Championing the Changemakers in Sustainable Design & Building

BuildingGreen

So, You Have Some IAQ Monitors. Now What?

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About BuildingGreen

BuildingGreen is an independent consulting and publishing company committed to providing accurate and timely information to help building industry professionals and policymakers improve the environmental performance and reduce the adverse impacts of buildings. Our purpose is to foster a thriving and equitable world through a regenerative and resilient built environment. To this end, BuildingGreen facilitates collaboration, learning, and trust to accelerate the transformation of the building industry into a force for positive change.

BuildingGreen also supports and facilitates peer networks for sustainability leaders interested in learning from each other and launching initiatives, including this white paper.

About BuildingGreen Peer Networks

BuildingGreen's Peer Networks offer shared space where leaders support one another and work together toward sustainable solutions as a community—intent on moving projects, the industry, and the world forward in the best possible way. We recognize the need and value in transcending competition as we work together, professionally and collectively, to advance our common cause, with a shared commitment to collaboration and improvement.

Championing the Changemakers in Sustainable Design & Building

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Overview and Purpose

The BuildingGreen Peer Network Air Quality Affinity Group published a white paper on continuous air-quality monitoring in 2022. It provided a good overview of what to consider when evaluating monitors for use in commercial buildings and how indoor-air-quality (IAQ) information from continuous monitoring compares to that from occupant surveys and point-in-time IAQ testing. Now, this white paper focuses on what the data mean.

The goal of this paper is not to define “good air quality” but to provide insight into how to manage IAQ using data from continuous air-quality monitors. We reference several standards that set thresholds for acceptable concentrations of contaminants—readings above those thresholds may be cause for concern. However, we also highlight the areas where these standards are not uniform, lack updates, or need to be considered in the context of specific buildings and occupant groups. Beyond avoiding hazards, we want to understand how to ensure indoor environments are not just good but exceptional and how they can positively influence health beyond what minimum building codes mandate.

To offer guidance for specific scenarios, we tailored this paper to the following audience:

- Building practitioners
- Building operators and property managers
- School superintendents, administrators, and maintenance staff (with or without monitors currently in their schools)
- Public health officials and policymakers
- Anyone interested in learning more about the current state of IAQ monitoring

This paper is written specifically for commercial and some institutional buildings. It does not apply to industrial or residential buildings, those with occupancies that have specific ventilation standards, e.g., ASHRAE Standard 170 for healthcare, or laboratories that are governed by industrial health and safety professionals.

Introduction

Our last paper focused on the selection of continuous air-quality monitors to collect ongoing data and identify IAQ trends, including particulate matter (PM), carbon dioxide (CO_2), total volatile organic compounds (TVOC), temperature, and humidity. However, evaluating the data and assessing possible corrective actions can be a challenge. While many large organizations have dedicated environmental, health, and safety (EH&S) teams that can respond to IAQ concerns and incidents, not every school or organization has staff equipped to take on this role. Nonetheless, continuous monitoring data can inform targeted interventions.

This guidance document focuses on helping building owners and managers improve IAQ using available data from continuous monitoring trends. This guidance is not intended to address acute incidents that may significantly impact occupant health, such as chemical spills, regional wildfires, or pandemics. We have also excluded biological contaminants, even though some monitor technologies are beginning to track them.

Contextualizing IAQ Information

IAQ monitors do not directly improve IAQ. Rather, the data they generate can help owners effectively manage indoor air. Monitors will generate seemingly endless amounts of data, especially if they are deployed across multiple buildings. Organizations should allocate time to incorporating this data into operations. We recommend appointing an IAQ champion and pairing continuous air-quality monitoring with an occupant engagement strategy.

IAQ champion

The IAQ champion will manage, review, and interpret the data, communicate with stakeholders, and engage with experts and hygienists as needed.

The goal of continuous IAQ monitoring is to identify trends to improve building performance, not to alert occupants to acute contamination. Acute contamination must trigger immediate corrective action, but may not show in prolonged data trends. Continuous IAQ data is instead used to highlight TVOC, CO_2, PM, and/or other contaminant trends for building occupants, owners, and operators and teach them how to help correct the situation. For example, if TVOC levels always spike during the scheduled time for space cleaning, it is likely that the cleaning products used are contributing to the elevated concentrations of TVOC in the space. With good data, teams can identify, investigate, and implement mitigation strategies.

IAQ liability

Failing to take "reasonable and appropriate" action on data that indicate poor air quality is a potential liability issue. However, "reasonable and appropriate" actions are still a legal gray area because there are not adequate precedents; therefore, they are not clearly defined. As a result, many entities hesitate to monitor IAQ, fearing that their responses might not be considered adequate. However, it is the opinion of this paper's authors that this should not be an excuse to turn a blind eye to IAQ. Making an action plan for specified data indications will likely offer owners protection—as long as they implement the action plan. Having risk management professionals review the IAQ action plan before implementation can further reduce the perceived risk.

Getting feedback from occupants

Continuous air-quality monitors generate useful data points and show trends over time, but as we discussed in our original paper, occupant feedback is sometimes needed to identify the source of the problem and inform corrective action. Occupants may complain about the stuffiness, comfort, odor, and other conditions of air in a building. To respond to such concerns, a facility manager must first understand the duration of the issue. Is an odor fleeting, or might it have been present for hours or days? This type of information can help determine its cause.

Some common sources of odor-causing indoor air contamination are:

- Construction and renovation activities
- Janitorial or cleaning practices

- Occupant activities (science projects in schools, high-volume printing, personal hygiene)
- Equipment problems (HVAC dampers and controls)
- Plants and other organic material
- Interior or exterior pest control programs
- External factors in ambient air, such as forest fires or smog

Calibrated monitors can also help determine if occupant complaints are, in fact, *not* an air quality-related issue. In some cases, occupants can perceive environmental conditions as air quality. For example, we know that lack of air movement can be perceived as stuffiness. The use of a fan to promote air movement does not improve the air quality in the space but could reduce the feeling of "stuffiness."

Engaging building occupants through feedback programs brings another benefit: studies have shown that formal feedback programs alone can improve occupant satisfaction. Feeling their concerns are heard can improve occupant perception of air quality. And educating occupants on how they can contribute to healthy IAQ can empower them, build morale, and require only inexpensive improvements.

General mitigation strategies

Of course, the idea behind having continuous air-quality monitoring is to inform a strategy for ensuring or improving IAQ. We plan to release a third paper in this series, which will provide mitigation strategies specific to each contaminant. However, as a general overview, there are some basic mitigation strategies that will improve IAQ in most scenarios:

1. **S**ource control: Source control eliminates the root source of the contaminants. To minimize the generation and emission of pollutants, select low-emission equipment, materials, and products and adopt green cleaning practices with environmentally friendly, low-VOC cleaning solutions.
2. Filtration: Use appropriate filters in HVAC systems to remove and reduce the concentration of some contaminants. Consider MERV 13, HEPA, or activated carbon filters, depending on your space.
3. Ventilation: To maintain proper ventilation, increase the outdoor air intake of air exchange systems, use suitable filters, and ensure adequate exhaust in areas with potential pollutant sources.
4. Building envelope: To minimize infiltration of outdoor moisture and pollutants, improve the performance of the building's envelope, by sealing gaps and leaks.
5. Education and awareness: To encourage occupants to contribute to a healthy indoor environment, educate them about the importance of good IAQ and the potential negative health effects of indoor contaminants.

Interpreting Data on Specific Contaminants

There are a variety of contaminants that can contribute to degraded indoor air. Some contaminants have known health impacts, and others are used as markers of poor ventilation. Continuous monitors often measure multiple contaminants and use proprietary algorithms to display a single air-quality index score. There are limitations to this method of generating a single score (more on that later in the article), but it is usually possible to dig further into the data provided by continuous IAQ monitors to see contaminant-specific trends.

CO_2

Human health

CO_2 is a byproduct of human respiration and fossil fuel combustion in buildings. As such, CO_2 is a surrogate for human occupancy—as more people enter a space, CO_2 levels rise. CO_2 has thus become a useful proxy for air quality, though other air contaminants present in the air may have more direct and measurable impacts on health.

Many commercial buildings have demand control ventilation (DCV) that will increase ventilation once the CO_2 reaches a predetermined programmed level. Ventilation systems bring in outside air to dilute CO_2 concentrations (and concentrations of other contaminants as well). Increasing ventilation rates increases energy consumption—both to power the ventilation equipment and to heat or cool spaces where outside air is being introduced. This may encourage some owners or operators to use less stringent thresholds for CO_2 in order to save energy. Note there will be a time lag if CO_2 is used for DCV (CO_2 takes time to build up). There are also other options to monitor occupancy including use of digital human tracking to control DCV in real time.

Possible thresholds

Because CO_2 is used as a proxy for contamination of indoor air, it is impossible to set a standard threshold that will ensure good IAQ across project types using CO_2 alone. For one thing, even though CO_2 levels often trigger DCV systems, there may be other contaminants present in the facility. Furthermore, threshold levels of CO_2 vary for legitimate reasons by project type. The goal of this paper is not to identify and define the "acceptable level" of CO_2 for a building but rather to point to widely referenced and reputable thresholds that may assist organizations in setting their own science-backed standard.

Many engineers, control contractors, and building operators use 1000 parts per million (ppm) of CO_2 as a limit, citing ASHRAE Standard 62.1 as their source. However, Standard 62.1 has not contained an indoor CO_2 limit since the 2001 standard suggested 700 ppm above ambient levels, which was subsequently eliminated in 2004, and no current ASHRAE standard includes one, either. The ASHRAE 62.1 Standard was developed not because of the health implications of CO_2 but to maintain olfactory comfort. As it turns out, to maintain olfactory comfort for 80% of occupants, the number of fresh air changes typically result in CO_2 limits of approximately 1000 ppm. This corresponds to ASHRAE's historic intent, although the standard does not currently limit CO_2 for olfactory or health concerns.

NASA permits up to 5000 ppm of CO_2 on space missions (the high threshold is due to equipment and technology limitations) but also recognizes the negative impact of high CO_2 levels on the well-being of their astronauts. The RESET Standard, a third-party certification for projects maintaining best-in-class air quality, limits CO_2 to 600 ppm. This limit may reflect the role of CO_2 as an occupancy indicator and the understanding that additional fresh air reduces the concentration of all contaminants. Per the ASHRAE Position Document on Indoor Carbon Dioxide, several groups have explored the cognitive effects of short-term exposure (2 to 8 hours) to pure CO_2 at concentrations between 600 and 5000 ppm. Some of these studies demonstrated concentration-dependent impairment, an indicator of a causal effect, but other studies did not show any effects on cognition.

More recently, the measurement of indoor CO_2 has been discussed in the context of airborne infectious disease transmission. However, many applications of indoor CO_2 do not reflect a sound technical understanding of the relationship between indoor CO_2 concentrations, ventilation, and IAQ.

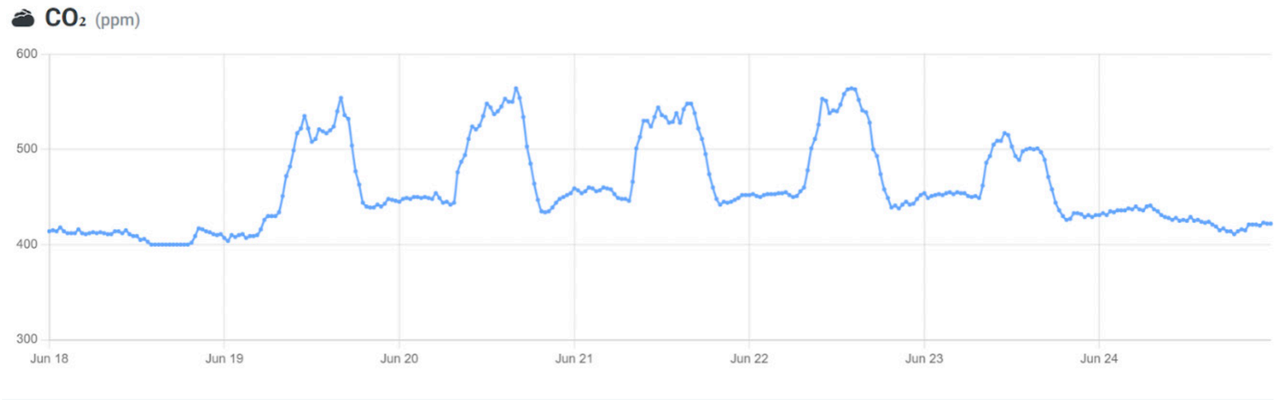
Lastly, the program and function of an indoor space can help determine appropriate CO_2 thresholds. Spaces like lecture halls, offices, or classrooms may require lower CO_2 levels to maintain optimal cognitive performance and productivity. Settings with unique constraints, like NASA space missions, may have higher acceptable CO_2 levels due to equipment limitations and energy requirements. Thus, the variance in CO_2 thresholds arises from balancing the specific requirements of various indoor environments with the diverse needs of occupants.

Probable trends and patterns

The CO_2 levels in a building frequently trend along occupancy rates. As occupants enter a building, the CO_2 rate tends to rise gradually. In settings such as classrooms, where groups of people arrive over a short period, the CO_2 may rise quickly. In buildings with DCV systems, operators can adjust the CO_2 threshold to a higher setpoint to conserve energy or lower it to increase ventilation, as many did during the COVID-19 pandemic. Any sustained, high levels of CO_2 during occupied hours should trigger a review of the control sequence for that space.

A lesson learned from the pandemic is that spaces with optimal filtration and that meet ASHRAE 62.1 minimum ventilation rates perform better in energy efficiency and infection control than spaces with poor filtration and higher ventilation rates. In short, it is best to opt for improved filtration (MERV 13 or higher) before increasing ventilation above code levels. To that end, ASHRAE has recently issued Standard 241-2023 - Control of Infectious Aerosols, the first-ever pathogen mitigation standard.

The graph below shows a week of “normal” CO_2 levels in an open office space. Note the peaks during each weekday and the lower level during the weekend. Also of note are the variations in CO_2 levels between weekdays, which likely result from typical changes in occupancy throughout the day.



Credit: Provided by BranchPattern using Awair and AirGradient dashboards

TVOC

Human health

Volatile organic compounds (VOCs) are carbon-containing gasses and vapors, such as fuel fumes and solvents, that evaporate easily at room temperature—hence the term “volatile.” Though many standards set specific limits for individual VOC compounds (like formaldehyde or benzene), the ability of continuous air-quality monitors to measure individual VOCs is currently limited. Instead, VOCs are measured as a group. This cumulative measurement is called total volatile organic compounds (TVOC) and is not specifically defined in the industry. Depending on the laboratory doing the testing or the monitor used, TVOC may comprise different chemical contaminants or even proxy compounds. Some experts posit that the referenced chemical profiles are substantially similar, and that it’s the cumulative effect of these chemicals that impacts health and comfort.

Many VOCs, such as benzene and formaldehyde, are highly toxic, and prolonged exposure can cause cancer and other serious health problems. The severity of the health effects from VOCs depends on the type of organic compound present, the exposure time, and a person’s vulnerability. As of the writing of this paper, more information is becoming available about gas-fired appliances introducing significant amounts of benzene.

Typical indoor VOC sources include paint, cleaning supplies, furnishings, glues, permanent markers, methane and natural gas leaks, pest control applications, printing equipment, or even personal hygiene and body care products. VOC levels can be higher when ventilation is limited.

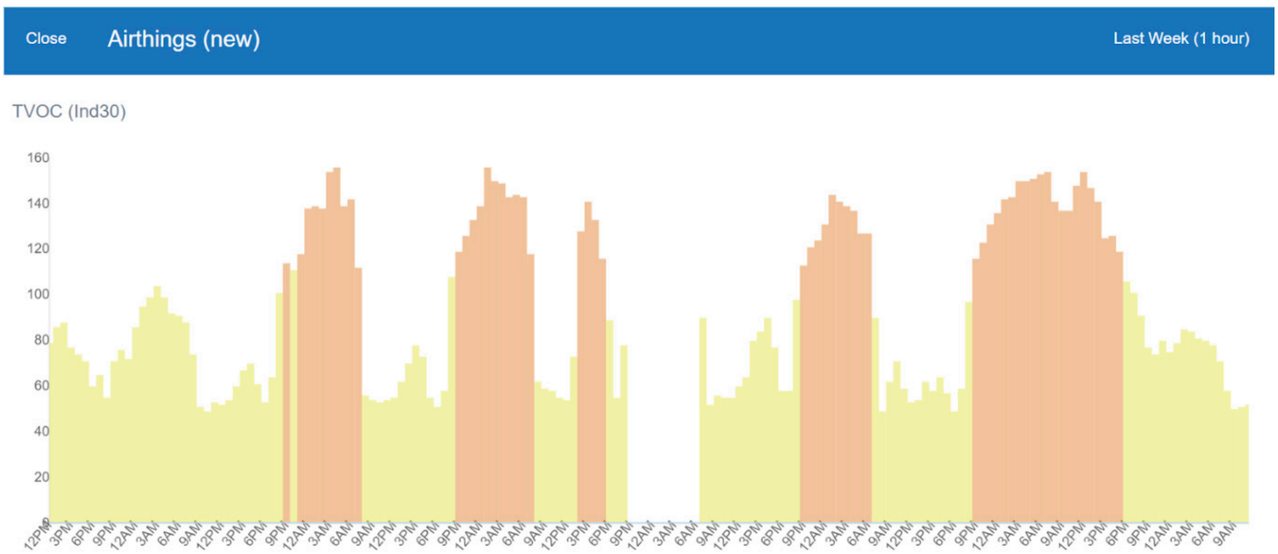
Possible thresholds

Establishing threshold limits for TVOC can be challenging due to the wide variety of compounds included in the measurement and their varying effects on human health. However, the World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA) proposed some guidelines to minimize health risks. The WHO suggests a precautionary guideline value of 300 $\mu g/m^3$ for TVOC in indoor air to minimize acute health effects and 200 $\mu g/m^3$ for long-term exposure. The EPA recommends maintaining indoor TVOC levels below 500 $\mu g/m^3$ to ensure a healthy indoor environment.

Probable trends and patterns

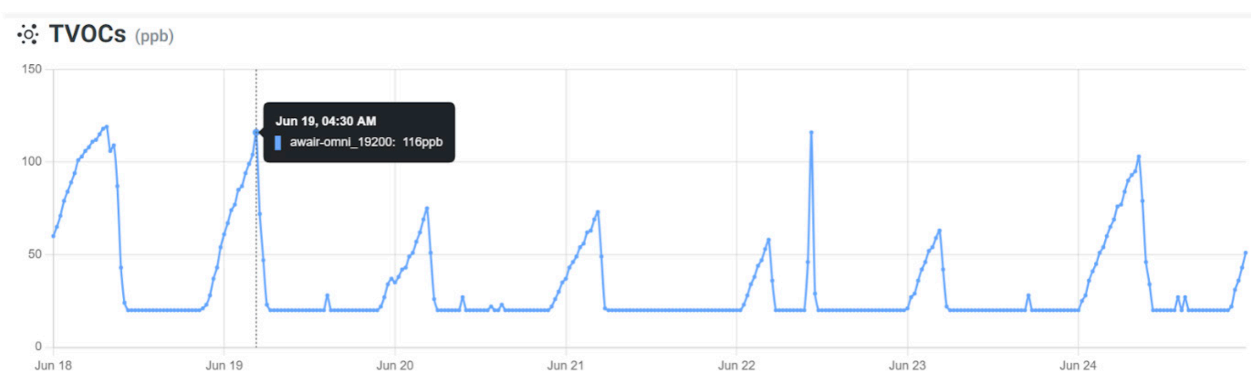
In most instances of elevated TVOC, the level spikes and diminishes quickly as the offending activity passes. Operators should investigate any sustained or long-term patterns of elevated TVOC, which could indicate a problem with carbon filters. When such patterns correspond with occupancy, HVAC setbacks, or other trends, identify and address the associated activity (such as cleaning supplies, material off-gassing, chemical or gaseous contaminant build-up during off-hours, or pest control chemicals).

The graph below shows a week of TVOC data from a school. The lower TVOC levels on the weekends are expected. Spikes during the weekdays (in orange) are likely from classroom cleaning events, marker board or hand sanitizer use, and other such functions. The white gap in the middle depicts when the monitor went offline during a Wi-Fi connectivity loss.



Credit: Provided by BranchPattern using Awair and AirGradient dashboards

Another example of TVOC data, below, shows the build-up of TVOC in a conference room during unoccupied hours with an HVAC temperature setback. There's a sharp drop-off when the system goes into occupied mode at the start of the day. Note the large spike—attributable to some activity—on June 22. Its rapid drop-off demonstrates good air circulation.



Credit: Provided by BranchPattern using Awair and AirGradient dashboards

PM

Human health

Particulate matter (PM) is a group of small solid or liquid particles that are suspended in the air. Like TVOC, PM is not a specific substance but can consist of a variety of small particles.

- $PM_{2.5}$, the most studied contaminant of indoor air, is fine particulate matter with a diameter of 2.5 micrometers or smaller, such as dust, pollen, smoke, soot, and pollutants emitted from vehicles and industrial processes. Due to their small size, $PM_{2.5}$ particles can remain suspended in the air for long periods and be inhaled deep into the respiratory system, penetrating lung tissue.
- PM_{10} is inhalable particulate matter with a diameter of 10 micrometers or smaller. These larger particles can include dust, pollen, mold spores, and other fine particles. While PM_{10} particles are also inhalable, they tend to be filtered out by the nose and throat and are less likely than $PM_{2.5}$ particles to penetrate deep into the lungs. However, prolonged exposure to high levels of PM_{10} can still lead to respiratory issues and other health problems.

Research has linked PM pollution to lung and heart disease, strokes, cancer, and reproductive harm. People with heart or lung diseases such as coronary artery disease, congestive heart failure, and asthma or chronic obstructive pulmonary disease (COPD), children, and older adults may be at greater risk from PM exposure. Scientific studies have linked PM exposure to a variety of health impacts, including:

- Eye, nose, and throat irritation
- Aggravation of coronary and respiratory disease symptoms or conditions, such as asthma
- Premature death in people with heart or lung disease.

There are various indoor and outdoor sources of PM contamination. Here are some examples:

Indoor sources of PM contamination:

1. Cooking: Cooking, especially frying or using high heat, can release fine particles and aerosols into indoor air. Smoke, oil droplets, and cooking byproducts can contribute to PM contamination.
2. Tobacco smoke: Smoking indoors can release significant amounts of fine and coarse particulate matter and harmful chemicals and gasses.
3. Cleaning products and aerosols: Certain cleaning products, air fresheners, and aerosol sprays can emit fine particles that contribute to indoor PM contamination. This is especially true for products that contain volatile organic compounds (VOCs).
4. Building materials and furnishings: Construction materials, paints, varnishes, carpets, furniture, and other household items can emit particulate matter, including dust and microscopic fibers. These particles can accumulate indoors and contribute to PM pollution.

Outdoor sources of PM contamination:

- Vehicle emissions: Exhaust from vehicles, including cars, trucks, buses, and motorcycles, is a significant source of outdoor PM pollution. Combustion of fossil fuels produces fine and coarse particles and other pollutants.
- Industrial emissions: Industrial processes, such as manufacturing, power generation, and construction, can release PM pollutants into the outdoor air. These may include smoke, dust, soot, and emissions from chimneys and stacks.
- Natural sources: Dust and soil particles, pollen, spores, and particles from wildfires and volcanic eruptions can contribute to outdoor PM levels.

The main differences between indoor and outdoor PM contamination lie in its sources and the extent to which it can disperse. Indoor PM usually comes from a localized source, and contamination can accumulate due to limited ventilation or poor filtration. Outdoor PM sources are often more distributed, and air currents can help disperse particles. However, outdoor pollution can also enter indoor spaces through ventilation systems, open windows, and gaps in the building envelope. The type and concentration of PM contamination can vary depending on a building's geographic location, surrounding environment, and building use.

PM is considered one of the most hazardous IAQ contaminants, but it is often easy to identify its source. PM-generating activities tend to occur over longer durations than those producing TVOC (think construction projects or regional wildfires versus an occupant wearing perfume or off-gassing from a fresh coat of paint).

Possible thresholds

PM threshold limits should account for potential air contamination from outdoor sources in addition to the specific needs of the occupants in the building.

WHO, EPA, and the RESET Standard for Commercial Interiors all provide widely recognized threshold limits for $PM_{2.5}$ and PM_{10} (see Comparison of Regulatory and Green Building Frameworks). The default threshold limits assume that outside air has low ambient particulate levels. There are different acceptable threshold limits for projects where the annual average ambient $PM_{2.5}$ level is ≥ 35 µg/m3 (when the building is in an EPA nonattainment area for $PM_{2.5}$ or a local equivalent). View the real-time ambient outdoor particulate levels ($PM_{2.5}$, PM_{10}) for locations across the U.S. here.

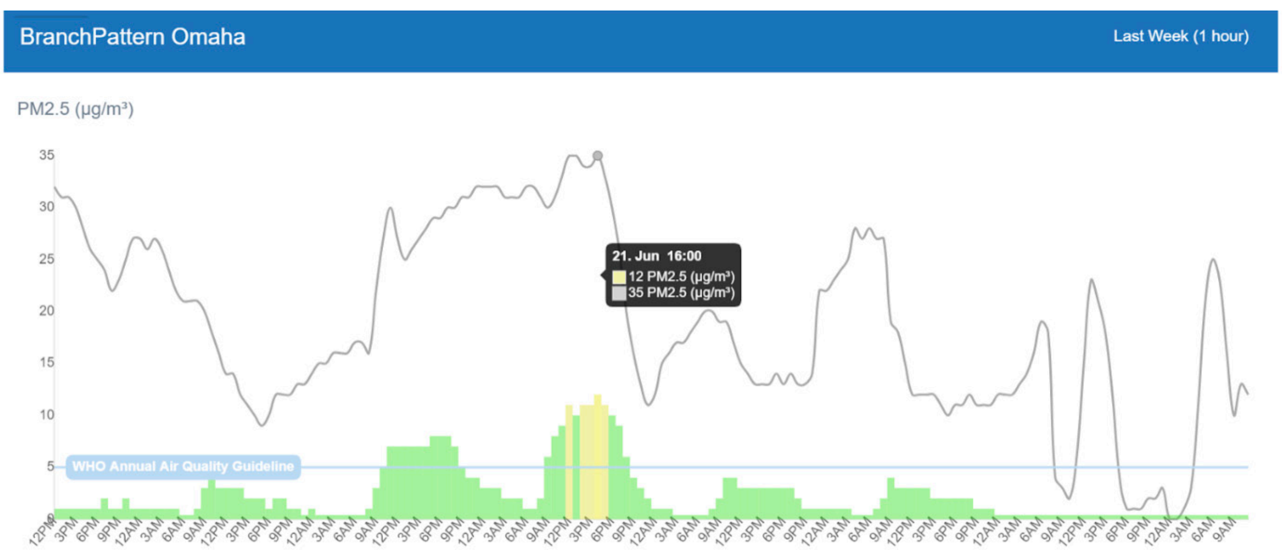
Probable trends and patterns

- Continuous IAQ monitoring can reveal trends in particulate matter levels, which can help building managers and occupants identify the sources and contributing activities. Some common trends observed in indoor PM levels include:
- Daily patterns: PM levels may follow a daily pattern with higher concentrations during peak occupancy and lower levels during off-peak hours. This could indicate that occupant activities, such as cooking, cleaning, or movement in a space after a period of inactivity (e.g., kids standing up at once at the end of a class) contribute to increased PM levels.

- Seasonal variations: PM concentrations may vary seasonally, with higher levels during certain seasons or weather conditions. For example, during colder months, indoor heating systems may contribute to increased PM levels, while pollen could cause elevated levels during warmer times of the year.
- Correlation with outdoor air quality: Outdoor air quality may influence indoor PM levels, particularly if the building's ventilation system draws in outdoor air without adequate filtration. In such cases, poor outdoor air quality can directly impact indoor PM concentrations.
- Construction and renovation activities: Construction or renovation activities within or near the building can cause temporary spikes in indoor PM levels. These activities can generate dust and other particulate matter that can infiltrate indoor spaces.
- HVAC system operation and maintenance: The operation and maintenance of the building's HVAC system can influence PM levels. A well-maintained system with proper filtration can help reduce indoor PM levels, while a poorly maintained system may contribute to increased concentrations.

The direct comparison of outdoor and indoor PM levels can provide a real-time picture of the effectiveness of HVAC system filtration. Outdoor PM data can be readily obtained from low-cost continuous monitors or open-access reference data (e.g., https://explore.openaq.org/).

The bar graph below shows a week of indoor $PM_{2.5}$ levels overlaid by a gray line representing the corresponding outdoor $PM_{2.5}$ levels. Note that the yellow bars, which represent the periods of highest indoor PM concentration (around 12 ug/m3), correspond to the peak outdoor $PM_{2.5}$ level of 35 ug/m3.



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CO

Human health

Carbon monoxide is a colorless, odorless, and tasteless gas that can cause significant health issues when inhaled. It binds to hemoglobin in the blood, preventing oxygen from reaching the body's organs and tissues. Low levels of exposure can lead to symptoms such as headache, dizziness, nausea, and fatigue. Prolonged or high levels of exposure can result in more severe symptoms, including confusion, unconsciousness, and even death.

Possible thresholds

Carbon monoxide (CO) is measured in parts per million (ppm). The Occupational Safety and Health Administration (OSHA) has set an acceptable exposure limit of 50 ppm CO over an 8-hour workday. The World Health Organization (WHO) suggests a maximum indoor air value of 9 ppm CO for an average 8-hour period. Exposure to levels above these recommended thresholds can increase the risk of adverse health effects, with higher concentrations posing higher risks, especially to vulnerable populations. See the threshold summary table for further details.

Probable trends and patterns

Carbon monoxide is commonly produced from the incomplete combustion of fossil fuels, such as within vehicle engines, gas stoves, and heating systems. Poorly maintained or malfunctioning appliances, inadequate ventilation, and idling vehicles in enclosed spaces can lead to elevated indoor carbon monoxide levels. Outdoor carbon monoxide levels tend to be higher in urban areas with heavy traffic congestion.

Building owners or operators should investigate and correct any detected elevation of indoor CO. It's worth noting that standards, such as WELL, acknowledge commercial kitchens may have "normally" elevated indoor levels of CO and NO_2 due to their use of gas-fired appliances—one more argument for electrification.

Ozone

Human health

Ozone (O_3) is a highly reactive gas that can negatively impact human health, particularly at elevated concentrations. Short-term exposure to ozone can cause respiratory irritation, exacerbate asthma and other pre-existing respiratory conditions, and reduce lung function. Long-term exposure to ozone may lead to chronic respiratory diseases, reduced lung function, and increased susceptibility to respiratory infections. Additionally, ozone can irritate the eyes, nose, and throat, causing discomfort.

Possible thresholds

To minimize health risks, the EPA advises maintaining indoor ozone levels below a threshold of 0.07 ppm, though local regulations and healthy building standards may set a lower threshold. Comparison of Regulatory and Green Building Frameworks for IAQ contains additional ozone thresholds.

Probable trends and patterns

Continuous IAQ monitors can help identify trends in ozone levels, which may vary throughout the day and across different areas of a building. Outdoor air infiltration, office equipment (e.g., printers and copiers), and some air cleaning devices (e.g., ozone generators or ionizers) are common sources of indoor ozone. Chemical reactions between other indoor air pollutants can also lead to elevated indoor ozone levels. For example, the reaction between volatile organic compounds (VOCs), nitrogen oxides (NOx), and sunlight forms ozone.

In response to the COVID-19 pandemic, many building teams installed ionization devices to improve air quality and curb the spread of the virus. However, some of these devices generate ozone as a byproduct. This unintended ozone creation further underscores the importance of monitoring IAQ. The benefits of ionization devices, such as disinfection, must be balanced with the potential health risks associated with increased indoor ozone levels. ANSI/ASHRAE Addendum aj to ANSI/ASHRAE Standard 62.1-2016 noted that ozone creates risks for human health by introducing formaldehyde, unsaturated aldehydes (produced during the reaction of ozone with ketones and alcohols), and ultrafine particles (secondary organic aerosols). It continues, “However, there is no consensus on the safe level of ozone.” The addendum included requirements for devices that may generate ozone, later refined in the 2019 and 2022 versions of the standard.

Formaldehyde

Formaldehyde is a VOC, but because it is of particular concern to human health, it is typically monitored as a discrete contaminant rather than a part of a TVOC measurement. The threshold for formaldehyde is much lower than that for other VOCs.

Building materials, furniture, adhesives, paints, and certain consumer products emit formaldehyde. Pressed wood products (such as composite wood, particle board, and plywood) used in cabinets, furniture, flooring, and construction materials often contain it. And the manufacturing of resins, plastics, textiles, and some household cleaning products uses it.

Human health

Formaldehyde is a colorless gas with a strong odor. Considered a common IAQ contaminant, it can negatively affect human health, particularly at high concentrations or with extended exposure. Prolonged or chronic exposure to formaldehyde is associated with respiratory issues, allergies, asthma exacerbation, and an increased risk of certain cancers. Short-term exposure can cause eye, nose, and throat irritation, coughing, and respiratory symptoms.

Possible thresholds

Several organizations have established guidelines and thresholds for formaldehyde exposure, of which there is a wide range. WHO suggests a guideline value of 0.08 parts per million (ppm), while OSHA has set a permissible exposure limit of 0.75 ppm for formaldehyde in the workplace. See the summary table for more details.

Probable trends and patterns

Continuous indoor air monitoring for formaldehyde is still new, but some sensors have the capability. Monitoring might show elevated formaldehyde levels after activities like painting, varnishing, or installing certain household products that contain the compound, such as pressed wood furniture and cabinetry, laminate flooring, and some insulation materials. High humidity and heat can increase the off-gassing of formaldehyde from these sources, leading to even higher concentrations indoors.

If detecting formaldehyde is not part of continuous monitoring, it could be measured through point-in-time testing over short periods. This is currently encouraged by the LEED and WELL rating systems.

Radon

Radon is a naturally occurring radioactive gas formed from the decay of uranium and radium found in soil, rocks, and groundwater, and a significant indoor air pollutant. Radon is odorless, colorless, and tasteless, making it difficult to detect without proper testing. It generally enters buildings through cracks in the foundation and is commonly found on lower levels and sub-grade spaces. Temperature and wind differentials can create negative pressure inside a space, which increases the opportunity for radon to enter a building.

Human health

Radon exposure is a serious concern for human health. When inhaled, radon decay products can damage lung tissue and increase the risk of developing lung cancer. Radon is the second leading cause of lung cancer after smoking, responsible for thousands of deaths worldwide each year.

Possible thresholds

WHO set a reference level of 100 becquerels per cubic meter (Bq/m^3) for radon concentration in indoor air, above which it recommends corrective action be taken. Guidelines may vary by country, but generally, they aim to reduce radon levels as much as possible. There is no safe level of radon exposure. Additional radon thresholds are provided in the summary table.

Probable trends and patterns

It's common to see higher radon levels in building basements compared to upper floors. Radon levels can vary based on geographic location, soil composition, building characteristics, and ventilation conditions. Short- and long-term testing is a common first step in determining if radon is an issue. EPA publishes a Map of Radon Zones to help determine the relative risk of sites. However, building owners and operators should always conduct site-specific testing—even if a building is not in an elevated radon risk area.

More on Contaminant Thresholds

Users of continuous monitoring may value using their monitors as a real-time indicator of the health of their indoor air, as well as a tool to highlight IAQ changes over time. Many monitors use a proprietary air-quality index to display air-quality results depicted by colors or numerical values. For example, the Kaiterra Sensedge has a display that is colored green if air quality is within normal threshold ranges and red if not. This approach combines the results into one consolidated score, but different models may monitor different contaminants. Between models and brands, there is also no standard calculation methodology or threshold limits. Furthermore, these scores can be weighted in favor of factors that are unknown to and out of the control of both the design team and building users and operators.

In the following section, we will further describe the limitations of consolidated IAQ grades and describe when a more granular analysis by contaminant is needed. This granular approach emphasizes the importance of choosing an appropriate threshold. Therefore, this section concludes with more guidance on setting contaminant thresholds for your building.

What those 'grades' mean

Many IAQ continuous monitors use simplified ranges to indicate how "good" the air quality is. The grades (some use 1-100 scores, others use colors) are frequently based on proprietary algorithms and may vary depending on the device used. Because of this inconsistency, building owners and operators should focus on changes in the grade over time – sudden spikes or gradual increases rather than its actual value—to monitor and maintain acceptable IAQ. The habitual idling of trucks on a loading dock, new furniture, and high-emitting cleaning products can all cause increases in contamination levels.

Not every grade change is a cause for alarm. The seriousness depends on which contaminant is responsible for the grade of your space and the sensitivities of occupants. It is, therefore, important to understand what threshold is reasonable for each contaminant. Aggregate grades can provide a glance summation of overall air quality. But if the score is consistently not good, you should dig deeper into the individual contaminant data. Like energy benchmarking, you can check IAQ status at a portfolio or a building level using dashboard summary interfaces, automatic alarms, mobile applications, and summary reports—though the availability of these services depends on the manufacturer and device. Consulting professionals may be able to help analyze the underperforming buildings or spaces.

Choosing a threshold

There are no universal limits for acceptable concentrations of indoor air contaminants. Though multiple organizations attempt to address some contaminants, no one organization sets limits for all. And there are some contaminants for which thresholds have not been set.

One might think that concern for public health would drive the development of acceptable thresholds for air-quality contaminants. However, there are so many variables, including occupant age, vulnerability, and duration of occupancy in a space, that a single threshold number for a given contaminant could not apply to all building types and populations. Furthermore, conducting controlled research on human users and breaking down findings to isolate exposure to specific IAQ contaminants presents challenges and is understandably daunting.

When referencing the guidelines that do exist, consider their source and applicability to the indoor environment of concern. If published guidance does not exist for a particular contaminant, a review of the toxicological and epidemiological evidence—with appropriate consultation—can help set a threshold. However, the evidence on the health effects of many contaminants will likely be insufficient. *In these cases, an organization must determine the acceptable level or range for each contaminant based on occupancy, location, programming needs, and acceptable level of risk*.

The table on the following pages contains air contaminant thresholds from reputable U.S.-based sources. It includes the *minimum* criteria for LEED and WELL to differentiate between maximum allowable concentrations and recommended control points for healthy indoor environments. Though this information is a good starting point, a more in-depth approach may be warranted for some organizations.

The most important thing to remember is that monitored air-quality values are not absolute and do not usually control HVAC systems or drive ventilation quantities. For now, these values are most often used to indicate air quality, although improvement in sensor technology could expand their use in the future. To maximize the value of continuous monitoring, conduct daily or weekly analyses—especially at first. Once trends are understood and depending on a system's available dashboard alerts, intervals between readings can increase.

Comparison of Regulatory and Green Building Frameworks for IAQ

Pollutant	NAAQS / EPA[1]	OSHA[2]	MAK[3]	Canadian[4]	WHO[5] / Europe	NIOSH[6]	ACGIH[7]	LEED[8]	WELL[9]	RESET
Carbon Dioxide (CO_2)	1,000 ppm	5,000 ppm over 8 hr time-weighted average (TWA)	5,000 ppm over 8 hr TWA	1,000 ppm	1,000 ppm	5,000 ppm over 8 hr TWA	5,000 ppm over 8 hr TWA	1,000ppm based on Arc Performance Pathway	900 ppm	Acceptable: 1000 ppm High Performance: 600 ppm
Carbon Monoxide (CO)	9 ppm over 8 hr TWA	50 ppm over 8 hr TWA	30 ppm over 8 hr TWA	10 ppm for long-term (24-hour average) exposure and below 25 ppm for short-term (1-hour average) exposure	9 ppm for an 8-hr average & 25 ppm for a 1-hr average	35 ppm over 10 hour TWA & ceiling limit of 200 ppm	25 ppm over 8 hour TWA	No more than 2 ppm above outdoor levels or 9 ppm	Acceptable: 10 mg/m³ (9 ppm) High Performance: 7 mg/m³ (6 ppm)	Acceptable: 9ppm

[1] U.S. Environmental Protection Agency. 2008. Code of Federal Regulations, Title 40, Part 50. National Ambient Air Quality Standards. The National Ambient Air Quality Standards (NAAQS) do not set specific limits for indoor CO_2 levels. The U.S. Environmental Protection Agency (EPA) recommends maintaining indoor CO_2 levels below 1,000 ppm (parts per million) to ensure occupant comfort.

[2] U.S. Department of Labor, Occupational Safety and Health Administration. Code of Federal Regulations, Title 29, Part 1910.1000-1910.1450. www.osha.gov. Permissible Exposure limit.

[3] Maximum Concentrations at the Workplace and Biological Tolerance Values for Working Materials 2000, Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, Federal Republic of Germany.

[4] Health Canada. 1995. Exposure Guidelines for Residential Indoor Air Quality: A Report of the Federal Provincial Advisory Committee on Environmental and Occupational Health. Ottawa: Health Canada. www.hc-sc.gc.ca/hecssesc/air_quality/pdf/tr-156.pdf. Health Canada recommends maintaining indoor CO_2 levels below 1,000 ppm for comfort purposes.

[5] World Health Organization. 2000. Air Quality Guidelines for Europe, 2nd Edition. World Health Organization Regional Publications, European Series No. 91. World Health Organization, Regional Office for Europe, Copenhagen, www.euro.who.int/document/e71922.pdf. (more current here: https://apps.who.int/iris/handle/10665/345329) The World Health Organization (WHO) does not set specific limits for indoor CO_2 levels. However, they recommend keeping CO_2 levels below 1,000 ppm to maintain comfort and avoid potential health risks.

[6] NIOSH. 2004. NIOSH Pocket Guide to Chemical Hazards (NPG). National Institute for Occupational Safety and Health, February. www.cdc.gov/niosh/npg/npg.html.

[7] ACGIH. 2005. Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. American Conference of Governmental Industrial Hygienists, 1330 Kemper Meadow Drive, Cincinnati, OH 45240-1634. www.acgih.org.

[8] LEED BD+C: New Construction v4, Indoor air quality assessment credit (2018), non-Healthcare projects unless noted otherwise. https://www.usgbc.org/node/2614245?return=/credits.

[9] WELL v2.1, A01 (2018). Fundamental Air Quality. https://v2.wellcertified.com/v2.1/en/air/feature/1.

Pollutant	NAAQS / EPA[1]	OSHA[2]	MAK[3]	Canadian[4]	WHO[5] / Europe	NIOSH[6]	ACGIH[7]	LEED[8]	WELL[9]	RESET
Particulate Matter ($PM_{2.5}$)	Was 12 and as of Jan 6 2023, EPA is proposing to lower to 9-10) 15 µg/m3	OSHA does not have specific permissible exposure limits (PELs) for $PM_{2.5}$ and PM_{10}. However, they do have a PEL for "particulates not otherwise regulated" at 15 mg/m³ for total dust and 5 mg/m³ for the respirable fraction for an 8-hour TWA in the workplace.	The German Maximum Workplace Concentration (MAK) values for $PM_{2.5}$ and PM10 are not specifically provided. However, they do provide limits for "granular biopersistent particles without known significant specific toxicity" at 4 mg/m³ for the inhalable fraction and 1.5 mg/m³ for the respirable fraction for an 8-hour TWA.	Health Canada recommends maintaining indoor $PM_{2.5}$ levels below 10 µg/m³ for an annual average and 28 µg/m³ for a 24-hour average.	The World Health Organization (WHO) recommends an air quality guideline of 10 µg/m³ for $PM_{2.5}$ for an annual average and 25 µg/m³ for a 24-hour average.	NIOSH does not have specific recommended exposure limits (RELs) for $PM_{2.5}$ and PM10. However, they do have a REL for" particulates not otherwise regulated" at 15 mg/m³ for total dust and 5 mg/m³ for the respirable fraction for a 10-hour TWA and a ceiling limit of 10 mg/m³ for the respirable fraction.	$PM_{2.5}$ and PM_{10}: The American Conference of Gov-ernmental Industrial Hygienists (ACGIH) does not have specif-ic threshold limit values (TLVs) for $PM_{2.5}$ and PM10. How-ever, they do have a TLV for "particles (insoluble or poorly soluble) not otherwise specified" at 10 mg/m³ for the inhalable fraction and 3 mg/m³ for the respirable fraction for an 8-hour TWA.	Projects in areas with high ambient levels of $PM_{2.5}$ (known EPA nonattainment areas for $PM_{2.5}$, or local equivalent) meet 35 ug/m3 limit, all other projects should meet the 12 ug/m3	Projects in areas with high ambient levels of $PM_{2.5}$ (known EPA nonattainment areas for PM2.5, or local equivalent) 25 ug/m3 limit, all other projects should meet 15ug/m3	Acceptable: 35 µg/m3 High Performance: 12 µg/m3

Pollutant	NAAQS / EPA[1]	OSHA[2]	MAK[3]	Canadian[4]	WHO[5] / Europe	NIOSH[6]	ACGIH[7]	LEED[8]	WELL[9]	RESET
Particulate Matter (PM_{10})	150 µg/m3		4 mg/m3	Specific Canadian guidelines for indoor PM10 levels are not readily available.	The WHO recommends an air-quality guideline of 20 µg/m³ for PM10 for an annual average and 50 µg/m³ for a 24-hour average.		10 mg/m3	50 µg/m3 (Healthcare; 20 µg/m3)	Acceptable: 50 µg/m3 Better: 30 µg/m3 High Performance: 20 µg/m3	Not Listed
Ozone (O_3)	0.070 parts per million (ppm) for an 8-hour average in outdoor air.	0.1 ppm for an 8-hour Time-Weighted Average (TWA) in the workplace.	0.2 ppm for a 15-minute average, with a peak limitation of category I, which means that the average value should not be exceeded more than twice per work shift.							
Formaldehyde (CH_2O)	Not listed	0.75 ppm measured as an 8-hour time weighted average	0.3 ppm	0.1 ppm	0.081 ppm	0.016 ppm	0.3 ppm	16 ppb or 20 µg/m3	Acceptable: 0.027 ppm High Performance: 0.013 ppm	Not Listed
Radon (Rn)	Not listed			800 Bq/m3	100 becquerels per cubic meter (Bq/m³)			Homes in EPA Zone 1 must install radon mitigation measures. Zone 1 is 4 pCi/L or greater.	0.15 Bq/L or 4 pCi/L	Not Listed

Pollutant	NAAQS / EPA[1]	OSHA[2]	MAK[3]	Canadian[4]	WHO[5] / Europe	NIOSH[6]	ACGIH[7]	LEED[8]	WELL[8]	RESET
TVOC[10]	Not Listed				Suggests a precautionary guideline value of 300 µg/m^3 for TVOCs in indoor air to minimize acute health effects, and a value of 200 µg/m^3 for long-term exposure			500 µg/m3	500 µg/m3	Acceptable: 500 µg/m3 High Performance: 400 µg/m3
Nitrogen Dioxide (NO_2)								N/A	40 µg/m^3 (21 ppb)	

[10] LEED air-quality testing credit (Indoor Air Quality Assessment, v4 BD+C) also currently requires individual target volatile organic testing for 35 different compounds, whereas the WELL v2 Air Quality precondition allows for either TVOC or individual compound testing (3 compounds). The Enhanced Air Quality optimization adds another 6 individual compounds.

Conclusion

As buildings become smarter and rating systems—like LEED, WELL, RESET, and Living Building—evolve, IAQ management through continuous monitoring is more necessary than ever. IAQ monitors offer new possibilities for proactive IAQ management, informed decision-making, and improved occupant well-being. This helps to ensure a healthy indoor environment, minimizes IAQ liabilities, and supports compliance with various rating systems and standards.

Continuous monitoring provides valuable insights into real-time IAQ conditions. When the monitors indicate sudden changes in the IAQ grades or scores, this should prompt a deeper dive into contaminant-specific measurements. Building owners and operators can then identify potential issues and take appropriate actions to mitigate them. This process is easier with an IAQ champion, feedback from building occupants, and mitigation strategies tailored to the context and situation.

Organizations must also align around desired thresholds and be aware of the causes behind the trends they are seeing. The information consolidated in this paper is intended to provide directional guidance.

In conclusion, continuous IAQ monitoring is a useful tool for building managers. It provides building owners, operators, and occupants with the information to make data-driven decisions, mitigate risks, improve occupant health and well-being, and align with evolving rating systems and standards. By investing in continuous IAQ monitoring, we have a tool to help create healthier, more resilient, more sustainable, and smarter indoor environments.