

Understanding Indoor Air Quality

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Abstract

In this paper we explore the critical issue of poor indoor air quality (IAQ), explaining its impact on human health, cognition, and productivity. This paper underscores the disproportionate risks faced by children in environments with poor IAQ, particularly in preschools, childcare centers, and schools. The fiscal impact of poor IAQ, the need for facility upgrades and the role of industry standards are also discussed. The authors advocate a 3-step process – Assess, Address, and Assure – to improve IAQ and to help provide sustainable health and fiscal benefits through preventative and proactive measures.

We All Deserve to Breathe Healthy Air

Poor indoor air quality (IAQ) is an invisible threat, and we are now beginning to understand just how dangerous it can be. It can be frustrating to those aware of its dangers because we personally have little control over it. We can decide what food we eat, but we have no choice about the air we breathe! We are victims of our environment.

Many of us recall seeing the grayish-orange smog often blanketing large cities like Los Angeles in the 70s. This was pollution we could easily see, and we knew it was unhealthy. Fortunately, government mandated emission controls on motor vehicles and stricter industry standards have dramatically reduced outdoor air pollution. This is obviously important when we are outside, but outdoor air pollution also has a significant impact on indoor air quality.

Most people in the U.S. (United States) spend over 90% of their time indoors, so indoor air pollution has a significant impact on our health. Outdoor air pollution affects indoor air quality because indoor air is typically replenished with air from the outside. Additionally, there are sources of pollution within buildings, and those pollutants invariably diminish indoor air quality.

The Impact of Poor IAQ

Health issues due to poor IAQ have been known for decades, and the term “Sick Building Syndrome” (SBS) is often used to describe a wide range of health and comfort effects associated with time spent in a building.^[1] These effects include degradation of cognitive abilities, as well as both short-term and long-term physical health issues. Various types of air pollutants and their effects are described below.

Carbon Dioxide

Carbon Dioxide (CO₂) is a natural byproduct of our metabolism, and as a result, people exhale some CO₂. Outside air has a CO₂ concentration of approximately 400 ppm (0.04%) and is somewhat higher in metropolitan areas. However, a crowded room with insufficient ventilation may have a CO₂ concentration well above 1,000 ppm. Because increased indoor CO₂ concentration is primarily caused by people, CO₂ concentration is often used as a proxy to measure the adequacy of ventilation.

Even though elevated CO₂ levels generally do not pose serious health risks, they can cause drowsiness, significant reductions in cognitive performance, attention, retention, and productivity. Research measuring declines in students' cognitive performance showed a 13% decrease when the CO₂ concentration increased from 600 to 1,000 ppm, and a 24% decrease at 1,800 ppm.^[2] Similar cognitive performance reductions are seen with workers in buildings with high CO₂ concentrations.

Particulates

Airborne particulate matter (PM) is a major source of indoor air pollution. We are now beginning to fully understand the serious health impacts PM can have on people. While there are some indoor sources of particulates like gas stoves and cooking, many more come from outdoor sources like gasoline and diesel engine exhaust. Even microscopic lead particles are carried by air near airports where gasoline powered aircraft still burn leaded fuel.^[3]

Large airborne particles are visible in smoke, but the most damaging particles are exceedingly small and classified as PM_{2.5} (less than 2.5 microns or 1/30 the thickness of a human hair) and are invisible to the naked eye. These tiny particles are the most damaging because they penetrate the alveoli deep within our lungs. Particulates can cause respiratory problems such as asthma and COPD (Chronic Obstructive Pulmonary Disease) for those with compromised respiratory functions.

Numerous studies have linked PM_{2.5} to a growing range of serious long-term health issues such as lung cancer, cardiovascular disease and dementia, and these issues may not be apparent until years after exposure. It also appears that PM_{2.5} has no boundaries. As we now know, these extremely tiny particulates can enter the bloodstream via the alveoli and even penetrate the placental barrier, reaching an unborn child.^[4] This means particulates can impact the health of even unborn children, potentially resulting in miscarriage, low birthweight, impaired neurological development, and respiratory complications.^[5]

Biologic Particulates

The particulates described above generally do not contain biologic material. However, there are many familiar biologic particulates with origins in living sources.

We are all familiar with allergens, such as pollen, that are often seasonal in nature. Mold spores are also biologic particles released by mold infestations (often hidden from sight) resulting from

insufficient ventilation and moisture collection. Household dust usually contains a mixture of dust mites, insect and rodent excrement, dead skin cells from human occupants, plus dirt and fecal matter brought in on the soles of our shoes. These particulates can be stirred up while walking, making them airborne. Although seldom deadly, these airborne particulates can still result in serious allergic responses including asthma attacks.

Some other biologic particulates can be far more deadly. Viruses such as SARS-CoV-2 (the virus that causes COVID-19) are only 0.18 micron long but can be carried by aerosols exhaled by people. *Clostridioides difficile* (abbreviated as *C. diff*) is a bacterium that releases spores which can be deadly to people with compromised immune systems. These can be made airborne by flushing the toilet which creates fecal aerosols. *C. diff* results in half a million infections and 15,000 deaths each year in the U.S.^[6]

Carbon Monoxide

Carbon Monoxide (CO) is an odorless and colorless deadly gas which is usually a byproduct of incomplete combustion. CO is extremely dangerous because it often goes undetected until its effects have incapacitated the victim. Defective furnaces are a common source of CO poisoning, but other sources exist such as exhaust fumes from nearby vehicles and construction equipment.

Each year a dozen or more cases of acute CO poisoning occur in U.S. K-12 schools.^[7] These are life-threatening events where students and staff are vomiting and/or unconscious from extreme CO poisoning. Most building codes in the U.S. require that a CO detector be installed in newly constructed homes; however, it is disturbing to realize most U.S. schools do *not* have CO detectors because they are not required!

Extreme cases of CO poisoning are documented because paramedics are called, but there are undoubtedly thousands of cases every year where students and workers are unknowingly affected by moderate CO concentrations. The EPA and WHO have established 9 ppm as the maximum permitted indoor CO concentration.^[8] Even at this low level, cognitive and cardiac functions are already being impaired.

Purchasing a conventional CO detector from the hardware store provides mediocre protection due to the poor sensitivity of such devices. The UL standard for CO detectors requires them to alarm within 90 minutes (about 1 and a half hours) when exposed to 100 ppm, 35 minutes when exposed to 200 ppm, and 15 minutes when exposed to 400 ppm. After five hours exposure to 100 ppm, people experience headaches, tiredness, nausea, and damage to both the heart and brain! We need CO sensors with much higher sensitivity to keep adults and children safe.

Radon

Just like carbon monoxide, radon (Rn) is an odorless, colorless gas. Unlike carbon monoxide, there are no immediate effects from exposure, so radon often goes undetected. But the long-term impact of radon inhalation can be serious health issues, including death.

Radon is created by the natural radioactive decay of uranium ore in the earth. Uranium deposits are scattered around the globe, so radon is always seeping out of the ground in varying concentrations. Just like uranium, radon is also radioactive, and it releases high-energy alpha and beta particles when it undergoes decay into other elements. When radon is inhaled, these alpha and beta particles can cause genetic mutations in cells deep within human lungs.

The mutations caused by ionizing radiation can result in lung cancer later in life. Radon is the number one cause of lung cancer among non-smokers, according to the EPA.^[9] It is now estimated that radon inhalation results in approximately 21,000 lung cancer deaths each year in the U.S.^[9]

Some geographic locations are known to have a greater likelihood of dangerous radon concentrations, and radon testing is usually required only where it is believed to be dangerous. This is a flawed policy because the potential for dangerous radon exposure is *always* present, and performing a single radon test in a building may not identify dangerous levels of radon. Because the radon gas escapes by fissures and cracks in the ground, one location may have a very low concentration, while another only 100 yards away may have a high concentration. Due to these factors and the serious potential for harm, radon should be monitored in every ground floor room in a building to ensure healthy conditions.

Other Pollutants

There are even more air pollutants that can cause us harm. Volatile organic compounds (VOCs) are quite common because they are emitted by a wide range of sources. Motor vehicle exhaust contains high levels of VOCs, but many indoor sources such as paint, cleaners, manufactured wood products^[10], air fresheners, fragrances and even dry-cleaned clothing can emit VOCs. Nitrous oxides (NOx) are primarily caused by coal-fired power plants and motor vehicle emissions and have long been recognized as a source of 'acid rain'. Agricultural areas can also have high NOx emissions from livestock, fertilizer and even some crops such as rice.^[11]

Ozone (O₃) is produced by UV radiation from sunlight reacting with VOCs and NOx in the atmosphere. In dense metropolitan areas, motor vehicle exhaust and industrial emissions are the primary sources of ozone, but photocopiers and disinfecting devices are also possible indoor sources.

VOCs, NOx, and ozone can all impact lung health especially in children, the elderly and those with compromised respiratory systems.

The Financial Impact of Poor IAQ

Clearly, poor IAQ has a significant impact on health, but it also costs us money! As explained above, poor IAQ has a significant impact on cognitive ability and productivity, and that can have a direct impact on company profits. Healthier employees are happier, so IAQ can also have an impact on employee attraction and retention.

Employees who become sick due to poor IAQ have higher rates of absenteeism. This obviously reduces overall productivity, and in the case of schools, results in increased expenses to hire and pay substitute teachers. Poor health may also impact insurance premiums paid by employers and employees.

Even with the positive financial impacts listed above, facility managers may use the cost of IAQ improvements as a reason to delay implementation. In a recent letter signed by six former Surgeons General, a compelling case was made regarding the savings resulting from IAQ improvements.^[12] For private businesses, even an investment of just \$40 per employee could save about \$7,000 per person per year, according to Joseph Allen, director of the Healthy Buildings program at the Harvard T.H. Chan School of Public Health.^[13]

The authors of this whitepaper absolutely agree that sensible facility IAQ improvements will almost always decrease overall expenses and increase profits for companies.

Children Are Most at Risk

Ask any parent “what is the most precious thing in your life?” and their answer will usually be “our children.” Yet we unknowingly send them to school where they may breathe unhealthy air! It is not because parents do not care – it is because they are unaware of the dangers.

Children are most vulnerable to poor air quality because their lungs are larger proportionally to their bodies, and they breathe more air per unit of body weight compared to adults. Infants are born with only 20% of their lungs developed and it is not until young adulthood that lungs are fully formed.

Asthma is one of the leading causes of school absenteeism, causing an estimated 13.8 million lost school days in U.S. children aged 5-17. Children with asthma are especially vulnerable to environmental asthma triggers often found in school buildings.^[14]

Although many of the effects of poor IAQ can be detected in children during exposure, some physiological and neurological damage can take years to become apparent and may be permanent. Children’s health issues resulting from poor IAQ should not be regarded as a mere nuisance, but as something that may result in serious mental and physical health issues they must deal with for the rest of their lives.

Many Schools Need Facility Upgrades

To make matters worse, we send many of our children to schools with inadequate, failing or no HVAC systems. According to a GAO national survey of school districts^[15], an estimated 54% of U.S. public school districts need to update or replace their HVAC systems.

This begs the question, why aren’t schools being upgraded to improve IAQ? There are several potential reasons:

- School districts are unaware of the impact of poor IAQ
- Health problems have not been experienced so their schools are believed to be safe
- Reluctance to measure IAQ due to potential liability (required to make changes)
- Prioritizing other issues (e.g., staffing issues, other facility upgrades)
- Budget constraints

Many of the oldest schools with antiquated HVAC systems are in poor school districts with limited funds available for facility maintenance and improvement. These older schools also tend to be located closer to industrial and heavy vehicle traffic areas, so the outdoor air quality is often poor. Sadly, this worsens the education challenges faced by students from underprivileged families by forcing them to attend schools with poor IAQ.

Billions of dollars of state and federal funds are presently available for school facility improvements. Unfortunately, obtaining those funds usually involves a complicated application process with which schools are completely unfamiliar. Various non-profit organizations are now offering free services to help schools get access to these desperately needed funds.

Ignorance Is Not Bliss

For decades, most facility managers have taken an “if it isn’t broken, don’t fix it” attitude towards IAQ. But building occupants and parents are becoming keenly aware that what they do not know *can* hurt them. A wide range of new standards and laws are now being enacted requiring IAQ to be monitored continuously... and for good reason!

Buildings have become more energy efficient through the years, and an unintended consequence is often degraded IAQ. In older buildings windows could be opened to let fresh air in, but new buildings are typically tightly sealed and insulated with few windows opening to reduce energy consumption. Modern HVAC systems draw in a controlled amount of outside air, but that increases energy consumption because the air must be heated or cooled to maintain inside temperature. Consequently, outside air injection is usually well below optimal levels, resulting in high CO₂ concentrations in occupied spaces.

Industry Standards to Improve IAQ

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE®)^[16] is an organization that sets standards for HVAC systems. Given its 100+ year history and broad industry expertise, its standards are often used by commercial and governmental organizations. The recently published ASHRAE Standard 241 establishes minimum requirements aimed at reducing the risk of disease transmission through exposure to infectious aerosols. This standard sets new guidelines for air filtration and recommends at least five air changes per hour (ACH) in occupied spaces.

New buildings are often LEED® certified^[17], and this may give occupants the impression air quality must be healthy in such environmentally green buildings, but that is not necessarily the

case. LEED focuses on environmental impact and sustainability instead of IAQ. Internal VOC concentration is the only IAQ parameter measured for LEED certification; the other pollutants discussed above are not measured.

About ten years ago the WELL™ Building Standard (WELL)^[18] was introduced and is now recognized as a benchmark to attain health and well-being in buildings around the world. WELL takes a holistic approach to indoor health by setting standards for IAQ, water, nourishment, light, fitness, and comfort. Given reference to ASHRAE standards, a WELL certified building is more likely (but not guaranteed) to provide healthier indoor air to its occupants.

How to Improve IAQ

Creating and maintaining healthy indoor air is a 3-step process: Assess, Address and Assure. Each of these steps is explained below:

Assessing IAQ Status

W. Edwards Deming, a leader in the field of quality improvement, has said, “Measurement is the first step that leads to control and eventually to improvement. If you cannot measure something, you cannot understand it. If you cannot understand it, you cannot control it. If you cannot control it, you cannot improve it.”

The authors of this whitepaper wholeheartedly agree. The first step to improving indoor air quality should be assessing a building’s indoor air quality by using accurate IAQ monitors. IAQ can vary greatly from room-to-room and in different areas of a facility, so it is important to place monitors in all populated areas of a building for evaluation.

Many IAQ monitors only measure a limited set of parameters such as temperature, humidity, CO₂ and possibly VOCs. It is important to select an IAQ monitor with a comprehensive set of measured parameters which also include carbon monoxide (CO), ozone (O₃), nitrous oxides (NO_x) and particulates (PM_{2.5}).

As emphasized earlier, we now understand the dangers of radon and how it often goes undetected. In the past, radon was usually measured in just one location in a building, but radon concentration can vary significantly from room-to-room. Radon should be continuously measured in all the same locations as other IAQ parameters to ensure that any radon hot spots are detected.

Addressing IAQ Problems

Multiple interventions may be necessary to mitigate IAQ problems (referred to as a multilayer approach). These include ventilation, particulate filters, activated charcoal filters and UVC ultraviolet light. The types of interventions, their functions and where they are introduced depend on analysis of the IAQ data collected during the assessment stage.^[19]

Particulate Filters

Air filters are a basic function in all HVAC systems and are intended to remove particulates from the air; but not all filters are created equal. ASHRAE has defined the Minimum Efficiency Reporting Value (MERV)^[20] to classify the effectiveness of air filters.

Most buildings and residences are equipped with MERV 8 filters which can capture particles as small as 3 microns. These filters will trap most dust, pollen, and pet dander, but are ineffective at trapping hazardous PM2.5 particulates.

MERV 13 filters are significantly more effective and capture a high percentage of PM2.5 particulates. Upgrading facilities from MERV 8 to MERV 13 air filters is the most effective and inexpensive way to significantly reduce PM2.5 concentration.

Even higher efficiency HEPA filters are available (effectively MERV 17), but the higher cost and reduced airflow rate make them justifiable only for extremely critical applications such as hospital operating rooms, laboratories, and clean rooms. Additionally, most HVAC systems cannot accommodate HEPA filters because their air resistance is too high, potentially damaging the HVAC system.

Activated Charcoal Filters

Activated charcoal filters (also called activated carbon filters) are used to remove gaseous pollutants from the air. They are typically used in conjunction with particulate filters and can remove VOCs (associated with odors), NO_x, carbon monoxide, ozone, and radon. However, these filters cannot remove CO₂ (more on this below).

UVC Ultraviolet Light

Ultraviolet UVC light is effective for inactivating biologic particulates such as viruses, bacteria, and mold spores because its high-energy photons damage RNA/DNA and prevent reproduction. UVC light produced by low-pressure mercury vapor lamps can also prevent mold from growing on the evaporator coils inside HVAC ducts. However, some types of UVC lamps produce significant amounts of ozone, and those should be avoided due to ozone health hazards. Although UVC disinfection may have minor impact on IAQ measurements, it can significantly reduce the transmission of airborne pathogens.

Ventilation

Ventilation refers to the introduction of clean air into a space and is typically measured in air changes per hour (ACH). ASHRAE now recommends at least five air changes per hour in occupied rooms. This air comes from two sources: filtered recirculated indoor air and outdoor air.

Injecting a high percentage of outdoor air into the HVAC system usually improves IAQ because the outdoor air is usually less polluted than the indoor air (this may not be the case near heavy vehicle traffic, industrial areas or during wildfires). However, the permissible percentage of recirculated air may be higher in HVAC systems with efficient filtration.

CO₂ is a particularly important parameter to measure. Because the primary source of CO₂ inside a building is people exhaling, CO₂ concentration is an excellent proxy for ventilation effectiveness. High CO₂ concentration in an occupied room almost always indicates insufficient ventilation. But CO₂ is an unusual gas; unlike other gas pollutants, it cannot be removed by filtration. The only practical way to reduce CO₂ concentration in a building is by replacing it with outside air, otherwise known as dilution through ventilation.

Radon is also an unusual pollutant because it only seeps from the ground into the lowest floor of a building. Although radon can be removed from the air by activated charcoal filters, the most effective mitigation strategy is removal at the source. This is done by sealing or ventilating seeping radon at the lowest building surface and exhausting it outside of the building using fans.

Assuring Continuous Healthy IAQ

If your doctor prescribes high blood pressure medicine, they will also require you to monitor your blood pressure daily to assure the medication is producing the desired result. This is also the case once IAQ improvements have been implemented. IAQ must be continuously monitored in multiple locations to assure indoor air remains healthy.

Many factors can affect a building's IAQ and those will change daily and over time. Outdoor weather, outdoor air quality, the number and location of building occupants, and filters nearing end-of-life are just a few factors that can have a significant impact on IAQ. The only reliable way to assure healthy air inside a building is by continuously monitoring IAQ in every occupied space.

Some IAQ monitors can send real-time IAQ measurements to the cloud where they are permanently stored in a database. A cloud-based application can also provide a real-time IAQ summary to building management on a mobile app, as well as sending alert messages whenever hazardous conditions are detected. This same data can be analyzed to provide recommended actions to improve IAQ.

In the future, more buildings will have building management systems (BMS) or building automation systems (BAS) utilizing real-time IAQ information on a room-by-room basis. These systems can adjust airflow rates and outdoor air injection to simultaneously provide optimized IAQ with minimum energy consumption.

Summary

The Pandemic brought much needed attention to indoor air quality and how it can affect our health. The invisible threat of poor indoor air quality results in a wide range of mental, physiological, and even financial challenges. As a society we must focus on the potential benefits of improving indoor air quality; not focusing on what it will cost, but what it can save. Long-term health consequences increase healthcare costs and reduce the quality of life and lifespan. We must advocate for increased awareness, proactive measures, and continuous

monitoring to ensure healthy indoor air for everyone. Greater attention to this critical aspect of public health can ensure healthier indoor spaces, save needless suffering, and better prepare us for the next pandemic.

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