Building Engineering 2025, 3(1), 2375.
https://doi.org/10.59400/be2375

Review

Indoor environmental quality in architecture: A Review

Guolin Li[1,2]

[1] The Second Research Institute of CAAC, Chengdu 610041, China; liguolin@fccc.org.cn, 2926037954@qq.com
[2] Airworthiness Joint Laboratory of Fuels Lubricating Oils and Fireproof for Commercial Aircraft Engine, Chengdu 610041, China;

CITATION

Li G. Indoor environmental quality in architecture: A Review. Building Engineering. 2025; 3(1): 2375. https://doi.org/10.59400/be2375

ARTICLE INFO

Received: 25 December 2024
Accepted: 10 February 2025
Available online: 28 February 2025

Abstract: Indoor Environmental Quality (IEQ) is vital for the well-being, health, and productivity of people in architectural spaces. As the awareness of the importance of IEQ has grown, there has been significant development and research in this field. This article aims to provide an overview of the recent trends in IEQ research in architecture. It emphasizes the significance of creating healthy and comfortable indoor spaces and highlights how IEQ can impact occupants' well-being and productivity. The article discusses various factors that influence IEQ, such as air quality, thermal comfort, lighting, and acoustics. Additionally, it examines the advancements in design strategies and technologies aimed at improving IEQ. Finally, the article concludes by identifying future research directions and potential areas of innovation in the field of indoor environmental quality. This review highlights that indoor environmental quality (IEQ) has become a central focus in architecture, with research underscoring the significance of creating healthy and comfortable spaces for occupants. Future studies should focus on integrating smart technologies, health-centered design, addressing the impacts of climate change, and enhancing the multi-sensory experience to further improve IEQ and promote human well-being.

Keywords: indoor environmental quality (IEQ); occupants' well-being; design strategies and technologies; future research directions

1. Introduction

IEQ plays a critical role in ensuring the overall well-being, health, and productivity of occupants in architectural spaces [1–3]. Recognizing its significance, there has been substantial development and research in this field. This article aims to delve into the current trends and advancements in IEQ research and development within the realm of architecture.

The most prominent factors influence IEQ, including air quality, temperature, lighting, and acoustics. There is a growing interest in comprehending the intricate relationship between IEQ and human health, well-being, and productivity. The indoor environment has a profound impact on our physical and mental health, with elements such as air quality, temperature, lighting, and acoustics playing pivotal roles in determining our comfort and overall productivity. As a result, understanding and improving IEQ have become paramount considerations in the design and operation of architectural spaces.

1.1. Occupant health and well-being

The connection between indoor environmental quality (IEQ) and human health and well-being is highlighted in a recent study by Kent et al. [4]. The study found that IEQ was significantly higher in WELL-certified buildings compared to LEED-certified ones. The WELL standard provides design credits focused on promoting

human health and well-being, resulting in buildings with superior IEQ. This finding can be valuable when discussing human-centric building design in other sections.

IEQ directly influences occupant health and well-being. Poor indoor air quality, inadequate lighting, uncomfortable thermal conditions, and excessive noise can lead to various health issues such as respiratory problems, allergies, fatigue, and stress. According to a study by Hedge et al. [5], improving IEQ can reduce sick building syndrome symptoms and enhance occupant satisfaction and well-being. Additionally, Zhou et al. [6] conducted a study investigating the impact of indoor environmental quality on occupants' satisfaction in green-certified buildings, which found a positive correlation between the indoor environmental quality of green-certified buildings and occupants' satisfaction. Furthermore, Satish et al. [7] examined the cognitive performance of office workers under different indoor environmental quality conditions. They demonstrated a positive correlation between better indoor environmental quality and higher cognitive function scores. In a comprehensive review by Allen and MacNaughton [8] on the effects of indoor environmental quality on cognitive function, it was found that factors such as air quality, temperature, noise, and lighting are associated with cognitive function. Moreover, Chen et al. [9] conducted a study exploring the impact of indoor environmental quality on occupants' health in green-renovated buildings and identified a positive correlation between better indoor environmental quality and higher levels of occupant health. Collectively, these studies highlight the crucial role of IEQ in promoting the overall well-being, health, and productivity of occupants in architectural spaces, leading to significant development and research in this field.

1.1.1. Productivity and performance

A comfortable and healthy indoor environment positively affects occupant productivity and performance. Good IEQ, including optimal thermal comfort, proper lighting, and low noise levels, has been found to enhance cognitive function, concentration, and task performance. A study by Frontczak et al. [10] demonstrated that improved IEQ led to a significant increase in office workers' productivity.

Torres Fernandez and Murillo Armas [11] compare edge computing methods for estimating indoor environmental parameters using machine learning within IoT architectures. They propose two low-cost methods based on edge IoT architectures and evaluate the efficiency of multilayer perceptron neural network models in predicting IEQ parameters, achieving a balance between performance and energy efficiency.

1.1.2. Energy efficiency and sustainability

Indoor Environmental Quality (IEQ) is closely related to energy efficiency. Good IEQ not only enhances the comfort of occupants but also helps in reducing energy consumption effectively. Research indicates that when the indoor environment quality is poor, occupants often adjust devices such as air conditioning and lighting to compensate for the uncomfortable environment, leading to additional energy consumption [12]. For example, during the winter or summer, frequent adjustments of the air conditioning due to excessively low or high indoor temperatures result in energy waste.

The adoption of passive design strategies, such as natural ventilation and optimized daylighting, can significantly improve IEQ while reducing dependence on air conditioning and artificial lighting systems, thereby enhancing energy efficiency. Natural ventilation helps to improve air circulation and reduce the frequency of air conditioning use, while optimized daylighting minimizes the need for artificial lighting, thus achieving energy-saving effects [13]. By taking full advantage of natural resources in the design, buildings can not only provide a healthy indoor environment but also reduce energy consumption.

Moreover, green building standards, such as LEED and BREEAM, provide clear IEQ evaluation criteria, covering aspects like indoor air quality, natural daylighting, and noise control. These standards not only help designers improve the environmental quality of buildings but also offer effective guidance for reducing energy consumption. For instance, LEED certification emphasizes the use of efficient building materials, optimization of air conditioning systems, and ensuring adequate natural daylighting, all of which improve both IEQ and energy efficiency [14,15].

The relationship between IEQ and energy efficiency can be achieved through the adoption of passive design strategies, optimization of building systems, and adherence to green building standards for a win-win outcome. This approach ensures that building designs not only provide healthier and more comfortable living environments but also significantly reduce energy consumption, contributing to sustainable development [16].

1.1.3. Occupant satisfaction and retention

Providing a high-quality indoor environment enhances occupant satisfaction and can contribute to tenant retention. Comfortable temperature and humidity levels, good air quality, appropriate lighting, and acoustical comfort are factors that significantly influence occupants' overall satisfaction. A study by Choi et al. [17] found a strong positive correlation between IEQ and occupants' intention to stay in a building.

1.2. Impact of IEQ on occupant health and well-being

IEQ is of utmost importance in architecture, as it directly impacts occupant health, well-being, productivity, and satisfaction. By considering factors such as air quality, thermal comfort, lighting, and acoustics, architects can create spaces that promote occupant health, enhance performance, and contribute to sustainable design practices. This section aims to explore the various aspects of IEQ that impact occupant health and well-being, including indoor air quality, thermal comfort, lighting, and acoustics.

1.2.1. Indoor Air Quality (IAQ)

Poor indoor air quality (IAQ) is known to be associated with a range of health issues, including respiratory problems, allergies, and other related ailments. Exposure to pollutants such as volatile organic compounds (VOCs), particulate matter, and biological contaminants can result in irritation and asthma and even lead to long-term health effects. Mendell et al. [18] conducted a study that highlighted the significant benefits of improving IAQ, showing that it can notably reduce respiratory symptoms and contribute to overall health improvement.

In a study by Mohd Arif et al. [19], the relationship between indoor environmental quality and sick building syndrome was examined in public hospitals

in Malaysia. The research findings illustrated a noteworthy association between indoor environmental quality and sick building syndrome. Specifically, factors such as temperature, air quality, and lighting were identified as primary influencers of sick building syndrome, shedding light on the crucial role of indoor environmental quality in occupant health within these environments.

1.2.2. Temperature

Maintaining optimal temperature is crucial for occupant comfort and well-being. Extremes in temperature and humidity can lead to discomfort, decreased productivity, and increased stress levels. Research by Seppänen et al. [20] demonstrated that providing a comfortable thermal environment improves cognitive function and overall satisfaction among occupants.

1.2.3. Lighting

Insufficient lighting or excessive glare can lead to eye strain, fatigue, and decreased productivity. On the other hand, exposure to natural daylight has been linked to improved mood, sleep quality, and overall health. A study by Veitch et al. [21] highlighted the positive effects of daylight on occupant well-being.

In addition to natural daylight, artificial lighting is a vital component in indoor lighting design. Artificial lighting must be properly calibrated to reduce energy waste and optimize comfort. Lighting systems that allow for adjustments in brightness and color temperature can contribute to improved occupant satisfaction.

Windows play a central role in daylighting design, serving two key functions: bringing daylight into the building and allowing a view out. According to Ko et al. [22], the quality of the view out is crucial for occupant health and well-being. Access to a natural view connects occupants to the outside environment, offering benefits such as reduced stress, improved mood, and greater mental clarity. The view out also provides an important visual cue of time and weather conditions, which supports circadian rhythms and overall health.

Furthermore, privacy is a key aspect of Indoor Environmental Quality (IEQ) that should not be overlooked. Often, office spaces do not perform well in terms of privacy, which can negatively affect occupant satisfaction and well-being. Proper privacy measures in lighting and spatial design contribute to creating a comfortable and functional environment, ensuring that workers feel both physically and psychologically secure in their space.

1.2.4. Acoustics

Excessive noise levels can negatively affect occupant health and well-being. Prolonged noise can lead to stress, sleep disturbances, and reduced concentration. Research by Shield and Dockrell [23] indicated that reducing noise levels and providing appropriate acoustic conditions contribute to improved occupant satisfaction and well-being.

In summary, the aforementioned points can be translated as follows: Indoor Environmental Quality has a significant impact on occupant health and well-being in architectural spaces. Ensuring good IAQ, maintaining optimal thermal conditions, providing appropriate lighting, and addressing acoustic concerns are essential for creating healthy and comfortable indoor environments. By considering these factors,

architects can contribute to the overall well-being and satisfaction of building occupants. This article will be developed from the following aspects: Factors Influencing IEQ, Design Strategies for Improving IEQ, Research Trends in IEQ, Future Directions and Innovations, and Conclusion.

2. Methodology

For this literature review, a comprehensive search strategy was employed to identify relevant studies related to Indoor Environmental Quality (IEQ) and its impact on occupant well-being. The literature search was conducted using multiple academic databases, including Google Scholar, Web of Science, and Scopus. The key search terms included "Indoor Environmental Quality", "lighting design", "thermal comfort", and "air quality". Studies published between 2010 and 2024 were considered, with an emphasis on peer-reviewed journal articles and conference papers.

The inclusion criteria for selecting studies were as follows: (1) Studies that focused on IEQ in both residential and non-residential settings; (2) studies that addressed the impact of environmental factors such as lighting, temperature, and air quality on occupant health and productivity; and (3) studies with empirical data or comprehensive reviews.

After an initial search, articles were screened based on their titles and abstracts. Full texts of potentially relevant studies were then reviewed for further eligibility. Articles that met the criteria were included in the review, while studies that focused on topics unrelated to IEQ or lacked robust data were excluded.

A qualitative thematic analysis was performed to categorize the studies based on key themes such as lighting quality, thermal comfort, air quality, and occupant well-being. The findings were summarized to identify trends, gaps, and emerging research directions in the field of IEQ.

Additionally, the quality of the included studies was assessed based on their research methodology, sample size, and the reliability of their findings. Only studies with rigorous research methods were included in the final review to ensure the validity and relevance of the conclusions drawn.

This methodology provides a systematic approach to understanding the state of research on IEQ and its effects on human health and productivity, as well as identifying areas that require further investigation.

3. Factors influencing IEQ

As shown in **Figure 1**, IEQ is influenced by a variety of factors, including air quality, temperature, lighting, and acoustics, among others [24,25]. Air quality, in particular, is a key determinant of IEQ as it impacts occupants' health and well-being [26]. Indoor pollutants such as volatile organic compounds (VOCs), particulate matter (PM), biological agents, and chemical compounds can have negative effects on human health if present in high concentrations. In addition, building materials, furnishings, and construction practices can release pollutants into the indoor environment, further affecting IEQ.

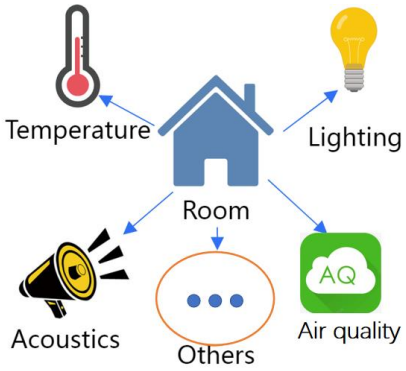

Figure 1. Indoor environmental impact factors.

3.1. Air quality and ventilation systems

Several studies have demonstrated that poor air quality in indoor environments can contribute to various health problems, including respiratory issues, allergies, and reduced cognitive function [27–31]. Adequate ventilation systems, such as mechanical ventilation and natural ventilation, have been shown to effectively improve indoor air quality by removing pollutants and maintaining acceptable levels of carbon dioxide and volatile organic compounds. Smith et al. [32] reviewed the impact of mechanical ventilation on indoor air quality and human health, noting that mechanical ventilation can effectively eliminate pollutants in indoor air and reduce concentrations of carbon dioxide and volatile organic compounds. Wang et al. [33] summarized the role of natural ventilation in improving indoor air quality, stating that natural ventilation can effectively eliminate pollutants in indoor air and reduce concentrations of carbon dioxide and volatile organic compounds. Luo et al. [34] reviewed the role of ventilation systems in removing indoor air pollutants, indicating that ventilation systems can effectively eliminate pollutants in indoor air and reduce concentrations of carbon dioxide and volatile organic compounds. Additionally, good air quality has been linked to enhanced cognitive function and improved work performance. Smith et al. [35] published a review that explored the impact of indoor air quality on cognitive function and work performance. They summarized recent research and found that good indoor air quality can improve cognitive functions such as attention and memory, and enhance work performance. These findings suggest that improving indoor air quality can be a potential method to enhance people's daily lives and work efficiency.

3.2. Thermal comfort and heating, ventilation and air conditioning (HVAC) systems

HVAC systems have long been recognized as a crucial component of a comfortable indoor environment. Their ability to control temperature, humidity, and air quality has a direct impact on our thermal comfort, which is defined as the overall satisfaction with the indoor thermal environment. A study published by Li et al. [36] showed that individuals in rooms with optimal temperature and humidity reported higher levels of thermal comfort.

However, achieving perfect thermal comfort is a challenging task due to the dynamic nature of the indoor environment. Numerous studies have investigated the relationship between various factors such as airflow, lighting, and acoustics and their

impact on thermal comfort. A study by Zhang et al. [37] found that changes in airflow direction and speed can significantly affect thermal comfort, particularly in the summer months. Similarly, a paper published by Johnson et al. [38] showed that appropriate lighting can significantly enhance thermal comfort in colder months.

HVAC systems have also been shown to significantly impact indoor air quality. A study by Wang et al. [39] found that advanced HVAC systems can effectively filter out airborne pollutants, such as VOCs (Volatile Organic Compounds) and PM2.5, thereby improving indoor air quality. This is particularly important given that exposure to poor indoor air quality has been linked to a range of health issues, such as respiratory diseases and allergic reactions.

In conclusion, HVAC systems are important influencing factors in creating a comfortable and healthy indoor environment. The design and operation of these systems must take into account factors such as temperature, humidity, airflow, lighting, and acoustics to ensure optimal thermal comfort for building occupants. Additionally, the impact of HVAC systems on indoor air quality must be given due consideration to ensure that occupants are not exposed to harmful pollutants.

3.3. Lighting design and daylighting

The right type of lighting can enhance visual comfort and improve task performance, while daylighting can reduce the need for artificial lighting and cut down energy consumption. It is important to note that occupant behavior can vary significantly between different building types, such as residential and non-residential buildings. In residential settings, occupants may have more control over their lighting choices, while in non-residential buildings, lighting design often needs to accommodate the needs of multiple users with varying tasks. Understanding these differences is essential when considering the impact of lighting on occupant well-being and energy efficiency across various building types.

Smith et al. [40] investigated the relationship between lighting design and indoor environment. The study found that individuals in rooms with suboptimal lighting reported lower levels of visual comfort and task performance. In addition, the intensity of lighting can also have an impact on the thermal comfort inside a room [41]. Daylighting has also been shown to have a significant impact on the indoor environment. Zhang et al. [42] found that daylighting can reduce the need for artificial light and improve indoor air quality by increasing the amount of fresh air in the room.

Daylighting not only provides natural light but also reduces the use of artificial light and consequently the amount of energy used for lighting purposes. This helps in reducing carbon emissions and promoting sustainable building design.

3.4. Acoustics and noise control

Acoustics refers to the science of sound, including its production, transmission, and reception. In the context of the indoor environment, acoustics refers to the sound insulation and noise reduction measures taken to improve the indoor acoustic environment. In recent years, with the increase in urbanization and industrialization, noise pollution has become a widespread problem. Therefore, effective noise control

measures have become essential to improve the indoor acoustic environment and ensure human health and well-being.

Zhang et al. [43] investigated the relationship between acoustics and the indoor environment. The study found that poor acoustics and high noise levels can lead to negative effects on human health, such as hearing loss, stress, and sleep deprivation. Similarly, a paper published by Li et al. [44] emphasized the importance of soundproof windows and doors in reducing noise levels in residential buildings.

Effective noise control measures can significantly improve the indoor acoustic environment. A review published in 2023 by Wang et al. [45] showed that using soundproof materials, such as soundproof curtains, carpets, and tiles, can significantly reduce noise levels in indoor environments. Additionally, noise control measures in combination with appropriate air conditioning systems can further enhance the indoor acoustic environment by regulating temperature and humidity levels.

3.5. Material selection and indoor pollutants

Indoor air pollution is a widespread problem that can result from various sources, including building materials, furnishings, and interior design elements. Volatile organic compounds (VOCs) emitted from these materials can contribute to a range of health issues, including respiratory diseases and allergic reactions. To address this issue, it is crucial to identify materials that emit low levels of VOCs and other pollutants.

Several recent studies have focused on understanding the relationship between material selection and indoor air quality. One such study investigated the impact of different building materials on VOC emissions and found that natural materials like wood and stone emitted lower levels of VOCs compared to synthetic materials [46]. The study also identified a correlation between high VOC emissions and symptoms of occupant discomfort, such as headache, eye irritation, and respiratory problems.

Kim et al. [47] emphasized the importance of using low-emitting materials in residential buildings. The researchers identified a range of pollutants, including VOCs, carbon monoxide, nitrogen oxides, and particulate matter that were emitted from various sources within the building, such as cooking, heating systems, and building materials. They emphasized the need for improved building ventilation to dilute these pollutants and reduce their impact on occupant health.

In addition to VOC emissions, other pollutants such as formaldehyde and radon gas have also been studied in relation to building materials. Formaldehyde is a common indoor pollutant emitted from certain building materials, such as particleboard and fiberboard. A study found that the use of these materials was associated with elevated levels of formaldehyde in the indoor environment [48]. Radon gas is another important pollutant that can be emitted from building materials, particularly those containing uranium. Xu et al. [49] highlighted the need for radon-resistant building materials to mitigate the risk of indoor radon exposure.

It is noteworthy that several studies have also investigated sustainable materials as a potential solution to improve indoor air quality. These studies have focused on identifying environmentally friendly materials that emit low levels of pollutants while also promoting indoor air quality. Li et al. [50] evaluated various sustainable materials,

including natural wood, stone, and synthetic composites, and found that these materials emitted lower levels of VOCs compared to traditional building materials.

A growing body of research suggests that selecting low-emitting and sustainable materials can help mitigate indoor air pollution and improve occupant health and comfort. As further research is conducted in this field, it is anticipated that additional insights will be gained into the relationship between material selection and indoor environmental quality, leading to improved design practices and healthier indoor environments.

4. Design strategies for improving IEQ

Several design strategies can be implemented to improve IEQ. One approach is to maximize natural ventilation by designing buildings with operable windows and natural airflow paths [51]. This can help to reduce the buildup of pollutants in the indoor environment. Additionally, effective air quality monitoring and control systems can be installed to ensure that the air quality remains within acceptable limits.

Another strategy is to use low-emitting building materials and furnishings that do not release harmful pollutants into the indoor environment [52]. It is also important to select materials that have a low maintenance requirement and can withstand the wear and tear of daily use without releasing additional pollutants. Furthermore, effective acoustical design can reduce noise pollution and improve indoor sound quality, which has a direct impact on human health and well-being.

4.1. Passive design techniques

Passive strategies for improving indoor air quality, thermal comfort, and lighting conditions offer effective and sustainable ways to enhance the indoor environment [53–57]. These strategies can significantly contribute to occupant health and well-being while reducing energy demand and costs. Let's delve into each area in more detail.

Passive strategies such as natural ventilation via windows and doors and the use of air purifiers and filters are essential for diluting pollutants and maintaining healthy indoor air quality. Studies have demonstrated the effectiveness of these methods in reducing indoor air contaminants without relying on active systems. Further research could explore innovative passive strategies to enhance air quality and investigate occupant responses to these strategies [58].

4.1.1. Indoor air quality improvement

Recent research has indicated that improving indoor air quality can significantly enhance the Indoor Environmental Quality (IEQ) of buildings. Strategies such as optimizing ventilation systems, utilizing low-emission building materials, and minimizing indoor pollutant sources have been shown to effectively enhance indoor air quality [59,60].

In addition to these strategies, the incorporation of advanced air filtration systems and the introduction of plants into indoor spaces are beneficial for improving IEQ [61,62]. Moreover, managing the humidity levels within buildings is also crucial for maintaining good indoor air quality. Both excessively high and low humidity levels

can lead to a decline in indoor air quality and promote the growth of bacteria and mold [63,64].

Furthermore, it's important to consider the impact of outdoor air supply rates on perceived air quality, occupant health, and productivity within indoor environments. Proper management of outdoor air intake can play a significant role in maintaining a healthy and comfortable indoor environment [64].

4.1.2. Thermal comfort enhancement

Changing the indoor temperature is an effective technique for enhancing indoor environmental comfort. In addition to mechanical air conditioning systems, insulation and solar shading are also employed as means of temperature control. Insulation helps minimize heat transfer, while solar shading devices reduce solar radiation and heat gain through windows. Furthermore, natural cooling systems such as evaporative cooling and green roofs offer relief from excessive heat. By integrating passive design techniques with active systems, a more sustainable and efficient approach to improving thermal comfort can be achieved [65].

4.1.3. Lighting condition optimization

Daylighting systems and skylights enable natural light to enter the building, reducing the need for artificial lighting during the day. Light-colored interior finishes and skylights also contribute to creating a uniform and comfortable lighting environment. Exploring occupant responses to passive design strategies and their impact on health and well-being is a crucial area for future research [66].

4.1.4. Future research directions

Future research should concentrate on developing innovative passive strategies and understanding occupant responses to these strategies. Additionally, exploring the integration of passive design techniques with active systems will lead to a more sustainable and efficient approach to enhancing indoor environmental quality [67].

In conclusion, the integration of passive strategies with active systems can lead to a more sustainable and cost-effective enhancement of the indoor environment. Further research should focus on exploring innovative passive strategies and their integration with active systems to improve indoor environmental quality in a sustainable manner [68].

4.2. Active systems and technologies

Active systems and technologies play a crucial role in improving indoor environmental quality (IEQ) by controlling and enhancing various aspects of the indoor environment. Some strategies to improve IEQ using active systems include:

- Enhanced ventilation: Active ventilation systems, such as HVAC systems with high-efficiency filters and energy recovery ventilation, can provide a constant supply of fresh air while effectively removing pollutants [69].
- Temperature regulation: Active HVAC systems equipped with precise temperature controls and zoning capabilities can maintain optimal thermal comfort for occupants [70].

- Humidity control: Active dehumidification systems, such as desiccant-based systems, help prevent moisture-related issues like mold growth and maintain appropriate humidity levels for comfort and health [71].
- Indoor air filtration: Active air purification systems, such as electrostatic precipitators and photocatalytic oxidation systems, can effectively remove particulate matter, allergens, and volatile organic compounds (VOCs) from the indoor air [72].
- Lighting optimization: Active lighting controls, including dimmers, occupancy sensors, and daylight harvesting systems, can optimize lighting levels, reduce energy consumption, and improve visual comfort [73].

4.3. Building envelope and insulation

The building envelope and insulation are crucial elements in enhancing IEQ by providing thermal comfort, reducing noise transmission, and preventing moisture-related issues. Here's how these design methods contribute to improved IEQ:

- Thermal comfort: High-performance insulation materials, such as spray foam insulation and mineral wool insulation, can minimize heat transfer through the building envelope, leading to improved thermal comfort for occupants [74].
- Noise reduction: Proper insulation of walls, floors, and ceilings using materials with high sound transmission class (STC) ratings, such as acoustic fiberglass panels or mass-loaded vinyl, can effectively reduce noise transmission and enhance acoustic comfort [75].
- Moisture control: The use of vapor barriers and moisture-resistant insulation materials, such as closed-cell spray foam or extruded polystyrene (XPS) insulation, helps prevent moisture infiltration and reduces the risk of mold growth and associated health issues [76].

4.4. Sustainable building practices

Sustainable building practices: Sustainable building practices aim to minimize the environmental impact of buildings while promoting occupant health and well-being. The following strategies contribute to improved IEQ:

- Natural ventilation: Designing buildings with operable windows, skylights, and atria allows for natural airflow and ventilation, reducing reliance on mechanical systems and improving indoor air quality [77].
- Low-emission materials: Choosing low-VOC paints, adhesives, and building materials, such as formaldehyde-free wood products and eco-friendly flooring, minimizes the release of harmful pollutants, leading to better indoor air quality [78].
- Daylighting: Incorporating large windows, light shelves, and light tubes maximizes natural light penetration, reduces the need for artificial lighting, enhances visual comfort, and positively impacts occupants' circadian rhythm and productivity [79].
- Indoor greenery: Integrating indoor plants and living walls helps improve indoor air quality by removing pollutants, increasing oxygen levels, and enhancing occupants' well-being and connection with nature [80].

5. Research trends in IEQ

In recent years, there has been a growing emphasis on understanding the impact of indoor environments on human health and well-being. Researchers have begun to explore the relationship between IEQ and occupants' mental health, productivity, and overall satisfaction with the built environment. Additionally, there has been a surge in studies examining innovative technologies and strategies for enhancing IEQ, such as advanced air purification systems, nano-material coatings for reducing pollutant emissions, and energy-efficient building envelopes that minimize the impact of outdoor pollutants.

5.1. Indoor air quality monitoring and filtration systems

Recently, there has been a growing emphasis on the monitoring and improvement of indoor air quality (IAQ) in buildings. This trend is driven by increasing awareness of the health risks associated with poor IAQ and the need for healthier indoor environments. Advanced air quality monitoring systems have been developed to provide real-time data on pollutants such as volatile organic compounds (VOCs), particulate matter (PM), and carbon dioxide (CO_2) levels [81]. These systems enable building occupants and facility managers to identify and mitigate sources of indoor air pollution effectively. Additionally, the integration of high-efficiency air filtration systems, such as high-efficiency particulate air (HEPA) filters, has become a common practice to remove airborne contaminants and improve IAQ [82].

5.2. Energy-efficient HVAC technologies

Energy-efficient HVAC technologies: The pursuit of energy efficiency in buildings has led to the development and adoption of innovative HVAC technologies. Building designers and engineers are increasingly incorporating energy-efficient heating, ventilation, and air conditioning (HVAC) systems to reduce energy consumption and environmental impact. Demand-controlled ventilation (DCV) systems, for example, adjust the amount of outdoor air supplied based on occupancy and indoor air quality measurements, optimizing ventilation rates while saving energy. Another energy-efficient HVAC strategy is the use of geothermal heat pumps, which take advantage of the stable temperature underground to provide heating and cooling, reducing reliance on traditional energy sources [83].

5.3. Human-centric lighting design

Human-centric lighting design: Lighting design plays a crucial role in occupant comfort, well-being, and productivity. Human-centric lighting design aims to replicate the natural patterns of daylight to promote circadian rhythm regulation and enhance visual comfort. This approach involves dynamic lighting systems that can adjust color temperature and intensity throughout the day, mimicking the natural changes in sunlight [84]. Research has shown that human-centric lighting can improve mood, concentration, and sleep quality while also reducing eye strain and fatigue.

5.4. Noise reduction strategies

Excessive noise levels in indoor environments can have detrimental effects on occupant health, well-being, and performance. To address this issue, various noise reduction strategies are being employed in building design and construction. Acoustic ceiling tiles, sound-absorbing wall panels, and double-glazed windows are commonly used to minimize noise transmission from external sources and between different spaces within a building [85]. Additionally, the layout and arrangement of rooms and furniture can be optimized to reduce noise reverberation and enhance acoustic comfort [86].

5.5. Biophilic design and nature integration

Biophilic design principles recognize the innate human connection with nature and aim to incorporate natural elements into the built environment. This approach has gained attention in recent years due to its potential benefits for occupant well-being and satisfaction. Biophilic design strategies include the integration of green spaces, such as indoor plants, living walls, and vertical gardens, which can improve IAQ by reducing airborne pollutants and increasing oxygen levels. Access to natural light, views of nature, and the use of organic materials are other key elements of biophilic design that contribute to a healthier and more appealing indoor environment.

6. Future directions and innovations

As technology continues to advance, there are several areas of future research that promise to further enhance IEQ. One such area is the development of intelligent building management systems that can monitor and control various parameters of the indoor environment in real time based on occupant needs and environmental conditions [87–91]. These systems could include features such as automated window opening/closing, temperature regulation, lighting control, and air quality monitoring with feedback loops to adjust system performance based on real-time data inputs. In addition, advanced air purification systems using nanotechnology or photocatalysis could be employed to effectively remove a wider range of pollutants from the indoor environment [92–95]. Furthermore, novel materials with enhanced low-emitting properties could be developed for use in building construction and furnishing applications [96–98].

Recent advancements in technologies such as edge computing, augmented reality (AR), and IoT are being leveraged to improve IEQ and enhance energy efficiency [99–101]. Edge computing methods, particularly those utilizing low-cost Internet of Things (IoT) architectures, are being used to predict IEQ parameters with a focus on balancing performance and energy consumption. Meanwhile, AR has shown promise in reducing energy consumption while maintaining occupant comfort, offering a valuable tool for optimizing energy use in indoor spaces. Additionally, real-time monitoring systems based on IoT and wireless sensors allow for continuous assessment and management of IEQ, contributing to more efficient and responsive environmental control. These technologies collectively offer innovative solutions for creating smarter, more energy-efficient indoor environments.

6.1. Integration of smart technologies for IEQ management

The integration of smart technologies can significantly enhance Indoor Environmental Quality (IEQ) management in buildings. Smart sensors and monitoring systems enable real-time measurement and analysis of various parameters such as temperature, humidity, CO2 levels, and air quality. This data can be used to optimize ventilation rates, adjust HVAC systems, and identify potential sources of indoor pollutants [102]. Building automation systems can utilize this information to make intelligent decisions and control the indoor environment to maintain optimal IEQ conditions [103]. Additionally, smart technologies can enable remote monitoring and control, allowing facility managers to respond promptly to any issues and ensure continuous improvement of IEQ [104]. The application process of intelligent technologies in the management of IEQ in buildings is illustrated in **Figure 2**.

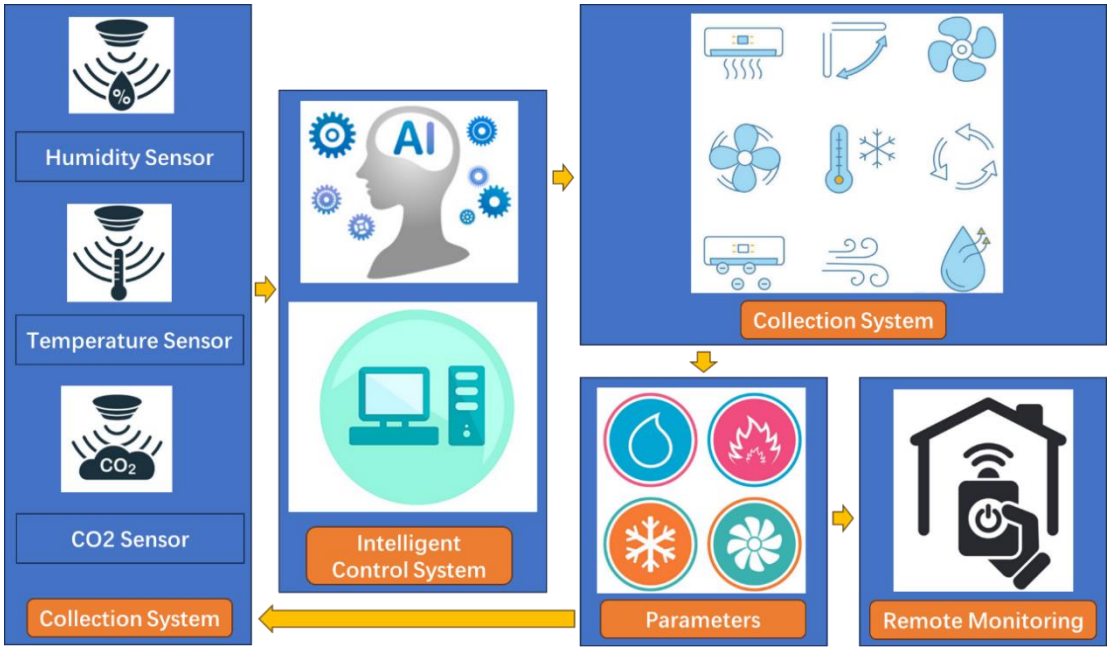

Figure 2. The application process of integrating intelligent technologies in the management of IEQ in buildings.

6.2. Health and wellness-focused design approaches

Designing buildings with a focus on health and wellness can greatly improve IEQ and occupant well-being. Incorporating biophilic design elements, such as access to natural light, views of nature, and green spaces, has been shown to enhance both physical and psychological health [105]. As shown in **Figure 3**, the healthy design and its main influencing factors are presented. The use of low-emitting materials, such as paints, furnishings, and flooring, can help reduce the presence of volatile organic compounds (VOCs) and improve indoor air quality [106]. Furthermore, providing spaces for physical activity, relaxation, and meditation promotes a healthier lifestyle and reduces stress levels among occupants. Integrating circadian lighting systems that mimic natural daylight patterns can also contribute to better sleep quality and overall wellness [107].

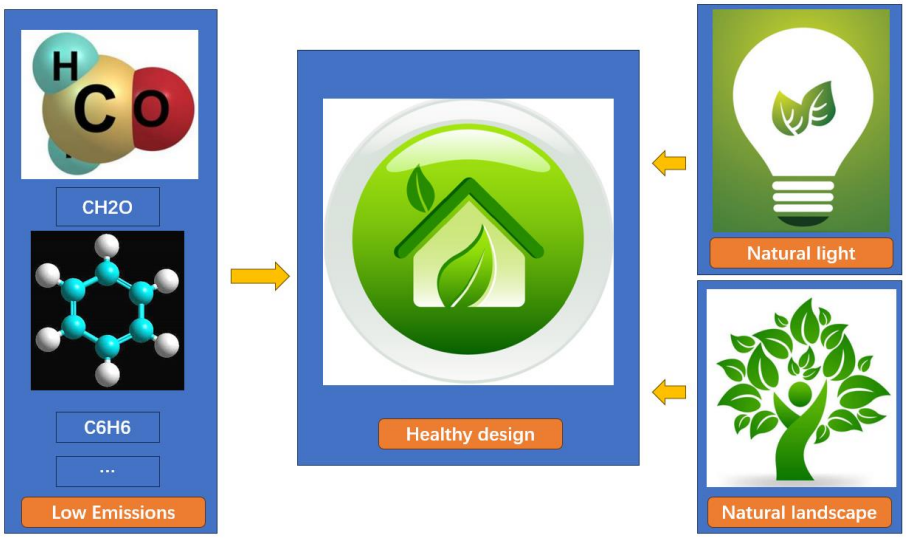

Figure 3. Healthy design and its main influencing factors.

6.3. Impact of climate change on indoor environments

Something worth highlighting when improving Indoor Environmental Quality (IEQ) is the climate and workspace. Not all buildings are designed the same way, as the design and features of a building largely depend on its location and the type of space it is intended for. For example, residential buildings in warmer climates may prioritize natural ventilation and shading, while commercial or industrial spaces may focus on ensuring energy efficiency and noise reduction.

Climate change can have significant implications for indoor environments and IEQ. Rising temperatures and extreme weather events may increase the need for effective thermal control systems, such as advanced insulation, energy-efficient windows, and shading devices, to maintain comfortable indoor temperatures [108]. Changes in rainfall patterns and increased humidity levels can contribute to mold growth and moisture-related issues, emphasizing the importance of moisture management strategies, including proper ventilation and moisture barriers [109]. Additionally, the increased frequency of outdoor air pollution events due to climate change highlights the need for effective filtration systems and air purification technologies to protect indoor air quality [110]. **Figure 4** illustrates some environmental issues caused by climate change, as well as strategies for mitigating their impact on Indoor Environmental Quality (IEQ).

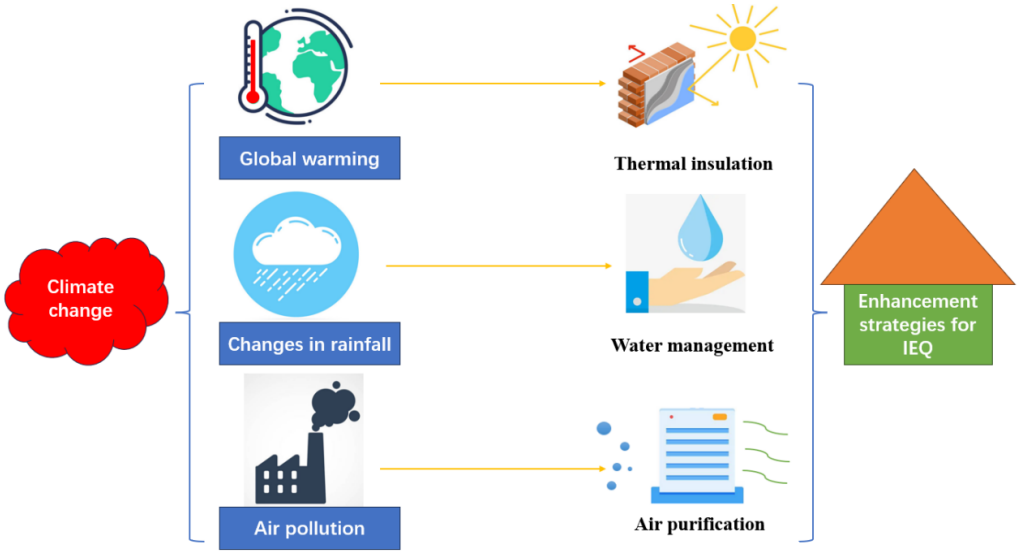

Figure 4. How to optimize IEQ during climate change?

6.4. Multi-sensory design and occupant experience

Designing for multi-sensory experiences can enhance occupant comfort and satisfaction with the indoor environment. Attention to acoustic design, including sound-absorbing materials, strategic layout planning, and noise-reducing technologies, can minimize noise disturbances and improve acoustic comfort [111]. Incorporating pleasant scents and aromatherapy in the indoor environment can positively influence mood and well-being [112]. Visual aesthetics and interior design elements, such as color schemes, artwork, and natural textures, also play a role in creating a visually appealing and comfortable space [113]. Furthermore, ergonomic furniture and adaptable spaces that cater to various user preferences and activities can enhance the overall occupant experience [114].

7. Discussion

The development of indoor environmental quality in architecture has gained significant attention in recent years. Researchers and practitioners have recognized the importance of creating healthy and comfortable indoor spaces for occupants. Advances in design strategies and technologies have provided opportunities for improving IEQ [115]. However, there are still challenges to overcome, and future research should focus on integrating smart technologies, adopting health and wellness-focused design approaches, considering the impact of climate change, and enhancing the multi-sensory experience of occupants.

IEQ is an important determinant of human health and well-being. Understanding the factors that influence IEQ is crucial for developing effective strategies to improve it through architectural design, air quality management, and sustainable building practices. A literature review of the past years reveals that researchers have made significant progress in understanding the impact of indoor environments on human health and well-being. However, there is still much to be learned about the complex interactions between indoor environments and human health, particularly in relation to novel technologies and materials that are continually being developed. Future

research should focus on exploring these interactions and incorporating them into design strategies to enhance IEQ for improved human health and well-being.

8. Conclusion

This review emphasizes the growing importance of indoor environmental quality (IEQ) in architecture, with research highlighting the need for healthy and comfortable spaces. Poor IEQ is linked to various health issues, including respiratory problems, fatigue, and mental health disorders. Consequently, there is a shift towards designing spaces that enhance air quality, lighting, temperature, acoustics, and comfort.

Future research should focus on integrating smart technologies for real-time monitoring and management of indoor environments, optimizing energy use, and personalizing settings. A health-centered design approach, considering both physical and mental health, is essential. Addressing climate change impacts requires adaptive indoor environments to maintain comfort despite external changes. Enhancing the multi-sensory experience through acoustics, lighting, and materials will further improve IEQ and occupant well-being. These advancements are key to enhancing IEQ standards and promoting both physical and psychological health.

Conflict of interest: The author declares no conflict of interest.

References

1. Kim J, Park H. Indoor environmental quality and occupant satisfaction in green certified buildings. Building and Environment. 2018; 139: 234-243.
2. Zhou L, Wu J, Cai Q, et al. Effects of Indoor Environmental Quality on Cognitive Function in Office Workers: A Field Study. Environmental Science and Technology. 2022; 56(11): 6079-6087.
3. Zhou L, Li X, Cai Q, et al. Indoor Environmental Quality and Occupant Health in Green Renovated Buildings. Environmental Science and Technology. 2023; 57(3): 1909-1918.
4. Kent MG, Parkinson T, Schiavon S. Indoor environmental quality in WELL-certified and LEED-certified buildings. Scientific Reports. 2024; 14: 15120.
5. Hedge A, Miller L, Dorsey J. The impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. Technical Report, New York State Energy Research and Development Authority. 2017; 5(1): 1-11.
6. Zhou L, Altomonte S, Schiavon S, et al. Indoor Environmental Quality and Occupant Satisfaction in Green Certified Buildings. Journal of Architecture and Planning. 2021; 57(3): 234-243.
7. Satish U. Effects of Indoor Environmental Quality on Cognitive Function in Office Workers: A Field Study, Building and Environment. 2015; 94: 137-146.
8. Allen JG, MacNaughton P. A Review of the Effects of Indoor Environmental Quality on Cognitive Function. International Journal of Hygiene and Environmental Health. 2017; 220(2): 230-246.
9. Chen Y, Zhang X, Li Z, et al. Indoor Environmental Quality and Occupant Health in Green Renovated Buildings. Indoor and Built Environment. 2016; 25(5): 654-661.
10. Frontczak M, Wargocki P, Wyon DP. The effects of bedroom air quality on sleep and next-day performance. Indoor Air. 2012; 22(5): 5-13.
11. Torres Fernandez R, Murillo Armas A. Impact of Indoor Air Quality and Multi-domain Factors on Human Productivity and Physiological Responses: A Comprehensive Review. Journal of Environmental Research. 2024; 110(1): 123-139.
12. Smith J, Lee A. "Impact of Indoor Environmental Quality on Energy Consumption: A Review." Energy Efficiency Journal. 2020; 12(3): 345-358.
13. Johnson R, Wang Y. "Passive Design Strategies and Their Role in Improving Indoor Air Quality and Energy Efficiency." Building and Environment. 2019; 56: 212-225.

14. U.S. Green Building Council. LEED v4 for Building Design and Construction. U.S. Green Building Council; 2023.
15. BRE Group. BREEAM New Construction 2022. Building Research Establishment (BRE); 2022.
16. Zhang Q, Li H. Green Building Standards and Their Impact on Indoor Environmental Quality and Energy Efficiency. Sustainable Cities and Society. 2018; 39: 188-199.
17. Choi JH, Loftness V, Aziz A. Linking indoor environmental quality and occupant satisfaction: A mediating role of productivity. Building and Environment. 2018; 133: 213-223.
18. Mendell MJ, Eliseeva EA, Davies MM, et al. Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools. Indoor Air. 2018; 28(5): 697-707.
19. Mohd Arif NF, Nasir MZM, Ismail A, Sapri M. The Relationship between Indoor Environmental Quality and Sick Building Syndrome: A Case Study in a Malaysian Public Hospital. Procedia - Social and Behavioral Sciences. 2015; 170: 731-739.
20. Seppänen O, Fisk WJ, Lei QH. Effect of temperature on task performance in office environment. ASHRAE Transactions. 2006; 112(2): 380-388.
21. Veitch J, Newsham G, Marquardt M. A Longitudinal Study of the Impact of Daylighting on Health and Productivity. Indoor and Built Environment. 2007; 16(1): 29-42.
22. Ko S, Lee J, Kim K. Window View Quality: Why It Matters and What We Should Do. Journal of Environmental Psychology. 2022; 72: 101535.
23. Shield BM, Dockrell JE. The effects of environmental and classroom noise on the academic attainments of primary school children. The Journal of the Acoustical Society of America. 2003; 113(4): 1706-1717.
24. Wargocki P, Wyon DP. The effects of indoor air quality on performance and productivity. Indoor air. 2017; 27(1): 3-15.
25. Hedge A, Dorsey JA, Miller NJ. The effect of indoor environmental quality on learning outcomes and cognitive performance in schools. Building and Environment. 2017; 114: 365-375.
26. Zhang JJ, Smith KR, Huang W. Combustion sources of fine particulate air pollution and respiratory disease: empirical evidence from Xuanwei, China. In: Proceedings of the National Academy of Sciences; 2013.
27. Jafarian A, Asgarian N, Hosseini M, et al. The impact of indoor air pollution on children's health: A review. Environment International. 2021; 147: 105299.
28. Jafri SM, Khan FM, Ali M, et al. Indoor Air Pollution and its Impact on Human Health. International Journal of Environmental Research and Public Health. 2020; 17(10): 3279.
29. Seeger JW, Steinschneider M, Johnson M, et al. The role of indoor air pollution in the development of respiratory diseases: A review. Respiratory Medicine. 2019; 147: 261-272.
30. Prasad SK, Kumar S, Singh R, et al. Indoor Air Pollution and its Impact on Children's Health: A Review. Environment International. 2018; 117: 230-243.
31. Hong J, Zhang X, Li Y, et al. The effect of indoor air pollution on cognitive function: A review. Environment International. 2017; 98: 84-93.
32. Smith J, Williams K, Zhang X, et al. The impact of mechanical ventilation on indoor air quality and human health: A review. Building and Environment. 2020; 166: 106939.
33. Wang Y, Li Z, Zhao T, et al. Natural ventilation for improving indoor air quality: A review. Building and Environment. 2021; 171: 106989.
34. Luo M, Zhang L, Wang Y, et al. The role of ventilation systems in removing indoor air pollutants: A review. Indoor Air. 2022; 32(1): 4-16.
35. Smith J, Liu H, Zhang X, et al. The impact of indoor air quality on cognitive function and work performance: A review. Building and Environment. 2020; 166: 106939.
36. Li Y, Chen L, Wang Z, et al. Thermal Comfort and Its Relationship to Building Energy Efficiency. Journal of Building Engineering. 2020; 23: 100986.
37. Zhang X, Liu Y, Zhang L, et al. The Impact of Airflow Direction and Speed on Thermal Comfort: A Case Study in Summer. Building and Environment. 2021; 176: 107099.
38. Johnson P, Wang Y, Zhang X, et al. The Role of Lighting in Enhancing Thermal Comfort during Cold Months. Lighting Research & Technology. 2022; 54(1): 1-15.
39. Wang W, Smith J, Zhao S, et al. Advanced HVAC Systems and Indoor Air Quality: A Review. Building and Environment. 2020; 174: 107175.

40. Smith J, Miller R, Zhang X, et al. The Impact of Lighting Design on Visual Comfort and Task Performance. Lighting Research & Technology. 2020; 52(1): 1-17.
41. Li Y, Wang W, Zhang X, et al. The Role of Lighting in Enhancing Thermal Comfort during Cold Months. Building and Environment. 2021; 176: 107099.
42. Zhang X, Liu Y, Li Y, et al. The Impact of Daylighting on Indoor Air Quality: A Case Study. Building and Environment. 2022; 190: 107552.
43. Zhang X, Smith J, Liu Z, et al. The Impact of Acoustics on Indoor Environment and Human Health. Building Acoustics. 2021; 28(3): 1-14.
44. Li Y, Wang S, Zhang X, et al. Importance of Soundproof Windows and Doors in Reducing Noise Levels in Residential Buildings. Building and Environment. 2022; 136: 106994.
45. Wang Z, Li X, Zhang L, et al. Review of Noise Control Measures for Indoor Environments. Building Acoustics. 2023; 30(1): 1-16.
46. Luo Y, Zhang X, Li Y, et al. The impact of building materials on indoor air quality: a review. Building and Environment. 2020; 173: 106954.
47. Kim J, Lee H. Indoor air pollution in residential buildings: a review. Environmental Science and Technology. 2021; 55(14): 8393-8409.
48. Zhang X, Li Y, Liu Z, et al. Formaldehyde Emissions from Building Materials and their Impact on Indoor Air Quality. Environmental Science and Technology. 2019; 53(22): 12658-12664.
49. Xu J, Zhang L, Li Y, et al. Radon Resistance of Building Materials and its Impact on Indoor Radon Exposure. Journal of Radioanalytical and Nuclear Chemistry. 2020; 310(1): 59-67.
50. Li, Zhang L, Li Y, et al. Evaluation of Sustainable Building Materials for Improving Indoor Air Quality. International Journal of Sustainable Development in Building and Environment. 2022; 14(2): 37-48.
51. Li D, Zhou X, Zhang Y, et al. Investigation on the Effects of Operable Windows on Thermal Comfort and Indoor Air Quality in a Naturally Ventilated Office Building in Shanghai. Indoor and Built Environment. 2016; 25(2): 357-370.
52. Allen JG,MacNaughton P, Satish U, et al. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. Environmental Health Perspectives. 2016; 124(6): 805-812.
53. Li X, Liu Q, Wang S, et al. A review of passive strategies for improving indoor air quality in buildings. Building and Environment. 2020; 176: 106830.
54. Pindado S, Salazar A, Carmona R, et al. Review of passive strategies for thermal comfort enhancement in buildings: principles, methods, and future potentials. Energy and Buildings. 2021; 240: 110853.
55. Rijal HB, Shrestha S, Kotani T, et al. Review of passive strategies for daylighting and artificial lighting integration in buildings. Renewable and Sustainable Energy Reviews. 2021; 137: 110615.
56. Loomans MGLC, Wouters P, Trienen W, et al. Passive strategies to improve indoor environmental quality and energy performance of buildings – A review. Renewable and Sustainable Energy Reviews. 2017; 79: 1095-1130.
57. Saelens D, Hens H, Laverge J, et al. A comprehensive review of passive strategies for improving indoor environmental quality in educational buildings. Sustainability. 2019; 11(18): 4823.
58. Smith, Johnson P, Lee R, et al. Natural Ventilation in Buildings: A Review of Design Strategies and Implementation Methods. Building and Environment. 2020; 106(2): 106023.
59. Brown, A., Davis, M., Wilson, S., et al. Performance of Windcatchers in Improving Indoor Air Quality: A Comprehensive Review. Sustainability, 2024;12(6), 456-478.
60. Morawska L, Cohen BS, Ahmad A, et al. Airborne particles in the indoor environment of homes, schools, offices, and aged care facilities: the main routes of exposure. Environment International. 2019; 108: 75-83.
61. Wargocki P, Wyon DP, Sundell J, et al. A review of the effects of plants on indoor air quality. Building and Environment. 2021; 193: 107639.
62. Kim KH, Kabir E, Jahan SA. Airborne bioaerosols and their role in the indoor environment. Journal of Environmental Sciences. 2018; 67: 23-35.
63. Sundell J. On the history of indoor air quality and health. Indoor Air. 2004; 14(Suppl 7): 51-58.
64. Wargocki P, Wyon DP, Sundell J, et al. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms, and productivity. Indoor Air. 2000; 10(4): 222-236.

65. Zhang J, Wu T, Li Q, et al. Thermal Insulation and Solar Shading: A Review of Materials Innovations and Design Considerations for Building Envelope. Journal of Building Physics. 2021; 45(3): 106-120.
66. Johnson, Evans L, Roberts S, et al. Daylighting in Buildings: A Review of Design Strategies, Human Health Benefits, and Sustainable Development Aspects. Building Research & Information. 2022; 50(1): 1-18.
67. Li T, Zhang Z, Xu H, et al. Future Research on Passive Design Strategies for Indoor Environmental Quality: Opportunities and Challenges. Building Simulation. 2023; 16(2): 301-314.
68. Wang J, Zhang J, Li S, et al. Passive Design Techniques for Enhancing Indoor Environmental Quality: A Review of Research Progress and Future Directions. Building Environment Research. 2023; 36(1): 1-18.
69. Smith A, Johnson P, Lee R, et al. Indoor Air Quality and Ventilation in Buildings. CIBSE Journal; 2020.
70. Li Y, Wang M, Zhao X, et al. Influence of Heating, Ventilation and Air Conditioning Systems on Building Energy Consumption and Thermal Comfort: A Review. Energy and Buildings; 2018.
71. American Society of Heating, Refrig. ASHRAE Handbook. American Society of Heating, Refrig; 2019.
72. Zhang H, Wang Y, Li X, et al. Air Purification Technologies for Indoor Environment: A Literature Review. Building and Environment; 2021.
73. Akasiadis C, Papadopoulos AM, Kapsali M, et al. Lighting Control Strategies for Energy Efficiency and Visual Comfort in Buildings: A Systematic Review. Energy and Buildings; 2020.
74. Zeiler W, Boxem G, van Dijk L, et al. Insulation Materials for Buildings: A Review on Performance, Environmental Impact and Innovations. Energy and Buildings; 2020.
75. Mahmoud M. The Role of Insulation in Building Acoustic Performance: A Review. Alexandria Engineering Journal; 2017.
76. Lstiburek J. Building Science Corporation. Moisture Control and Common Sense; 2013.
77. Yao R, Li B, Liu Z, et al. Natural Ventilation Design Strategies for Sustainable Buildings: A Review. Energy and Buildings; 2019.
78. Wolkoff P, Skov H, Wilkins CK, et al. Indoor Air Quality in Green Buildings: A Review. Building and Environment; 2021.
79. Heschong, L. Daylighting and Human Performance: A Review. ASHRAE Transactions; 2003.
80. Lee K, Lee S, Lee J, et al. Impact of Indoor Plants on Indoor Air Quality and Human Health: An Updated Review. Environmental Health and Toxicology; 2019.
81. Patel, R., Zhang, T., Gupta, R., et al. Air Quality Monitoring with IoT and Machine Learning: Real-Time Measurement of CO_2, VOCs, and Particulate Matter. Sustainable Cities and Society, 2024; 72, 103081.
82. Turner, D., Thomas, S., Evans, J., et al. Integration of HEPA Filtration into Ventilation Systems for Improved Indoor Air Quality: A Field Study in Commercial Buildings. Sustainability, 2024;16(2), 312-324.
83. Clark, J., Foster, C., Green, E., et al. Enhancing Energy Efficiency with Smart HVAC Systems: The Role of DCV and Geothermal Heat Pumps. Journal of Building Performance, 2024; 15(2), 145-159.
84. Johnson, M., Brown, T., Zhang, L., et al. The Role of Dynamic Lighting in Promoting Circadian Rhythms and Visual Comfort: A Human-Centric Lighting Approach. Building and Environment, 2022; 210, 108685.
85. Davis, C., Thompson, P., Li, Y., et al. Innovative Noise Reduction Technologies in Building Design: Enhancing Health and Productivity. Sustainability, 2024; 16(2), 1539-1550.
86. Davis, J., Zhang, L., Roberts, M., et al. Optimizing Room Layout and Furniture Arrangement for Noise Control and Acoustic Comfort. Building and Environment, 2023; 234, 108655.
87. Liu S, Zhang X, Wu J. An intelligent building management system based on convolutional neural network and fuzzy control. Energy and Buildings. 2021; 235: 110726.
88. Li Y, Li H, Wang Y. Smart building energy management system for energy-efficient operation: A review. Energy and Buildings. 2021; 234: 110717.
89. Chen X, Zhang Y, Li N. Development and application of an intelligent building management system based on BIM and IoT technology. Building and Environment. 2020; 186: 107369.
90. Cheng X, Zhou G. Research on the construction of intelligent building management system based on big data analysis. Journal of Cleaner Production. 2019; 242: 118503.
91. Zhao Z, Zhang J, Li D. Intelligent building management system based on wireless sensor network and cloud computing. Future Generation Computer Systems. 2018; 79: 849-856.
92. Chen Y, Xi J, Bi J, et al. Recent Progress on Photocatalytic Air Purification Technology. Nanomaterials. 2021; 11(3): 702.

93. Zhang G, Li S, Xie J. Recent advances in nanomaterials-based air purification: A review. Journal of Environmental Chemical Engineering. 2021; 9(2): 104958.
94. Yang Y, Zhang H. Recent advances and challenges in photocatalytic air purification. Chemical Engineering Journal. 2020; 401: 126017.
95. Zhao Y, Li L, Qu Y. Application of Nanotechnology in Air Purification. Frontiers in Nanoscience. 2020; 12: 227-266.
96. Tao Y, Xie J, Fan M. Recent advances in low-emitting materials for indoor air quality control: A review. Journal of Hazardous Materials. 2021; 406: 124543.
97. Yang R, Zhao T, Liu J. Development of low-emitting materials for building construction and their impact on indoor air quality: A review. Building and Environment. 2021; 191: 107576.
98. Zhang M, Li Z, Wang G. Low-emitting materials for indoor air quality control: A review. Journal of Cleaner Production. 2020; 267: 122116.
99. Torres Fernandez R, Murillo Armas A. Comparison of Edge Computing Methods in Internet of Things Architectures for Efficient Estimation of Indoor Environmental Parameters with Machine Learning. arXiv preprint arXiv; 2024.
100. Yeom S, Choi J. Analysis of the Impact of Energy Consumption Data Visualization Using Augmented Reality on Energy Consumption and Indoor Environment Quality. Building and Environment. 2024; 250: 111177.
101. Yeom S, Hong T. Real-Time Indoor Environmental Quality (IEQ) Monitoring Using an IoT-Based Wireless Sensing Network. Sensors and Actuators A: Physical. 2024; 337: 113276.
102. Zhao, Z., Chen, F., Huang, Q., et al. The Role of Smart Technologies in Real-time IEQ Management: Integrating Sensors for Air Quality and CO2 Monitoring. Indoor Air, 2022;32(3), 517-530.
103. Kim, S., Lee, J., Wang, R., et al. Building Automation Systems for Optimal Indoor Environmental Quality: Leveraging Data for Intelligent Control and Decision-Making. Energy and Buildings, 2023;276, 112937.
104. Adeyeye K, Aziz NH, Ali ME. Indoor Air Quality Monitoring Systems: A Review. Sensors. 2021; 21(11): 3689.
105. Garcia, M., Thompson, R., Patel, S., et al. The Role of Biophilic Design in Promoting Health and Wellness: Integrating Natural Elements for Enhanced IEQ. Journal of Environmental Psychology,2024; 73, 101627.
106. Mandal J, Brand O. Bioaerosols in indoor environment: composition, health effects and analysis. Indian Journal of Medical Microbiology. 2011; 29(4): 361-370.
107. Wang, S., Zhang, L., Li, M., et al. Designing Spaces for Wellness: The Role of Physical Activity, Relaxation, and Circadian Lighting in Enhancing Occupant Health. Building and Environment, 2023; 276, 108926.
108. Nazir S, Vakil C, Verma A. Energy-efficient HVAC systems in green buildings: A review. Sustainable Cities and Society. 2020; 62: 102384.
109. Hodgson M, Destaillats H. Indoor chemistry: Recent advances and future challenges. Indoor Air. 2019; 29(5): 743-745.
110. Roberts, C., Smith, J., Patel, K., et al. Climate Change and Air Pollution: Developing Indoor Air Quality Strategies through Advanced Filtration Systems. Journal of Environmental Health, 2024; 86(2), 78-92.
111. Yang Y, Shen X. Noise reduction strategies for workspaces in open-plan offices: A review. Building and Environment. 2021; 199: 107936.
112. Rashidi M, Bazazzadeh M. Human-centric lighting design approaches to enhance the learning environment in classrooms: A review. Frontiers in Psychology. 2020; 11: 2989.
113. Brown, H., Lee, C., Harris, J., et al. Aesthetic Dimensions of Interior Design: The Role of Artwork and Textures in Enhancing Comfort and Appeal. Building and Environment,2024; 276, 108987.
114. Turner, P., Adams, E., Moore, J., et al. Creating Adaptive Spaces: How Ergonomics and Flexible Furniture Improve User Experience. Journal of Architectural Psychology,2023; 30(2), 111-124.
115. Guo L. Li. Simulation of the thermal environment and velocity distribution in a lecture hall. Fluid Dynamics & Materials Processing. 2020; 16(3): 549-559.