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Enhancing Indoor Environmental Quality in the Post-Pandemic Era:

Challenges, Strategies, and Solutions

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***Abstract*— The post-pandemic era has emphasized the need to review and improve indoor environmental quality (IEQ) to ensure the health and safety of people in buildings. This paper explores various aspects of IEQ, with a special focus on indoor air quality (IAQ), lighting, comfort, and temperature. It looks at the important signs, parameters, tools for measurement, and recommended levels required to create a strong framework for assessing and managing IEQ after the pandemic. The paper also explains strategies for controlling and improving IEQ, including advanced ventilation systems, air cleaning technology, and dynamic lighting systems. Additionally, it highlights the crucial role of design technology in reshaping buildings to promote better IEQ standards, incorporating innovative architectural and engineering solutions that prioritize the well-being of occupants. By combining research findings and real-world applications, this paper offers a comprehensive guide for architects, engineers, and policymakers to create healthier and more resilient indoor spaces in the post-pandemic era.**

Keywords—Indoor Environmental Quality; Indoor Air Quality; Visual Comfort; Thermal Comfort; Post-Pandemic; Indoor Spaces.

I. INTRODUCTION

Indoor environmental quality (IEQ) significantly influences the well-being, comfort, and productivity of building occupants. IEQ is especially critical in settings where people spend substantial time, such as homes, schools, and workplaces. In contemporary urban life, individuals increasingly spend more time indoors, with homes being the primary location (50–60%), workplaces or schools (about 30%), and other activities like transportation and public buildings (5%), totaling over 90%. The World Health Organization (WHO) underscores the importance of maintaining a healthy indoor environment, as it estimates around 12.6 million deaths result from unhealthy surroundings. This global concern has led to extensive research by scholars and governments [1].

Given IEQ's substantial impact on health and productivity, building professionals increasingly prioritize it in their designs and operations [2].

II. INDOOR ENVIRONMENTAL QUALITY FACTORS

IEQ is influenced by a multitude of factors that collectively shape the quality of our indoor spaces. The term encompasses a variety of factors, including indoor air quality (IAQ), visual, thermal comfort, temperature, acoustics, and ergonomics. Each of these components plays a pivotal role in determining the overall well-being, health, and productivity of individuals occupying indoor environments. Fig. 1 illustrates the categorization of these factors and their related indicators [3].

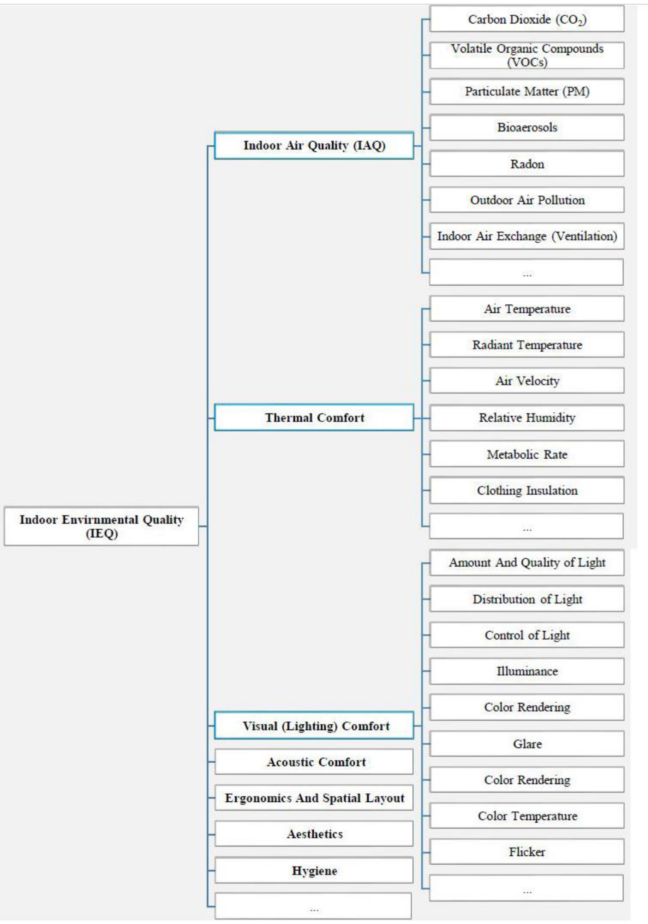

Fig. 1. Indoor environmental quality factors

A. *Indoor Air Quality*

IAQ refers to the air quality within a building. At present, the IAQ is crucial in a quality indoor environment, especially when considering the impact of pandemics. As shown in Fig. 1, current health concerns regarding IAQ include potential risks of asthma, cancer, and viruses caused by carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter (PM), bioaerosols, radon, outdoor air pollution, and indoor air exchange, all of which are significant issues. Another widespread cause of health problems is high indoor humidity, which promotes mold growth. in contrast, humidity removal can reduce health risks. IAQ is influenced by various indicators that can affect the health, comfort, and well-being of its occupants, according to the concentration of contaminants. Key indicators that contribute to IAQ are shown in Fig. 3.

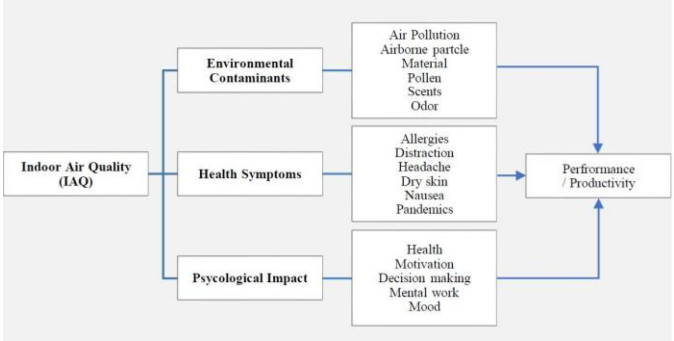

Fig. 2. Controlling indoor air quality

1) *Carbon Dioxide*

Carbon Dioxide (CO_2) is a colorless and odorless gas that is naturally present in the air. Elevated CO_2 levels can indicate inadequate ventilation in the spaces and can cause discomfort, drowsiness, and reduced cognitive performance [2].

a) *Measurement*

CO_2 is typically measured in parts per million (ppm) using CO_2 detectors or sensors.

b) *Parameters*

Referring to Fig. 3, indoor CO_2 concentration is influenced by various parameters, such as ventilation rates, duration of occupancy, educational spaces size, and the combustion of fossil fuels by vehicles near classrooms. Additionally, human activities within educational spaces, including the primary source of CO_2 from human respiration, can contribute to indoor CO_2 concentration.

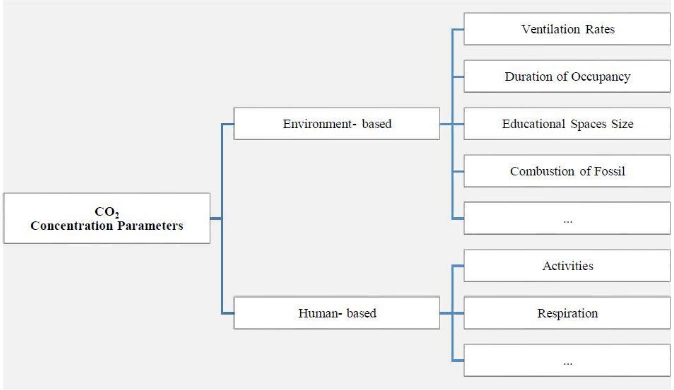

Fig. 3. CO_2 concentration parameters in educational spaces

c) *Guidelines for Post-Pandemic*

National standards dictate that the CO_2 concentration in the educational spaces during the pandemic should not exceed 1000 ppm [2]. This requirement aligns with the national ventilation code of Egypt, which classifies IAQ based on occupation densities, categorizing it as high, medium, or moderate. The education and skills funding agency (ESFA) recommends an acceptable indoor CO_2 concentration of 380 ppm to 1500 ppm for a healthy indoor environment, with a smaller value for green buildings. Extremely high concentrations of CO_2 (above 200,000 ppm) can lead to death [4].

2) *Volatile Organic Compounds*

Volatile organic compounds (VOCs) are emitted as gases from certain liquids or solids, such as building materials, furnishings, and cleaning products. These compounds, which include formaldehyde and phthalate plasticizers, can pose a threat to the health of occupants, particularly children and the elderly with sensitive immune systems, if their concentrations exceed established standards or guidelines. High concentrations of VOCs can cause both short-term and long-term health effects. Hutter et al. have established that the harmful effects of VOCs on health depend on several factors, such as the type and total amounts of VOCs, as well as the duration of exposure. Prolonged exposure to certain VOCs can increase the risk of pandemics [5].

a) *Measurement*

VOCs level can be measured using photoionization detectors (PIDs) or other specialized sensors. IAQ monitoring usually employs total volatile organic compounds (TVOC) as an indicator of the combined performance of various VOCs. The unit of measurement for TVOC is typically expressed in parts per billion (ppb) or micrograms per cubic meter ($\mu g/m^3$). TVOC can be measured using specialized air quality monitoring instruments called "TVOC meters" or "VOCs analyzers." High levels of TVOC can lead to sensory effects like irritation, dryness, and mild inflammation of the eyes and/or nose. TVOC concentration changes throughout the day, increasing in response to indoor pollutant sources, such as class activities and equipment used during the daytime while remaining relatively constant at night.

b) *Parameters*

Facilitating natural ventilation for the circulation of air within the building is advisable. This will dilute the concentration of VOCs present indoors and help remove them. Mechanical ventilation plays a significant role in removing VOCs and improving IAQ. In rooms with inadequate ventilation, TVOC concentrations can be more than three times higher compared to those with mechanical ventilation. Hernandez et al. have found that using mechanical ventilation can reduce TVOC concentrations by more than 340 $\mu g/m^3$ in less airtight rooms. Hu et al. have proposed an improved strategy for minimizing indoor VOCs pollution that uses the average concentration of VOCs as the optimization objective.

c) *Guidelines for Post-Pandemic*

The WHO has established guidelines for some specific VOCs to ensure good IAQ. For example, the guideline for formaldehyde, which is a common VOC, is 100 $\mu g/m^3$ for short-term exposure (30 minutes) and 40 $\mu g/m^3$ for long-term exposure (8 hours) [6].

3) Particulate Matter

Particulate matter (PM) refers to tiny particles suspended in the air, including dust, smoke, and other allergens. PM is categorized by size, such as PM_{10} (coarse particles) and $PM_{2.5}$ (fine particles). High levels of PM can negatively affect respiratory health. Particle counters or air samplers can measure PM concentrations, prolonged exposure to $PM_{2.5}$ and PM_{10} is linked to the onset of asthma-like symptoms and COVID-19 [2].

a) Measurement

The measure of PM for IAQ is typically expressed in micrograms per cubic meter (µg/m³). This unit indicates the concentration of particulate matter present in the indoor air, which includes particles of various sizes suspended in the air that can impact the overall air quality and potentially affect human health. The measurement is typically done using specialized instruments known as “PM monitors”.

b) Parameters

Various parameters contribute to the unacceptable concentration levels of $PM_{2.5}$ and PM_{10} indoors, with the impact of room occupancy differing based on the size of the particles. According to Poupart et al., infiltration of outdoor pollutants, primarily contributed by motor vehicle emissions, is the primary source of indoor $PM_{2.5}$. Becerra et al., Chan et al., and Yang et al. have found that indoor PM_{10} levels are dependent on particle suspension resulting from activities of occupants, such as cleaning, which can resuspend particles from carpets and furniture.

c) Guidelines for Post-Pandemic

The WHO guidelines recommended that $PM_{2.5}$ should not exceed 5 µg/m3, while 24-hour average exposures should not exceed 15 µg/m3 more than 3 - 4 days per year. Additionally, PM_{10} (particulate matter with a diameter of 10 microns or less) concentrations of 15 µg/m3 annual mean, 45 µg/m3 24-hour mean.

4) Bioaerosols

Bioaerosols consist of minute airborne particles containing biological contaminants such as mold, bacteria, and viruses. Prolonged exposure to these bioaerosols can result in respiratory issues, allergies, and asthma. Bioaerosols originate from two main sources: natural sources like soil, water, plants, and animals, and anthropogenic sources stemming from human activities like cleaning and cooking. Effective control measures, including proper ventilation and hygiene practices, are essential for managing the health risks associated with anthropogenic bioaerosols in educational settings [7].

a) Measurement

Bioaerosol levels are typically assessed using a specialized tool known as an aerosol sampler or bioaerosol sampler, designed to collect and gauge airborne particles possibly containing microorganisms or biological materials. The measurement units for bioaerosols can vary based on the specific parameter under examination [7]. Common units include Colony-forming units (CFU), Particles per cubic meter (p/m³), and Spore count(spores/m³).

b) Parameters

Environmental parameters affect the distribution of bioaerosols, with parameters such as humidity, temperature, wind characteristics, sunlight presence, seasonal changes, and air pollutants impacting their concentration, composition, and types. Seasonally, bioaerosol levels tend to be higher during fall, early winter, and spring, and there's a positive relationship with PM concentrations ($r = 0.75$, $p < 0.001$) [8].

c) Guidelines for Post-Pandemic

Following a pandemic, the WHO guidelines provide recommendations for the control of indoor bioaerosols, encompassing bacteria, fungal spores, and viruses, to ensure occupants' safety and well-being. These guidelines include:

- Total Bacterial Count: the WHO advises maintaining acceptable indoor levels, typically below a specified range like 500-1000 CFU/m³.
- Fungal Spores: Concentrations of fungal spores may vary by space and location, but common guidelines often target levels below 500-1000 spores/m³.

The WHO recommends that the total bioaerosol concentration indoors should not exceed 1000 CFU/m³ to reduce health risks [6] [9].

5) Radon

Radon is a naturally occurring radioactive gas that can accumulate in buildings, particularly in basements and ground floors. Long-term exposure to high radon levels can cause lung cancer. Radon is an odorless, colorless, and tasteless radioactive gas that occurs naturally due to uranium decay in soil, rocks, and building materials. When present in indoor environments such as homes, offices, and schools, radon levels can reach epidemiologically significant levels that surpass outdoor concentrations.

a) Measurement

Various methods and devices are available for detecting and measuring radon, including both passive and continuous detectors. Passive detectors are commonly used because of their affordability, simplicity, lightweight nature, and lack of power requirements, reducing the risk of clogging or power loss. Radon concentrations are typically expressed in Picocuries per liter (pCi/L) and Becquerels per cubic meter (Bq/m³) [10].

b) Parameters

The becquerel (Bq) is employed for measuring the radioactive substance's activity, representing one radioactive decay per second. In indoor environments, the degree of radioactive equilibrium between radon gas and its short-lived airborne progeny relies on several factors, such as aerosol concentration, size distribution, space's surface-to-volume ratio, and air exchange rate. Equilibrium is often quantified using the equilibrium factor (F factor), with an F factor of 1 indicating complete equilibrium. Various international studies have reported F factors in buildings ranging from 0.2 to 0.8, while a global typical F factor of 0.4 for indoor air has been adopted by UNSCEAR and ICRP. In outdoor air, F factors are generally slightly higher, ranging from 0.6 to 0.8 [6].

c) Guidelines for Post-Pandemic

The WHO has established a reference level for Radon concentration in indoor air, which is 100 Bq/m³. This means that Radon levels should be kept below 100 Bq/m³ to ensure good indoor air quality and reduce health risks associated with Radon exposure [10] [6].

6) Outdoor Air Pollution

Outdoor air pollution, such as traffic emissions or industrial pollution, can infiltrate buildings and contribute to poor IAQ. Filtration and ventilation systems play a crucial role in mitigating the impact of outdoor pollution on IAQ.

Vital to the well-being, Nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), and Ozone (O_3) are crucial air pollutants that are associated with respiratory distress-like syndrome and require extensive investigation, NO_2 and O_3 indoor concentrations have a strong and positive correlation with outdoor pollutants. Additionally, the indoor environmental parameters' performance is influenced by the climate, with O_3 concentrations being significantly higher in the cold season, and Carbon monoxide (CO) and NO_2 concentrations being relatively higher in the warm season, apart from occupancy and educational building locations [2].

a) Measurement

The measure units of outdoor air pollution (NO_2, SO_2, and O_3) are typically expressed in micrograms per cubic meter ($\mu g/m^3$) or parts per billion (ppb).

b) Parameters

There exists a connection between specific air pollutants like NO_2, SO_2, $PM_{2.5}$, PM_{10}, and O_3 and the incidence and severity of COVID-19 infections. Research indicates that regions with elevated levels of these pollutants are linked to increased COVID-19 cases and more severe symptoms. Among the air pollutant parameters, NO_2, O_3, PM10, and $PM_{2.5}$ are associated with the total count of COVID-19 cases, while meteorological factors such as Relative Humidity (RH), Wind Speed (WS), and Solar Radiation (SR) display significant correlations with the outcome variable. In contrast, WS and SR demonstrate negative correlations with COVID-19 cases. Hence, statistical analysis underscores the notable impact of outdoor air pollution levels and meteorological conditions on COVID-19 infections [11].

c) Guidelines for Post-Pandemic

- O_3 concentrations of 100 $\mu g/m^3$ 8-hour mean.
- NO_2 concentrations of 10 $\mu g/m^3$ annual average and 25 μg/m3 24-hour mean [12].
- SO_2 concentrations of 40 $\mu g/m^3$ 24-hour mean.
- CO concentrations of 7 $\mu g/m^3$ 24-hour mean [12].

7) Indoor Air Exchange

Proper indoor air exchange (ventilation) is crucial for maintaining good IAQ. It helps remove indoor pollutants, control moisture, and bring fresh outdoor air into space. It refers to the rate at which the air inside a building is replaced with outdoor air. It is a quantitative measure of how frequently the entire volume of indoor air is replaced with fresh air from the outside.

a) Measurement

Ventilation effectiveness can be assessed by measuring the indoor air exchange rate, typically expressed in air changes per hour (ACH), which represents the number of times the entire volume of indoor air is replaced in one hour. Another unit that can be used is liters per second (l/s), which represents the volume flow rate of outdoor air entering the space per second [3, 13]. Cubic meters per hour (m^3/h) is another unit commonly used to measure indoor air exchange rates. It represents the volume of air exchanged per hour [4].

b) Parameters

Various ventilation methods encompass natural ventilation, mechanical ventilation, stack ventilation, and mixed-mode ventilation. Natural ventilation employs natural forces like wind and temperature disparities to usher fresh outdoor air into a building and expel stagnant indoor air, relying on passive airflow through openings like windows and vents. This approach enhances indoor air quality by diluting pollutants, lowering humidity, and establishing a connection with the outdoors, all while consuming less energy than mechanical systems [3]. Furthermore, it removes heat, provides fresh air, diminishes humidity, and disperses particles, contributing to superior indoor air quality. Additionally, natural ventilation can cool buildings overnight, bolstering daytime energy storage, and its effectiveness hinges on factors like building design, weather, and occupant habits (as shown in Fig. 4).

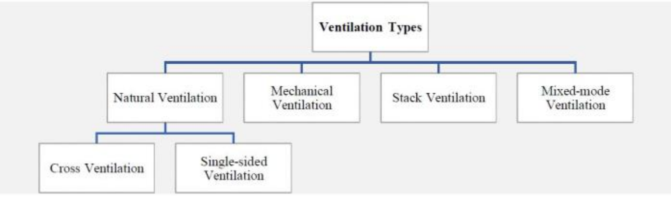

Fig. 4. Indoor air exchange (ventilation) types

c) Guidelines for Post-Pandemic

The national ventilation code of Egypt specifies ventilation rates ranging from a minimum of 3.3 l/s to a maximum of 7 l/s, with recommended air change rates of 4-6 times per hour [6].

B. Thermal Comfort

In accordance with ASHRAE/ANSI Standard 55-2010, thermal comfort perception is defined as "the mental state reflecting contentment with the thermal setting, assessed through subjective judgment." Since thermal comfort perception is subjective and varies among people, a specific temperature range cannot be universally defined. One approach to assess indoor thermal satisfaction is by conducting a comprehensive survey within a building, gauging user contentment with the thermal conditions. Typically, if 80% of occupants express satisfaction, the indoor thermal conditions are deemed favorable.

As depicted in Fig. 5, thermal comfort factors are categorized into two groups: those associated with human factors and those linked to the environment.

1) Air Temperature

Air temperature (AT) refers to the measurement of the temperature of the surrounding air within an indoor or outdoor environment. It is a crucial factor in determining thermal comfort because it directly affects the heat exchange between the human body and the surrounding environment.

a) Measurement

Temperature for assessing thermal comfort is typically measured using a thermometer, placed at different heights and locations throughout space to obtain a representative average temperature. The unit of measurement is degrees Celsius (°C) or degrees Fahrenheit (°F).

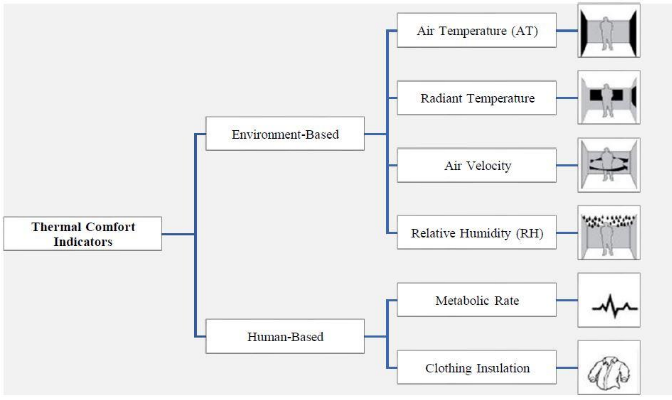

Fig. 5. Thermal comfort factors

b) Parameters

Individuals' thermal perception varies due to physiological, psychological, and contextual factors. These parameters include body composition, metabolic rate, adaptation, and perceived control, while the influence of age and gender is unclear. In educational buildings, it is difficult to select an optimal thermal comfort value for all occupants due to the variability in reported thermal comfort [14].

c) Guidelines for Post-Pandemic

- Maintaining suitable indoor temperatures is crucial during a pandemic, with the WHO recommending temperatures not drop below 18°C to prevent health issues from cold conditions. The upper temperature limit for pandemic risk remains undefined, but research shows that COVID-19's half-life is about 3 hours at temperatures of 21°C to 23°C, emphasizing the role of temperature control in infection prevention [14].

- SHASE recommends maintaining temperatures between 17°C to 28°C at a ventilation rate of 30 m^3/h per person for a comfortable and safe indoor environment during pandemics. ASHRAE's Standard 55 provides specific guidelines, defining "comfortable" temperature ranges as 22.78°C to 26.11°C in summer and 20°C to 23.61°C in winter, ensuring indoor comfort and safety throughout different seasons [15].

2) Radiant Temperature

Radiant temperature is the temperature of surfaces emitting thermal radiation and affects how people feel heat gain or loss. In contrast, Mean Radiant Temperature (MRT) considers all surfaces in a person's view, including walls, ceilings, and objects, influencing comfort by affecting radiant heat exchange. Unlike air temperature, MRT is a comprehensive measure impacting thermal comfort [16].

a) Measurement

To measure the radiant temperature of surfaces within a space, infrared thermometers or radiometers can be utilized.

b) Parameters

The parameters affecting MRT include Surface temperature, Surface emissivity, Surface area, Distance from surfaces, Solar radiation, Obstructions, Occupant location and posture [17].

c) Guidelines for Post-Pandemic

The MRT should fall within the range of 65 ° to 80 °F (18 ° to 27 °C), taking into consideration the clothing worn by individuals and the activities they engage in. During the winter season, proper insulation of walls, roofs, and floors, along with the use of window treatments such as double glazing, blinds, and drapes, in compliance with recommended design practices, should ensure that indoor surface temperatures do not deviate more than 5 °F (2.8 °C) below the indoor air temperature.

3) Air Velocity

Air velocity is a measure of how fast air moves across a person, which can affect their thermal comfort. If the air is cooler than the surrounding environment, it may help cool the person. However, still, or stagnant air in artificially heated indoor spaces can cause people to feel uncomfortable. Conversely, moving air in warm or humid conditions can reduce heat loss through convection [16].

a) Measurement

Anemometers or nanometers can be used to measure air velocity within space. It is typically measured in meters per second (m/s) or feet per minute (fpm).

b) Parameters

Increasing air velocity reduces indoor air pollutants like formaldehyde, TVOC, and CO_2. This change mainly affects how heat is transferred between the body and the environment, improving thermal comfort, and reducing air conditioning energy use in hot conditions. Studies show that when the temperature exceeds 28°C [18], higher air velocity can maintain comfort. For every 0.1 m/s increase in air velocity below 0.6 m/s, the comfortable ambient temperature for the body increases by 0.3°C. ASHRAE Standard 55-2017 suggests compensating for high temperatures by increasing air velocity, particularly in naturally conditioned spaces where occupants have control [19].

c) Guidelines for Post-Pandemic

- RITE establishes a recommended air velocity not exceeding 0.2 m/s [20].

- The air velocity of the airflow should fall within the range of 0.25 to 0.5 m/s, ensuring a pleasant perception [19].

4) Relative Humidity

Humidity affects thermal comfort by influencing the rate of evaporative cooling (i.e., perspiration) from the body. Relative humidity (RH) is the proportion of water vapor in the air to the total amount of water vapor it could hold at the current temperature. RH varies depending on temperature, weather, and location and can create an environment for common allergy or asthma triggers when too high or low [5].

a) Measurement

Hygrometers or psychrometers can be used to measure the RH within the space.

b) Parameters

Relative humidity (RH) parameters include air moisture content, indoor humidity, and moisture-holding capacity, affecting occupants' comfort. Maintaining optimal RH levels is vital for comfort and health. Low RH causes dryness, high RH promotes mold and bacteria [21], impacting both comfort and IAQ. Surprisingly, outdoor humidity has a stronger correlation with indoor RH in naturally ventilated buildings (0.52) than in air-conditioned ones (0.33) [22].

c) *Guidelines for Post-Pandemic*

- The WHO notes that low RH can cause speed spread of COVID-19 [14].
- The ASHRAE recommends that RH remain between 35%-55% to meet HVAC system and equipment design guidelines and that RH should be below 65% for health reasons to reduce microbial growth. The Mayo Clinic recommends RH levels between 30% and 50%, and the EPA suggests RH below 60% and preferably between 30% and 50%. In conclusion, indoor RH should be maintained between 30% and 60%.

5) *Metabolic rate*

Determining occupants' physical activity levels, which affect thermal comfort, can be difficult to assess individually. Yet, estimating average metabolic rates for different activities through standardized MET values is valuable, as physical exertion generates heat that needs to be dissipated to prevent overheating. Additionally, individual factors like weight, age, fitness, and gender should be factored into thermal comfort assessments, even when environmental conditions remain constant [16].

6) *Clothing insulation*

Clothing plays a significant role in thermal comfort, affecting both heat stress and cold injuries. Understanding its impact is crucial, and standardized insulation values (clo units) are used to estimate clothing insulation. Metrics like PMV and PPD, based on Fanger's model, help assess thermal comfort by considering various factors, simplifying the process despite challenges in direct measurement [16].

C. *Visual Comfort*

Natural light is the most eye-friendly illumination, promoting health, productivity, and energy efficiency. Tomás Franco highlights the importance of site orientation for maximizing natural light through well-designed openings. Incorporating daylighting reduces reliance on artificial lighting, offering superior illumination quality and energy savings. Design elements like facade shape, window size, and location play a role in optimizing daylight performance, aligning with strategies for passive heating and cooling [23].

1) *Visual Comfort Indicators*

Key aspects of lighting comfort, as shown in Fig. 6, include light level, contrast, and glare, with specific intensity requirements. "Contrast" relates to legibility, with higher contrast. José Tomás Franco emphasizes balancing natural and artificial lighting while considering factors like flickering, glare, and uniform light distribution for assessing environmental quality. Studies show daylighting's positive impact on well-being, satisfaction, performance, and productivity, but daylight levels must be managed for visual comfort. Consider these lighting characteristics affecting indoor comfort and well-being: light quantity, quality, distribution, and control) [24].

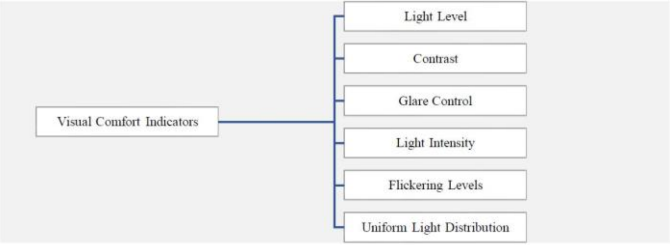

Fig. 6. Visual comfort indicators

2) *Visual Comfort Metrics*

Daylighting metrics are numerical values or measures used to quantify specific aspects of the daylighting environment [25]. Various metrics were defined by researchers to evaluate the quantity of natural light on task surfaces in the interior space. The most used metrics are discussed as shown in Fig. 7.

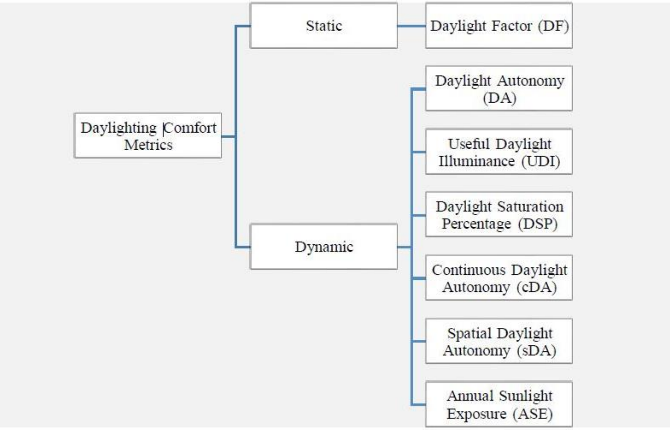

Fig. 7. Common daylight metrics

a) *Daylight Factor*

Daylight factor (DF) measures the ratio of the indoor illuminance to the outdoor illuminance under overcast sky conditions. DF is easy to measure and calculate, and its concept is intuitive. Thus, it is the most frequently used metric to evaluate the daylight condition of a building. However, DF is a static daylight metric, which means it does not change with the building location or orientation, and many daylighting design problems cannot be detected by DF [25].

b) *Daylight autonomy*

Daylight autonomy (DA) is the ratio of the number of hours in the year when the illuminance provided by daylighting is above the minimum illuminance requirement, to the total number of hours occupied in a year. DA is a dynamic daylighting metric. Dynamic daylight metrics are based on time series of illuminances, which are based on annual solar radiation data for the building site. The primary advantage of dynamic daylight performance metrics over static metrics is that they consider the quantity and features of daily variations of daylight together with irregular meteorological events.

c) *Useful Daylight Illuminance*

Useful daylight illuminance (UDI) is the ratio of the number of hours in the year when illuminance provided by daylighting is within a useful range, to the total number of occupied hours in a year (Nabil & Mardaljevic, 2005). UDI aims to determine the daylighting level that is neither too dark nor too bright (Reinhart, Mardaljevic, & Rogers, 2006). UDI is usually presented by three metrics: UDI <100 lux, UDI 100-200 lux, and UDI >2000 lux. The illuminance range that considered useful is between 100 lux to 2000 lux. Illuminance below 100 lux is considered as too dark, and illuminance above 2000 lux is considered too bright.

d) Continuous Daylight Autonomy

Continuous Daylight Autonomy (cDA) is similar as DA, but it provides partial credit to the times when the illuminance is below minimum requirement. For example, the minimum illuminance requirement of a space is 300 lux, and at a certain time step the illuminance is 150 lux. DA would give it 0 credit, while cDA would give it 0.5 credit.

e) Spatial Daylight Autonomy

Spatial Daylight Autonomy (sDA) is the percentage of area that meets the minimum daylight illuminance for a specified percentage of hours in a year. It considers both the spatial and temporal characteristics of daylighting performance.

f) Annual Sunlight Exposure

Annual Sunlight Exposure (ASE) is the percentage of area that exceeds specified illuminance for more than a specified percentage of hours in a year. sDA and ASE are usually used together to evaluate the daylighting condition of the space.

D. Acoustic Comfort

Acoustic comfort depends on noise levels, sound insulation, and reverberation time. Noise can be measured in decibels (dB), and reverberation time assessed with impulse response systems [5]. Sound insulation is evaluated using sound transmission class (STC) ratings or field measurements. Acoustic comfort ensures a noise-free indoor environment, with noise sources from both inside and outside the building. Ideal noise levels vary by room purpose, and personal preferences may differ. Wong et al. (2007) gathered noise data in various office settings [26].

E. Ergonomics and Spatial Layout

Ergonomics and spatial layout affect occupants' physical comfort and ability to move freely within space. Measurements are typically qualitative, based on occupants' feedback and observations of space utilization. Space syntax analysis and other architectural analysis methods can help assess the effectiveness of spatial configurations [4].

F. Aesthetics

The visual appeal of a space and the integration of natural elements, such as plants and natural materials, can impact occupants' psychological well-being. Measuring the impact of aesthetics and biophilic design is primarily qualitative, relying on occupant surveys, interviews, or case study comparisons.

G. Hygiene

Hygiene plays a crucial role in maintaining a healthy indoor environment and ensuring the well-being of building occupants [27]. Adequate diseases are essential for minimizing the transmission of pathogens, preventing the spread of diseases, and creating a safe and clean indoor environment. The key hygiene considerations related to IEQ in buildings include cleaning and disinfection, hand hygiene, waste management, indoor air quality, and personal hygiene practices [28].

III. CONTROL STRATEGIES FOR INDOOR ENVIRONMENTAL QUALITY IN POST-PANDEMIC

Exploration of engineering controls is imperative for mitigating the transmission of infectious diseases [11]. The design of building ventilation systems is closely intertwined with the implementation of engineering control strategies aimed at reducing airborne transmission. Several studies have shown the effectiveness of engineering controls to reduce the transmission of viruses during pandemics as discussed in the following sections [29].

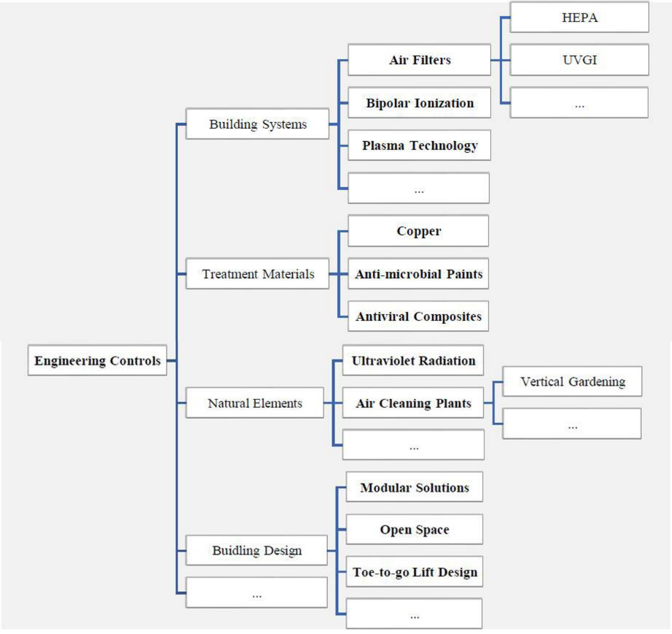

Fig. 8. Engineering controls to reduce the transmission of the COVID-19 disease

A. Building Systems

1) Air Filters

Ventilation methods encompass natural techniques like window opening and artificial means involving fans. HVAC systems are crucial in controlling disease spread, and during pandemics, they can be adapted to minimize transmission. Modifications include improving central air filters, introducing portable HEPA filters [30, 32], and extending system operation. Other adaptations involve enhancing outside air flow and fully opening dampers for 100% outdoor air circulation [29].

2) Bipolar Ionization

Needlepoint bipolar ionization (NBPI) is an air purification method that generates ions, both positive and negative, dispersing them throughout the air to eliminate pathogens like viruses, mold, and bacteria. Additionally, NBPI improves filtration efficiency by aiding particle assembly and oxidizes odorous gases, converting them into odorless compounds. Research reveals that NBPI can inactivate approximately 84.2% of viruses in 10 minutes, increasing to about 92.6% and 99.4% after 15 and 30 minutes [33]. Like UV radiation, NBPI offers odor control and reduces VOCs. By producing reactive ions and oxygen species, NBPI disrupts hydrogen bonds vital for virus mutation and growth, improving indoor air quality in various settings like hospitals, schools, hotels, and offices [34].

B. Treatment Materials

The longevity of the coronavirus on various materials was examined, including aerosols, copper, cardboard, stainless steel, and plastic. Notably, the study revealed that the SARS-CoV-2 virus was undetectable on copper surfaces after four hours, while it persisted for 3, 2, and 1 day on plastic, stainless steel, and cardboard, respectively [33].

1) Copper

Copper is recommended for post-COVID-19 buildings due to its ability to eliminate over 99.9% of germs within two hours, but it's costly to use and maintain. Plastics can be combined with metals like copper, silver, and zinc to create antimicrobial materials that prevent virus multiplication. Alternative coatings and wall treatments like silver nanocoating, gold nanocoating, and fabric coverings also have potential for antiviral applications in post-COVID-19 buildings [35].

2) Hygienic Cladding

Hygienic coatings and coverings should possess characteristics such as resistance to cold cracking, heat aging, crocking, scrub-ability, and chemicals. Hygienic cladding is an example of a cost-effective, easy-to-clean, and chemically resistant option [36].

3) Antibacterial Paints

Antibacterial paints are effective in preventing the growth of mold, fungus, and bacteria on walls and floors. Biocote is a highly efficient antimicrobial paint with over 99% resistance to microbes due to its antimicrobial technology [36].

4) Antiviral Composites

Green building materials (GBMs), including bio composites with natural ingredients, can enhance indoor air quality (IAQ) and reduce health risks.

C. Natural Elements

1) Ultraviolet Radiation

Germicidal ultraviolet (GUV) light, a form of UV radiation, effectively deactivates pathogens like bacteria and viruses by disrupting their DNA, reducing transmission risks within buildings. For air disinfection against SARS-CoV-2, UV radiation at 265 nm is highly efficient, with a reported inactivation rate constant (m^2/J) of 0.08528 m^2/J. Upper-room ultraviolet germicidal irradiation (UVGI) technology is a safe method, creating an irradiation field above occupants' heads without direct exposure, making it suitable for retrofitting existing buildings with easy installation [35].

2) Air Cleaning Plants

Indoor plants contribute significantly to creating a healthy and comfortable indoor environment by efficiently absorbing pollutants and aiding in temperature and humidity regulation. They also reduce VOC levels, enhance mental health and mitigate sick building syndrome, while their phytoremediation process purifies indoor air by breaking down toxic substances. Vertical gardening, or living walls, is an emerging green building strategy with environmental and social benefits that can be integrated into both traditional and zero-emission buildings for air purification and biofiltration, making it a subject of interest for designers and architects [37].

IV. EMBRACING DESIGN TECHNOLOGY TO ENHANCE INDOOR ENVIRONMENTAL QUALITY

Technological advancements have simplified the monitoring and enhancement of IEQ. Real-time IEQ monitoring systems can track variables like temperature, humidity, CO_2, and VOCs, pinpointing areas needing improvement. Kinetic building technologies can further optimize IEQ by adjusting ventilation and lighting based on occupancy and activity. Amid the pandemic, buildings must incorporate innovative technologies for improved ventilation. Strategies like ergonomic furnishings, daylighting, operable shading, green landscaping, and IAQ enhancement are now widely embraced in various building types to facilitate increased fresh air intake and natural ventilation. In addressing pathogen risks, assessing potential pathogen-hosting areas is crucial. While new tech reduces transmission, regular surface cleaning remains essential. Automation, touchless tech, and AI-based systems can minimize contact transmission. It's noteworthy that over 80% of infectious diseases stem from contact with contaminated surfaces [38].

To create a touch-free environment, it's advisable to prioritize touchless methods like smartphone-controlled elevators, removing the need for handles and keys, and utilizing automatic opening doors [15]. These contactless systems can also extend to applications such as remote temperature control and automated pathogen cleaning. An example of these technologies in action is the Chicago Office Tower, Fulton East, which proudly boasts the title of the "*First Post-Covid Building*", shown in fig. 9, this 12-story complex, innovative features include touchless elevators with foot-activated call buttons, featuring MAD Elevator Inc.'s Toe-To-Go (T2G) hands-free lift system, marking a global first [35].

Fig. 9. Real photos of the Fulton East building

The Fulton East building employs non-thermal plasma technology (airPHX) to enhance air quality and reduce contamination risks, resulting in a significant reduction (90-99%) in viruses, bacteria, and mold in both air and on surfaces. With its 985 m^2 (10,605 ft^2) floor plan, Fulton East prioritizes physical distancing and personalized space planning to create a safer environment, following a comprehensive post-pandemic design strategy [35].

V. CONCLUSION

In conclusion, the significance of enhancing indoor environmental quality (IEQ) in the post-pandemic era cannot be overstated. This paper has addressed critical aspects of IEQ, including indoor air quality, lighting, thermal comfort, and temperature control, offering a comprehensive understanding of their measurement parameters, assessment tools, and recommended post-pandemic levels. The control strategies discussed herein, ranging from advanced ventilation and air purification systems to adaptive lighting technologies, present practical avenues for improving IEQ and safeguarding occupant health. Furthermore, the integration of design technology and innovative architectural solutions holds promise in reshaping-built environments to prioritize IEQ as a fundamental aspect of sustainable building design. As we navigate the challenges posed by the pandemic, embracing the recommendations and strategies outlined in this paper will pave the way for healthier, more resilient indoor spaces that promote the well-being and productivity of their occupants.

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