. This consolidated information will be crucial for interpreting our findings and understanding the context of air quality concerning the specific pollutants under investigation.

Pollutant	Averaging time	Number of limits	Minimum (µg/m^3)	Maximum (µg/m^3)
Particulate Matter $PM_{2.5}$	Ceiling	2	35	50
	15-minute			
	30-minute			
	1-hour	1	15	
	8-hour			
	24-hour	19	15	60
	1 year	17	5	40
	Undefined	8	10	35

Pollutant	Averaging time	Number of limits	Minimum (mg/m^3)	Maximum (mg/m^3)
Carbon Monoxide (CO)	Ceiling	2	12	31
	15-minute	7	10	125
	30-minute	5	6	60
	1-hour	8	10	44
	8-hour	13	8	80
	24-hour	8	3	12
	1 year	1	30	30
	Undefined	4	5	11

Pollutant	Averaging time	Number of limits	Minimum (ppm)	Maximum (ppm)
Carbon Dioxide (CO_2)	Ceiling	7	800	1500
	15-minute	3	15000*	30000*
	30-minute			
	1-hour	1	≤0.10 %	
	8-hour	9	700	5000
	24-hour	2	1000	
	1 year			
	Undefined	35	600	5000

* These values are specific to occupational safety and aren't intended for the general public.

Pollutant	Averaging time	Number of limits	Minimum (µg/m^3)	Maximum (µg/m^3)
Ozone (O_3)	Ceiling	2	120	200
	15-minute	2	100	400
	30-minute			
	1-hour	2	100	160
	8-hour	14	30	200
	24-hour	2	100	150
	1 year	1	100	
	Undefined	9	20	200

Pollutant	Averaging time	Number of limits	Minimum (µg/m^3)	Maximum (µg/m^3)
Formaldehyde (CH_2O)	Ceiling	2	80	100
	15-minute	4	123	2456
	30-minute	13	35	100
	1-hour	3	80	123
	8-hour	9	30	2500
	24-hour	3	20	100
	1 year	2	10	50
	Undefined	16	10	370

Pollutant	Averaging time	Number of limits	Minimum (µg/m^3)	Maximum (µg/m^3)
Nitrogen Dioxide (NO_2)	Ceiling	4	94	9400
	15-minute	5	300	9400
	30-minute			
	1-hour	12	40	288
	8-hour	7	40	5600
	24-hour	2	21	25
	1 year	5	10	40
	Undefined	9	96	200

Pollutant	Averaging time	Number of limits	Minimum (Bq/m^3)	Maximum (Bq/m^3)
Radon (Rn)	Ceiling	2	148	
	15-minute			
	30-minute			
	1-hour			
	8-hour	2	150	200
	24-hour			
	1 year	4	200	300
	Undefined	26	100	400

Appendix D

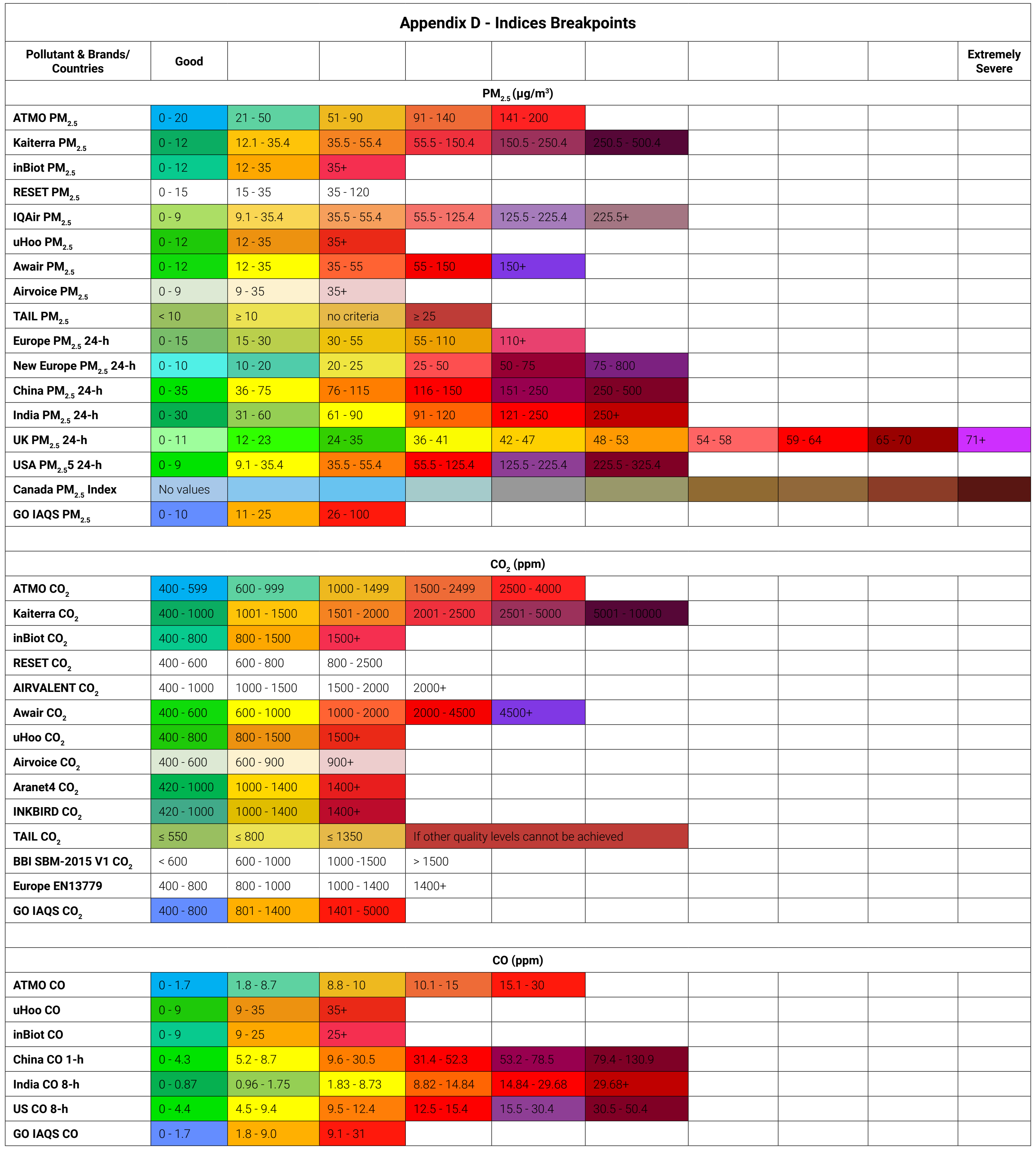
Analysis comparing proprietary Indoor Air Quality (IAQ) Indices with country-oriented Outdoor Air Quality Indices revealed several distinct approaches to reporting air quality.

We observed that most outdoor indices typically employ six breakpoints, though notable exceptions exist, such as the UK and Canada Indices with their ten plus breakpoints, which significantly complicates colour differentiation across levels, even for individuals without colour vision deficiencies. Furthermore, some country-specific outdoor indices, like the older and newer European and Indian Indices, appear to manipulate colour schemes, potentially to downplay the perceived importance of certain pollutant concentrations. In contrast, proprietary indoor air quality indices largely base their PM$_{2.5}$ colour codes and breakpoints on guidelines from environmental agencies, particularly the US EPA. Companies such as Kaiterra and IQAir adopt the same established breakpoints and colours as the US EPA, with IQAir making subtle adjustments to its palette, opting for paler shades to enhance the readability of text and numbers displayed within darker coloured categories like dark cherry or deep purple.

Across the board, green is predominantly used to signify good air quality, with only a few indices, including GO IAQS, deviating to a blue-ish hue. This is noteworthy as approximately 8% of the male and 0.5% of female population experiences green-blindness and struggles to distinguish green scales, while blue has a better correlation with the clear blue sky representing good air quality and does not present such a high number of visual impairments.

Ultimately, a higher number of breakpoints in an index appears to increase the likelihood of ambiguity for the public, making it harder to discern meaningful distinctions between various air quality levels.

Note: During our research, we were unable to find clear information regarding the low and high concentration values for the different breakpoints within the Canadian Air Quality Index and we encountered many colour inconsistencies. This lack of detailed data suggests a need for greater transparency.



Appendix D - Indices Breakpoints

Pollutant & Brands/ Countries	Good									Extremely Severe
PM$_{2.5}$ (µg/m³)										
ATMO PM$_{2.5}$	0 - 20	21 - 50	51 - 90	91 - 140	141 - 200					
Kaiterra PM$_{2.5}$	0 - 12	12.1 - 35.4	35.5 - 55.4	55.5 - 150.4	150.5 - 250.4	250.5 - 500.4				
inBiot PM$_{2.5}$	0 - 12	12 - 35	35+							
RESET PM$_{2.5}$	0 - 15	15 - 35	35 - 120							
IQAir PM$_{2.5}$	0 - 9	9.1 - 35.4	35.5 - 55.4	55.5 - 125.4	125.5 - 225.4	225.5+				
uHoo PM$_{2.5}$	0 - 12	12 - 35	35+							
Awair PM$_{2.5}$	0 - 12	12 - 35	35 - 55	55 - 150	150+					
Airvoice PM$_{2.5}$	0 - 9	9 - 35	35+							
TAIL PM$_{2.5}$	< 10	≥ 10	no criteria	≥ 25						
Europe PM$_{2.5}$ 24-h	0 - 15	15 - 30	30 - 55	55 - 110	110+					
New Europe PM$_{2.5}$ 24-h	0 - 10	10 - 20	20 - 25	25 - 50	50 - 75	75 - 800				
China PM$_{2.5}$ 24-h	0 - 35	36 - 75	76 - 115	116 - 150	151 - 250	250 - 500				
India PM$_{2.5}$ 24-h	0 - 30	31 - 60	61 - 90	91 - 120	121 - 250	250+				
UK PM$_{2.5}$ 24-h	0 - 11	12 - 23	24 - 35	36 - 41	42 - 47	48 - 53	54 - 58	59 - 64	65 - 70	71+
USA PM$_{2.5}$5 24-h	0 - 9	9.1 - 35.4	35.5 - 55.4	55.5 - 125.4	125.5 - 225.4	225.5 - 325.4				
Canada PM$_{2.5}$ Index	No values	🟦	🟦	🟦	⬜	🟩	🟫	🟫	🟫	🟫
GO IAQS PM$_{2.5}$	0 - 10	11 - 25	26 - 100							
CO$_2$ (ppm)										
ATMO CO$_2$	400 - 599	600 - 999	1000 - 1499	1500 - 2499	2500 - 4000					
Kaiterra CO$_2$	400 - 1000	1001 - 1500	1501 - 2000	2001 - 2500	2501 - 5000	5001 - 10000				
inBiot CO$_2$	400 - 800	800 - 1500	1500+							
RESET CO$_2$	400 - 600	600 - 800	800 - 2500							
AIRVALENT CO$_2$	400 - 1000	1000 - 1500	1500 - 2000	2000+						
Awair CO$_2$	400 - 600	600 - 1000	1000 - 2000	2000 - 4500	4500+					
uHoo CO$_2$	400 - 800	800 - 1500	1500+							
Airvoice CO$_2$	400 - 600	600 - 900	900+							
Aranet4 CO$_2$	420 - 1000	1000 - 1400	1400+							
INKBIRD CO$_2$	420 - 1000	1000 - 1400	1400+							
TAIL CO$_2$	≤ 550	≤ 800	≤ 1350	If other quality levels cannot be achieved						
BBI SBM-2015 V1 CO$_2$	< 600	600 - 1000	1000 -1500	> 1500						
Europe EN13779	400 - 800	800 - 1000	1000 - 1400	1400+						
GO IAQS CO$_2$	400 - 800	801 - 1400	1401 - 5000							
CO (ppm)										
ATMO CO	0 - 1.7	1.8 - 8.7	8.8 - 10	10.1 - 15	15.1 - 30					
uHoo CO	0 - 9	9 - 35	35+							
inBiot CO	0 - 9	9 - 25	25+							
China CO 1-h	0 - 4.3	5.2 - 8.7	9.6 - 30.5	31.4 - 52.3	53.2 - 78.5	79.4 - 130.9				
India CO 8-h	0 - 0.87	0.96 - 1.75	1.83 - 8.73	8.82 - 14.84	14.84 - 29.68	29.68+				
US CO 8-h	0 - 4.4	4.5 - 9.4	9.5 - 12.4	12.5 - 15.4	15.5 - 30.4	30.5 - 50.4				
GO IAQS CO	0 - 1.7	1.8 - 9.0	9.1 - 31							

CH_2O (ppb)										
ATMO CH_2O	0 - 50	60 - 100	110 - 300	310 - 750	760 - 1000					
uHoo CH_2O	0 - 500	500 - 750	750+							
inBiot CH_2O	0 - 57	57 - 97	97+							
TAIL CH_2O	< 24.4	≥ 24.4	no criteria	≥ 81.4						
BBI SBM-2015 V1 CH_2O	< 16	16 - 40	40 - 81	> 81						
GO IAQS CH_2O	0 - 27	28 - 100	101 - 500							
O_3 (ppb)										
ATMO O_3	0 - 25	26 - 60	61 - 75	76 - 100	101 - 300					
Kaiterra O_3	20 - 50	51 - 100	101 - 165	166 - 205	206 - 405	406 - 605				
uHoo O_3	0 - 70	70 - 125	125+							
inBiot O_3	0 - 51	51 - 122	122+							
Europe O_3 1-h	0.0 - 30.6	30.6 - 61.2	61.2 - 91.8	91.8 - 122.4	122.4+					
New Europe O_3 1-h	0.0 - 25.5	25.5 - 51.0	51.0 - 66.3	66.3 - 122.4	122.4 - 193.9	193.9 - 408.2				
China O_3 8-h	0.0 - 51.0	51.5 - 81.6	82.1 - 109.6	110.1 - 135.1	135.6 - 408					
India O_3 8-h	0.0 - 25.1	25.6 - 50.2	50.7 - 84.3	84.8 - 104.4	104.9 - 375.3	375.3+				
UK O_3 8-h	0.0 - 16.8	17.3 - 33.7	34.2 - 51.0	51.5 - 61.2	61.7 - 71.4	72.0 - 81.6	82.1 - 95.4	95.9 - 108.7	109.2 - 122.4	123.0+
US O_3 8-h	0 - 54	55 - 70	71 - 85	86 - 105	106 - 200					
GO IAQS O_3	0 - 25	26 - 100	101 - 300							
NO_2 (ppb)										
uHoo NO_2	0 - 53	53 - 100	100+							
Europe NO_2 1-h	0.0 - 26.6	26.6 - 53.1	53.1 - 106.3	106.3 - 212.5	212.5+					
New Europe NO_2 1-h	0.0 - 21.3	21.3 - 47.9	47.9 - 63.8	63.8 - 122.3	122.3 - 180.9	180.9 - 531.9				
China NO_2 1-h	0.0 - 53.1	53.7 - 106.3	106.8 - 372.0	372.5 - 637.7	638.2 - 1243.5	1244.0 - 2040.6				
India NO_2 24-h	0.0 - 21.3	21.8 - 42.6	43.1 - 95.7	96.3 - 148.9	149.5 - 212.8	212.8+				
UK NO_2 1-h	0.0 - 35.6	36.2 - 71.3	71.8 - 106.4	106.9 - 142.0	142.6 - 177.7	178.2 - 212.8	213.3 - 248.4	248.9 - 284.0	284.6 - 319.1	319.7+
US NO_2 1-h	0 - 53	54 - 100	101 - 360	361 - 649	650 - 1249	1250 - 2049				
GO IAQS NO_2	0 - 21	22 - 100	101 - 250							
Rn (Bq/m^3)										
Airthings Rn	0 - 100	100 - 150	150+							
aranet Rn	0 - 100	100 - 300	300+							
TAIL Rn	< 100	≥ 100	no criteria	≥ 300						
BBI SBM-2015 V1 Rn	< 30	30 - 60	60 - 200	> 200						
GO IAQS Rn	0 - 100	101 - 150	151 - 300							
Breakpoints: Global Open Indoor Air Quality Standards Index (GO IAQS Score)										

GO AQS