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The Value of IAQ: A Review of the Scientific Evidence Supporting the Benefits of Investing in Better Indoor Air Quality

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The Value of IAQ

A review of the scientific evidence supporting the benefits of investing in better indoor air quality

White Paper

[aiha.org](https://www.aiha.org)

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Executive Summary

Improved indoor air quality (IAQ) has been shown to result in higher productivity, better cognitive performance, reduced absenteeism, less reported job stress, and increased job satisfaction. Specific IAQ improvements associated with these gains include increased ventilation, decreased pollutant emissions, improved air filtration, improved temperature and humidity control, and reduced dampness and mold in buildings. The benefits of improved building performance and air quality can offset the costs of implementation through increased productivity and work performance of the occupants. Well-documented guidelines exist for improving IAQ during building design, construction, renovation, and ongoing maintenance. This information can help building owners and managers take the best actions to increase productivity and prevent illness in building occupants, and to maximize their return on investment.

Many studies have demonstrated the relationship between IAQ and occupant performance and productivity. Specifically, poor IAQ has been found to be associated with adverse impacts on productivity and performance, while improved IAQ has been found to be associated with increased productivity and performance. Real or perceived poor IAQ has an important economic cost in terms of both presenteeism (going to work despite illness or injury) as well as absenteeism. While improving IAQ can help reduce reported health concerns, reducing presenteeism and absenteeism can also improve performance and productivity.



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Other studies have examined how ventilation rates, combined with the presence of pollutant sources, can affect productivity. These studies provide evidence that increased ventilation, including increases above common guidance levels such as ASHRAE's ventilation standards, improve occupant productivity. Increased occupant control over ventilation has also been shown to improve productivity.

Higher indoor carbon dioxide (CO₂) levels have been directly associated with impaired work performance and increased health symptoms. Historically, it was believed that these associations exist only because higher indoor CO₂ concentrations, resulting from lower outdoor air ventilation rates, are also correlated with higher levels of other indoor-generated pollutants that directly cause the adverse effects. More recent studies, however, have found that CO₂ itself, even at levels previously considered acceptable, may have adverse effects.

Considering the benefits and demonstrated return on investment, building owners and operators should consider proactive methods of improving IAQ. Established strategies and guidelines are readily available to help identify and implement IAQ-related improvements. These include recognizing and addressing potential and real IAQ issues during the design, construction, renovation, and ongoing maintenance of buildings. Research has found that the benefits of IAQ improvement far outweigh the costs, with estimates of 3–6 times returns for increased ventilation, 8 times returns for increased filtration, and up to 60 times returns when all improvements and related benefits are combined. Collectively, the scientific literature demonstrates that improved workplace productivity and reduced absenteeism from improved IAQ have been shown to provide substantial financial benefits, with the benefits often greatly outweighing the associated costs.

Introduction

People in modern societies spend more than 90 percent of their time in indoor environments.^(1,2) Research on ventilation and health and comfort started in the late 19th century, and by the mid-20th century, a good understanding of minimum ventilation rates in non-industrial workplaces had been obtained.⁽³⁾ In the U.S. after 1940, installations of water-cooled air conditioning for public buildings increased by 10 percent per year, such that by 1965 nearly two billion gallons of water per day was being used for this purpose.⁽⁴⁾ This increased the potential for indoor condensation issues during the summer, and associated mold growth, in a much larger percentage of the building stock. Ventilation rates began to decline in the 1960s to save heating and cooling energy, but decreased even more during the 1970s in response to the American energy crisis.⁽⁵⁾ Also by the 1970s, building materials that were more biodegradable, and some that were prone to emitting high concentrations of volatile organic compound (VOCs), including formaldehyde, entered use. Finally, with the rise in carpeting use, buildings became harder to clean.

These changes—decreasing reliance on natural ventilation, reduction of outside air intake, usage of new, moisture-susceptible building materials, increasing reliance on air conditioning, and widespread installation of carpeting—led to a steep rise in complaints in non-industrial workplaces, schools, and homes, which affected real and perceived occupant health, comfort, and productivity. By the mid-1980s, this public health burden inspired the creation of large-scale research efforts on occupants and worker health in relation to indoor air quality (IAQ) and ventilation by the National Institute for Occupational Safety and Health (NIOSH), Health Canada, Harvard University, and the U.S. Environmental Protection Agency (USEPA). The first World



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Health Organization (WHO) meeting on IAQ and health was held in 1988. The research and public policy effort that began in the 1980s has generated a great deal of reliable information on the impact of degraded IAQ on worker health and productivity. Additionally, despite furious arguments,⁽⁶⁾ smoking was eliminated in Federal buildings in Canada in 1989, and gradually throughout the North American continent, which further focused attention on the issues noted above.

The term “indoor environmental quality” (IEQ) refers to the quality of the overall indoor environment. This encompasses microbial, volatile, gaseous, and particulate contaminants, as well as such elements as lighting, acoustics, thermal comfort, ergonomic design, and work-related stress.^(7,8) Indoor air in non-industrial workplaces may contain different pollutants. These include biological contaminants such as mold, bacterial endotoxins, and allergens (such as those from pet dander, house dust mites, cockroaches, and rodents). Other important sources of contamination include degraded outdoor air quality, arising from poor location of heating, ventilation, and air-conditioning (HVAC) system air intakes—which can introduce traffic particulates, nitrous oxides (NOx), ozone, and other outside pollutants—and VOCs and particulates from office equipment or machines (e.g., printers) in the building without adequate source control.⁽⁹⁾

“Indoor air quality,” which is a subset of IEQ, refers more specifically to the air quality and contaminants that may be present or elevated within and around buildings and structures that may impact the health and comfort of building occupants. “Acceptable” IAQ is defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) in their Standard 62.1 - Ventilation for Acceptable Indoor Air Quality as “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction.”⁽¹⁰⁾

Foundational elements of a healthy and productive building include IAQ, ventilation, thermal conditions, moisture, dust and pests, and water quality.⁽⁸⁾ IAQ issues generally come from an inadequately cleaned or maintained environment, insufficient ventilation, pollutants emitted from sources and activities inside the building, and contamination from outside sources. The relationships between indoor building conditions and the wellbeing (health and comfort) of occupants are complex,⁽¹¹⁾ but understanding how IAQ relates to value can help building owners and managers select the best actions to take to prevent complaints, improve occupant comfort, and maximize their return on investments in environmental health.

This document provides a review of the scientific literature regarding the value of IAQ related to the impact on building occupants, although it is recognized that similar relationships are also found when evaluating overall IEQ in a building. Understanding how IAQ relates to value can help building owners and managers select the best actions to take to prevent building-related illness (BRI), to improve occupant comfort, and to maximize their return on investments in environmental health.

Health Effects

When buildings have “poor” or inadequate IAQ, occupants can suffer from real or perceived health effects caused by building conditions. It is well known that individual contaminants in the indoor environment can cause specific health concerns. For example, formaldehyde, which can off-gas from building materials and



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furnishings, can cause eye, nose and throat irritation, respiratory symptoms, exacerbation of asthma, and sensitization.^(10,12) Ozone, which can come from both the outside air, as well as inside from some office machines, can cause asthma, irritated eyes, mucous membrane irritation, and reduced lung function.^(10,12) Even CO₂, which is generated by humans as they breathe, has been associated with headache,^(12,13) fatigue,^(12,13) drowsiness,⁽¹²⁾ and difficulty concentrating.⁽¹²⁾ Clearly, reduction of these, and other similar contaminants, can create value in the form of reduced occupant health effects.

Over the past 30 years, there has been an evolution of the terminology used for health concerns related to IAQ. Most of the burden of disease today would be defined as BRI, which is causally linked to indoor environmental exposures within a building. This includes building-related allergic or inflammatory disease from microbes and their byproducts, and infectious disease from bacteria such as *Legionella*. Recent studies conducted in the U.S. and Europe suggest the population with concerns about IAQ in compliant buildings appear to be a subset with various health issues, particularly respiratory health concerns.^(14,15) Higher incidences of airborne disease infections in commercial and institutional buildings are directly associated with low ventilation rates,⁽¹⁶⁾ and indirectly with higher indoor CO₂ levels, which is used as an indicator of low ventilation rates.⁽¹⁷⁾ An analysis of the number of sick days lost in the U.S. to minor respiratory disease showed that this category of disease is not normally considered very serious, yet has a very large impact on workplaces. Health problems, including sinusitis, asthma, headache, and allergic rhinitis, result in loss of work equal to diseases with seemingly greater impact such as cancer and heart disease.^(18,19)

The final category, nonspecific building-related symptoms, includes complaints such as mucous membrane irritation, headache, and difficulty concentrating—sometimes referred to as “sick building syndrome.”^(14,20) Often, these complaints affect a number of building occupants but are reported to disappear shortly after the occupants leave the building.⁽²⁰⁾ One cause central to most reports of health concerns in the 1980s was the reduction of outside air ventilation to conserve energy, with employees subject to a total reliance on ventilation systems for IAQ.⁽²¹⁾ Given this close association, some studies refer to the problem as “tight building syndrome”⁽²²⁾ or “sealed building syndrome.”⁽²³⁾ On the other hand, outdoor ventilation rates (that is, bringing in outside air to dilute indoor contaminants) in offices are associated with reduced reported symptoms.⁽²⁴⁻²⁶⁾ This is why the Occupational Safety and Health Administration (OSHA),⁽¹²⁾ ASHRAE,⁽¹⁰⁾ NIOSH,⁽²⁷⁾ and many other organizations recommend either maintaining minimum outside air intake ventilation rates, or monitoring acceptable ventilation rates through evaluating and maintaining acceptable CO₂ levels as an indicator of ventilation effectiveness. Unfortunately, while it is desired that commercial buildings meet these minimum ventilation guidelines, the most recent data from the U.S. Energy Information Agency (EIA) indicate that about half of the U.S. building stock was built before 1980.⁽²⁸⁾ Assuming that the distribution of ventilation rates is similar to that found in the USEPA BASE studies,⁽²⁹⁾ it is likely that a large number of these buildings are under-ventilated.

Accordingly, real or perceived poor IAQ has an important economic cost in terms of both presenteeism^(14,30) and absenteeism. Presenteeism can result in productivity loss from employees not fully functioning because of those health issues.⁽³⁰⁾ Absenteeism also costs employers money. While improving IAQ can help reduce reported health concerns, reducing presenteeism and absenteeism can also improve performance and productivity.



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Performance and Productivity

Many studies have demonstrated the relationship between IAQ and occupant performance and productivity. Specifically, poor IAQ has been found to be associated with adverse impacts on productivity and performance, while improvements in IAQ have been found to be associated with increased productivity and performance.

Ventilation rate studies provide strong evidence for improved IAQ affecting occupant welfare and productivity.⁽³¹⁾ Higher ventilation rates have also been linked to higher productivity in offices,⁽³²⁾ better performance on cognitive ability tests,⁽³²⁾ and improved general work performance.⁽²⁵⁾ Improvements in performance with increased outdoor air ventilation rates are most detectable with initial ventilation rates below 20 liters per second per person (L/s-person), or about 42 cubic feet per minute (cfm) per person, while performance increases with increased ventilation rates appear to diminish as ventilation rates become high (over 50 L/s-person).⁽³³⁾

Several studies have identified an improvement in student performance associated with improved ventilation rates. Wargocki and Wyon⁽³⁴⁾ observed that the speed at which 10–12 year old children performed two (2) numerical and language-based tasks improved significantly when the outdoor air supply rates increased from 3.0 L/s (6.4 cfm) per person to 8.5 L/s (18 cfm) per person, resulting in indoor CO₂ concentrations decreasing from 1300 parts per million (ppm) to 900 ppm. Bako-Biro et al.⁽³²⁾ determined that faster and more accurate responses were recorded for computerized performance tasks by students in primary schools when ventilation rates maintained indoor CO₂ levels at or below 1000 ppm. Maddalena et al.⁽³⁵⁾ reported that, in simulated office experiments, reductions in either occupant-based or floor-area-based ventilation rates had a significant negative impact on most decision-making measures. Petersen et al.⁽³⁶⁾ reported that increasing outdoor air supply from an average of 1.7 to 6.6 L/s per person (3.6–14 cfm), which corresponded to a decrease in CO₂ concentrations from 1500 to 900 ppm, significantly improved the children's performance in four tests, including addition, number comparison, grammatical reasoning, and reading and comprehension.

There are some studies where both ventilation and the presence of pollutants affect productivity. Wargocki et al.⁽³⁷⁾ placed a 20 year old carpet behind a screen in a mock office. Total volatile organic compound (TVOC) concentrations were not different when the carpet was present versus when it was not present, but the mixture of VOCs was different.⁽³⁷⁾ The authors reported that subjects worked significantly more slowly when the old carpet was present ($p = 0.003$), typing 6.5 percent less text and making 5 percent more errors than when the carpet was absent.⁽³⁸⁾ Subjects scored higher on the creative thinking task when the ventilation rate was increased from 3 to 10 L/s (6.4 to 21.2 cfm) per person. Overall, every twofold increase in ventilation rate above 3 L/s (6.4 cfm) per person produced a 1.1 percent increase in overall performance in the text typing task and a 2.1 percent increase in overall performance in the addition and proofreading tasks.⁽³⁷⁾ These studies were confounded by the likely presence of additional air particulates from the carpet. Often when buildings have poor air quality, it is because inhalation of particle burdens in settled dust.⁽³⁹⁻⁴¹⁾

Increased occupant control over ventilation has also been shown to improve productivity. In an experimental study by Menzies et al.,⁽²⁶⁾ workers were provided with individually-controlled ventilation systems at their workstations, which allowed the worker to control the ventilation supplied to his or her workstation. Four months after installation, workers reported fewer work-related symptoms that reduced their capacity to



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work, compared to a control population that did not have the ability to regulate their ventilation systems.⁽²⁶⁾ Sixteen (16) months after installation, the workers with the ventilation systems indicated that the improved IAQ increased their productivity by 11 percent, in contrast to a 4 percent decrease in productivity among the control group of workers.⁽²⁶⁾ Recognizing that perception of control of the thermostat, whether actual or not, can impact occupant comfort by having a sense of control over their work environment,⁽⁴²⁾ Menzies et al. indicated that the persistence of the intervention's effect for at least 16 months suggests that the device may have had more than a placebo effect, which might be expected to dissipate after more than a year.⁽²⁶⁾

Higher indoor CO₂ levels have been directly associated with impaired work performance and increased health symptoms.^(43,44) Higher indoor CO₂ concentrations, resulting from lower outdoor air ventilation rates, are correlated with higher levels of other indoor-generated pollutants that directly cause the adverse effects. However, even at moderate concentrations there is some evidence that small but significant differences in cognitive performance can be affected by CO₂.⁽⁴⁵⁾ Concentrations of 1,000 ppm CO₂, compared with 600 ppm, were associated with statistically significant and meaningful reductions six (6) of nine (9) metrics of decision-making performance among study participants.⁽⁴⁴⁾ At a concentration of 2,500 ppm, compared with 600 ppm, performance was significantly reduced in seven (7) of nine (9) metrics of performance.⁽⁴⁴⁾

Some studies have looked at the association between occupant health symptoms and performance. Nunes et al.⁽⁴⁶⁾ measured the relationship between occupant symptoms, such as headache, fatigue, difficulty concentrating, and eye, nose, and throat irritation, and worker performance. Workers who reported any of these symptoms took significantly longer ($p < 0.001$) to respond in computerized performance tests and had higher symbol-digit substitution test error rates ($p = 0.07$).⁽⁴⁶⁾ While these isolated studies are not conclusive, the results suggest that circumstances in which IAQ conditions are not ideal can reduce worker productivity through increased errors, resulting in more time to identify and correct those errors, or overall slower productivity.

Perceived air quality is also related to worker performance. Seppanen and Fisk⁽⁴⁷⁾ reported performance decreases of 1.5 percent on basic tasks (such as typing, addition, and proofreading) per each additional 10 percent of workers dissatisfied with air quality. To prevent those negative effects, proactive IAQ measures can assist with worker satisfaction and, as a result, improve performance.

Absenteeism

The productivity gains from improved IAQ discussed above have also been found to reduce absenteeism. Fisk and Rosenfeld⁽⁴⁸⁾ suggest that a productivity increase of 1 percent corresponds to reduced sick leave of two (2) days per year. Reduced absenteeism has been associated with a variety of IAQ related factors, including improved ventilation rates, improved air filtration, and reduced dampness in buildings. In fact, Fisk⁽⁴⁹⁾ concluded that improvements in the indoor environment, such as increased ventilation, reduced recirculation of indoor air, and improved air filtration, may reduce sick leave due to infectious diseases by 9 to 20 percent.

Increased ventilation rates are associated with reduced absenteeism in both offices⁽⁴⁸⁾ and classrooms.⁽⁵⁰⁾ Milton et al.⁽⁴⁸⁾ reported an association between outdoor air supply rates and absenteeism among 3,720



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manufacturing workers in 40 buildings. They reported that the absence rate was about 35 percent lower in buildings with ventilation rates of approximately 24 L/s (50 cfm) per occupant vs. 12 L/s (25 cfm) per person.⁽⁴⁸⁾ Fisk et al.⁽⁵¹⁾ reported that a 12 L/s (25 cfm) per person increase in ventilation rate was similarly associated with a 35 percent reduction in short-term absence in office workers. Mendell et al.⁽⁵⁰⁾ reported that ventilation rates below recommended minimum levels impacted student illness absences, and stated that increasing ventilation rates above the minimum levels is associated with an estimated 11–17 percent reduction in illness-related absences. They also noted that reducing concentrations of chemicals and other indoor contaminants, through the use of air cleaning systems and reducing the indoor emission of such contaminants, may be a viable alternative to simply increasing ventilation rates.⁽⁵⁰⁾

There is a large body of evidence that supports the concept that exposure to damp indoor environments is associated with increased respiratory illnesses and infections.⁽⁵¹⁾ Fisk et al. found that reducing dampness (and associated mold) in a building lead to improved performance and reduced occupant-reported symptoms. Absenteeism can also be significantly reduced.⁽⁵¹⁾ They also projected that a 30 percent reduction in dampness and mold in U.S. office buildings could eliminate 1.5 million absence days annually, with a value of \$500 million.⁽⁵¹⁾ Overall, the evidence is clear: good IAQ helps keep workers on the job and students in school.

Cost-Benefit & Return-on-Investment

Improved workplace productivity and reduced absenteeism from improved IAQ have been shown to provide substantial financial benefits. The benefits typically outweigh the associated costs.

Historically, particularly during the energy crises of the 1970s and early 1980s, it was recognized that the more outside air was introduced into a building, the more energy is consumed in conditioning it. As such, it was a common energy conservation practice to reduce the amount of outside air introduced into buildings to save money on energy costs.⁽⁵²⁾ In 2000, when ASHRAE updated the minimum outdoor air intake recommendations from 5 cfm to 20 cfm per person, the USEPA estimated that the impact of this increased outdoor air supply rate on increased energy costs would range from 2 to 18 percent.⁽⁵²⁾ Given this, many building owners chose to focus only on the overall operating costs, and minimized ventilation rates to their buildings. However, there is evidence that any increase in energy costs resulting from increasing ventilation rates are readily offset by increases in worker productivity.

Measures taken to improve IAQ are highly cost-effective when health and productivity benefits are taken into consideration. Based on estimations that worker salary costs exceed building energy and maintenance costs by a factor of approximately 100,^(53,54) even doubling energy or maintenance costs to improve IAQ that results in as little as a 1 percent increase in productivity should be sufficiently justified. MacNaughton et al.⁽⁵⁵⁾ reported that the health benefits associated with increased ventilation rates far outweighed the per-person energy costs relative to their salary costs. Doubling ventilation rates from the ASHRAE-recommended minimum of 9.4 L/s (20 cfm) per person was predicted to increase energy costs by less than \$40 per person per year in office buildings in all climate zones investigated.⁽⁵⁵⁾ The same change in ventilation resulted in an 8 percent worker performance improvement, determined to be an equivalent value of \$6,500 per office



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worker and \$15,500 per manager.⁽⁵⁵⁾ Therefore, the health benefits associated with enhanced ventilation rates were shown to far exceed the per-person energy costs, relative to salary costs.⁽⁵⁵⁾

Fisk et al. reported that increasing minimum ventilation rates from 8 L/s (17 cfm) per person to 10 L/s (21 cfm), or even 15 L/s (32 cfm), per person, has significant overall economic benefits in comparison to decreasing ventilation rates to 6.5 L/s (14 cfm) per person for energy savings purposes.⁽²⁵⁾ Using a correlation of ventilation rates with short-term absences, and the relative risk of increased prevalence of occupant-reported symptoms, Fisk et al. estimated the benefits and costs of each scenario.⁽²⁵⁾ Using 2008 values, they estimated \$13 billion in total annual economic benefits from increasing minimum ventilation rates from 8 to 10 L/s (17–21 cfm) per person, and \$37.5 billion from increasing minimum ventilation rates from 8 to 15 L/s (17–32 cfm) per person, including an average 0.33 and 0.91 percent increase in performance, and 5.2 and 15 percent decreases in weekly reported symptoms, respectively.⁽²⁵⁾ In 2011 dollars, increasing the ventilation rates in all U.S. office buildings to 10 L/s (21 cfm) per person was estimated to provide a benefit of \$139 per worker; increasing the ventilation rate to 15 L/s (32 cfm) per person provided an estimated benefit of \$334 per worker, and adding economizers, when absent, provided an estimated benefit of \$292 per worker.⁽²⁵⁾ When attempting to save money and energy through decreasing ventilation rates from 8 to 6.5 L/s per person (17–14 cfm), the estimated \$40 million in annual energy-related benefits are miniscule compared to the projected annual costs of \$12 billion in decreased productivity and increased short-term absence due to health symptoms related to poor IAQ.⁽²⁵⁾ In another study, Fisk⁽⁴⁹⁾ calculated benefit-to-cost ratios for increased ventilation ranging from 3:1 to 6:1 for increased ventilation. Benefits of increasing minimum ventilation rates far exceeded energy costs.

Djukanovic et al.⁽⁵⁴⁾ modeled an office building in both hot and cold North American environments to determine the cost effectiveness of increasing the design ventilation rate from 4 L/s (8.5 cfm) per person to up to 39.8 L/s (84 cfm) in a “low-polluting” building, and from 6.3 L/s (13.4 cfm) per person to up to 63.2 L/s (134 cfm) per person in a building that was not considered “low-polluting.” In all cases, the direct cost of ventilation rate increased, as well as energy and maintenance costs, which would be recovered in no more than four (4) months.⁽⁵⁴⁾ In addition, the increase in productivity was estimated to be worth at least ten (10) times the added energy and maintenance costs, based on 2004 dollars.⁽⁵⁴⁾

Fisk et al.⁽⁵¹⁾ modeled five (5) scenarios for possible IAQ improvements to examine benefits and the cost of implementation, based on the existing conditions and the prevalence of occupant-reported IAQ-related symptoms from 100 representative U.S. office buildings surveyed by the USEPA. Two (2) scenarios involved increasing the ventilation rate of outside air, one (1) involved adding economizers, one (1) involved keeping indoor temperatures lower than 23°C (73°F) during the winter, and the last scenario involved reducing the number of office buildings with dampness and mold by 30 percent. Each of the five (5) scenarios resulted in combinations of benefits, with the largest projected economic benefit being an improvement in work performance. This benefit is followed by a reduction in the number of days of short-term absences used. Finally, the benefit of a decrease in weekly occupant-reported symptoms were reported.⁽⁵¹⁾ Even when the cost of increased energy consumption and equipment are added in, the overall economic benefit from improved IAQ exceeded the cost of implementation.⁽⁵¹⁾



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Both improved health and reduced absenteeism have repeatedly been shown to occur with increased ventilation. Milton⁽⁴⁸⁾ reported that the additional cost of delivering added outdoor air to workers would be more than offset by the savings from reduced sick leave, and that a net savings of \$400 per employee per year (in 2000 dollars) may be obtained with increased ventilation.

Another reason that is often cited to promote reducing outdoor ventilation rates is that the reduced energy usage lowers the amount of emissions from the combustion of fuel to generate that energy. With energy recovery ventilation systems added to typical office HVAC systems, MacNaughton et al. estimated that the energy costs and associated emissions of doubling the ventilation rate from the ASHRAE minimum (from 20 cfm/person to 40 cfm/person) would only rise slightly and overall costs would be less than \$40 per person per year in all climate zones investigated.⁽⁵⁵⁾ The same change in ventilation improved the performance of workers by 8 percent, equivalent to a \$6500 increase in employee productivity each year (using 2015 dollars).⁽⁵⁵⁾ The authors concluded that the health benefits associated with enhanced ventilation rates far exceed the per-person energy costs⁽⁵⁵⁾ and with retrofits and adequate initial design, there would be minimal environmental consequences from the added energy usage to accommodate increased ventilation.

There is, however, one important consideration regarding increased ventilation that should not be overlooked. When buildings increase their outdoor air intake, outdoor-to-indoor pollutant transport can also occur, potentially increasing indoor contaminants, such as particulates and ozone.⁽⁵⁶⁾ Ben-David et al. evaluated the cost and impact of increased ventilation vs. increased outside air contaminants, and the impact on productivity and health-related symptoms. They found several strategies that saved energy and achieved profitable IAQ benefits, as indicated by the change in the work performance.⁽⁵⁶⁾ When outdoor environments have high particulate matter (PM) levels, reductions in indoor PM levels can be economically achieved through basic modifications to the HVAC systems.^(56,57) Ben-David et al. reported that higher filter efficiency is a more important determinant in reducing indoor PM concentrations than ventilation rates.⁽⁵⁶⁾ Two (2) studies examining the cost-benefit of improved air quality in office buildings in Hong Kong also determined that investments in higher-efficiency primary air filters for HVAC systems, leading to a decrease in indoor PM concentrations, can result in net cost savings for employers who are also responsible for building maintenance costs.^(57,58) As a result, using Hong Kong's air quality and costs estimated at the time of that study (2004), employers could expect to find reduced health expenses by about \$250 U.S. for every 10 $\mu\text{g}/\text{m}^3$ decrease in PM_{10} level, with the majority of the savings coming from a reduced number of activity delays.⁽⁵⁷⁾ Additionally, society can reduce overall health expenses by about \$1,820 US (in 2007 dollars) for every 10 $\mu\text{g}/\text{m}^3$ decrease in PM_{10} .⁽⁵⁷⁾ Fisk⁽⁵⁹⁾ estimated the benefit-to-cost ratios for the expected gains in productivity due to reductions in health effects by 1) increasing ventilation rates, and 2) increasing filter system efficiency, to be 14:1 and 8:1, respectively. Overall, these studies concluded that demonstrable net cost savings in employee sick time and healthcare costs for the employer could be achieved. Reductions in indoor PM levels, via improved filtration, can contribute significant improvement in health outcomes while also resulting in net cost savings. The results of these reductions in exposure levels are anticipated to contribute to significant improvement in health outcomes that will be beneficial to building owners, occupants, and society as a whole.⁽⁵⁷⁾



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For society as a whole, Mudarri⁽¹⁹⁾ estimated the 2016 direct medical costs and wage-related losses for the entire U.S. population for several allergy-caused medical conditions from exposure to dampness and mold in housing. Direct medical expenses were estimated to be \$2.26 billion for allergic rhinitis, \$880 million for asthma, and \$287 million for acute bronchitis.⁽¹⁹⁾ Losses due to sick days (including the care of sick children) and reduced productivity at work, were estimated to be \$335 million for allergic rhinitis, \$156 million for asthma, and \$56 million for acute bronchitis.⁽¹⁹⁾ He did not provide an estimate for economic costs related to similar type exposures in workplaces or schools. Fisk⁽²⁵⁾ estimated an annual benefit of \$500 million, in 2011 dollars, for reducing dampness and mold in office buildings by 30 percent.

Mendell et al.⁽⁶⁰⁾ estimated health impacts of contaminants in indoor work environments in the U.S. and the potential benefits of improved indoor environments. The research team calculated economic costs by applying available estimates of the costs of health care, of absence due to illness, and of other performance losses to the numbers of workers with each kind of health effect.⁽⁶⁰⁾ Estimates of the total adverse health effects produced by U.S. indoor work environments, and the proportions of adverse effects preventable by improving these environments, could be as much as an annual reduction in 5 to 7 million communicable respiratory infections (an estimated \$3 to \$4 billion in annual savings), a 6–15 percent reduction in exacerbations of asthma among the 4.7 million indoor workers with asthma, and a 20–50 percent reduction in nonspecific building-related symptoms.⁽⁶⁰⁾ The researchers report that their data suggested that improving building environments may result in health benefits for more than 15 million of the 89 million U.S. indoor workers, with estimated total economic benefits of \$5 to \$75 billion annually.⁽⁶⁰⁾

Unfortunately, commercial building owners, managers, and operators often do not recognize the benefits of good IAQ.⁽⁶¹⁾ Hamilton et al.⁽⁶¹⁾ surveyed U.S. building industry stakeholders on the costs and benefits of IAQ, and showed that a majority of respondents either did not think, or did not know, that good IAQ measures could lead to increased productivity, reduced absenteeism, and improved health benefits. In fact, those stakeholders with green building certifications were less likely than the surveyed population at large to recognize a connection between productivity, absenteeism, or health benefits, and increased ventilation or filtration.⁽⁶¹⁾ Even among respondents that did recognize a benefit, quantitative estimates of the benefit varied widely, and differed from scientific technical best estimates based on the IAQ literature.⁽⁶¹⁾

Productivity gains from IAQ improvements are difficult to quantify. Fisk and Rosenfield⁽⁵³⁾ estimated the annual value gained by multiplying the average annual employee compensation by the percentage of improvement and the number of workers. Other benefits of improved indoor environments include a savings in health care costs from reductions in adverse health effects.⁽⁵³⁾ For tenants, costs of improved indoor environments may include increased energy bills, while benefits may include the value of increases in productivity, reduced absenteeism, and possibly reductions in health insurance coverage rates. For owners, costs may include higher initial costs for the costs of retrofits for HVAC systems, while benefits may include the ability to charge premium rents and reduced tenant turnover. For society in general, costs may include increased environmental emissions, while benefits include reductions in medical costs. In fact, Wyon stated that a strong economic case can be made that the benefits for improving IAQ beyond the minimum standards exceed costs by a factor of about 60, and that payback times for investing in good IAQ will usually be around two (2) years.⁽⁶²⁾



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Collectively, the scientific literature demonstrates that improved workplace productivity, and reduced absenteeism, from good or improved IAQ will provide substantial financial benefits that often greatly outweigh the associated costs.

Impact of Poor Response to IAQ Complaints

Another cost of poor IAQ that should be considered is the impact of failing to respond effectively to IAQ complaints. If not handled appropriately by building management, worker complaints regarding IAQ can result in communications problems, conflicts between divisions, rumors, poor opinions of the employer, building owner, or manager, lower morale, and further reductions in performance and productivity, with associated financial impacts.⁽⁴⁷⁾ IAQ issues that are not addressed, or are not addressed appropriately and in a timely fashion, can be quite costly in terms of lost work time, reduced occupant productivity, building or mechanical system repairs, legal costs, and negative publicity.⁽⁶³⁾ Reduced occurrence of issues leading to complaints will reduce these issues and any associated financial losses.⁽⁴⁷⁾ Beyond financial costs, failing to respond effectively can erode the trust relationship between occupants and building management, along with the associated damage to workplace morale.

Federspiel⁽⁶⁴⁾ has shown that responses to temperature-related complaints impose a significant cost in office buildings. In a study of 575 U.S. buildings, 18.4 percent of total complaints handled by building management were due to indoor environmental issues, and 77 percent of those complaints were related to temperature (that is, the building was too hot or too cold).⁽⁶⁴⁾ Potential savings due to better temperature management, leading to reduced response requirements, include an estimated 12 percent reduction in the labor cost of HVAC maintenance each year.⁽⁶⁴⁾

Approaches to Improving IAQ

Considering the benefits and demonstrated return on investment, building owners and operators should consider proactive methods of improving IAQ. There are many strategies and approaches for doing so. The American Industrial Hygiene Association (AIHA) document *Technical Framework: Indoor Air Quality Practitioner* inventories the knowledge and skill sets that professional IAQ practitioners should possess to implement these strategies, from routine and proactive management, to incident and complaint response, to IAQ enhancement.⁽⁶⁵⁾ A discussion of approaches to improving IAQ in buildings during design, construction, maintenance, and renovation follows.

Design of New Buildings

ASHRAE recommends that, since design approaches for good IAQ can also impact thermal comfort, illumination, acoustics, and energy efficiency, an integrated approach should be taken when designing new buildings.⁽⁶³⁾ By incorporating good IAQ concepts early in the design process, stakeholders can ensure that outdoor contaminant sources, activities expected to occur in the building, and local conditions, such as water table and moisture sources, are addressed early on.⁽⁶³⁾ Examples of building design considerations to support good IAQ, balanced with energy efficiency requirements, include selective placement of outdoor air intakes, use of appropriate ventilation rates, appropriate treatment of outdoor and recirculated air (if



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necessary), appropriate design and installation of building envelope and vapor barriers, minimizing water vapor intrusion, and selection of low-emitting building materials.⁽⁶³⁾

Green Building Practices

In the past 20 years, green building standards have had a significant impact on construction practices. Green building standards address the impact of a building and its operations on energy and water use, IAQ, material selection, and the possible contaminants in the soil beneath the building throughout the life cycle of a building.⁽⁶⁶⁾ These programs often focus on building ventilation rates and the selection and use of building materials, furnishings, and cleaning products that have minimal impact on both occupants and the environment. Careful management of occupant, custodial, pest control, maintenance, and contractor activities is required.⁽⁶⁷⁾

Some green building programs, such as the Leadership in Energy and Environmental Design (LEED) criteria set by the U.S. Green Building Council (USGBC), provide a point and credit system based on the extent to which strategies meeting the expected building design and construction standards are achieved.⁽⁶⁸⁾ Various surveys of occupants in green buildings (principally designed to LEED criteria) versus occupants in conventional (non-green) buildings, have shown that, in general, occupants in the green buildings reported:

- better perceptions of ventilation, air movement, and reductions in humidity and stale air;
- higher satisfaction for air quality, general building satisfaction, cleanliness, and thermal comfort;
- significantly lower absenteeism attributable to asthma and respiratory allergies;
- fewer work hours affected by asthma and respiratory allergies;
- fewer work hours affected by depression and stress; and
- increased productivity related to improved IAQ.⁽⁶⁹⁾

MacNaughton et al. reported that workers in green certified buildings scored 26.4 percent higher (95 percent CI: 12.8–39.7percent) on cognitive function tests, and had 30 percent fewer symptoms, than those in non-certified buildings.⁽⁵⁵⁾

LEED certification for a building is intended to be a measure of “sustainable design,” and IEQ is just one component of sustainable design considered under LEED certification schemes. As a result, it is possible for buildings to earn the highest LEED certification level (LEED-Platinum) while meeting only the minimum number of required IEQ credits. In addition, ongoing LEED re-certification requirements allow for minimal to no quantitative measurements of IAQ parameters. For all the reasons outlined above, a building’s achievement of LEED certification should not be considered a strong indicator that the building’s IAQ is any better than a similar, non-certified building, particularly if the certified building was not recently constructed.

Newer standards with greater focus on IAQ have recently been developed, such as the WELL Building Standard™. Parts of the WELL verification methods include standards for volatile substances, particulates, inorganic gases, mold, VOC reduction, indoor air monitoring, and ventilation effectiveness.⁽⁷⁰⁾ WELL’s greater focus upon the quantitative evaluation of IAQ, and narrower overall focus upon the health and wellbeing of occupants, would suggest the potential for greater IAQ improvements in WELL-certified buildings. However,



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the body of peer-reviewed scientific literature, focused on the impact of WELL certification on IAQ, is still minimal.

Improvements to Existing Buildings

A basic premise to improving IAQ is that increasing ventilation rates (that is, bringing more outdoor air inside) dilutes indoor air contaminants. Certain contaminants, such as VOCs, are often controlled by dilution with outdoor air. Other contaminants, such as radon and soil vapors, are typically managed by sub-slab depressurization changing air pressure relationships between adjoining areas. However, increasing the outdoor air supply to meet the criteria of ASHRAE 62.1 may require design and installation of additional heating, cooling, or dehumidification systems to prevent comfort- or moisture-related problems. More air movement in duct work, or increasing fan sizes, may also increase ambient noise levels. Nevertheless, a well-designed and well-maintained HVAC system may be able to improve the work environment enough to pay for itself through improved occupant productivity.

Filtration is also often used to control indoor air contaminant levels, especially when the source of the contaminant is outside the building. Control strategies include installing higher efficiency air filters in existing HVAC systems for particulates, and installing filters impregnated with activated charcoal or potassium permanganate to remove VOCs, corrosive gases, and odors. Upgrading the efficiency of existing filters, if compatible with the HVAC system, can help improve IAQ. Research has shown that this practice offers substantial benefits in increased productivity, including work efficiency and reduced absenteeism. However, the benefit of increasing outdoor air intake should be balanced against the need to treat the outside air, the cost of additional energy to condition the outdoor air, and the environmental cost of the outdoor emissions resulting from the production of that additional energy. The installation and use of air-to-air energy recovery systems or economizers may partially, or even completely, offset such energy and environmental costs.^(48,55) Improving existing filtration methods can reduce particulate levels,^(56,57) which can contribute to significant improvement in health outcomes while resulting in net cost savings.⁽⁵⁷⁻⁵⁹⁾

Renovation and maintenance activities in existing buildings can also affect IAQ. Best practices for facility additions and operations include isolating the construction area and HVAC system,^(65,67) using low-VOC emitting products—including paints and cleaning fluids—and materials wherever possible,^(67,71) scheduling use of other chemicals after hours (such as painting on weekends)^(65,67), and daily housekeeping activities, such as prompt cleanup of dust and disposal of waste materials. All of these measures will help to minimize the IAQ impact of construction and maintenance activities.⁽⁷¹⁾

Routine Inspections and Maintenance

Other ways of proactively maintaining good IAQ include developing, implementing and maintaining an IAQ management plan for the operation of buildings to enhance IAQ through practices that prevent the development of IAQ problems in buildings, investigating and correcting IAQ problems when they occur, and maintaining IAQ that enhances the well-being of the occupants.⁽⁶⁵⁾ This can also include developing processes and schedules for preventive maintenance activities to prevent IAQ problems, and developing and educating occupants and workers on activities and materials that may impact IAQ.⁽⁶⁵⁾



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AIHA recommends that building owners and managers develop a performance profile of the building ventilation system, including analysis of the system, and understanding the impact of the system's operation on comfort and ventilation throughout the building.⁽⁶⁷⁾ This profile can be accomplished through routine inspection of the system for any obvious deficiencies, malfunctions, design issues, or contamination. More technical evaluations can include measuring air velocities, verifying outdoor air, supply and return airflow rates, collecting temperature and relative humidity measurements, and determining air balance (that is pressure differentials) in representative areas, zones, or rooms, of the building.⁽⁶⁷⁾ Routine inspection and evaluation may reveal problems before they develop into situations that significantly impact occupants.

ASHRAE Standard 62.1 recommends that an Operations and Maintenance (O&M) manual, which includes ventilation system operating and maintenance schedules, be developed and maintained.⁽¹⁰⁾ Examples of scheduled maintenance includes visually inspecting, or remotely monitoring, outdoor air dampers at least once every three (3) months, cleaning humidifiers at least once every three (3) months, inspecting drain pans at least once per year, and inspecting outdoor air intake louvers at least once every six (6) months.⁽¹⁰⁾

AIHA's *Technical Framework: Indoor Air Quality Practitioner* recognizes the importance of developing procedures for managing responses to water intrusion events.⁽⁶⁵⁾ It also discusses the importance of understanding how to apply proactive source reduction through evaluation of products and materials (including selection of building materials, cleaning processes/materials, furniture, fixtures, and equipment) that may enter the building and affect IAQ.

Conclusion

It is well understood that problems with IAQ have the potential to cause illness in building occupants, and the value in taking steps to protect occupant health is clear. However, there are further value gains to be realized from investments in improving IAQ. Research has repeatedly demonstrated that improvements to IAQ have resulted in increased workplace productivity, better academic performance as measured by cognitive ability tests, and better task execution and decision-making. Improvements in IAQ parameters have likewise been found to result in reduced employee absenteeism, less reported job stress, and increased job satisfaction. Specific IAQ improvements that have been associated with these gains include increased ventilation, reduced emissions of chemicals and other pollutants, improved air filtration, improved temperature and humidity control, and reduced dampness and mold in buildings.

There are several established strategies and guidelines to identify and implement IAQ-related improvements. These include recognizing and addressing potential and real IAQ issues during building design, construction, renovation, and ongoing maintenance. Research has found that the benefits of IAQ improvement can far outweigh the costs, with estimates of 3–6 times returns for increased ventilation, 8 times returns for increased filtration, and up to 60 times returns when all improvements and related benefits are combined. This data demonstrates that efforts to improve IAQ not only protect the health and well-being of building occupants, but can also yield substantial financial returns on investment.



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