Chapter

Introductory Chapter: Indoor Environmental Quality

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1. Overview

The term "indoor environmental quality" (IEQ) represents a domain that encompasses diverse sub-domains that affect the human life inside a building. These include indoor air quality (IAQ), lighting, thermal comfort, acoustics, drinking water, ergonomics, electromagnetic radiation, and many related factors [1], as depicted in **Figure 1**. Enhanced environmental quality can improve the quality of life of the occupants, increase the resale value of the building, and minimize the penalties on building owners.

IEQ in offices and other workplaces has a crucial role on the return on investment of businesses. A workplace with high IEQ obviously improves the workers' health and mood, thereby increasing their productivity. Therefore, the additional cost of maintaining high IEQ levels in workplaces will be paid back in a reasonable period and generates additional monetary returns thereafter. It should be noted that buildings being rated as "sustainable and green" do not truly guaranty their compliance with the desired IEQ level [2–5]. Therefore, IEQ should be given specific focus while designing new buildings as well as in building retrofit plans.

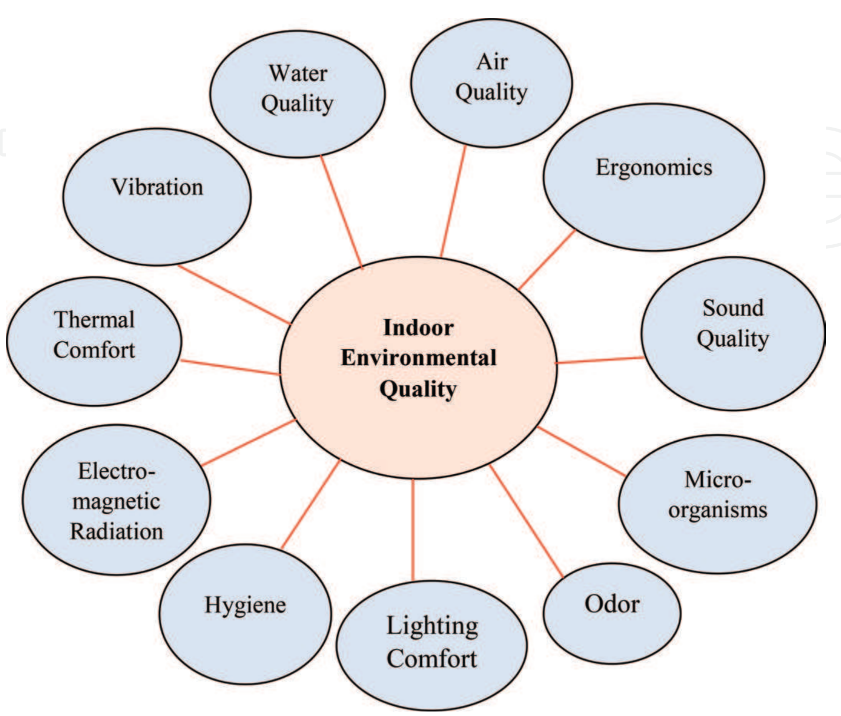

Figure 1.
IEQ components.

2. Indoor air quality

Indoor air quality (IAQ), which depends on airborne contaminants inside a building (or in a broader sense, any other enclosure such as a vehicle or an animal house), is one of the crucial factors that determine the quality of the indoor environment. Providing adequate air quality for the occupants is one of the most important functionalities of a building. Lung cancer (due to radon), Legionnaires' disease, carbon monoxide poisoning, allergy, and asthma are among the serious health implications of poor IAQ [6]. The "sick building syndrome" resulting from inadequate levels of IAQ significantly affects the health and productivity of office employees [7]. Though tremendous efforts are in progress to realize energy-efficient, green, and sustainable buildings, maintaining a safe level of IAQ in these buildings is an ongoing challenge. This is due to the fact that many energy-efficient measures in a building (such as reduced outdoor air ventilation rate, increased thermal insulation, and efficient cooling equipment) can have a detrimental impact on IAQ. Thus, alongside energy efficiency and sustainability, there has been a growing concern over air pollution inside buildings. Therefore, attempts to ensure energy efficiency and sustainability in buildings should simultaneously ensure enhanced health, comfort, and productivity of the occupants [6].

There are two major approaches to tackle IAQ issues in buildings: one is to increase the ventilation rate of outdoor air into the building, and the other is to minimize or control the sources of air pollution within and outside the building. Having said that, the first strategy would work only when the outdoor air is clean enough to improve IAQ [7]. The various sources that affect IAQ are, but not limited to, volatile organic compounds, biological pollutants, oxides of carbon and nitrogen, particulate matter, tobacco smoke, radon, mold, formaldehyde, pesticides, and combustion products. Heseltine and Rosen [8] outlined health issues associated with building moisture and biological agents, and the most important health problems identified are respiratory symptoms, allergies, asthma, and perturbation of the immunological system. A recent review [9] has revealed that carpets play a crucial role in IAQ, as they act as a sink for indoor air pollutants such as particles, allergens, and other biological pollutants.

3. Thermal comfort

The term "thermal comfort" refers to a condition that is governed by many environmental and human factors; in other words, physiological, physical, and sociopsychological factors. The environmental factors include air temperature, air velocity, humidity, radiant temperature, and relative humidity, while the major human factors are clothing and metabolic heat. The various other factors include physical health, mental condition, availability of food and drink, and acclimatization. This condition is mostly subjective, which cannot be directly quantified. It has been established that the thermal comfort level is acceptable if at least 80% of the occupants feel comfortable with it. Djongyang et al. [10] and Taleghani et al. [11] provided detailed insights into the thermal comfort in buildings.

4. Lighting comfort

Visible light falls in a narrow range in the electromagnetic spectrum, between ultraviolet and infrared wavelength ranges. Light has both particle and wave properties; when treated as a wave, light has a frequency that depends on the color of the struck surface. For instance, white surface reflects back most of the incident light, while a black surface absorbs most of it. The main aspects of lighting comfort are light level (intensity or brightness), contrast, and glare. The light intensity requirement depends on the type of activity in the building; for instance, operating rooms need a brighter level than living rooms. The term "contrast" refers to the ease of understanding or legibility; higher contrast gives higher clarity (e.g., black text on white paper provides the highest contrast). Glare is always undesirable as it causes a high level of discomfort in viewing the objects and affects the retina.

The visual comfort level is evaluated by means of some established glare metrics or indices; for example, glare probability (DGP) and daylight glare index (DGI) are used for assessing discomfort due to daylighting, while unified glare index (UGI), visual comfort probability (VCP), and CIE glare index (CGI) are employed for measuring the discomfort level of artificial lighting [12–15]. Several other indices are also available, as summarized by Carlucci et al. [12]. Galatioto and Beccali [16] reviewed the various aspects and concerns associated with the assessment of indoor daylighting.

5. Acoustic comfort

Building acoustics deals with controlling the quality of sound inside a building. It has two parts, namely, room acoustics and building acoustics, which deal with the sound propagation within a room and between rooms (through walls, doors, and floors), respectively. While the room acoustics focuses mainly on the sound quality (e.g., easy communication and high level of intelligibility in office spaces), the building acoustics is concerned with the "unsolicited" sound (e.g., the noise in a room should not be a nuisance to other rooms). The acoustic comfort in a building has a crucial impact on the health, well-being, communication, and productivity of the occupants. The acoustic comfort can be affected by factors such as the geometry and volume of a space, generation of sound within or outside the space, airborne noise transmission, impact noise, and the acoustic characteristics (absorption, transmission, and reflection of sound) of the interior surfaces. The measuring unit of sound intensity is decibels (dB), and of sound pitch is hertz (Hz). The comfortable range of sound for humans is typically 20–20,000 Hz.

The common parameters used for evaluating the acoustic performance of a building are reverberation time (RT), sound pressure level (SPL), early decay time (EDT), clarity (C_{50} for speech and C_{80} for music), sound definition or speech intelligibility (D or D50), and speech transmission index (STI). RT is defined as the time for the sound level to decay by 60 dB after a sound source has been switched off. EDT is similar to RT, but it is the initial rate of sound decay in a room, measured as the slope of a line 0–10 dB decay below the maximum sound level. D50 is defined as the ratio of the early received sound energy (0–50 ms after direct sound arrival) to the total received energy. Clarity is defined as the ratio of the energy in the early sound (received in the first 80 ms) to that in the reverberant sound. STI is a measure of speech transmission quality, which indicates the degree to which a transmission channel degrades speech intelligibility. STI ranges from 0 to 1; a speech transferred through a channel with STI of 1 is perfectly intelligible, but the intelligibility reduces as the STI approaches zero. International standards and guidelines (e.g., ISO 18233) are available for the measurement of these characteristics.

Extensive researches are in progress, on the acoustic comfort in buildings. In recent works, Tong et al. [17] studied the acoustical performance of classrooms and laboratories in a public school exposed to traffic environment, while Jeong et al. [18] focused on the acoustic design and evaluation of a concert hall. Tan et al. [19] introduced application of building information modeling to improve indoor acoustic performance. Few other studies include those reported by Lam et al. [20], Imran et al. [21], and Renterghem [22].

6. Ergonomics

Ergonomics deals with the design of objects, systems, and environment, in a manner that ensures human comfort. In fact, ergonomics encompasses all components of IEQ, simply because the prime objective of IEQ is human health and comfort. It covers diverse disciplines such as anatomy, physiology, psychology, and design. An indoor ergonomist should be specialized in the interrelationship between the human mind and body and the various aspects of a building such as architecture, interior design, building services, structure, materials, and microclimate. In general, environmental ergonomics deals with the interaction between people and their physical environment with particular importance on thermal comfort, lighting, noise, and vibration. Similar to ergonomics in a residential environment, ergonomics in offices and workplace is also a scientific discipline and a topic of research. Edmonds [23] defines the following factors that affect the workplace ergonomics: tasks, tools, equipment, area and space, environment, and organizational pattern. The Southeast Asian Network of Ergonomics Societies (SEANES) has introduced ergonomic checkpoints for indoor and outdoor workplaces for the purpose of motivating workers to recognize hazards in the work environment and adopt precautionary measures accordingly [24]. Similarly, Ushada et al. [25] developed environmental ergonomic control system for small and medium sized, by using worker workload and workstation temperature difference.

7. Electromagnetic field and radiation

Electromagnetic field is created by moving electric charges, microwaves, radio waves, electrical currents, and transformers. The low-frequency electromagnetic radiation prevailing mostly in indoors (due to electrical appliances, computers, wireless devices, etc.) can have detrimental effect on human health, and there are international regulations to deal with this problem (e.g., International Radiation Protection Association (IRPA)) [26]. Most of the regulations agree that exposure to electromagnetic field beyond the safe range of 0–300 Hz is harmful for the human body [27]. The possibility of health hazards such as acute lymphoblastic leukemia in children due to electromagnetic field exposure was well established decades ago [28] and continues to be a significant topic of research [26, 29–31].

8. Water quality

Adequate, safe, and accessible supply of drinking water is vital for the sustenance of human life especially in indoor environments where access to natural sources of water such as wells, ponds, rivers, and lakes is limited. Drinking water quality has a direct impact on human health. Infants, young children, weak and elderly people, and those who live in unhygienic environment are largely prone to waterborne deceases [32]. There is no universally applicable legislative framework for the implementation of standards to maintain drinking water quality. An approach that works in one country or region may not be suitable for other countries. Therefore, each country should develop its own legislation according to its requirements and capacity for implementation. However, while developing standards, the most common aspects that need to be taken into account are microbial safety, chemical safety, radiological safety, disinfection, and acceptability [32].

9. IEQ research trends

A huge number of literatures are available on the research on various aspects of IEQ, and a comprehensive review of these literatures is beyond the scope of this chapter. Many researchers have compiled them in their review articles [7, 33–42]. However, a brief overview of the exemplary researches is presented here. Most of the researches were on post-occupancy evaluation (POE) on IEQ of different types of common buildings (e.g., healthcare, office, educational, residential, etc.), through field measurements and user satisfaction surveys, while many other researchers were interested on POE of sustainable and green buildings. In these researches, the findings are usually compared with the prevailing local or global (as applicable) standards, and recommendations are made to address the issues identified.

9.1 IEQ of common buildings

Reynolds et al. [43] measured the physical, mechanical, and environmental factors affecting IEQ of office buildings in the United States (US). The measurements included endotoxin, total bioaerosols, and psychosocial parameters. Addressing the impact of IEQ on the occupant's productivity in offices, Kang et al. [44] investigated open-plan research offices in 19 Chinese universities by conducting survey on 231 subjects. The study identified five factors that significantly affected the office productivity, which are layout, air quality, thermal comfort, lighting, and acoustic comfort, where the acoustic comfort had the maximum impact. In a similar study [45], experiments were performed on the effect of indoor temperature on the IEQ user perception and productivity in office buildings, by choosing 9 females and 12 males. The parameters measured were air temperature, globe temperature, relative humidity, carbon dioxide (CO_2) concentration, and lighting and noise comforts. The indoor air temperature was varied by keeping the other IEQ parameters fixed. It was shown that the thermal environment had a significant impact on the thermal comfort and other IEQ factors. Kim et al. [46] focused on the impact of IEQ and work stress on the physiological responses of office workers and concluded that the most noticeable result of the experiment in this study is that a high CO_2 concentration and work stress could detrimentally influence the physiological and physiological responses, leading to abnormal variations in blood pressure. Similar studies on the effect of IEQ on office workers' performance are those reported by Haapakangas et al. [47], Suk [14], Zuo and Malone Beach [48], Ali et al. [49], Huang et al. [50], Frontczak et al. [51], Wong et al. [52], and Kosonen and Tan [53, 54].

Almeida and De Freitas [55] performed onsite measurements of temperature, relative humidity, CO_2 concentration, and ventilation rates in the classrooms of nine retrofitted and non-retrofitted school buildings in Portugal. The measurements were done during winter, mid-season, and summer conditions. In their observations, the non-retrofitted schools lack in the desired IEQ level, while retrofitted buildings did not have mechanical ventilation systems. Shan et al. [56] investigated the influence of indoor thermal condition and IAQ on students' health and performance through life cycle costing (LCC) approach, by considering two university classrooms. In the proposed LCC approach, metrics were defined for students' health (or well-being) and performance, which were subsequently translated into monetary values to quantify the impact of IEQ. The indicators considered for health and performance were sick leave and students' grade achievement, respectively. The findings of this study indicated the significance of incorporating students' health and performance into the design and operation of educational buildings. Few other researches focusing on educational buildings are those of Kim et al. [57], Vilčeková et al. [58], Jamaludin et al. [59], De Giuli et al. [60], and Nasir et al. [61].

Lai et al. [62] developed an IEQ assessment model for residential buildings in Hong Kong. The empirical model developed by using the data collected from 125 occupants from 32 residential buildings was useful to assess the acceptance level in terms of operative temperature, CO_2 concentration, and acoustic and lighting comforts. The study revealed that both thermal and acoustic comforts were the decisive contributors, while IAQ was the least. Huang et al. [63] studied the effect of IEQ of long-term care (LTC) facilities on the occupants' behavior, through survey. Garcia et al. [64] performed retrospective descriptive secondary analyses on the data collected (air exchange rates, temperature, and humidity) from indoor, outdoor, and personal air in residential buildings. Addressing the IEQ of healthcare buildings, Andrade et al. [65] performed user perception survey on hospital buildings in Portugal, considering physical and social aspects. De Giuli et al. [66] conducted survey and field measurements of three medical wards in a general hospital in Italy.

9.2 IEQ of sustainable and green buildings

As already mentioned, the IEQ level of sustainable and green buildings has been a concern of many researchers. Choi [67] proposed an explanatory model to understand the relationships among the occupants' perceptions on the IEQ level, overall facility, productivity, and sustainability ethic, in sustainable buildings. Hwang and Kim [68] performed post-occupancy evaluation (POE) of open offices in a Korean building that was certified as "1st Grade Building" Green. The studied parameters were indoor temperature, relative humidity, vertical temperature distribution, air velocity, predicted mean vote (PMV), radiant temperature, outdoor temperature, and humidity. Measurements were also done on the major indoor air contaminants, illuminance, and SPL. An online survey was also conducted among the occupants to know their perception on the IEQ level. The performance of this building was found to be satisfactory in terms of PMV and lighting, while it was weak for IAQ and acoustic comfort. Ravindu et al. [69] explored the IEQ level of a LEED-certified factory building in Sri Lanka, through questionnaire survey. They found that the building was performing low with regard to thermal comfort, ventilation, and ability to control indoor the environment. Altomonte et al. [3] studied the occupant satisfaction on IEQ in LEED- and BREEAM-certified office buildings and highlighted the importance of incorporating IEQ in the criteria for sustainable and green building certifications.

10. Concluding remarks

Indoor environmental quality is a very important scientific domain that deals with various aspects that govern the health, comfort, and productivity of the occupants and determine the value of a building. However, even though there is increasing awareness on the demand for sustainable, green, and high-performance buildings, ensuring the desired level of IEQ is often not given the deserving care. Consequently, most of the sustainable and green buildings lack in complying with the IEQ requirements. The building owners should rewrite their mindset to take into account the enormous potential for monetary returns and health benefits through improving the IEQ of the building. The following good practices are generally recommended to ensure a comfortable level of IEQ:

- Follow scientific practices of design, construction, renovation, operation, and maintenance, in compliance with the international standards.

- Adopt "source control" by minimizing the causes that lead to poor IEQ.

- Enhance the esthetics and indoor environment by proper integration of natural and man-made facilities.

- Minimize the dependence of artificial lighting and electrical equipment such as air conditioner, elevator, and fans, with a view to improve human health and minimize energy consumption.

- Ensure thermal comfort through proper design of the interior and microclimate.

- Facilitate proper ventilation and maintain acceptable air quality, by following standard guidelines.

- Adopt proper design and maintenance of HVAC system, and proper design and construction of the envelope, to prevent mold, fungi, airborne bacteria, and radon.

- Minimize the spread of pathogens by minimizing exposure to washrooms and by proper maintenance procedures.

- Avoid using products and materials, which contain harmful ingredients (such as formaldehyde) and produce harmful emissions.

- Ensure noise comfort and privacy, by suitably adopting the materials for walls, floors, and ceiling, and other standard means for acoustic comfort.

- Avoid unpleasant odors through selective use of products, regular and safe waste disposal, careful selection of cleaning products, isolation of contaminants, prohibition of smoking, and related measures.

- Establish a comfortable and healthy indoor lighting, through optimum integration of artificial and natural lightings, and use of energy-efficient, user-friendly, and eco-friendly artificial lighting.

- Maintain availability and accessibility of safe and clean drinking water in compliance with the water quality standards.
- Restrict and be aware of exposure to electromagnetic field and radiation, in the indoor environment.
- Ensure indoor ergonomic quality by providing ergonomic furniture and other facilities.
- Regularly conduct occupant surveys and post-occupancy evaluations.

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