# Abstract

Indoor air quality (IAQ) is vital for wellbeing and productivity. The U.S. Environmental Protection Agency (USEPA) defines IAQ as the condition of air within and around buildings and structures, focusing on occupant health, comfort, and wellbeing. Contrary to common assumptions, indoor environments often exhibit pollution levels up to ten times higher than those found outdoors. This is due to the accumulation of pollutants in confined spaces, where air circulation is limited [1]. Elevated indoor pollution is a growing public health concern as people spend 80–90% of their time in different indoor environments [2-5]. Indoor sources of pollutants include emissions from cooking, heating, smoking, and incense burning, as well as off-gassing from paints, textiles, carpets, building materials, and furnishings. Additionally, personal care products, pesticides, and the resuspension of particulate matter (PM) during activities like cleaning and walking also degrade IAQ [6-10]. The infiltration of outdoor particles further worsens IAQ [11].

Among the wide range of pollutants contributing to poor IAQ, $PM_{2.5}$ and $CO_2$ are of particular concern due to their direct impacts on health and work performance. Exposure to PM has been linked to numerous health issues, ranging from asthma and cardiovascular diseases to pulmonary conditions. Additionally, it is associated with both acute and chronic respiratory illnesses, as well as tuberculosis and adverse perinatal outcomes [12]. Similarly, in poorly ventilated spaces with higher occupancy, $CO_2$ concentrations can rise significantly, leading to potential health impacts such as headaches, fatigue, and reduced cognitive performance [13-14].

Settled dust (SD) indoors is another important contributor to IAP. It is present in indoor environments as a composite of PM resulting from internal and external sources, and it can act as a reservoir for various harmful elements, including heavy metals [15-18]. Elements in SD are particularly concerning due to their persistence, non-biodegradability, and potential for bioaccumulation, posing significant environmental risks [15,19]. It can enter the body through various pathways, including inhalation, ingestion, and dermal contact [20-21]. As a result, understanding the composition and impact of SD is crucial for mitigating its potential health risks and improving overall IAQ.

Prolonged exposure to poor IAQ, especially in buildings with insufficient ventilation or prevalent pollutants, can lead to Sick Building Syndrome (SBS). While definitions of SBS vary, Joshi [22] described it as a condition where building occupants suffer from acute health or comfort issues directly linked to their time spent inside the building. SBS is often linked to elevated levels of indoor pollutants, such as volatile organic compounds (VOCs) and PM, which irritate the mucous membranes and can trigger symptoms like headaches and respiratory discomfort. In confined spaces with poor ventilation, the accumulation of these pollutants exacerbates SBS, leading to physical and mental health issues among occupants [23-24]

Several studies have extensively reported IAQ and the heavy metal composition of SD in various indoor environments such as offices, schools, colleges, universities, and homes [25-30]. In the Indian context, some studies have documented the elemental composition of SD from both households and educational institutions [31-35]. Additionally, numerous studies have monitored IAQ in various indoor settings while evaluating occupants' perceptions of IAQ [36-42].

However, there remains a significant gap in research on IAQ and SD in Northeast India, with a few studies conducted in this region [43-46]. Most existing research does not employ real-time monitoring of key parameters such as temperature (T), relative humidity (RH), $PM_{2.5}$, and $CO_2$. These dynamic parameters are essential for capturing daily variations in air quality and understanding how indoor environmental conditions vary in response to occupancy and ventilation. Furthermore, there is a marked absence of integrated physicochemical analysis of SD alongside IAQ measurements. Such integration is necessary to assess long-term exposure to heavy metals and other persistent pollutants, which accumulate over time in dust reservoirs and may pose chronic health risks. To address this gap, the present study was conducted in Guwahati, the largest metropolis in Northeast India, and Tezpur, an urban agglomeration in Assam, Northeast India. Given the rapid urbanization and industrial development in these areas, understanding IAQ in these regions is critical. This is the first comprehensive study to simultaneously characterize indoor air pollutants, the physicochemical properties of SD and residents' perceptions of IAQ. By examining all these parameters in households and educational settings, the study aims to provide a more holistic understanding of the overall indoor environment, offering a more comprehensive assessment of IAQ. The research objectives of the present study are-

1. **Characterization of indoor air in educational institutions and households of Guwahati and Tezpur, Assam**
2. **Physicochemical characterization of settled dust in different indoor environments**
3. **Health risk assessment and association of indoor air with sick building syndrome (SBS)**

Initially, a pilot study was conducted across nineteen schools in Tezpur to assess IAQ and elemental exposure risks. One-hour sampling was performed using the Side Pak™ aerosol monitor and the Testo 400-Universal IAQ instrument and Air quality probe 088. Settled dust samples were also collected and analysed via Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) after aqua regia digestion. $PM_{2.5}$ levels exceeded World Health Organisation (WHO) guidelines in all schools, while $CO_2$ levels indicated adequate ventilation. For SD, enrichment factor (EF) value showed high enrichment for Pb, Cd, Ni, and Zn in all classrooms. Moreover, the average EF for the Traffic Related Elements (TREs) was highest in urban schools, followed by suburban and rural schools. The degree of contamination ($C_{degree}$) values suggested a moderate level of contamination in all schools. The Pollution Load Index (PLI) values were below 1, indicating low to negligible pollution. Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) analyses of classroom dust samples showed that quartz, calcite, and haematite were the most common minerals. Although non-carcinogenic and carcinogenic risks were within safe limits, the overall Total Lifetime Cancer Risk (TLCR) for rural (1.37E-04), suburban (1.09E-04), and urban (1.08E-04) areas were slightly above the acceptable limits. Insights from this pilot study has enabled further study on IAQ and settled dust along with the associated health risks in different indoor environments.

## Characterization of indoor air in educational institutions and households of Guwahati and Tezpur, Assam

IAQ was assessed across various educational institutions and households in Assam. Two university campuses were examined: one located within the urban core of Guwahati city, the largest city in Assam, representing an urban campus, namely Cotton University (CU); and the other situated approximately 13 kilometers from Tezpur city in Sonitpur district, representing a rural campus, i.e., Tezpur University (TU). IAQ monitoring was also conducted in 14 residential households, six in Guwahati and eight in Tezpur. In Guwahati, two households each were selected from commercial, industrial, and residential areas. In Tezpur, three households were selected from urban residential areas, three from commercial areas, and two from rural residential areas. The parameters measured across all sites included $PM_{2.5}$, $CO_2$, T, and RH. A Side Pak™ personal aerosol monitor (Model: AM520), a battery-operated laser photometer pre-calibrated by the manufacturer with ISO 12103-1 using A1 Arizona test dust, continuously measured the indoor $PM_{2.5}$ levels. The equipment was placed centrally in rooms, away from windows, doors, and corners, and set at a height corresponding to the occupant's breathing zone. All indoor air quality parameters were recorded at a one-minute logging interval to ensure high-resolution temporal data. In addition to $PM_{2.5}$, T, RH, and $CO_2$ concentrations were measured using the Testo 400-Universal IAQ instrument and Air quality probe 088, configured to log data at one-minute intervals. Samples were collected from both indoor and outdoor air. Furthermore, the deposition of particles in the human respiratory system was evaluated using the multiple-path particle dosimetry (MPPD) model (MPPD v3.04). The model simulates the overall and regional lung deposition as well as deposition for each lung lobe.

*Educational Institutions*

At CU, located in urban campus, the average T and RH across all assessed classroom microenvironments (CR1_U, CR2_U, CR3_U, and CR4_U) were $25.57 \pm 1.24$ °C and $73.01 \pm 4.09\%$, respectively. Similarly, at TU located within the rural campus (RC) included an eatery (ET1_R), classrooms (CR2_R and CR3_R), and a library (LIB4_R). Across these microenvironments, the average T and RH were $28.78 \pm 2.33$ °C and $72.64 \pm 6.85\%$, respectively.

The average $PM_{2.5}$ concentrations were significantly higher ($p < 0.001$) at CU ($114.49 \pm 28.58$ μg/m³) than TU ($71.61 \pm 27.88$ μg/m³). Furthermore, $PM_{2.5}$ concentrations in all indoor microenvironments were substantially higher than the WHO 24-hour guideline value of 15 μg/m³, indicating potential health risks from prolonged exposure. $CO_2$ concentrations remained within the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 62.1) recommended limit of 1000 ppm. The total deposited mass of

$PM_{2.5}$ (μg) and the deposition density (μg/m²), as estimated by the MPPD model, were approximately 1.54-1.55 times higher at CU than TU.

*Households*

The average T across all households in Guwahati and Tezpur remained below ASHRAE's comfort threshold of 27 °C, while the average RH exceeded the recommended limit of 65%. The average $PM_{2.5}$ concentrations were significantly higher ($p < 0.001$) in the six households of Guwahati (206.17±106.85 μg/m³) compared to the eight households of Tezpur (41.01 ± 21.95 μg/m³), with a mean difference of approximately 165 μg/m³ which is approximately five times higher in Guwahati. All households exceeded the WHO threshold limit. $CO_2$ concentrations remained within the ASHRAE 62.1 recommended limit across all the households of Guwahati and Tezpur. The total deposited mass of $PM_{2.5}$ (μg) and the deposition density (μg/m²), as estimated by the MPPD model, were found to be approximately 4.3 to 5.6 times higher for the households in Guwahati than Tezpur.

**Physicochemical characterization of settled dust in different indoor environments**

Settled dust samples were collected from different microenvironments of two universities and the same households where IAQ measurements were conducted. For elemental analysis, dust was gently collected from 1 m² floor areas using a soft paintbrush and plastic dustpan. Five samples were taken from the four corners and the centre of each room and combined to form a composite sample per site. The collected samples were sealed in airtight, labelled plastic bags for transport and storage. Subsequently, the labelled samples were sieved using a 53 μm pore-sized sieve to remove unwanted particles and hairs. The sieved samples were then dried in a hot air oven (Jain Scientific Glass Works; ISO 9001:2008 certified) at 105 °C for approximately 24 h [45]. The oven-dried samples were prepared for analysis. 0.5 g of dried dust was weighed using a microbalance (Radwag, Germany) and treated with 12 mL of aqua regia ($HNO_3$: HCl in 3:1 v/v), along with 3 mL of hydrofluoric acid (HF, 40%). The mixture was transferred into Teflon vessels and digested using a microwave digester (Anton Paar, Multiwave GO, Austria). Each batch included one blank sample. The digested samples were filtered and stored at 4 °C for elemental analysis using Inductively Coupled Plasma Optical Emission spectroscopy (ICP-OES). The mineralogical composition of selected dust samples was determined by recording the qualitative mineralogy using the XRD (Bruker model, D8 focus) technique FTIR (Perkin Elmer, Model Spectrum 100) in the range of 4000 to 400 $cm^{-1}$.

*Educational Institutions*

CU (3610.50±7744.05 mg/kg) showed higher average elemental concentrations compared to TU (3387.13±8830 mg/kg). The EF for Cd was classified as “extremely high” across both campuses. Additionally, Pb exhibited a range from very high to extremely high EF at the CU, while at the TU, EF values for Pb ranged from “high” to “extremely high”. All microenvironments exhibited a very high $C_{degree}$. The PLI values were less than 1 (low PLI) in only one classroom microenvironment in CU. Conversely, only one microenvironment (LAB8_S) had a PLI greater than 1 (considerable PLI) at TU. In general, the geoccumulation index ($I_{geo}$) was highest for Cd, followed by Pb across all microenvironments of both TU and CU. FTIR and XRD analyses confirmed the presence of minerals such as quartz, illite, and calcite as the most common minerals in the SD collected from educational institutions.

*Households*

Guwahati households recorded a higher average elemental load than Tezpur households (4207.42 mg/kg vs. 4199.09 mg/kg). Cadmium demonstrated “extremely high” EF in all households except RH5_G (a residential household in Guwahati). Lead followed closely, displaying EF values ranging from “high” to “extremely high”, indicating significant anthropogenic influence. All households of Guwahati and Tezpur exhibited a very high $C_{degree}$ except households located in residential areas of Guwahati, which recorded an average $C_{degree}$ of 22.04, indicating a considerable degree of contamination. Households in commercial areas exhibited the highest PLI values, with 1.25 in Guwahati and 2.02 in Tezpur. Households in industrial areas of Guwahati recorded a PLI of 0.94, followed by residential areas with 0.72. In Tezpur, urban residential households showed a PLI of 0.87, while rural residential households recorded a value of 1.17. The Igeo index showed the highest value for Cd, followed by Pb across all households. FTIR and XRD analyses confirmed that quartz, calcite, and hematite are among the most common minerals present in the SD of households.

**Health risk assessment and association of indoor air with sick building syndrome (SBS)**

Health risk assessment was calculated across all monitored sites, i.e., two universities and fourteen households in Guwahati and Tezpur. Exposure to harmful elements in classroom-settled dust was estimated through three pathways: ingestion, inhalation, and dermal contact [21]. The human health risks associated with non-carcinogenic and carcinogenic exposures were calculated using USEPA 2011.

Sick Building Syndrome (SBS) was investigated in Guwahati, the most urbanized and densely populated city in Northeast India, owing to its rapid urban expansion, high population density, and growing concern over IAQ. Five hundred fifty households were taken following Cochran's formula, each represented by a single respondent. Inclusion criteria specified that respondents must be eighteen or older and residents of Guwahati for at least 6 months to ensure familiarity with their indoor environment. Data were collected through both online and offline survey modes to maximize outreach and response rates.

The Health Risk Assessment (HRA) indicated that non-carcinogenic risks from elemental exposure were within acceptable limits for adults in all sites. However, the cumulative hazard index ($\sum HI$) exceeded the threshold value of 1 for children, suggesting potential health concerns. Among the three exposure pathways viz., ingestion, dermal contact, and inhalation, ingestion was identified as the primary route of exposure to dust particles, followed by dermal contact and inhalation. The individual lifetime cancer risks from chromium (Cr), cobalt (Co), Pb, nickel (Ni), and Cd remained within the acceptable range of $10^{-6}$ to $10^{-4}$ [47-48].

The study on SBS showed general complaints followed by aches and pains, nasal symptoms and dermal problems as the most frequently reported complaints. Logistic regression analysis of odds ratios revealed that factors such as gender, building age, smoking, moulds on wall, presence of visible dust and having a medical history, influenced the likelihood of experiencing various SBS symptoms.

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