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Indoor Air Quality Performance in Buildings – A Review

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Abstract: Indoor air quality (IAQ) is the term used to describe the quality of the air within buildings and other structures, particularly as it relates to the wellbeing and comfort of building users. This review covers the fundamentals of the parameters to be measured to determine the IAQ of a building. Reduced risk of indoor health issues can be achieved by understanding and managing common indoor contaminants. Within hours of exposure or perhaps years later, indoor air pollution can have a negative impact on health. Following a single exposure or several exposures to a pollutant, some health consequences such as headaches, dizziness, exhaustion, and irritation of the eyes, nose, and throat may become apparent. Therefore, IAQ assessment must be implemented to measure the parameters according to the standards and guidelines set.

Keywords: Indoor air quality, indoor health, parameters, IAQ assessment

1. Introduction

According to the Environmental Protection Agency (EPA) in 1997, dust, filth, and other contaminants can enter a structure from the outside or through inside activities. The human respiratory system is the primary source of CO2 in interior environments, particularly in overcrowded rooms, restricted spaces, and high-activity areas [1]. According to the study, CO, CO2, TVOC, and PM concentrations are significantly higher in older structures than in modern structures. CO and CO2 are acknowledged to be strongly associated with inadequate ventilation. CO2 is therefore an essential metric for determining IAQ and ventilation efficiency. In addition to CO and CO2, VOCs and Semi-Volatile Organic Compounds (SVOCs) are common indoor contaminants produced by furniture, coatings, office stationery, mold, and a variety of other sources [2].

Particulate matter is another prominent indoor pollutant that is frequently discovered in office settings. Smaller particles are more likely to be breathed in and stay in the breathing mechanism of humans. Particulates that are effortlessly consumed are usually less than 10 µm in size (PM10). Laser printers and copiers that are used on a regular basis generate ultrafine particles and VOCs [3]. Printing machines and copying devices are reported to be capable of releasing more VOCs than PCs, specifically toluene, styrene, benzene, and alkyl benzene. Computers, on the other hand, are a long-term producer of VOCs and SVOCs. Paper can also emit these compounds while printing or photostat jobs.

The physical indoor air is made up of variables such as the temperature of air and humidity, which are important in the occurrence of Sick Building Syndrome (SBS). In an indoor space, a small velocity of air denotes inadequate venting and a poor change of air particles. Inadequate ventilation and exposure to indoor contaminants can have a severe influence on the occupant's health and contribute to Sick Building Syndrome (SBS), Building Related Illness (BRI), and Multiple Chemical Sensitivities (MCS). The most common symptoms of SBS appear to be sensorimotor discomfort of the air sacs of the lungs (eyes, nose, and throat), neurotoxicity or overall health issues, skin problems, non-specific physiological disorders, and fragrance and taste stimulation. Table 1 below shows furnishings and equipment are prone to generating dangerous indoor pollutants. One source of pollution is the residents themselves.

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Table 1 - Possible Contaminant in an Office Environment

Possible Contaminant Sources	Pollutant Type
Paint, glue, plastic, wood preserver, air freshener, cleaning solution, dry cleaning solution, perfume, solvent, resin, plastic foam	Organic gases, vapors, VOC (xylene, toluene, perchloroethylene, benzene, styrene, 1, 1, 1-trichloroethane, methyl ethyl ketone, alcohol)
Paints, glue, Environmental Tobacco Smoke (ETS), acid hardening lacquer, processed wood product	Formaldehyde (Urea formaldehyde: UF and phenol-formaldehyde: PF), other aldehydes
Plastic, wallpaper, vinyl tile	Phthalates, Poly Vinyl Chloride (PVC), Styrene
Impregnated wood	Fluorides
Occupants, unvented combustions	CO_2
Paints	Lead (Pb), mercury, amino
Copy machines, electronic cleaners	Ozone (O_3), VOCs, SVOCs
Papers, textiles	Organic dust
Acoustic ceilings, insulations, gypsum board	Man-Made Mineral Fibers (MMMF), calcium sulfate
Outdoor dirt, building materials	Inorganic dust, lead
Disinfectant	Alcohol, quaternary ammonium compound (QAC), phenol
Pesticide	Chlordane, aldrin, dieldrin, heptachlor
Dust mites, molds, danders, plants, occupants	Biological dust, metabolic product of microorganisms

2. Parameters

Air temperature, velocity, relative humidity, biological contaminants, such as bacterial and fungal counts, and chemical contaminants, such as carbon monoxide (CO), formaldehyde (HCHO), particulate matter (PM), and total volatile organic compound (TVOC), are the factors to be considered when determining indoor air quality (IAQ).

2.1 Carbon Monoxide (CO

CO, commonly referred to as carbonous oxide, is a toxic gas that is created by the imperfect combustion of fuels. It has no taste, no odor, or any color [4]. If carbon dioxide production is hampered by a lack of oxygen during combustion, like when an engine that is operated internally combusted is used within a closed space, or when a cooker is used, CO will form. Combustion components such as fuel, convector, and furnace could all be CO sources [5]. Outdoor vehicle exhaust can cause high levels of CO to enter houses. Smoking tobacco is another type of CO pollution that is only present for a short time [6]. The use of a generator powered by gasoline during a power outage and the burning of coal during a cold season may cause short-term difficulties with high CO concentrations indoors. Even in well-ventilated rooms, paint remover contains a chemical called methylene chloride that metabolizes within the body that generates CO, and the usage can cause a substantial CO dose.

In a study on subjects exposed to the CO produced by 100 non-smokers in their homes, the US Environmental Protection Agency (EPA) discovered that the concentrations were extremely low, ranging between 2-4 ppm (roughly 2.3-4.7 g /m3) [7]. Numerous neurological symptoms can also be brought on by severe low-level CO inhalation. This was demonstrated in a study of individuals who were exposed to CO from household stoves for up to 2.5 hours, which discovered that their capacity for planning and learning, as well as their attention spans and levels of focus, had declined [8]. Fatigue, headaches, nausea, and dizziness are symptoms of severe carboxyhemoglobin (COHb) exposure (10–30%) that are frequently misdiagnosed or go unnoticed. The acute effects of CO exposure are most harmful to organs with high oxygen requirements, such as the heart and brain. This is because CO has a higher oxygen requirement than oxygen. The most dangerous sources of severe CO poisoning are malfunctioning external vents and damaged combustion equipment, which can cause spasms and collapse (COHb 50–60 percent), while higher exposures can cause coma or death [9]. Even if a patient survives a severe CO inhalation, they may still experience neurological and psychiatric effects later on, especially if they lose consciousness.

2.2 Formaldehyde (HCHO

One of the most frequent aldehydes observed on a regular basis is formaldehyde gas. Because the methods of gas chromatography commonly employed for VOC studies are not capable of identifying formaldehyde, it is frequently regarded independently from other volatile chemicals [10]. At normal temperatures, formaldehyde is an odorless, transparent gas with a penetrating smell. Building products, for instance, like particle boards, resins, medium-density fiberboards, carpeting, plywood, and adhesives, are the principal sources of formaldehyde in indoor air.

Formaldehyde concentrations in the outdoors are commonly less than 0.1 ppm. The rate of HCHO production in interior spaces changes based on factors like humidity and temperature. Indoor levels of HCHO are usually higher than those found outdoors. Table 2 lists a variety of critical health effects linked to various formaldehyde concentrations. Coughing, sneezing, and slight eye irritation are common symptoms of formaldehyde exposure of less than 1 ppm. However, these symptoms usually go away quickly after exposure [11].

Table 2 - Exposure to formaldehyde health consequences

Formaldehyde concentration (ppm)	Observed health effects
<0.05	None reported
0.05-1.5	Neurophysiologic effects
0.05-1.0	Odor threshold limit
0.01-2.0	Irritation of eyes
0.10-25	Irritation of upper airway
5-30	Irritation of lower airway and pulmonary effects
50-100	Pulmonary edema, inflammation, pneumonia
>100	Coma, death

2.3 Particulate Matter (PM

Particulate matter is a term used in environmental science to describe suspended particulate matter or water vapor in the air, and it is among the most common forms of air impurity. The particulate matter's makeup is quite complicated, and it is mostly determined by its source. Smoke, for instance, is one of the causes of major constituents that are respirable particles [12]. Respirable particles have a lengthy residence time in the air, allowing tiny particles (about 6-7 μm or smaller) to gather in the lungs [13]. This has a tremendous impact on the health of the people who live there. Aromatic hydrocarbon molecules, trace metals, nitrates, and sulfates are among the organic and inorganic chemicals found in respirable particulate matter. Since biomass is commonly burned without sufficient ventilation in many buildings, smog is the generally significant source of respirable particles in developing countries' indoor areas. Natural gas and electricity have largely phased out the use of biomass for heating and cooking in developed countries [14]. Because of this, smoking is the main cause of particulate matter pollution in developing countries.

Harvard's study of 470 non-smoking homes in six cities found that the mean annual PM2.5 level (particles with a diameter of less than 2.5 μm) was 17 μg m^{-3} [15]. Many homes continued to use woodstoves for heating and cooking. When using airtight woodstoves, indoor concentrations of respirable particles were found to be slightly above background levels (up to 30 μg m^{-3}) and significantly higher (200-1900 μg m^{-3}) when using non-airtight stoves. Homes with wood burners have an average 4 μg m^{-3} greater interior particle volume fraction than homes without them when they are not in use.

Breathing in respirable particulates, such as smoke from wood burning, can cause airway constriction, particularly in sensitive individuals like children and newborns. Nonsmokers' lung functions will be reduced after a lengthy period (over twenty years) of exposure to huge amounts of indoor particulates [16]. A fat-soluble chemical, PAHs (polycyclic aromatic hydrocarbons), can be found in burning wood. PAH is formed when wood is burned incompletely and contains organic compounds with multiple benzene rings [10]. Once breathed, PAH chemicals are easily absorbed into the breathing system, increasing the risk of cancer in the lungs [17].

2.4 Total Volatile Organic Compound (TVOC

In conventional, room-temperature conditions, volatile organic compounds (VOCs) have a high vapor pressure, covering from 50 to 260°C. VOC and comparable materials have the ideal attributes of being economical, as well as insulation that is enough, resistance to heat, and easy installation. A list of common VOCs detected indoors is shown in Table 3.

Table 3 - Typical VOC sources in indoor air [10]

Sources	Examples of Typical Contaminants

Consumer and commercial products	Aliphatic hydrocarbon (n-decane, branched alkanes), aromatic hydrocarbons (toluene, xylenes), halogenated hydrocarbons (methylene chloride), alcohols, ketones (acetone, methyl ethyl ketone), aldehydes (formaldehyde), esters (alkyl ethoxylate), ethers (glycol ethers), terpenes (limonene, alpha-pinene).
Paint and associated supplies	Aliphatic hydrocarbons (n-hexane, n-heptane), aromatic hydrocarbons (toluene), halogenated hydrocarbons (methane chloride, propylene dichloride), alcohols, ketones (methyl ethyl ketone), esters (ethyl acetate), ethers (methyl ether, ethyl ether, butyl ether).
Adhesives	Aliphatic hydrocarbons (hexane, heptane), aromatic hydrocarbons, halogenated hydrocarbons, alcohols, amines, ketones (acetone, methyl ethyl ketone), esters (vinyl acetate), ethers.
Furnishings and clothing	Aromatic hydrocarbons (styrene, brominated aromatics), halogenated hydrocarbons (vinyl chloride), aldehydes (formaldehyde), ethers, esters.
Building materials	Aliphatic hydrocarbons (n-decane, n-dodecane), aromatic hydrocarbons (toluene, styrene, ethylbenzene), halogenated hydrocarbons (vinyl-chloride), aldehydes (formaldehyde), ketones (acetone, butanone), ethers, esters (urethane, ethyl acetate).
Combustion appliances	Aliphatic hydrocarbons (propane, butane, isobutane), aldehydes (acetaldehyde, acrolein).
Potable water	Halogenated hydrocarbons (1,1,1-trichloroethane, chloroform, trichloroethane).

Although indoor VOC levels are typically five times higher than outdoor air levels, they are still significantly lower than the odor critical limits [18]. It is found that indoor air VOCs comprise a wide spectrum of chemical compounds in varying amounts, depending on the indoor environment. Therefore, the majority of standards and publications refer to TVOCs rather than specific VOC amounts. VOC exposure has the potential to cause both immediate and chronic health consequences. People with asthma and respiratory problems, such as nocturnal dyspnea, are more sensitive to low dose VOC exposures than others. For 22 VOCs at 25 $\mu g/m^3$, low dose VOCs can cause fatigue, headache, sleepiness, and disorientation [19]. Other hazards were eye and respiratory tract irritation, which could lead to allergic responses involving the skin, eyes, and lungs. At levels over 35,000 $\mu g/m^3$, some VOCs might cause altered neuro-behavioral function [20], also unconsciousness, seizures, and possibly fatal [21].

2.5 Carbon Dioxide (CO2

CO_2 is an odorless, colorless gas that is the source of indoor pollution emitted by humans and is linked to metabolic activity. Human CO2 emissions account for a significant portion of indoor CO_2 pollution in the absence of additional sources such as burning fuel [22]. Apart from human respiration, combustion, which includes kerosene, gas, and wood or coal-fired equipment, is the largest source of CO_2. CO_2 levels range from 700 to 2000 ppm in the absence of any external sources (about 3657 mg^{-3}). When using equipment without ventilation, indoor temperatures can reach 3000 ppm [23]. CO_2 is a toxic gas that can cause irritation to the respiratory system. For most locations, the ratio of indoor CO_2 concentration to outdoor CO_2 concentration is between 1 and 3, with serious health concerns only occurring when CO2 levels exceed 30,000 ppm or 54860 mg^{-3} [24]. When concentrations exceed 15,000 ppm (27430 mg^{-3}), breathing can be affected to a certain degree. [25]. Exposure levels above 30,000 ppm may cause health issues such as nausea, vertigo, and headaches.

2.6 Air Temperature

Dry-bulb and wet-bulb temperature readings are the two forms of air temperature measurements. The air temperature is usually regarded as being the same as the temperature of the dry bulb. Wet-bulb temperature, unlike dry-bulb temperature, takes into consideration the moisture count in the air. Temperature has been hypothesized to have health repercussions for patients, in addition to thermal illnesses. In an investigation encompassing 12 cities across the United States, it was discovered that as the temperature rises, heart disease admissions climb as well [26].

2.7 Air Velocity

In a building, air velocity refers to the rate at which cubic meters of air move through a certain place, also known as airflow or mass flow (m^3/s). The airflow is caused by pressure gradients, which push the air from higher pressure zones to lower pressure zones. Individuals may detect an accumulation of airborne toxins indoors due to insufficient air renewal, ranging from chemical products (such as formaldehyde, carbon monoxide, asbestos, and others) to natural product accumulation (such as mold spores and other pathogens proliferating in the area). In this situation, a lack of air renewal could lead to irritation of the skin, eyes, and nose, a feeling of being out of breath, and an abrupt rise in toxic exposure could cause neurological shock. In fact, suffocation and loss of consciousness are caused by an increase in chemical exposure, dizziness, headaches, and coordination problems. On the other hand, too much indoor air renewal can cause a sudden drop in temperature inside the building. This can cause health problems like hypothermia, colds, migraines, muscle pain, and joint swelling in people with arthritis, among other things.

2.8 Relative Humidity

The quantity of water mist content in the air is referred to as humidity. Humidity is a crucial dominant element to consider when doing air conditioning and mechanical ventilation (ACMV) procedures. Humidity affects the thermal sensation of humans because the human body regulates its temperature through evaporative cooling. Since the rate of heat transfer is slower when humidity is high, the respondent feels warmer than when humidity is lower at the same temperature.

2.9 Bacterial and Fungal Counts

A microbe is a microscopic organism that consists of a single cell or a group of cells. Bacteria, fungus, archaea, protists, microscopic plants, and mammals are all examples of microorganisms. In interior conditions, fungus and bacteria can be found in organic detritus as a result of these microorganisms. On the other hand, outdoor air entering indoor surroundings may provide a significant supply of fungus and materials for indoor environments, particularly during summer and fall, which are hot and warm seasons [27]. Building function, according to research, has a minor impact on fungal composition, which is largely governed by weather. This suggests that excessive humidity encourages the development of mold and fungi.

In a 26-month study of 163 households in the United Kingdom, it was discovered that the geometric mean count of bacteria and fungi in the air was 365.6 and 234 colony forming units (CFU) m^{-3}, respectively, where Penicillium seems to be the most commonly isolated fungus, detected in 53% of specimens, while bacillus is the most commonly identified bacteria [28]. In Yokohama, Japan, the amounts of fungal spores in indoor environments were measured in the range of 13 to 3750 CFU m^{-3} [29]. In 2001, it is reported an assessment of microbiological contaminants for air-conditioned offices using air sampling for the occupants, with bacteria and fungus ranging from 79-334 CFU m^{-3} and 70-132 CFU m^{-3}, respectively in Singapore [30]. Table 4 summarizes several revealed illnesses and symptoms linked to specific fungus and bacteria. One of the most common symptoms is allergies and asthma, which are both related to the human respiratory and breathing systems.

Table 4 - Diseases and illness syndromes linked to bacterial and fungal exposure

Disease/Syndrome	Examples of Casual Organisms
Rhinitis (and other upper respiratory symptoms)	*Alternaria, Cladosporium, Epicoccum*
Asthma	*Various aspergilla and penicillia, Alternaria, Cladosporium, Mucor, Stachybotrys, Serpula*
Humidifier fever	*Gram-negative bacteria and their lipopolysaccharide endotoxins, Actinomycetus and fungi*
Extrinsic allergic alveolitis	*Cladosporium, Sporobolomyces, Aureonasidium, Acremonium, Rhodotorula, Trichosporon, Serpula, Penicillium, Bacillus*
Atopic dermatitis	*Alternaris, Aspergillus, Cladosporium*

A discovery in the United Kingdom, which established a link between allergic respiratory and breathing problems are linked to fungus spores, supports this theory [31, 32]. Recent research suggests that breathing problems are possibly not caused by spore exposure [33]. Instead, they are related to fungal mycotoxins, which are easily absorbed via membranes [34].

3. Conclusion

IAQ must be emphasized and promoted on any indoor premises accordingly based on the standards and guidelines set. Understanding and awareness are essential to prevent IAQ-related diseases among the occupants while maintaining their working performance. Building owners should take responsibility to have their IAQ assessed on schedule.

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