Evaluation of the occupant perception of air quality within the indoor setting in the composite climate of Delhi

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1. Abstract

In India, the ill effects of a poor indoor environment are seen as the cause of about 2 million premature deaths per year, wherein 44% are due to pneumonia, 54% from chronic obstructive pulmonary disease(COPD), and 2% from lung cancer. Conventional studies typically take lesser consideration of indoor occupancy than would be found in real surroundings. These studies often evolve in artificial conditions, which lack authenticity. This work uses field research and a data-driven approach to assess contaminants in inhabited indoor spaces, such as carbon dioxide (CO2) and particulate matter (PM2.5) along with indoor climate measurements of Indoor Operative Temperature (IOT), Relative Humidity(RH), and air velocity. This paper reports the findings of a pilot field study carried out to understand the effect of CO2, IOT, PM2.5, RH, age, sex, general health condition, and perception of odours on occupant's perception of IAQ and perceived thermal comfort, during the summer monsoon season in the composite climate of Delhi. Participants were asked to rate their perceived thermal comfort on standardized scales and provide PIAQ votes based on their satisfaction with indoor air quality. Data analysis included correlation analyses and multiple regression modelling. Our findings reveal a statistically significant inverse relationship between perceived Indoor Air Quality (PIAQ) votes and perceived thermal comfort. Building occupants who rated the indoor air quality more favourably (higher PIAQ votes) tended to report lower levels of perceived thermal comfort, while those who expressed dissatisfaction with indoor air quality reported higher thermal comfort levels.

Keywords - Thermal Sensation, Perceived Indoor Air Quality, Correlation, CO2, PM2.5

2. Introduction

The World Health Organization (WHO) defines health as, "A state of complete physical, mental and social well being and not merely the absence of disease or infirmity."[1] Human health not only includes the physical state of individuals but also is a state of complete physical, psychological, and social well-being [2]. Exposure to environmental physical, chemical, biological, and radioactive toxins are some of the several factors that can have an impact on human health resulting in adverse effects such as chronic illness. People spend more than 80% of their time in indoor spaces, either in offices or at home. Compared to the air quality of outside surroundings, IAQ is more likely to have an impact on people's health, quality of life, and ability to work. People who spend a lot of time indoors, for instance, may experience uncomfortable symptoms like headaches, coughs, and exhaustion as well as be diagnosed with several serious conditions like respiratory, cardiovascular, and cerebrovascular disorders as well as an increased chance of developing cancer. As a result, indoor air quality has a significant impact on occupant health, perhaps even more so than outdoor air quality. According to the studies, those who have had underlying medical conditions including cancer, high blood pressure, diabetes, chronic respiratory disease, or even diabetes and cardiovascular disease are predicted to be more vulnerable to exposure to poor air quality.

SBS, tight building syndrome, and illnesses related to buildings, such as nausea, skin irritation, lethargy, etc., are some of the general terms used to describe the negative effects of poor IAQ on health. SBS symptoms are challenging to identify because they are predominantly characterized by sensory reactions, which are poorly understood even from a medical standpoint.[3] SBS is characterized as a collection of subclinical symptoms without a known explanation. Building inhabitants frequently respond to their surroundings in distinctly different ways, making it challenging to pinpoint the causes of specific issues. The symptoms seen in building occupants vary, and they are significantly influenced by thermal factors such as air and wall surface temperatures, air velocity, temperature variations, relative humidity, clothing, etc. pollutants, lighting, psychosocial workplace aspects, personal control, job happiness, relationships with coworkers, etc[4]

According to the findings of Wargocki et al., improvement of PIAQ, reducing the severity of some SBS symptoms, and increasing some aspects of occupant productivity can all be accomplished by reducing the pollution load on indoor air, as advised by CEN CR 1752 (1998).[5] In another study, thirty women took part, where each environmental condition was experienced for 4.6 hours. Throughout their presence in these conditions, the participants engaged in simulated office tasks while evaluating their perceived indoor air quality(PIAQ). The research reaffirmed prior observations regarding how temperature and humidity influence PIAQ.[6]

Moreover, Heudorf et al., found that the level of carbon dioxide (CO2) can be an indicator of adequacy of ventilation and a comfort parameter. Although it was assumed that CO2 concentration >1000 ppm may also indicate poor PIAQ, CO2 concentration <1000 ppm does not guarantee acceptable PIAQ[7].

The information summarized above shows that indoor air parameters like temperature, relative humidity, and CO2 concentration affect the PIAQ while the impact of general health conditions and pollutants like particulate matter require further elucidation. The present study aims to investigate whether PIAQ and its acceptability are influenced by these indoor air parameters and also investigate the relationship of parameters with each other. In the present study, we aimed to assess the relationship between indoor temperature, relative humidity, CO2, PM2.5 concentration, age, gender, general health condition, perceived odours, and perceived indoor air quality and thermal sensation for residences located in the South Delhi area of the National capital territory of Delhi.

Since the perception of IAQ in India is quite new, studies conducted on finding the linkage between indoor air parameters and PIAQ have been limited so far. Another novelty of this research is that it involves both, measurements of indoor environment parameters and concurrent questionnaire surveys over the summer-monsoon season, which has high levels of temperature and varying relative humidity levels, causing thermal discomfort in many instances as compared to other seasons. This research will also help in promoting public awareness to maintain a healthier indoor environment.

3. Materials and Methods

3.1 Setting

The study was carried out in Delhi, which falls under composite climate zone {Reference}, during the summer monsoon season. The study site is located in a residential locality in South Delhi that was developed in the 1950s. All the houses have 1 living room, 2 bedrooms, 1 study, 1 Kitchen, 1 Toilet and 1 Bathroom. All the houses have the same typical layout. The cooking fuel is the same for all houses (Piped Natural Gas, PNG). Every room has operable windows that open to an outdoor environment.

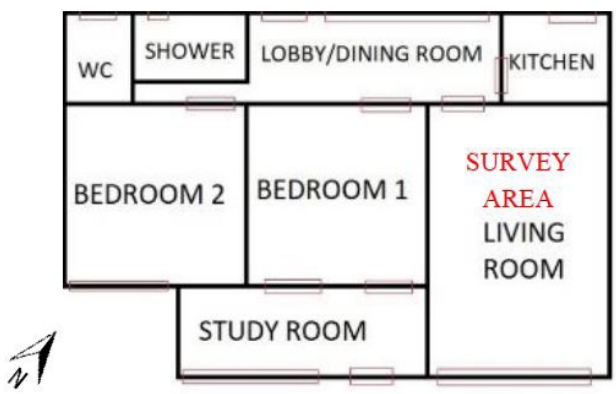


Figure 1: Typical Floor layout of study sites

The study site is close to a Ring Road with heavy traffic; a metro station located at 300 m distance and a fuel station at 350 m. The population density of the area is approximately 94 people per km2, and local public transportation consists mainly of cars and auto rickshaws.

Temperatures in Delhi usually range from 2 to 46 °C (35.6 to 114.8 °F), with the lowest and highest temperatures ever recorded being −2.2 and 49.2 °C (28.0 and 120.6 °F), respectively. The air quality index is generally moderate (101–200) level between January and September, and then it drastically deteriorates to Very Poor (301–400), Severe (401–500), or Hazardous (500+) levels in the three months between October and December.

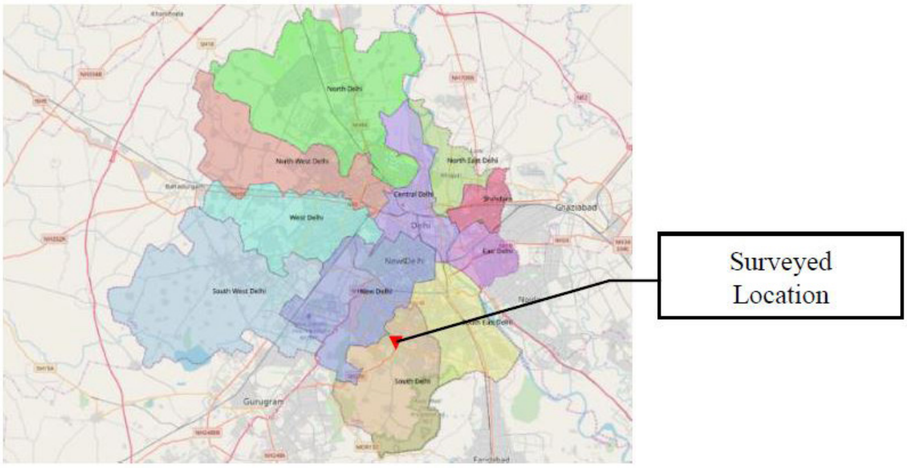


Figure 2: Map of the National Capital Territory (NCT) of Delhi

The study was conducted in July-August duration. Quantitative measurement of perceived indoor air quality and perceived thermal comfort is done using ASHRAE's psycho-physical scale[8] using a questionnaire-based survey of occupants' perceptions of indoor air quality. The indoor air parameters were sampled in 1-minute intervals for CO2, temperature, air velocity, and relative humidity and then were transformed into 5-minute averages, which were merged to generate a time-series matrix. The PM2.5 monitoring was sampled as 5 min averages. The indoor climate and air quality measurements were continuously obtained for a period of 2-h every day during the study period.

3.2. Participants

To begin with, 25 sampling sites were identified where 50 participants volunteered to be subjects for monitoring. Of them, only 30 were available for monitoring. Hence, the sample size of this study was 14 male and 16 female occupants. At each sampling site, a questionnaire was given to the occupants to assess the perception of indoor air quality in the space and related comfort levels. The occupants were asked to stay in their usual ventilation and environment conditions during the monitoring period, and normal activities were performed without any other interference. The indoor sensors were placed 1.5 m above the ground at each sampling point near the participant. Participants were asked to provide a PIAQ vote on a scale from 1 to 7 (1-breathable, 2-Very stuffy, 3-Slightly Stuffy, 4-Neutral, 5- Slightly Fresh, 6-Fresh, 7-Very Fresh) to indicate their satisfaction with indoor air quality. They were also asked to rate their perceived thermal comfort on a scale from 1 (very uncomfortable) to 7 (very comfortable).[9]. The general health condition of participants was also recorded and converted to a scale of 1(very good) to 5(poor).

3.3 Air Quality Monitors

To conduct on-site measurements, portable real-time air monitors were used to measure Temperature, RH, CO2, Air flow velocity, and PM2.5. Table 2 provides details of the devices used to measure respective air quality parameters in indoor environments. These monitors were placed inside the households for 24 hours in a room where residents spent most of their time, calculations. The monitors collected data on the concentration of PM2.5 once per minute. Output was in the form of an Excel spreadsheet with summary measures, and a time stamp.

Table 1: Instruments used for indoor measurements

IAQ Variable	Instrument Used	Model	Resolution	Range
Temperature, RH	IAQ monitor	Testo 400	0.1°C ±0 %RH	0 to +50 °C 5 to 95 %RH
$PM_{2.5}$	IAQ monitor	SPS 30	0 to 100 μg/m3 : ±10 μg/m3 100 to 1000 μg/m3 : ±10 % m.v.	0.3 to 2.5 μm
CO_2	IAQ monitor	Testo 440	1 ppm	0 to 10000 ppm
Air velocity	Hot wire probe	Testo 400	0.01 m/s	0-50 m/s

3.4 Data Analysis

Data were collected in Microsoft Excel and analyzed using Excel and MATLAB 2023. The contribution of monitored levels of IAQ parameters with the PIAQ vote among the participants was investigated. We examined the relationship between measured data and responses from the survey questions to provide further insights.

The study also excluded the impact of TVOCs on PIAQ as none of the spaces had any new furniture or any renovation done in the last year. In the current study, It is also assumed that the effect of socioeconomic background and physical habits on the subjective evaluation of IAQ is neutral.

4. Results

The number of subjects monitored was 30 with 16 female and 14 male participants. The average age of the participants was 34.6 years. The study was completed by collecting indoor air and climate measurements and questionnaires. The study site was visited at per convenience of the participants and hence 24-hour data measurement was not possible. The majority of the participants were indoor workers, children, and housewives. Of these, 30 participants included in the analysis, two had 1 min data (0.07%) missing and the rest had no missing data during the monitoring period. It was tried to maintain an equal proportion of age groups amongst both genders. There weren't any smokers among the participants. Additional information about the building was also recorded and the respondent's location was marked on the floor layout. Table 2 summarizes the indoor T, RH, CO2, and PM2.5 concentrations during the study period.

Table 2: Summary of indoor T, RH, CO2, and PM2.5 concentrations during the study period

Parameter	N#	Mean	Max
Indoor Measurements			
Temp (◦C)	402	30.46	32.7
RH (%)	402	70.57	77.1
CO2	402	521.4	721
$PM_{2.5}$	80	15.79	25.07

No. of data points

4.1 Correlation among different parameters and mean PIAQ votes per person

4.1.1 Mean PIAQ votes per person vs. Age

The questionnaire responses were used to set up a correlation between mean PIAQ votes per person and different measured parameters. The results of the overall PIAQ vote, as shown in Fig. 3, show that under studied indoor environment conditions, 50% of the occupants felt 'neutral' towards the environment they live in, 16% felt 'stuffy' or 'slightly stuffy', 33% felt that the indoor environment was 'fresh'. It was also found that the participants who felt that the environment had good indoor air quality were a mix of occupants who prefer thermal comfort over IAQ even when the CO2 levels rose to a maximum recorded value of 721ppm and PM2.5 value exceeded the WHO prescribed limit of 12µg/m^3 within 24-h period,[10] as well as occupants who preferred more fresh air where CO2 levels were as low as 422 ppm and temperatures as high as 31.7°C. The latter category of participants also voted that they were 'very satisfied' with the thermal comfort and that the thermal comfort conditions were 'acceptable' to them.

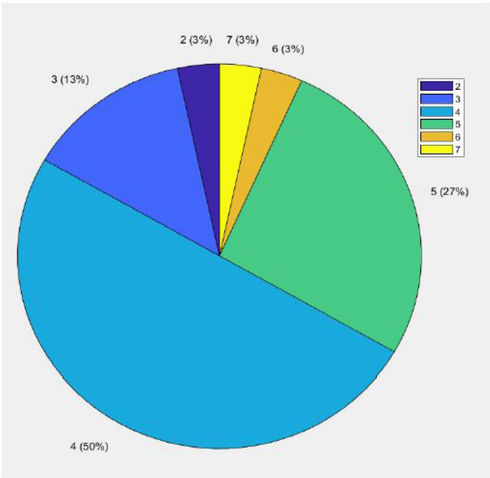


Figure 3: Overall PIAQ vote

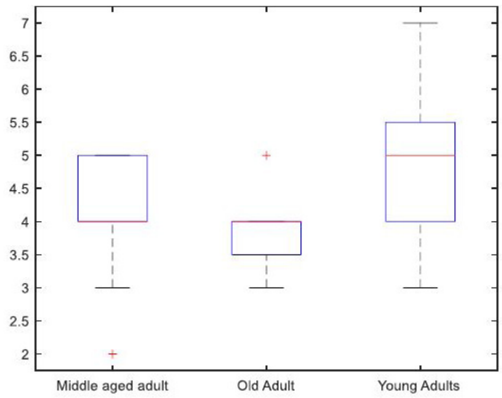


Figure 4: Distribution of mean PIAQ votes among studied age groups

Fig. 4, shows the distribution of overall PIAQ vote amongst different age groups that participated in the study. In the 'middle-aged adult' group, 25% of the respondents rated PIAQ as 4 or lower on the scale used in the graph. The interquartile range (IQR), spans from 4 to 5, indicating that the majority of respondents in the 'middle age' category fell within this range, with some perceiving indoor air quality as poor or suboptimal (25th percentile) and others perceiving it as moderately satisfactory (75th percentile). A significant portion of individuals within the 'old adult' group had relatively lower levels of satisfaction with indoor air quality, with the median and 25th percentile values both falling below the midpoint of the scale. This indicates that a substantial portion of respondents perceived the indoor air quality as less than satisfactory or neutral.

The interquartile range (IQR), in the 'young adult' age group, spans from 4 to 5.5, indicating the variability in satisfaction levels within this age group. For most individuals within this age group, PIAQ is moderately satisfactory, with a smaller subgroup expressing less satisfaction.

4.1.2. Mean PIAQ votes person vs. Occupant's Gender

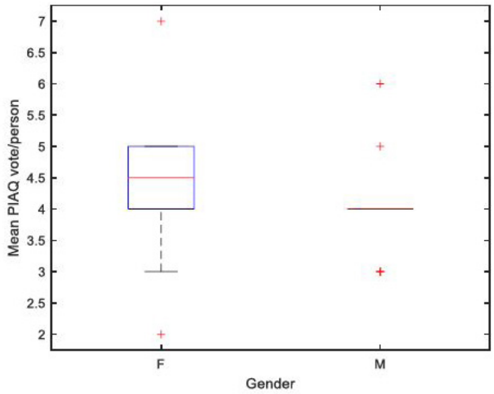


Figure 5: Distribution of mean PIAQ votes among male and female participants

90% of the females, who participated in the study, were housewives who spent more time in indoor surveyed environments as compared to surveyed males. Fig. 5, shows that the 50% quartile among females was 4.5 and among males was 4. Previous investigations carried out in different countries also reported that females were more susceptible to SBS symptoms than males.[11]

4.1.3. Mean PIAQ votes person vs. Perceived Odour

Occupants perceiving any type of odours in an indoor surveyed environment reported lower mean PIAQ rating, 4.06, and acceptability as compared to occupants, 4.43, who do not perceive any kind of odour indoors. (Fig. 6).

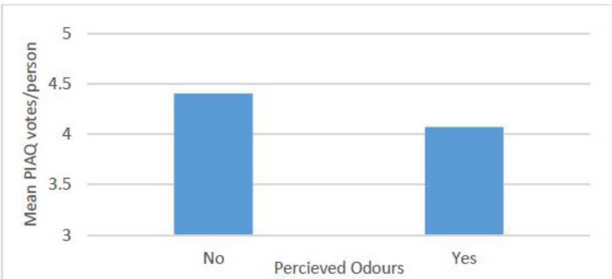
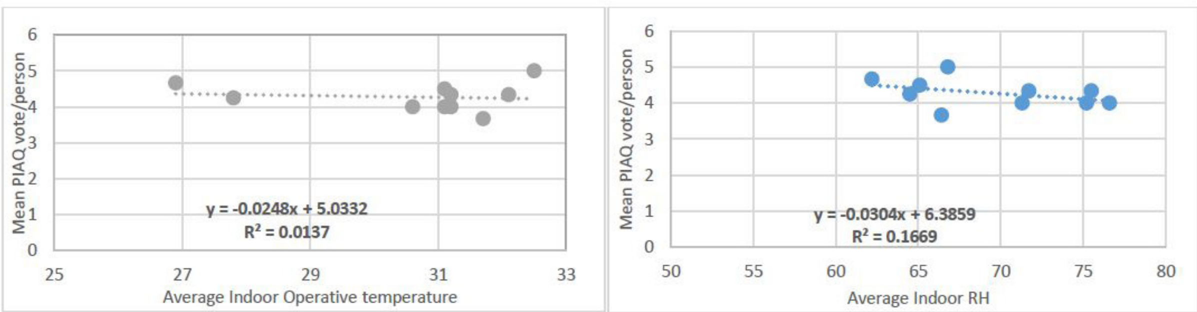


Figure 6: Mean PIAQ/person vs. perception of odour in the indoor environment

4.1.4. PM2.5, RH and CO2 as an indicator of IAQ



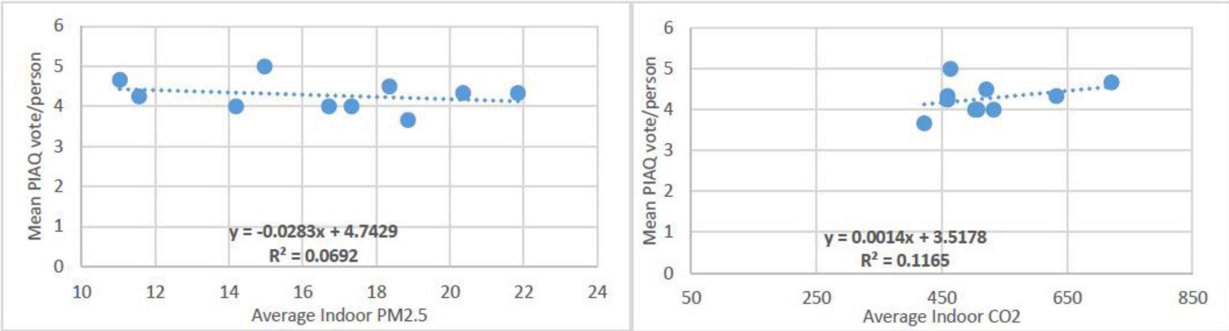


Figure 7: Variation of Mean PIAQ vote with (a) Average Indoor Operative Temperature, (b) Average RH, (c) Average Indoor PM2.5, (d)Average CO2

Fig. 7a-d, describes the relationship between measured values of Average Indoor Operative Temperature, Average RH, Average Indoor PM2.5, and Average CO2 with Mean PIAQ votes per person (at p>0.05). It can be observed from the above plots that PIAQ is 'less likely' to be dependent on Indoor Operative temperature and 'very likely' to be dependent on Relative humidity (R2=0.167) and Indoor CO2(R2= 0.12). Although the R2 values seem to be low, it provides a gateway to conduct more investigation in a controlled and/or real-time environment with a relatively large number of data points to calculate a more effective coefficient of correlation.

The above analysis also does not necessarily imply that PM2.5 (R2= 0.069) does not affect the perception of Indoor air quality. The above three parameters act as an 'indicator' or 'marker', indicating likely contamination of indoor air. The low R^2 value between the Mean PIAQ vote and Indoor operative temperature indicates that only 1.37% of the variance in the Mean PIAQ vote can be explained by changes in indoor operative temperature. In other words, temperature alone has very limited predictive power when it comes to assessing the acceptability or comfort of the thermal environment.

4.2. PM2.5, and CO2 as a function of Average Indoor Operative Temperature

The study attempted to also evaluate the possible effects of Average Indoor temperature on the concentration of CO2 and PM2.5 in indoor spaces. The negative slope in the linear relationship between Average Indoor temperature and Average CO2 (at p>0.05) indicates an inverse or negative correlation between two variables, meaning that as one variable increases, the other tends to decrease, whereas in the case of Average PM2.5, the correlation is positive.

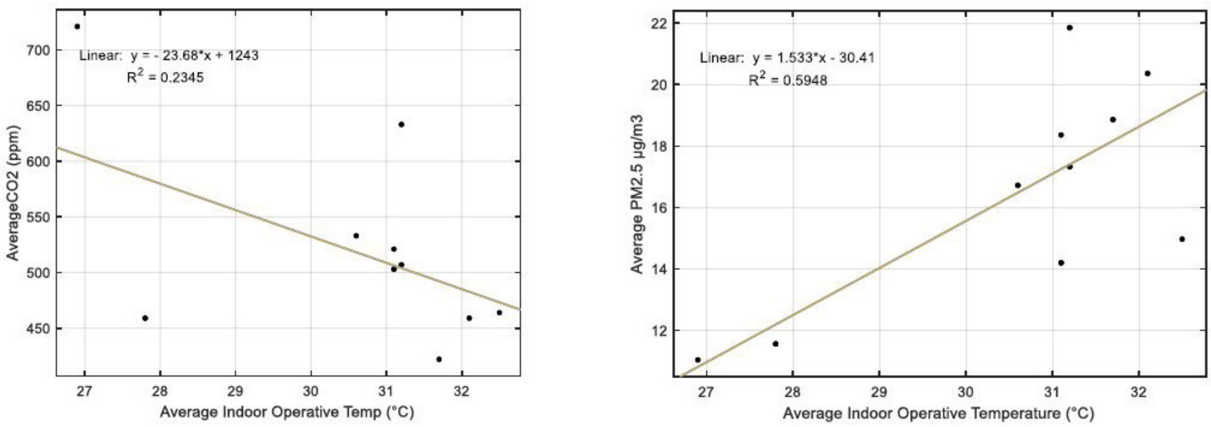


Figure 8: Relation of Average Indoor Operative Room Temperature with Average CO2 and Average PM2.5 in indoor spaces

4.3 PM2.5 as a function of Average relative Humidity

The non-zero slope and R2=0.261 between Average PM2.5 concentration and relative humidity, Fig, 9, in indoor space, expresses the probable relation of the thermal comfort equation with perceived indoor air quality. Their relationship can be complex and can be influenced by various factors. High humidity can contribute to the formation of secondary aerosols, which can increase PM2.5 concentrations.

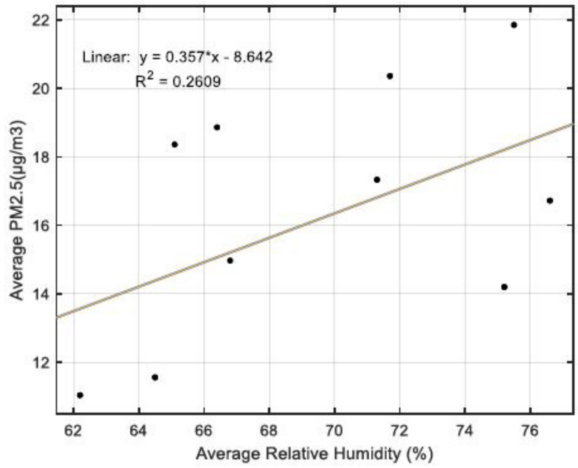
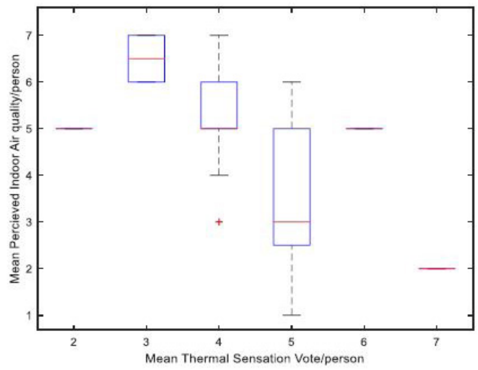


Figure 9: Relation of Average relative Humidity with Average PM2.5 in indoor spaces

4.4. PIAQ and Thermal Sensation

The concentration of the measured parameters in the indoor space may lie within ASHRAE standard limits but the occupants may still complain about sick building symptoms affecting the PIAQ..[12] The below graphs (Fig. 10), explain the above hypothesis. At a lower score of Mean thermal sensation (more thermal discomfort), the perception of IAQ is better with a median of 5, 6.5, and 5 at TSV 2, 3, and 4 respectively whereas the PIAQ vote is low (poor perceived IAQ) at a good score of TSV.



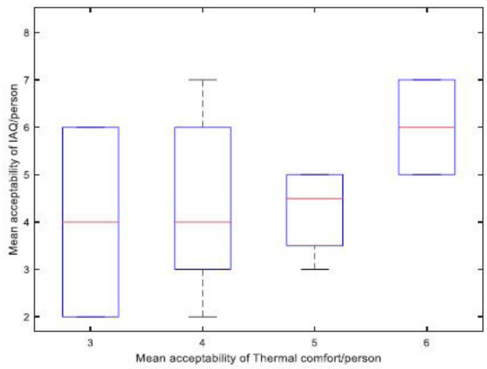


Figure 10: Relation of PIAQ with thermal sensation rating and their acceptability

However, when we surveyed the acceptability of the Thermal sensation and perceived IAQ, the occupants, despite being dissatisfied with either thermal comfort and/or IAQ, accepted the currently prevailing thermal and indoor air conditions. This shows that occupants were adaptive to the environment they lived in despite the discomfort. This could be due to other social, psychological, and physiological factors.[13]

4.5. General health conditions of the participants vs. PIAQ

General health conditions among the participants were recorded. Participants stated their general health condition on a scale of 1(very good) to 5(very bad). 27% reported their general health condition to be 'very good' whereas 30% reported 'good', 40% reported 'moderate' and 3% reported 'bad'. The results show that participants with 'very good' and 'good' health conditions felt 'neutral' to 'fresh' within the indoor setting. Participants with 'moderate' and 'bad' health conditions felt 'slightly stuffy' to 'neutral' in their indoor air quality (Fig.11).

In terms of the acceptability of the indoor environment, all the participants except those who had 'bad' health conditions felt that the indoor air quality could have been better and expressed their acceptability from 'unacceptable' to 'slightly unacceptable'.

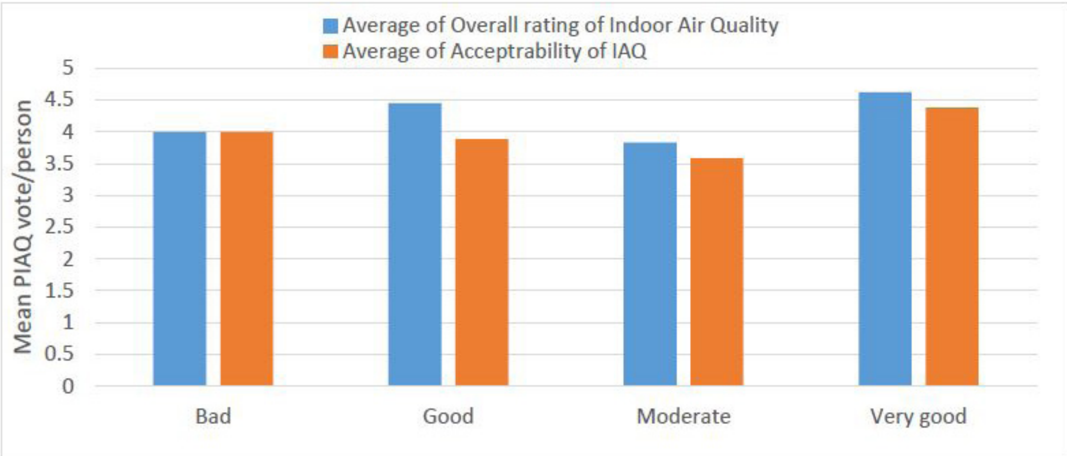


Figure 11: Distribution of mean PIAQ per person among participants according to their general health condition

4.6 Predicted response vs. Actual response

Unlike, in many earlier studies, both the PMV model and TSV model in the current study, have a non-zero slope, Fig. 12. This implies that PMV can be used here as a method to predict the thermal adaptability of the occupants. However, the PIAQ model has almost a zero slope with R^2=0.014, which indicates that Indoor Operative temperature may be 'less likely' to affect the perception of Indoor air quality in the presented study.

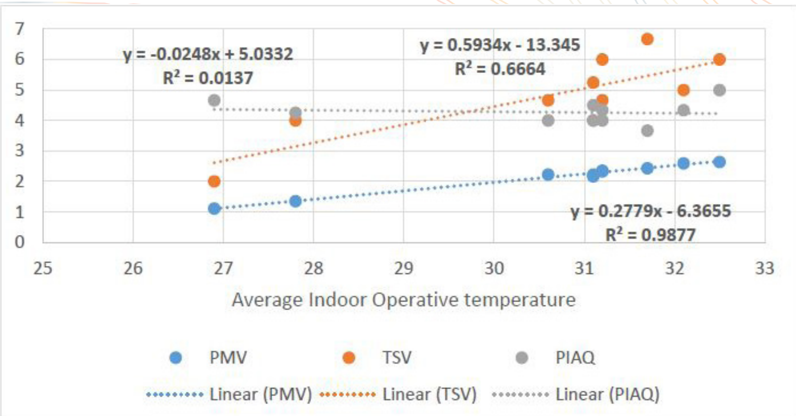


Figure 12: Correlation between calculated PMV, actual TSV, and PIAQ vote vs. Indoor Operative Temperature.

5. Discussion

In the present study, 77% of the spaces were naturally ventilated whereas 23% were mixed-mode. It is also worth mentioning that even though air conditioners were operating in some spaces, the doors were kept open to indoor connected spaces. While the low R^2 between Mean PIAQ vote/person and measured parameters suggests a weak linear relationship, it's possible that the relationship between them and Mean PIAQ vote is nonlinear. Exploring potential nonlinear relationships or interactions with other variables may reveal more insights into the PIAQ assessment.

Another noteworthy observation was that despite experiencing discomfort at some level due to indoor air quality in terms of respiratory and overall health issues, 83% of the overall participants were satisfied and/or felt better in the indoor environment. This could also be attributed to the possibility of their comparison of perception with poor Outdoor air quality. Thus, in further studies, it is also important to monitor Outdoor air quality in the studied region. of 12

This study also shares an insight that the perception of Indoor Air Quality is "unlikely" to be a function of Indoor Operative Temperature. This implies that people's responses were largely unaffected by the temperature settings they were in. The possible theory behind this is that the subjects/occupants were surveyed in the environment they usually live in for maximum time of the day.

The current study is a pilot experiment on quantitative and qualitative assessment of indoor air quality. However, it is limited to 30 participants. A clearer picture could be painted with more participants, 24-hour data monitoring, and conducting the study in an environment that is in the vicinity of more pollution sources. The study can also include variations in PIAQ over seasons to account for a wide range of climatic variations and ventilation conditions. Individual differences in perception and sensitivity to indoor environmental factors must also be acknowledged. E.g. the Differences due to Body Mass Index(BMI), health practices like yoga, meditation, etc. While our study reveals a general trend, it is essential to recognize that some individuals may be more resilient to variations in indoor air quality, while others may experience discomfort more acutely. Future research should explore these individual differences to tailor indoor environmental solutions effectively.

6. Conclusion

The questionnaire analysis indicated that occupants of the study site experienced a variety of illness symptoms that occurred 'often' or 'always'. The main symptoms prevailing were headache, lethargy, fatigue, shortness of breath, and dryness in mucous.
Results depicted that males were more susceptible to poor IAQ symptoms (50% more) as compared to females. Significant relationships between Mean PIAQ per person and age, gender, CO2 concentration, PM2.5 concentration, perceived odours, and relative humidity. Occupants in the 'middle-aged adult' and 'young adult' age group were less 'dissatisfied' as compared to occupants in the 'old adult' group. The general health condition also had a significant effect on the PIAQ as people with 'very good' health conditions also perceived that the IAQ was also towards a fresher side whereas participants with a 'bad' health condition perceived that IAQ was towards a 'stuffy' side.

CO2 concentration, PM2.5 concentration, perceived odours, and relative humidity varied linearly with the PIAQ vote, which shows that they may be categorized as an 'indicator' or 'marker' of IAQ.
A notable conclusion from the above study was that at lower values of mean TSV, the mean PIAQ vote per person was 'slightly fresh' to 'very fresh', The relationship between mean TSV per person and the mean PIAQ vote per person indicates that a good PIAQ does not necessarily indicate good Perceived thermal comfort. Thus, it is imperative to understand the optimal range of conditions that ensures occupant satisfaction both in terms of thermal comfort and indoor air quality for the overall health and wellness of the occupants.

In conclusion, the findings of this study provide compelling evidence of an inverse relationship between the PIAQ vote and TSV in indoor environments. Our research underscores the importance of considering not only thermal comfort but also indoor air quality as integral components of occupant satisfaction and well-being within indoor spaces.

In conclusion, the inverse relationship between PIAQ vote and perceived thermal comfort sheds light on the intricate dynamics within indoor spaces. Recognizing and acting upon this relationship can lead to improved indoor environmental quality, benefiting the health and satisfaction of building occupants. Further research and practical interventions are warranted to harness the full potential of this insight and create indoor environments that are truly conducive to human well-being.

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