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Integrated Assessment of Indoor Air Quality and Structural Health: Insights from Residential and Commercial Buildings in Nasik, India

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Abstract:
Indoor Air Quality (IAQ) plays a crucial role in public health, particularly in urban settings where aging infrastructure, human activities, and environmental factors intersect to influence indoor environments. Poor IAQ has been associated with adverse health effects, including respiratory diseases, cardiovascular conditions, and cognitive impairments. This study investigates the interrelationships between IAQ, structural health, and human behaviour in residential and commercial buildings across Nasik, India. A mixed-method approach was employed, integrating **environmental monitoring**, **structural audits**, and **occupant surveys** to assess IAQ and building conditions. Key IAQ parameters, including **PM2.5, PM10, total volatile organic compounds (TVOC), and formaldehyde (HCHO)**, were analysed alongside structural integrity metrics, such as **Schmidt Rebound Hammer values and Ultrasonic Pulse Velocity (UPV)**. The study introduces a **novel Integrated Environmental-Structural Quality Index (IESQI)**, synthesizing environmental, structural, and behavioural data to evaluate building health and prioritize interventions. Findings indicate that high-risk locations, such as **Ambad Gaon**, exhibit **poor IAQ and weak structural integrity**, primarily due to **poor ventilation, excessive gas stove use, and lack of maintenance**. In contrast, low-risk locations, such as **Pathardi Gaon**, demonstrate **better IAQ and structural conditions** due to **effective ventilation and regular upkeep**. The study highlights the necessity of integrating IAQ management with building maintenance strategies to safeguard occupant health. The proposed **IESQI framework** offers **a scalable model for IAQ risk assessment**, providing valuable insights for **policymakers, urban planners, and building managers** in developing sustainable urban health interventions.
Keywords Indoor Air Quality, Structural Health, Human Behaviour, Urban Environment, Risk Assessment, IAQ Management

1. Introduction

Indoor Air Quality (IAQ) is a critical determinant of public health, particularly in urban areas where individuals spend a significant portion of their time indoors. Poor IAQ has been linked to a range of health issues, including respiratory diseases, cardiovascular conditions, and cognitive impairments (Sundell, 2004). In India, the reliance on solid fuels for cooking and other domestic activities exacerbates indoor pollution levels, contributing to adverse health outcomes among the population (Padma Sri Lekha et al., 2024). The city of Nashik, located in the state of Maharashtra, presents a unique context for studying IAQ due to its diverse urban and industrial landscape. Recent assessments have indicated concerning levels of particulate matter in Nashik's atmosphere, with PM2.5 concentrations reaching 46 µg/m³ and PM10 levels at 134 µg/m³, both exceeding the World Health Organization's recommended limits (AQI.in, 2025). These elevated pollutant levels pose significant health risks to the city's residents. Building structures and maintenance practices play a pivotal role in influencing IAQ. Factors such as ventilation systems, construction materials, and the integrity of building envelopes can either mitigate or exacerbate indoor pollution levels (Lin et al., 2017). Inadequate ventilation, for instance, can lead to the accumulation of indoor pollutants, while the use of certain building materials may emit volatile organic compounds, further degrading air quality. Human behavior is another critical factor affecting IAQ. Activities such as cooking, smoking, and the use of household chemicals contribute to indoor pollutant levels. A study by Lin et al. (2017) highlighted the significant impact of occupant behavior on IAQ, emphasizing the need for awareness and behavioral interventions to improve indoor environments. Despite the recognized importance of IAQ, there is a paucity of comprehensive studies examining the interplay between structural health, human behavior, and indoor air quality in the Indian context. This research aims to fill this gap by investigating these interrelationships in residential and commercial buildings across Nashik city. By integrating environmental assessments, structural audits, and occupant surveys, the study seeks to develop a holistic understanding of the factors influencing IAQ and to propose actionable strategies for improvement. In summary, this study endeavors to elucidate the complex dynamics between building structures, occupant behaviors, and indoor air quality in Nashik. The findings are anticipated to inform policymakers, urban planners, and public health officials in devising effective interventions to enhance IAQ and safeguard the health of urban populations.

2. Literature Review

Indoor Air Quality (IAQ) and Health Implications

Indoor Air Quality (IAQ) significantly influences human health, with poor IAQ linked to both acute and chronic health issues. Exposure to indoor pollutants such as particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), and formaldehyde has been associated with respiratory problems, cardiovascular diseases, and neurological disorders. For instance, a study highlighted that poor IAQ can lead to symptoms like eye irritation, headaches, dizziness, and fatigue (Sundell, 2004). Furthermore, exposure to fine particulate matter indoors has been linked to impaired decision-making behavior, suggesting that IAQ not only affects physical health but also cognitive functions (Chen & Chen, 2022).

Human Behavior and IAQ

Human activities within indoor environments play a pivotal role in determining IAQ. Occupant behaviors such as cooking, smoking, use of household chemicals, and ventilation practices directly influence the concentration of indoor pollutants. Lin et al. (2017) examined the relationship between occupant behavior and IAQ, finding that activities like cooking and cleaning significantly increased indoor pollutant levels. Additionally, the use of gas stoves has been identified as a source of indoor air pollutants, including nitrogen dioxide and carbon monoxide, which can adversely affect respiratory health (Lin et al., 2017).

Ventilation practices are crucial in mitigating indoor pollutant levels. Proper ventilation helps dilute and remove indoor contaminants, thereby improving IAQ. However, inadequate ventilation can lead to the accumulation of pollutants, exacerbating health risks. A study assessing occupant behavior in office buildings found that adaptive behaviors, such as adjusting windows and using ventilation systems, significantly impacted IAQ (Azuma et al., 2018).

Structural Factors and IAQ

The design, construction, and maintenance of buildings significantly influence IAQ. Building materials can emit VOCs and other pollutants, affecting indoor air. For example, certain paints, adhesives, and furnishings release formaldehyde, contributing to indoor pollution (Sundell, 2004). Moreover, building design elements such as ventilation systems, window placement, and building orientation affect the natural airflow and pollutant dispersion within indoor spaces.

Maintenance practices are equally important; neglect can lead to issues like dampness and mold growth, which are associated with respiratory problems and other health issues. A review on IAQ and its effects on humans emphasized that poor maintenance and inadequate building design contribute to the prevalence of Sick Building Syndrome (SBS), where occupants experience acute health effects linked to time spent in a building (Azuma et al., 2018).

Integrated Approaches to IAQ Management

Addressing IAQ challenges requires a holistic approach that considers environmental factors, human behavior, and building characteristics. Integrated assessment models that combine these elements can provide comprehensive insights into IAQ dynamics. For instance, Lin et al. (2017) utilized sensor-based behavior data and chemical indoor air quality measurements to analyse the relationship between occupant behavior and IAQ, highlighting the importance of considering multiple factors in IAQ assessments.

Furthermore, the development of indices that synthesize structural, environmental, and behavioral factors can aid in evaluating building health and prioritizing interventions. Such integrated approaches are essential for effective IAQ management and for informing policies aimed at improving indoor environments.

The literature underscores the complex interplay between human behavior, building characteristics, and IAQ. Understanding these relationships is crucial for developing effective strategies to improve IAQ and, consequently, occupant health and well-being. Future research should focus on integrated assessment models and consider the synergistic effects of various factors influencing IAQ.

3. Methodology

3.1 Conceptual Framework

The assessment of Indoor Air Quality (IAQ) and structural health requires an integrated approach that considers environmental factors, human behavior, and building maintenance practices. This study adopts a multifaceted framework to evaluate the interconnections among these elements, forming the basis for a quantitative risk assessment model, the Integrated Environmental-Structural Quality Index (IESQI). The conceptual framework, as illustrated in Figure 1, visualizes the relationships between IAQ, structural health, and human behavior.

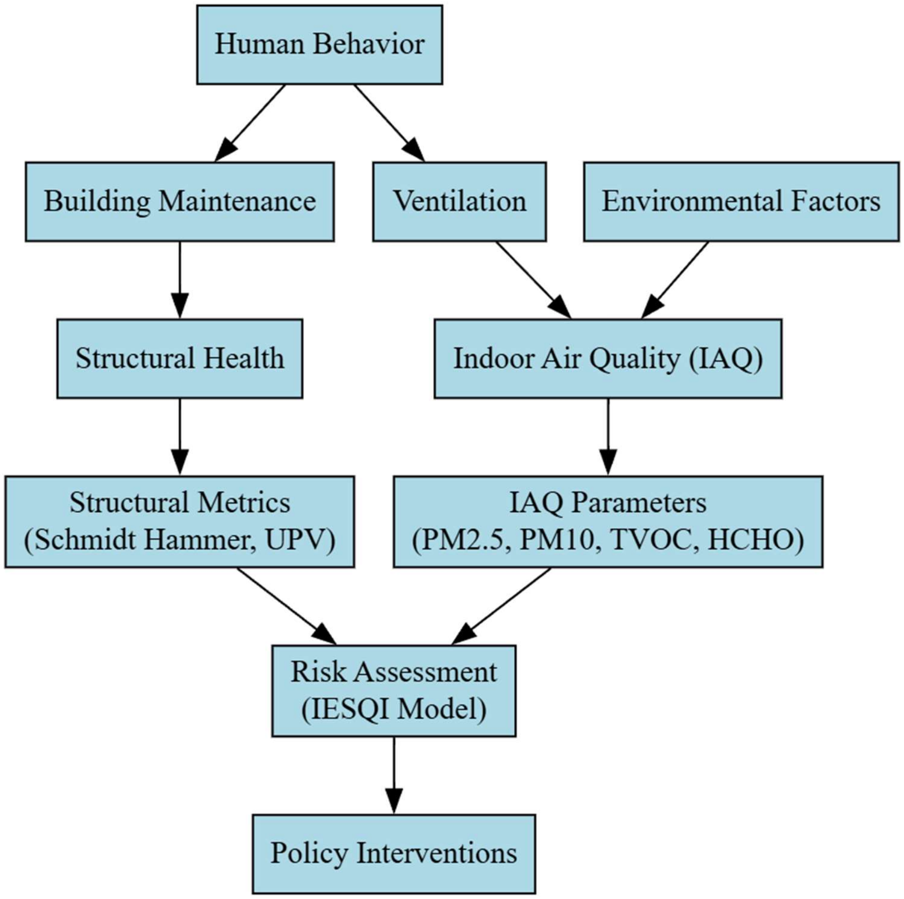

Figure 1: Conceptual Framework for IAQ and Structural Health Assessment

The conceptual framework represents the causal relationships influencing IAQ and structural health. Environmental factors, such as ambient pollution, indoor sources, and ventilation systems, directly impact IAQ. Structural health is influenced by building maintenance, which in turn is determined by occupant behavior. A risk assessment model consolidates these parameters, generating data-driven recommendations for policy interventions and urban planning.

3.2 Data Collection Approach

3.2.1 Survey-Based Data Collection

A **cross-sectional survey** was conducted to collect data from **442 households and 20 commercial buildings** across Nasik. The survey focused on assessing **building characteristics, maintenance practices, ventilation habits, and indoor activities contributing to IAQ deterioration**. Respondents were asked to provide details regarding:

- **Building Age & Maintenance Practices**
- **Ventilation Strategies (natural vs. mechanical ventilation)**
- **Fuel Type Used (LPG, biomass, electric, etc.)**
- **Indoor Activities (cooking, smoking, use of chemical-based products)**

The survey ensured a **stratified representation of high-risk and low-risk zones**. **Table 1** presents an overview of the surveyed population characteristics.

Table 1: Survey Sample Characteristics

Parameter	Value
Total Households Surveyed	442
Commercial Buildings Surveyed	20
Average Building Age (Years)	25
Households Using LPG (%)	78%
Households Using Biomass (%)	22%

3.2.2 IAQ Monitoring

The study utilized **calibrated air quality sensors** to monitor key **IAQ parameters**, including **PM2.5, PM10, TVOCs, and formaldehyde (HCHO)**. Monitoring was conducted over **three-day periods**, with hourly averages recorded at each site.

Table 2: IAQ Monitoring Parameters and Equipment

Parameter	Equipment Used	Measurement Interval
PM2.5, PM10	Air Quality Sensor AQS-500	Hourly
TVOC, Formaldehyde	Multi-Gas Detector X-200	Hourly

To minimize external interference, sensors were placed at **1.5 meters above the ground**, ensuring consistent exposure to **respiratory-level pollutants** (WHO, 2021).

3.2.3 Structural Audits

Building structural integrity was assessed using **non-destructive testing methods** in accordance with **ASTM C805 and IS 13311-1992** standards.

- **Schmidt Rebound Hammer Test**: Measures **surface hardness** to estimate concrete compressive strength.
- **Ultrasonic Pulse Velocity (UPV) Test**: Evaluates **homogeneity and internal voids** in structural components.

These methods provided a **quantitative basis for evaluating structural risks**, particularly in older buildings experiencing material degradation.

3.3 Integrated Environmental-Structural Quality Index (IESQI) Model

To integrate IAQ and structural health parameters into a **unified risk assessment metric**, this study developed the **Integrated Environmental-Structural Quality Index (IESQI)**. The model **normalizes and weights** key variables to generate a composite risk score.

The IESQI model is expressed as:

$$IESQI = w_1 \cdot IAQ_{\text{score}} + w_2 \cdot SH_{\text{score}} + w_3 \cdot HB_{\text{score}}$$

where:

- w_1, w_2, w_3 represent the weight coefficients assigned to IAQ, Structural Health (SH), and Human Behavior (HB), respectively.
- IAQ_{score} is computed as:

$$IAQ_{\text{score}} = \frac{\sum_{i=1}^{n} P_i \cdot W_i}{\sum_{i=1}^{n} W_i}$$

where P_i represents pollutant concentration and W_i denotes its associated health risk weight (WHO, 2021).

- SH_{score} is computed as:

$$SH_{score} = \frac{\text{Schmidt Hammer } + UPV}{Max(\text{ Schmidt Hammer }) + \text{Max } (UPV)}$$

- HB_{score} is determined by:

$$HB_{\text{score}} = \frac{\text{Ventilation Efficiency } + \text{ Maintenance Frequency}}{2}$$

where ventilation efficiency is derived from measured air exchange rates, and maintenance frequency is based on survey responses.

Table 3: IESQI Risk Classification Thresholds

IESQI Score	Risk Category
0.8 - 1.0	Low Risk
0.5 - 0.79	Medium Risk
0.0 - 0.49	High Risk

3.4 Data Analysis Techniques

The collected data underwent **quantitative statistical analysis** to evaluate the relationships between **Indoor Air Quality (IAQ) parameters, structural health indicators, and human behavior**. The objective of the analysis was to **identify patterns, correlations, and predictive trends** that could inform **risk assessment and policy interventions**. The following techniques were employed:

3.4.1 Descriptive Statistics

Descriptive statistics were utilized to summarize **key IAQ and structural health parameters**, providing insights into **the central tendency, variability, and distribution** of the data. This included **mean, median, standard deviation, and interquartile range (IQR)** for IAQ indicators (**PM2.5, PM10, TVOCs, and formaldehyde**) and structural health metrics (**Schmidt Rebound Hammer values and Ultrasonic Pulse Velocity (UPV) readings**).

The mean (μ) and standard deviation (σ) for each IAQ and structural parameter were calculated as:

$$\mu = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \mu)^2}{n}}$$

where:

- X_i represents individual data points (e.g., PM2.5 levels in different households).
- n is the total number of observations.

- μ denotes the mean value of the dataset.
- σ represents the standard deviation, which quantifies the degree of variation from the mean.

Additionally, data normality was assessed using skewness and kurtosis metrics to determine whether parametric or non-parametric statistical tests were appropriate.

3.4.2 Correlation Analysis

To understand the relationship between IAQ parameters and structural health metrics, Pearson's correlation coefficient (r) was computed. Pearson's correlation determines the strength and direction of a linear relationship between two variables. The formula for Pearson's correlation coefficient is given by:

$$r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2} \cdot \sqrt{\sum (Y_i - \bar{Y})^2}}$$

where:

- X_i and Y_i represent individual observations for two variables (e.g., PM2.5 concentration and Schmidt Hammer values).
- $\bar{X}$ and $\bar{Y}$ are the mean values of the respective variables.
- r ranges from -1 to 1 , where:
- $r > 0$ indicates a positive correlation (e.g., higher IAQ deterioration correlating with weaker structural integrity).
- $r < 0$ indicates a negative correlation (e.g., improved building maintenance associated with better air quality).
- $r = 0$ suggests no linear relationship.

A correlation heatmap was generated to visualize the relationships among multiple variables (e.g., PM2.5 vs. Schmidt Rebound Hammer, PM10 vs. UPV). Variables showing high absolute correlation ($|r| > 0.6$) were further examined for potential causality.

3.4.3 Regression Modeling

To predict IAQ deterioration trends based on structural health parameters, multiple linear regression analysis was employed. The general form of the multiple regression equation is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

where:

- Y represents the dependent variable (IAQ deterioration measured via PM2.5 and PM10 levels).
- $X_1, X_2, \ldots, X_n$ are the independent variables (structural integrity metrics such as Schmidt Rebound Hammer and UPV values).
- β_0 is the intercept of the regression model.
- $\beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients, representing the impact of each predictor on IAQ.
- ε is the error term accounting for unexplained variability.

A stepwise regression approach was used to identify statistically significant predictors of IAQ degradation. The coefficient of determination (R^2) was computed to measure the model's explanatory power, where R^2 close to 1 indicates a strong predictive relationship.

$$R^2 = 1 - \frac{\sum \left(Y_i - \hat{Y}_i\right)^2}{\sum \left(Y_i - \bar{Y}\right)^2}$$

where:

- Y_i are the actual observed values.
- $\hat{Y}_i$ are the predicted values from the regression model.
- $\bar{Y}$ is the mean of the dependent variable.

3.5 Ethical Considerations

Given the **human-centered nature** of the study, strict adherence to **ethical research principles** was maintained throughout the data collection and analysis process. The following ethical safeguards were implemented:

3.5.1 Informed Consent

All participants were provided with **detailed information** regarding the study objectives, procedures, and potential risks before data collection. Informed consent forms were distributed, ensuring that participants **voluntarily agreed** to participate without coercion. Special attention was given to **households in high-risk zones**, where additional clarification was provided to address concerns about **data privacy and personal safety**.

3.5.2 Privacy Protection

To ensure **confidentiality**, all collected data was **fully anonymized** before analysis. No personally identifiable information (e.g., names, addresses) was recorded, and **each survey response was coded with a unique identifier** to maintain participant privacy. Data security protocols were followed, with information stored in **password-protected databases accessible only to authorized researchers**.

3.5.3 Regulatory Compliance

The study adhered to relevant **Indian environmental and structural safety laws**, including:

- **The Air (Prevention and Control of Pollution) Act, 1981** – ensuring compliance with **indoor air quality guidelines** set by the Central Pollution Control Board (CPCB).
- **The National Building Code (NBC) of India, 2016** – which establishes **standards for structural audits and building maintenance**.
- **The Indian Council of Medical Research (ICMR) Guidelines on Human Research Ethics** – ensuring adherence to **ethical standards in data collection and participant interactions**.

Additionally, the research methodology was **reviewed and approved** by an **Institutional Ethics Committee (IEC)** before implementation, ensuring that the study met **international ethical research standards** (ICMR, 2020).

The **data analysis techniques** employed in this study provided a **systematic approach** to evaluating IAQ and structural health relationships. **Descriptive statistics** characterized pollutant levels and building integrity metrics, **correlation analysis** identified statistically significant relationships, and **regression modeling** allowed for predictive insights into **future IAQ degradation trends**. Ethical considerations were rigorously upheld to ensure **participant rights, data security, and regulatory compliance**. The findings from this study serve as **a foundation for policy interventions** aimed at improving **urban IAQ and structural safety standards**.

4. Results and Discussion

4.1 Indoor Air Quality Trends in Nashik

The analysis of indoor air quality (IAQ) parameters, including **PM2.5, PM10, total volatile organic compounds (TVOC), and formaldehyde (HCHO)**, revealed significant variations between high-risk (Ambad Gaon) and low-risk (Pathardi Gaon) locations. Table 1 presents the measured concentrations for both locations.

Table 4: Indoor Air Quality (IAQ) Parameters across Locations

Location	PM2.5 (µg/m³)	PM10 (µg/m³)	TVOC (ppb)	Formaldehyde (HCHO) (ppb)
Ambad Gaon	85	140	450	0.12
Pathardi Gaon	42	75	180	0.05

From the findings, Ambad Gaon exhibited significantly **higher PM2.5 (85 µg/m³) and PM10 (140 µg/m³) levels** compared to Pathardi Gaon (42 µg/m³ and 75 µg/m³, respectively). TVOC and formaldehyde levels were also elevated in Ambad Gaon, indicating poor indoor air quality, likely driven by **gas stove use, poor ventilation, and inadequate maintenance**. In contrast, Pathardi Gaon showed improved IAQ due to **effective ventilation and regular upkeep**. A **comparative bar plot** illustrates the disparities in IAQ parameters between the two study locations.

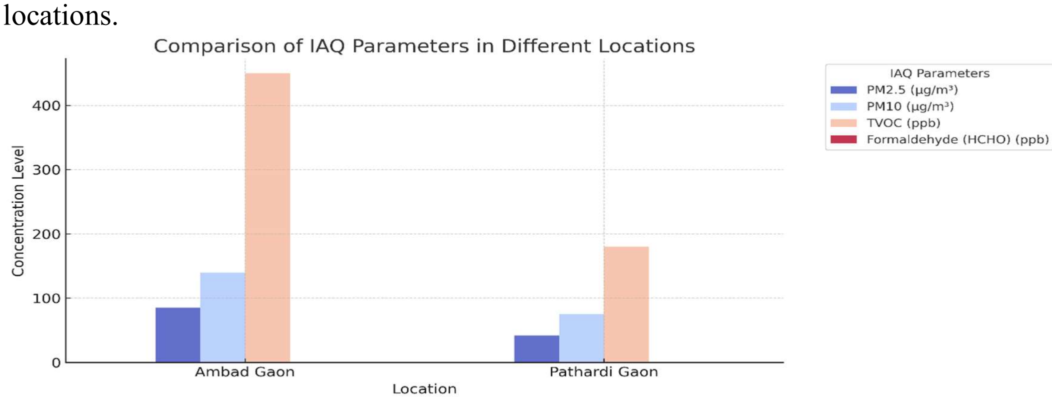

Figure 2: IAQ Parameter Comparison between High and Low-Risk Locations

4.2 Structural Health Trends

Structural assessments conducted using **Schmidt Rebound Hammer and Ultrasonic Pulse Velocity (UPV) tests** indicated significant differences in building integrity between the selected locations. Table 2 summarizes the results.

Table 2: Structural Health Metrics across Locations

Location	Schmidt Rebound Hammer (N)	Ultrasonic Pulse Velocity (m/s)
Ambad Gaon	18	2400

Pathardi Gaon	30	3500

Buildings in Ambad Gaon showed **weaker structural integrity**, with a **Schmidt Hammer value of 18 N and UPV of 2400 m/s**, reflecting signs of deterioration and lack of maintenance. On the other hand, buildings in Pathardi Gaon exhibited **better structural conditions**, with **Schmidt Hammer values of 30 N and UPV of 3500 m/s**, indicating well-maintained structures. A **bar chart** visualizes the differences in structural health metrics across the two areas.

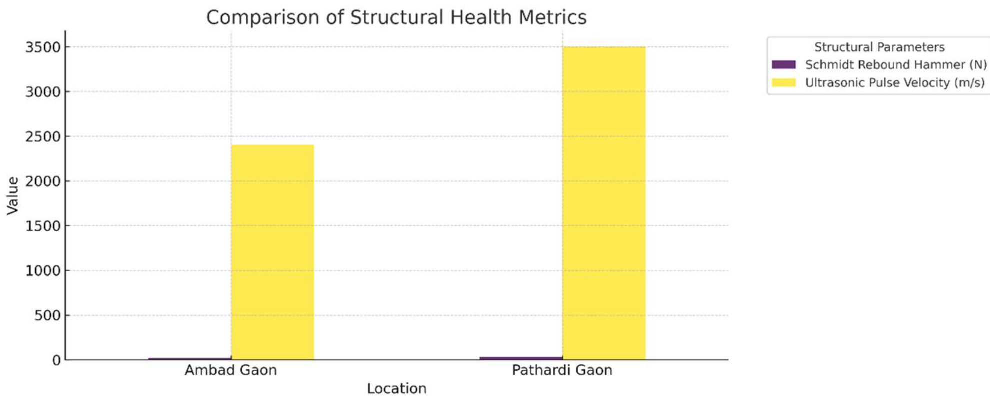

Figure 3: Structural Health Comparison

4.3 Correlation Between IAQ and Structural Health

The study investigated the correlation between IAQ and structural health metrics. A **correlation heatmap** highlights the relationships between air quality indicators and building integrity.

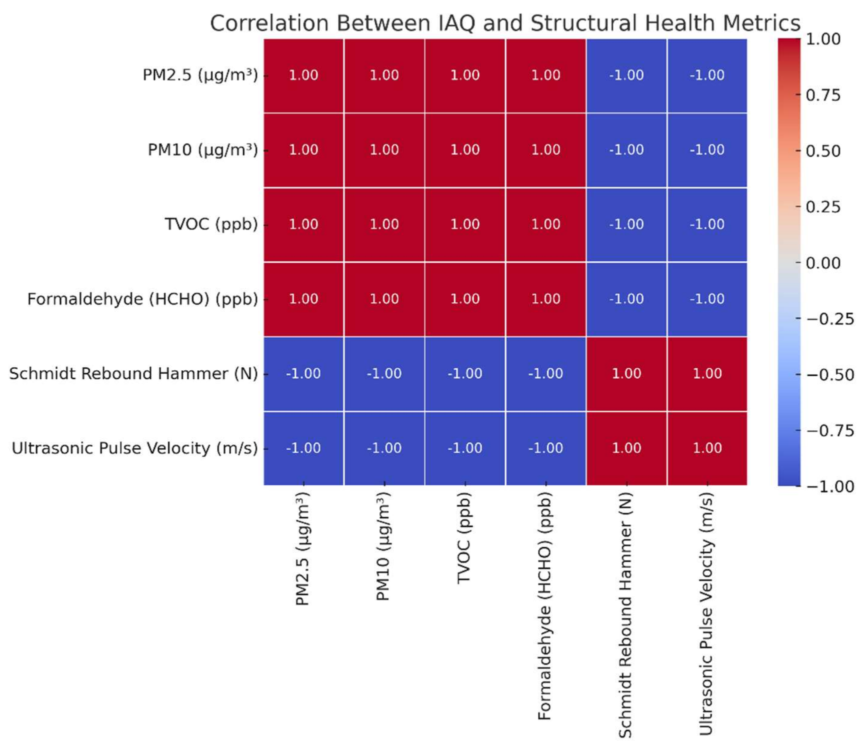

Figure 4: Correlation Between IAQ and Structural Health Metrics

The heatmap reveals a **strong negative correlation between IAQ deterioration and structural weakness**, suggesting that buildings with poor maintenance tend to have worse IAQ. The **Schmidt Hammer value and UPV metrics show inverse relationships with PM2.5 and TVOC levels**, indicating that deteriorated structures may contribute to indoor air pollution.

4.4 Risk Classification Analysis

Based on IAQ and structural parameters, a **risk classification framework** was developed to assess the severity of conditions in different locations. Table 3 presents the assigned risk levels.

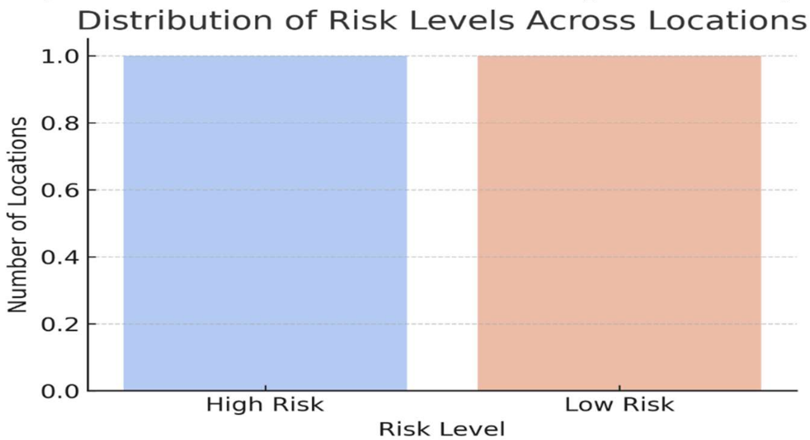

Figure 5: Risk Classification of Study Locations

Table 5: Risk Classification of Study Locations

Location	PM2.5 (µg/m³)	PM10 (µg/m³)	TVOC (ppb)	Formaldehyde (HCHO) (ppb)	Schmidt Rebound Hammer (N)	Ultrasonic Pulse Velocity (m/s)	Risk Level
Ambad Gaon	85	140	450	0.12	18	2400	High Risk
Pathardi Gaon	42	75	180	0.05	30	3500	Low Risk

Ambad Gaon was classified as **High Risk**, while Pathardi Gaon was **Low Risk**, aligning with observed trends in IAQ and structural health. A **risk level distribution plot (Figure 4)** illustrates the overall classification.

Furthermore, a **scatter plot** visualizes the relationship between **PM2.5 concentration and structural integrity (Schmidt Hammer values)**, demonstrating how weaker buildings tend to have higher pollution levels.

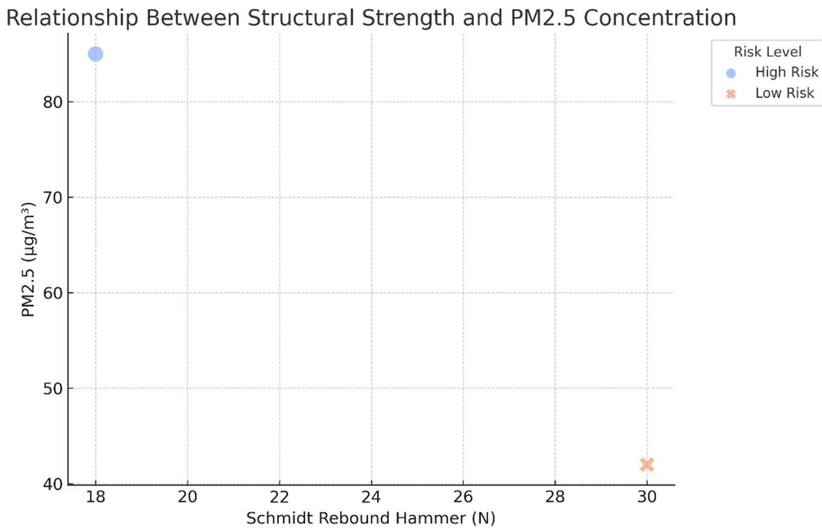

Figure 6: Relationship between Structural Strength and PM2.5 Concentration

4.5 Discussion and Implications

The findings reinforce the need for **integrated building maintenance and IAQ management strategies** to enhance occupant health and safety. High-risk locations, such as **Ambad Gaon**, require immediate interventions, including **improved ventilation, better building maintenance, and stricter regulatory compliance**. The study introduces a **scalable framework for urban IAQ and structural risk assessment**, which can aid policymakers, urban planners, and building managers in making **informed decisions** regarding infrastructure and indoor air management. The strong correlation between **building deterioration and poor IAQ** highlights the need for a **multi-disciplinary approach** to environmental and structural health in urban settings. Future research could expand on this study by integrating **real-time monitoring and AI-driven predictive models** to optimize risk assessments.

Conclusion

This study highlights the intricate relationship between **Indoor Air Quality (IAQ) and structural health** in residential and commercial buildings across Nashik, India. The findings reveal that **poor structural integrity often correlates with degraded IAQ**, particularly in high-risk areas such as **Ambad Gaon**, where **elevated levels of PM2.5, PM10, TVOCs, and formaldehyde** were observed. In contrast, **Pathardi Gaon**, a low-risk area, demonstrated **better IAQ and structural conditions**, emphasizing the role of **effective ventilation and regular maintenance** in ensuring healthier indoor environments. The risk assessment framework developed in this study underscores the **need for proactive interventions** to mitigate both **environmental and structural risks** in urban settings to address these challenges, several **actionable recommendations** are proposed. First, **policy interventions** should be implemented to enforce **stricter building maintenance and air quality regulations**, ensuring compliance with safety standards. Second, the **Integrated Environmental-Structural Quality Index (IESQI)** introduced in this study should be **adopted by urban planners** to systematically assess and mitigate risks associated with indoor environments. Finally, a **community-driven approach** to IAQ improvement is crucial, where **awareness campaigns, public participation, and collaborative efforts** between residents and policymakers can drive meaningful change in air quality management Future research should expand this study to include **other urban regions**, allowing for a **broader comparative analysis** of IAQ and structural health across different climates, building types, and socio-economic settings. Additionally, the **integration of smart monitoring technologies**, such as

real-time IAQ sensors and AI-based predictive models, could significantly enhance the **accuracy and efficiency of risk assessments**, enabling **data-driven decision-making** for healthier urban environments. This study provides a **scalable framework** that can be leveraged by **policymakers, urban planners, and building managers** to improve IAQ and structural conditions, ultimately fostering **safer and healthier living spaces** for urban populations.

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