REVIEW OF LITERATURE Chapter 2

2.1 Indoor Air Pollution

Air pollution and exposure to poor air quality pose a significant environmental threat to global public health [1]. In 2019, air pollution ranked as the fourth leading risk factor for mortality worldwide, responsible for nearly 6.75 million early deaths [2]. Approximately 2.3 million of these cases are attributed to household air pollution (HAP), primarily resulting from the burning of solid fuels for cooking in low- and middle-income countries. HAP refers to air pollution generated within and around homes due to the incomplete combustion of these fuels. The term distinguishes it from broader indoor air pollution (IAP), as emissions from household fuel combustion often disperse into the surrounding environment, contributing to ambient air pollution affecting overall air quality [3]. Remarkably, air quality in urban areas with typical traffic can be cleaner than inside a household living room [4]. According to the United States Environment Protection Agency (USEPA), indoor air quality (IAQ) can be two to five times more polluted than outdoor air [5]. Since most people spend their time inside, IAP considerably influences human health and their effectiveness in the workplace [6]. Traditionally, IAP has received significantly less attention than outdoor air pollution [4]. Following the energy crisis of the 1970s, the importance of energy efficiency in buildings led to more airtight and insulated buildings, inadvertently limiting ventilation and increasing indoor pollutant concentration [7]. Furthermore, the enhancement of living standards has led to increased use of synthetic materials and chemicals in indoor construction and decoration (e.g., pesticides, cleaning chemicals, air fresheners, cooking gases, etc.) [6, 8]. Exposure to elevated levels of indoor air pollutants can lead to both short-term and long-term health effects [9]. Thus, addressing IAP is essential in improving public health outcomes, as well as creating healthier, more sustainable indoor environments.

2.2 History of Indoor Air Pollution

Indoor air is one of the primary environments where people are exposed to pollutants [10]. However, it has only recently emerged as a significant focus in environmental research, especially when compared to earlier concerns such as energy use, sustainability, and outdoor air pollution. The historical emphasis on outdoor air pollution over indoor air quality (IAQ) can be attributed to several factors. Outdoor air pollution has long been linked to significant public health issues, including widespread illness and mortality, as highlighted by major events like the London smog [11]. Additionally, it is easier to collect public health data and air quality measurements for outdoor environments than for indoor ones. This is largely due to the significant changes in indoor pollutants resulting from new construction materials, household products, and building systems, which made IAQ a more complex issue to study [12]. Furthermore, the understanding of how indoor air affects health is relatively recent and has rapidly evolved in last few decades.

The recognition of IAQ as a public health concern gained momentum in 1980s, primarily driven by the increasing airtightness of buildings and the widespread adoption of low-ventilation designs aimed at energy efficiency [13]. This shift inadvertently contributed to the accumulation of indoor pollutants, which prompted the emergence of IAQ investigation as a distinct field. In response to these challenges, the American Industrial Hygiene Association (AIHA) established the Indoor Environmental Quality (IEQ) Committee in 1983. This committee organized the first series of International Symposia on Indoor Air Quality (IAQ) in 1987. Additionally, the Healthy Buildings Conference, held in Stockholm in 1988, provided an interdisciplinary platform for researchers, practitioners, and policymakers to address indoor environmental health risks [14]. These developments illustrate how the 1980s marked a critical turning point in shifting scientific and regulatory attention from outdoor air pollution to the more complex realm of indoor air environments.

In 1992, the International Society of Indoor Air Quality and Climate (ISIAQ) was founded by a group of 109 international scientists and professionals following the 5th International Conference on Indoor Air Quality and Climate, held in Toronto in 1990 (Indoor Air '90) [14]. ISIAQ's key activities include publishing the high-profile journal Indoor Air, which reports original research in the broad field of indoor environments in non-industrial buildings [13, 14]. In 1993, the United States Green Building Council (USGBC) was established, marking the beginning of the development of the Leadership in Energy and Environmental Design (LEED) certification. The integration of energy efficiency and IAQ as critical components in the LEED guidelines marked a transformative shift, leading to the emergence of companies specializing in green building construction [14, 15]. In 1995, the Indoor Air Quality Association (IAQA) was founded in the United States to support IAQ professionals, remediation companies, and building owners in tackling IAQ issues.

The 2000s saw a surge in public concern in the United States regarding microbial contamination, particularly in schools and residential buildings, which contributed to the rapid expansion of the IAQ field, especially in mold remediation and inspection [14]. Concurrently, the Green Building movement gained significant momentum with newer versions of the LEED certification and the rise of alternative building evaluation systems. However, while these systems emphasized energy efficiency, many gave limited attention to IAQ, resulting in buildings with insufficient ventilation and an increase in IAQ complaints from occupants [10, 13, 14]. A decade later, in 2010, attention shifted towards airtight buildings, net-zero energy buildings, the relationship between IAQ and productivity, and the importance of adequate ventilation.

2.3 Indoor Air Characterization Parameters

2.3.1 Particulate Matter ($PM_{2.5}$)

Fine particulate matter with aerodynamic diameter < 2.5 µm ($PM_{2.5}$) is the particle fraction most closely linked to harmful health effects as it can deeply penetrate into lungs leading to adverse health outcomes [16, 17]. Numerous epidemiological studies have demonstrated a connection between $PM_{2.5}$ exposure and several harmful health effects, including preeclampsia in pregnant women, preterm birth, asthma, behavioural problems in children, ischemic heart disease, cerebrovascular disease, lung cancer, lower respiratory infections, and chronic obstructive pulmonary disease [18-22]. Ambient $PM_{2.5}$ has emerged as the fifth leading risk factor for mortality, contributing to an estimated 4.2 million deaths annually [23].

However, since individuals spend majority of their time indoors, the primary source of exposure is indoor $PM_{2.5}$, which may originate from ambient $PM_{2.5}$ that has infiltrated indoor environments [24]. The extent to which outdoor $PM_{2.5}$ penetrates a building is influenced by the building's design and operational features. Air filters in ventilation systems can help eliminate $PM_{2.5}$ from the outdoor air before it is circulated into occupied areas [25]. However, in countries such as India, air filters in ventilation systems are not common, and most households and classrooms rely on natural ventilation [26-29].

In addition to outdoor infiltration, indoor sources of $PM_{2.5}$ play a significant role in overall exposure. In households, among the other sources, cooking, combustion activities (such as using open fires or gas stoves, mosquito coil combustion), cleaning tasks (like vacuuming), and human movement are recognized as some of the primary sources of $PM_{2.5}$ in indoors [30, 31]. Cooking activities are a significant source of $PM_{2.5}$, with different cooking methods emitting varying amounts of particles. Frying and grilling, in particular, produce up to thirty- and ninety-times higher levels of $PM_{2.5}$, respectively, compared to those found in naturally ventilated homes. Smoking, on the other hand, can lead to concentrations up to three times higher than the background levels [32]. Additionally, incense burning, a prevalent spiritual practice in Eastern cultures, significantly raises $PM_{2.5}$ levels in homes where incense is burned, with mean concentrations reaching up to 825.5 $\mu g/m^3$ (at 1-minute peak) during burning events [30]. In classroom environment, the main indoor sources of $PM_{2.5}$ were recognised as resuspension of dust due to human activities, high occupancy, infrequent classroom cleaning, detrition of building materials and chalk dust [33-35].

Several studies across different regions have documented the extent and sources of indoor $PM_{2.5}$ in educational environments. Alameddine et al. [34] found that the immediate surroundings play a crucial role in predicting indoor air quality (IAQ), with a notable correlation between indoor and outdoor $PM_{2.5}$ levels. Similarly, Amato et al. [36] demonstrated that children are exposed to elevated $PM_{2.5}$ levels due to factors such as the infiltration of outdoor urban sources, proximity to road traffic, suspended particles from unpaved playgrounds, and notably, the contribution from Organic/Textile/Chalk sources. In another study conducted by Khumukcham and Khoiyangbam [37] in Imphal, India, the highest indoor levels of $PM_{2.5}$ were recorded at 58.3 $\mu g/m^3$ in a school located in the city center, while a school located away from the city center had lower levels of 25.0 $\mu g/m^3$. The study noted that these $PM_{2.5}$ levels exceeded the permissible limits set by the National Ambient Air Quality Standards (NAAQS) in over half of the sampling sites, further emphasizing the impact of environmental surroundings on IAQ. Further supporting these observations, Nath et al. [38] reported indoor $PM_{2.5}$ levels in classrooms of Tezpur, Northeast India, far exceeding the World Health Organization's (WHO) 24-hour limit of 15 $\mu g/m^3$. The I/O ratio was greater than 1, indicating contributions from sources like dust resuspension and poor cleaning, though a strong correlation with outdoor levels was still observed.

Beyond classrooms, households are also important microenvironments contributing to indoor $PM_{2.5}$ exposure, especially due to the extended time spent indoors and the presence of various emission sources. Dai and Liu [39], in their study in Chinese homes, reported that only about 2% of the sampled locations were able to maintain indoor $PM_{2.5}$ concentrations below 75 µg/m^3, highlighting the widespread challenges in achieving safe indoor $PM_{2.5}$ levels. Similarly, Li et al. [40] found that indoor $PM_{2.5}$ levels varied significantly depending on the type of cooking fuel used. Shukla and Dutta [41] observed that the I/O ratios for $PM_{2.5}$ were greater than 1 in all sampled locations, reflecting significant $PM_{2.5}$ emissions from cooking activities. Alarmingly, even in households using LPG for cooking, indoor $PM_{2.5}$ concentrations exceeded the WHO's maximum limit raising serious IAQ concerns.

2.3.2 Carbondioxide (CO_2)

Carbon dioxide (CO_2) is a colorless, tasteless, odorless, and non-flammable gas that is denser than air. It can accumulate in lower areas, potentially leading to an oxygen deficiency [42]. Typically, outdoor CO_2 concentrations are around 380 ppm, however, in urban areas, they can increase to as high as 500 ppm due to anthropogenic activities [43]. In indoor environments, the main source of CO_2 is human metabolism, but elevated outdoor CO_2 levels can also contribute to higher indoor concentrations [44]. Moreover, efforts to reduce energy consumption often led to lower ventilation rates, which may further cause an increase in indoor CO_2 levels [45]. As a result, CO_2 serves as a key indicator of ventilation, with higher concentrations suggesting inadequate airflow and often correlated with poorer IAQ [46].

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 62.1, the recommended indoor CO_2 concentration should be within 1000 ppm. The United Kingdom mandates a maximum CO_2 concentration of 1500 ppm in classrooms, whereas the Hong Kong Indoor Air Quality Management Group (IAQMG) considers classrooms with an average CO_2 concentration below 800 ppm to be "excellent" [47-49]. Indoor CO_2 concentrations greater than 1400 ppm can cause headaches, breathing issues, stuffiness, reduced attention, unpleasant odors due to bioeffluents, drowsiness, and general discomfort [50, 51].

In a study by Kang et al. [52], the effects of ventilation on sleep quality and health were investigated. The findings showed that the sleep quality improved when the increased bedroom ventilation reduced the CO_2 concentration to 750 ppm. As CO_2 levels rose to 1000 ppm, sleep quality decreased, resulting in lower sleep efficiency and increased restlessness. Again, further increase in CO2 levels due to poor ventilation causes negative changes in sleep structure and health, potentially leading to sleep disorders and chronic fatigue over time. Branco et al. [53] reported that indoor CO_2 concentrations in educational buildings are influenced by seasonal and climate variations, with infiltration patterns differing between cold and warm seasons. They also noted that factors such as building design, floor area, volume of the room, ventilation, and occupancy, significantly impact classroom CO_2 levels, which often exceed the recommended 1000 ppm threshold. Further, the study by Dumala et al. [54] indicates that for the majority of the day (91.9–98.6%), students are exposed to classroom environments where CO_2 concentrations exceed 1,000 ppm. Singh et al. [55] found that in Delhi, CO_2 levels in air-conditioned classrooms were much higher than the 1000 ppm limit set by ASHRAE, with an average of 2023.51 ppm. On the other hand, naturally ventilated classrooms had lower CO_2 concentrations, ranging from 587.7 to 771.5 ppm, which were within the recommended limits.

2.3.3 Comfort Parameters

Thermal comfort i.e., maintaining suitable temperature and humidity is vital for human health and well-being [56]. ASHRAE defines it as the psychological state in which an individual feels satisfied with the surrounding thermal environment [57]. In tropical regions with hot and humid conditions, occupants of naturally ventilated buildings often experience heat-related discomfort, requiring enhanced air movement to sustain indoor comfort [58]. Several factors that influence indoor thermal comfort include a building's thermal insulation, orientation, the surrounding outdoor climate, and occupant density [59]. Moreover, high moisture content may cause structural damage of a building, reduce thermal resistance, alter the physical properties of building materials, deform structural elements, and shorten a building's service life [60].

For students, the thermal environment significantly affects work performance, perceived comfort, and overall health [61]. Deng and Lau [62] found that increasing indoor temperatures from 20°C to 25°C can notably impair students' academic outcomes. Additionally, prolonged exposure to low humidity can irritate the eyes and airways and negatively impact cognitive performance and sleep quality [63]. The study by Asif et al. [59] revealed that indoor temperature and relative humidity in classrooms of academic buildings with various Heating, Ventilation, and Air Conditioning (HVAC) systems were influenced by outdoor climate and building orientation. Indoor temperature was found to have frequently exceeded standard thresholds, while relative humidity (RH) levels were observed to have remained below the ASHRAE-recommended 65%. Liu et al. [64] further highlighted the significant role of RH in shaping college going student's learning environments. While high humidity made students feel more uncomfortable, low humidity adversely affected their cognitive performance—largely due to discomfort-like eye and respiratory dryness. At 40% RH, marked improvements were observed in fatigue levels, reading speed, and attention, compared to conditions at 20% RH, underscoring RH as a critical factor in educational indoor air quality assessments [64]. Furthermore, Bhandari et al. [27] investigated how non-uniform fan-induced airflow affected thermal comfort in naturally ventilated lecture halls under warm, humid conditions. Their study also revealed notable comfort differences across seating zones. They proposed a new adaptive comfort model that incorporates air velocity to address these variations more effectively. Beyond educational settings, Psomas et al. [65] examined low indoor RH in Swedish apartments during the heating season, noting its severity in homes with high indoor temperature. They suggested climate-specific moisture supply values and linked low humidity to possible health symptoms, stressing the need for improved humidity control in cold climates to safeguard health and building integrity. The study by Tasgaonkar and Murari [66] identified extreme indoor temperature as a growing health threat in rural India, with tin-roofed homes in Wardha reaching up to 40 °C. Around 80% of residents reported heat-related symptoms, commonly fatigue, heavy sweating, intense thirst, dry mouth, leg cramps, and headaches, underscoring the urgent need for better housing and local heat mitigation efforts.

2.4 Settled Dust

Indoor settled dust (SD) has been recognized as a potential vector for inorganic and organic contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAH), and pesticides [67-70]. Heavy metals (HMs) are metals with specific densities over 5 g/cm^3, occurring naturally in minimal quantities on Earth [71]. They are present in trace amounts in the earth's crust, and are introduced into the surface environment through anthropogenic activities, thereby increasing their natural background levels [72]. HMs in SD are significant toxic micropollutants that have gathered considerable attention from researchers over the past three decades [73].

The presence of HMs and other elements in SD is crucial for understanding their harmful effects on human health [74]. These elements can contribute to respiratory conditions, neurological issues, allergies, and more severe health problems like ischemic heart disease and anemia due to chronic exposure [73, 75, 76]. Furthermore, exposure to toxic metals like Cd, As, and Pb has been linked to carcinogenic effects in various organs, including the skin, liver, lungs, and bladder [76].

Olujimi et al. [77] investigated elemental concentrations in dust from classrooms, households, and other indoor settings, identifying Al, Ca, Fe, K, Mg, Na, and Ti as the most abundant elements. They observed higher concentrations of carcinogenic metals in living rooms (Pb > Ni > Co > As > Cd) compared to classrooms (Pb > Co > Ni > As > Cd). Similarly, Kumar and Jain [78], in Dhanbad, analyzed household dust and found elements such as C, O, Si, Ca, Mg, Al, Fe, Cl, K, Na, S, and Ti, with C and O making up the bulk. Their study also revealed the presence of functional groups like $-CH_3$, –COOH, and –C=O, and minerals such as calcite, dolomite, and quartz, suggesting varied sources of indoor dust. Nath et al. [38] in Tezpur, Northeast India found urban school dust to be more enriched with anthropogenic elements like Cu, Cd, and Pb compared to rural schools. Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD) analyses confirmed quartz, calcite, and haematite as dominant minerals, pointing to soil, chalk, and anthropogenic origins. Gohain and Deka [79] found that Cd was the highly enriched element, followed by Pb, Zn, and Ni in different indoor environments of Tezpur University, Assam, India.

Comparative studies further emphasized the environmental and spatial influence on dust contamination. Hejami et al. [80] identified laboratories as having the highest concentrations of toxic metals (Cd, Cu, Pb, Zn), significantly exceeding those in households and classrooms, indicating strong anthropogenic influence. Okoro et al. [81] reported that dust from Nigerian classrooms contained high levels of As, Pb, and Co, with statistically significant variation across classrooms ($p \leq 0.05$). Dubey et al. [82] found that roadside schools harbored higher elemental loads in indoor settled dust compared to residential schools, highlighting location as a key determinant of exposure risk. Khajooee et al. [83] had reported high levels of Zn, Cu, and Pb in SD of households in Tehran. They attributed this to urban overpopulation, traffic congestion, and poor ventilation. These factors exacerbate indoor dust contamination in densely built environments.

2.5 Sick Building Syndrome

Sick Building Syndrome (SBS) is defined by a collection of symptoms that lack a known explanation. Symptoms of SBS can include eye, nose, and throat irritation, headaches, and various other disorders. These symptoms can be grouped into five categories: (1) Eye irritation, such as tired or strained eyes, dryness, and itching; (2) Nonspecific symptoms, including headaches, fatigue, stress, anxiety, low to no concentration, dizziness, and nausea; (3) Upper respiratory issues, like a sore or dry throat, nasal congestion or a runny nose, coughing, and sneezing; (4) Lower respiratory problems, such as asthma; and (5) Skin irritation, including dry skin and rashes [84-89].

SBS symptoms have been reported in a variety of settings, including office buildings, houses, schools, public facilities, healthcare establishments, and recreational spaces [85, 90]. Besides building characteristics and occupant activities, certain personal factors, including female gender and infants, a history of atopy or allergic disorders, smoking status, as well as most urban dwellers of any age have been frequently associated with a greater incidence of SBS due to high sensitivity [91-95]. For instance, individuals with a history of asthma may be more vulnerable to developing asthma exacerbations due to SBS. The symptoms of SBS can vary from person to person; while some individuals may experience certain symptoms, others may not show any at all [96].

Numerous studies have established a correlation between IAQ and SBS, highlighting the necessity to examine how real parameters such as temperature, relative humidity; CO_2 concentration, and ventilation alongside chemical pollutants collectively affect SBS through overall IAQ [97, 98]. In a study by Fard et al. [99] on building characteristics and SBS among primary school students in Qom, Iran, it was found that 24% of students experienced SBS symptoms. Gender, along with indoor environmental factors such as ventilation, school building age, and psychosocial factors like students' satisfaction with classroom size and lighting, were significant contributors to SBS. Similarly, Mohan [89] had observed tiredness or lethargy among 54.1%, 48.8%, and 31.7% of occupants in silver, gold, and platinum LEED certified buildings in India, respectively. Similarly, headaches were reported by 43.2% of occupants in silver, 48.9% in gold, and 56.1% in platinum LEED-certified buildings. Furthermore, Ganji et al. [100] found that air conditioner users experienced a higher prevalence of SBS-related respiratory and allergic symptoms compared to those in naturally ventilated buildings, leading to increased absenteeism. Identifying SBS in the workplace and exploring protective measures to mitigate air conditioning system related risks is therefore crucial. Belachew et al. [101] found high SBS prevalence which was associated with fungal growth, building cleanliness, presence of functional windows, and fan availability. Their study suggests that improving sanitation and housekeeping practices could reduce SBS prevalence.

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