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Evaluation of comfort perception of passengers in urban underground metro stations

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ABSTRACT

Indoor thermal comfort levels in underground metro platforms and trains in Chennai metropolitan city are assessed in the present research study to determine the comfort perception of passengers. The field measurements were conducted in 7 underground metro stations during summer (Mar-Jun 2019) and winter seasons (Dec 2019 - Feb 2020). The thermal comfort of metro passengers is investigated through environmental parameters and a subjective survey. Results indicated that the percentage of unacceptability in metro platforms is in the range of 36.7–98.8%, while inside the metro trains it is less than 12%. This indicates the efficiency of the in-train air-conditioning systems compared to metro platforms. Good agreement is found between the findings of the thermal comfort investigation and the comfort perception of passengers. A linear and very strong positive correlation is found between operative temperature and the percentage of passengers dissatisfied. No relation is found between the metro stations' indoor and outdoor thermal conditions. Thus, it is inferred that internal factors such as the functioning of stations, operation of metro trains, and high density of passengers contribute significantly to indoor heat generation. During both seasons, the thermal conditions in all metro stations surpassed the ASHRAE-55 and ISO7730 guidelines. Stations with low passenger traffic are maintained with high operative temperatures to save energy costs. Based on the prevailing thermal conditions and ASHRAE recommendations of operative temperature, a Predicted Percentage of Dissatisfied (PPD) value of up to 40% could be deemed a thermal comfort metric that can be acceptable in underground metro stations.

Introduction

The subway or underground (UG) metro network is rapidly expanding in many cities around the globe. The UG metro stations are reported to be polluted and thermally unstable environments (Wen et al., 2020). Thermal parameters have a significant influence on indoor environment quality (Chen et al., 2016; Passi et al., 2021a). Over the past two decades, several research studies have been conducted to assess indoor air quality (IAQ) in metro stations (Mao et al., 2019; Passi et al., 2021b; Ye et al., 2010). Few studies were also carried out to investigate the thermal comfort of commuters (El-Bialy & Khalil, 2011; Guan & Zhang, 2009; Katavoutas et al., 2016). Thermal comfort in an enclosed building depends on various factors. Environmental conditions such as temperature, relative humidity, and air velocity; personal aspects of occupants like clothing ratio, body surface area, and activity level; and behavioral control factors such as opening/closing of windows/doors, controlling the speed of the fan, controlling the temperature of air-conditioning, and reducing/increasing clothing levels are some of the primary factors influencing the level of human comfort (Dhaka et al., 2013; Dili et al., 2010). In UG metro stations, these behavioral control options are not available to the general public. The indoor environment of metro stations is fully enclosed and airtight. The thermal conditions are centrally controlled through Heating, Ventilation, and Air Conditioning (HVAC) systems. A high density of passengers per unit area and a lack of air-conditioning in UG metro stations lead to numerous adverse environmental and human health impacts (Liu et al., 2011; Moreno et al., 2014; Wen et al., 2020). Lack of natural ventilation and high cost of energy for air-conditioning results in the irregular operation of the HVAC systems in subway stations which causes thermal discomfort to transit passengers (Chow, 2002; Yu et al., 2009). The maintenance of high temperatures to save energy costs results in indoor air quality deterioration.

Most of the research studies conducted so far on thermal comfort assessment are in the office environment (Fu, 2020; Kumar et al., 2016), residential places (Kumar et al., 2016; Yu et al., 2017), and hostel buildings (Dhaka et al., 2013). The thermal characteristics of subway stations are not the same as other indoor environments. Due to the UG construction of subways, frequent operation of metro trains, high passenger

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traffic, and increased air pollutant load, thermal parameters have a significant role in impacting overall environmental quality (Fang, 1998; He et al., 2017; Passi et al., 2021a; Reinikainen et al., 1992). High-temperature level results in excess heat in the environment. Exposure to such an environment causes stroke, dehydration, and anxiety in passengers. High humidity results in microbial proliferation and impacts IAQ. It causes skin and airway infections. Low airflow rate results in stagnant/dead air zones and accumulation of high levels of air pollutants. This leads to breathing difficulty and respiratory inflammation. Further, the increased accumulation of air pollutants in subways due to prevailing indoor thermal conditions and station geometry results in greater incidences of viral disease transmission from close passenger-to-passenger contact (Chen et al., 2021; Guzman, 2021; Passi et al., 2021b).

The thermal comfort of an environment can be assessed objectively (using environmental sensors) and subjectively (using questionnaire survey). Two comfort indices, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), are widely used to evaluate indoor thermal comfort based on the norms provided by ASHRAE-55 (American Society of Heating, Refrigerating, and Air Conditioning Engineers) and ISO 7730 (International Organization for Standardization). ORDÓDY (2000) studied ventilation as the primary influencing thermal parameter in the Budapest metro and reported 80–90% passenger dissatisfaction. Assimakopoulos and Katavoutas (2017) conducted an objective thermal comfort assessment in metro stations located in Athens. They noted a significant variation in comfort conditions with an increase in the depth of the platform. Sinha and Rajasekar (2020) modeled thermal comfort in the Delhi UG metro station using RWI (Relative Warmth Index). They reported slightly warm discomfort. Similarly, Abbaspour et al. (2008) modeled passenger thermal comfort using RWI. The authors stated that a comfortable thermal environment was not achievable in Tehran UG metro stations on hot summer days unless measures were taken for it to be cooled. Nakano et al. (2006) conducted a seasonal study in Tokyo metro and reported that the operative temperature acceptability range was 11–32 °C. Ampofo et al. (2004) conducted a review of the thermal comfort assessment of metro stations in the UK. This study indicated that metro stations surpassed the ASHRAE guidelines by a 20% dissatisfaction rate. The study also concluded that passengers' dissatisfaction rate of more than 20% could be considered acceptable depending on the climate conditions of the study region because passengers stay only for a short period in metro stations.

The comprehensive review of past studies identified that the studies concerning thermal comfort investigation in urban UG metro stations were limited. Further, to the best of the authors' knowledge, no studies were conducted to evaluate the comfort perception of passengers in UG metro stations and related short-term health effects. Therefore, the present study aims to evaluate the comfort perception of passengers in urban UG metro stations and propose an acceptable percentage dissatisfaction rate. The main objectives of this study are: 1) To investigate the thermal environment conditions in urban UG metro stations, 2) To evaluate the comfort perception of passengers against in-field measurements, and 3) To propose a percentage dissatisfaction rate for UG metro stations that could be deemed a thermal comfort metric.

In the present study, the thermal comfort of metro passengers is investigated through field measurement and subjective assessment. Environmental parameters such as room air temperature (Ta), relative humidity (RH), room air velocity (V_A), wet bulb temperature (Tw), globe temperature (Tg), operative temperature (T_O), and mean radiant temperature (Tr) are monitored. Thermal comfort indices: WBGT (wet-bulb globe temperature), PMV, and PPD are calculated to evaluate thermal comfort. Further, the comfort perception of passengers is assessed through a passengers' questionnaire survey. The health effects associated with short-term exposure are assessed. ANOVA statistical test is performed to find the agreement between objective and subjective assessments and ensure the field and subjective survey reliability. The impact of outdoor thermal conditions on the indoor environment is identified. Finally, a percentage dissatisfaction rate for the metro environments is proposed based on the thermal comfort evaluation and ASHRAE recommendations.

Materials and methods

Description of the field study

The field study is conducted in the UG metro stations in Chennai city (13.082° N, 80.270° E, and 6.7 m from mean sea level), the capital of the state of Tamil Nadu, India. Chennai city has a tropical wet and dry climate. The weather of Chennai city is hot and humid for most of the year. The ambient temperature of the city typically varies from 21 °C - 36 °C and is rarely below 20 °C and above 39 °C. Chennai Metro commenced its service on 29th June 2015. Currently, two metro lines are functional, and there are 40 metro stations (19 AG (aboveground) and 21 UG), covering a distance of 54.15 km. Chennai Metro is the third-largest operating metro network in India. It has a daily average ridership of 1.25 lac (2019). Fig. 1 presents the map of the Chennai metro railway network with latitude and longitude of stations selected for the current study.

Metro Stations 1 and 6 are the high-density passenger travel stations (passengers travel per day >10,000). Stations 2, 3, and 4 are medium-density passenger travel stations (passengers travel per day 2000–5000). Stations 5 and 7 are low-density passenger travel stations (passengers travel per day ⟨2000) (chennaimetrorail.org). Further, Station 1 is a two-level UG metro station: lower underground (LUG) and upper underground (UUG). The UG stations are ventilated through central air-conditioning systems in platforms, air-conditioning units inside metro trains, and tunnel ventilation and exhaust fans inside metro tunnels.

Monitoring of environmental parameters

Thermal parameters inside selected UG metro station platforms and metro trains are monitored. Delta Ohm HD 32.3 (thermal comfort meter) is used to measure thermal parameters using SICRAM (Sistema Computerizado de Retransmissao Automatica de Mensagens) probes. Table 1 shows the details of SICRAM probes and sensor types used for measuring thermal parameters (deltaohm.com).

Questionnaire survey for the subjective assessment

A questionnaire is framed to assess the thermal comfort of metro passengers following the guidelines of regulatory agencies such as ASHRAE, EPA, and WHO (Anjani et al., 2021). The metro trains in Chennai city have a time headway of 5 min during operational hours. A simple questionnaire is developed, and each subject's responses are collected individually. The questionnaire comprises 14 questions (Appendix A). The age of subjects is categorized into five groups: below 20 y, 20–30 y, 30–40 y, 40–50 y, and above 50 y. Travel details such as their frequency of metro usage, occupation, and average time of journey in the metro are noted. Information regarding their perceptions with respect to the sensation of cold and hot, dry and humid, low and high airflow, a sense of odor inside metro spaces, overall satisfaction with comfort inside subways, comfort in comparison to other public transport modes, regular patronage by passengers, and short-term health impacts are recorded based on their travel experience. Anonymity is duly maintained, and personal information such as respondents' name and contact details are not gathered. Also, total volatile organic compound (TVOC) levels are checked in metro stations at the time of the questionnaire survey using a photoionization detection (PID) sensor to compare with passengers' perception of IAQ or sense of odor.

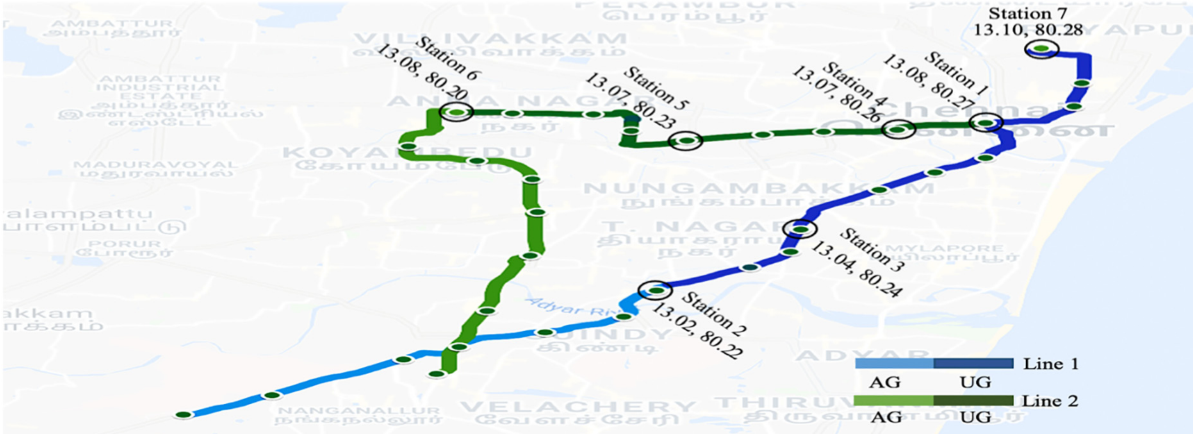

Fig. 1. Map of Chennai Metro railway network with latitude and longitude coordinates of selected stations.

Subjective assessment is conducted inside selected UG metro stations. The subjects participating in the study comprised of both men and women commuters. Brief details about the questionnaire and its purpose are first provided to the subjects to ensure that responses relevant to the study will be obtained. Most of the passengers accessing subway metro stations are office workers and students, both men and women. A total of 457 respondents participated throughout the thermal comfort assessment period. Table 2 presents the details of surveyed samples for the subjective assessment.

Calculation of thermal indicators and indices

Mean radiant temperature (MRT or Tr)

MRT is the weighted mean temperature of all objects, surfaces, and walls with respect to the body. MRT is estimated with Tg, Ta, and V_A. Metro station walls, roofs, and glazing warmness result in radiant asynchronism, causing discomfort to passengers. A globe of 50 mm diameter is used to determine the MRT, consisting of a copper sphere coated with matt black paint, with emissivity equal to 0.95 (as required by ISO 7726), and a Pt100 temperature sensor embedded inside. MRT is calculated using Eq. (1) presented by ASHRAE (2001).

$$Tr = \left[(Tg+273)^4 + \frac{1.1\times10^8\times {V_A}^{0.6}}{0.95\times D^{0.4}}(Tg-Ta)\right]^{\frac{1}{4}} - 273 \quad (1)$$

Where, D = diameter of the globe, 0.95 = globe thermometer predicted emissivity.

Operative temperature (T_O)

Operative temperature is another way of measuring indoor thermal comfort conditions. It is estimated with Ta, Tr, and V_A. It is calculated using Eq. (2), as per ISO 7726.

$$T_O = \frac{Tr + \left(Ta\times(10V_A)^{0.5}\right)}{1+(10V_A)^{0.5}} \quad (2)$$

Table 1
Details of SICRAM probes and sensor types used for the measuring thermal parameters.

Parameter	Probe	Sensor	Make	Range	Accuracy
Ta	HP3217.2R	Thin-film pt100	Delta Ohm	−40 to 80 °C	±0.1 °C
RH	HP3217.2R	Capacitive		0–100%	±1.5%
V_A	AP3203.2	NTC 10kohm		0.1–5 m/s	±0.2 m/s
Tg	TP3276.2	Pt100		−10 to 100 °C	±0.1 °C

Wet-bulb globe temperature (WBGT)

WBGT index is the measure of heat stress to which an occupant is subjected in the indoor or outdoor environment. It is estimated with Tw, Tg, and Ta (Parsons, 2006). It is calculated considering the effect of solar radiation using Eq. (3), as per ISO 7243.

$$WBGT = 0.7Tw + 0.2Tg + 0.1Ta \quad (3)$$

Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD)

The PMV and PPD indices, as specified by ASHRAE-55 and ISO 7730, respectively, are used to assess thermal comfort in the metro environment. ASHRAE-55 has provided a seven-point thermal sensation scale presented in Fig. 2.

ASHRAE-55 and ISO 7730 have recommended that the PMV limit should be in the range of −0.5 to +0.5 to achieve a state of thermal well-being, while −0.85 to +0.85 is considered as an acceptable environment. ASHRAE-55 has recommended the calculation of PPD, developed by Fanger and adapted in ISO 7730 standard. As per ASHRAE, the PPD index should be less than 20%, which means at least 80% of occupants should be satisfied to consider an environment as thermally comfortable. Eq. (4) is used to calculate the PPD index.

$$PPD = 100 - 95\times e^{\left(-0.03353\times PMV^4 - 0.2179\times PMV^2\right)} \quad (4)$$

Data collection and analysis

The field measurements are conducted in 7 UG metro stations (Fig. 1) selected from both metro lines from Mar-Jun 2019 in summer and Dec 2019 - Feb 2020 in the winter season. Each one-minute data was collected for seven continuous days in each selected UG metro station. Both objective and subjective data were compiled and analyzed using descriptive statistics. Analyzed data values were compared with regulatory standards (Table 3). A one-way ANOVA test is performed to check the agreement (accuracy) between field assessment and passengers' perception. Thermal characteristics in metro trains on Line 2 are also evaluated to compare both environments (metro station and train). The impact of outdoor thermal conditions on the indoor environment is studied. Finally, a percentage dissatisfaction rate for the subway metro environment is proposed. Fig. 3 presents the view of the Chennai UG metro station.

Results and discussion

This section discusses the results of thermal environment conditions: thermal parameters and indices, thermal comfort prediction and acceptability, comfort perception of passengers, and relationship of

Table 2
Details of surveyed samples for the subjective assessment.

Station details				Sample details			
Metro Line	Station	Station type	Depth (m)	Sample size	Male sample	Female sample	Proportion of female samples
1	Station 1 LUG	Junction	−28	88	68	20	22.7%
	Station 2	Wayside	−12.48	44	30	14	31.8%
	Station 3	Wayside	−14.57	46	32	14	30.4%
	Station 7	Terminal	−12	35	27	8	22.8%
2	Station 1 UUG	Junction	−17.2	81	69	12	14.8%
	Station 4	Wayside	−14.1	44	36	8	18.2%
	Station 5	Wayside	−14.1	51	39	12	23.5%
	Station 6	Wayside	−14.1	68	54	14	20.6%

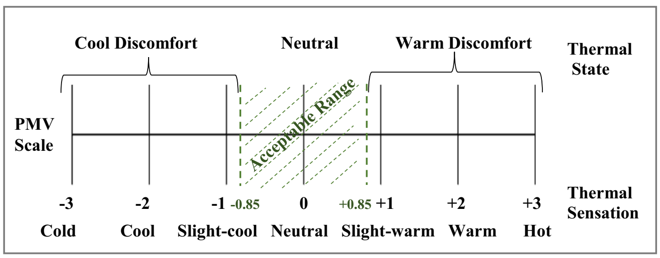

Fig. 2. ASHRAE seven-point thermal sensation scale.

Table 3
Regulatory standards associated environmental parameters and indices.

S. No.	Parameter	Prescribed Limit/Range	Units	Organization
1.	*Ta*	22.8–26.1 (Summer) 20–23.6 (Winter)	°C	ASHRAE-55
2.	RH	30–65 Around 50 (optimum)	%	ASHRAE-62.1
3.	V_A	0.1–0.3	m/s	ISO 7730
4.	WBGT	26	°C	ISO 7243
5.	PMV	−0.85 – +0.85	Unitless	ASHRAE-55
6.	PPD	< 20	%	ASHRAE-55

environmental parameters and passengers' perception in UG metro stations. Further, thermal conditions in metro trains and the impact of outdoor thermal conditions on indoors are discussed. Finally, recommendations to maintain good environmental quality in metro stations are also listed.

Thermal environment conditions in UG metro stations

Thermal comfort is influenced by environmental, physical, psychological, and behavioral aspects. Thermal parameters of the surrounding environment such as *Ta*, RH, V_A, and *Tr* influence thermal acceptability. Also, every human being has his/her own individual level of thermal comfort depending on factors like body surface area, clothing insulation, and metabolic rate. The metro stations in Chennai city are mostly used by office workers and students who have full clothing insulation, i.e., pant, shirt, shoes, and socks. So, the clothing level is taken as 0.8 Clo, as per the stipulated standard for work clothing. The metabolic rate is taken as 1.2 MET (for sitting and walking operation of passengers, ISO 9920). These values are calibrated in the instrument before the data collection. With the thermal environment parameters and physical parameters, thermal comfort indices (WBGT, PMV, and PPD) are calculated using the HD 32.3 Delta Ohm instrument. Table 4 presents the descriptive statistic summary of thermal parameters measured in selected UG metro station platforms in the summer and winter seasons.

The thermal conditions in the metro stations are found to be similar in both the summer and winter seasons. The overall minimum (maximum) values of *Ta*, RH, and V_A among selected metro stations are 25.99 (35.01), 60.10 (79.89), and 0.03 (0.34) in summer and 25.86 (30.11), 59.09 (67.61), and 0.04 (0.35) in winter, respectively. The T_O range is 25.98–34.84 °C in summer and 25.77–29.95 °C in winter. ASHRAE-55 and ISO 7730 have recommended the limits of *Ta*, RH, and V_A in order to maintain optimum comfort conditions inside an indoor space (Table 3). The overall comfort conditions in both seasons surpassed the recommended guidelines for maintaining optimum comfort inside the subway environment. A high temperature is maintained in Chennai subway stations to save energy costs. However, this impacts IAQ. There is a significant difference between mean *Tw* and *Ta*

Fig. 3. View of Chennai UG metro station.

Table 4
Descriptive statistic summary of thermal parameters measured in selected UG metro station platforms.

Stations	Statistic Variables	Summer							Winter						
		Ta (°C)	RH (%)	V_A (m/s)	*Tw* (°C)	*Tg* (°C)	*Tr* (°C)	*To* (°C)	*Ta* (°C)	RH (%)	V_A (m/s)	*Tw* (°C)	*Tg* (°C)	*Tr* (°C)	*To* (°C)
Station 1 LUG	Mean	26.59	73.09	0.03	22.92	26.40	26.30	26.40	26.54	67.61	0.04	22.05	26.33	26.22	26.34
	SD	0.16	1.56	0.01	0.31	0.15	0.15	0.16	0.27	5.40	0.01	1.02	0.28	0.28	0.28
	Min	26.28	70.08	0.02	22.46	26.09	26.00	26.09	26.13	62.16	0.03	21.03	25.92	25.81	25.92
	Max	26.78	74.94	0.04	23.26	26.59	26.49	26.60	26.90	75.15	0.05	23.41	26.70	26.60	26.70
Station 1 UUG	Mean	27.98	71.26	0.09	23.92	27.81	27.70	27.83	27.77	66.38	0.10	22.97	27.66	27.62	27.69
	SD	0.54	1.97	0.01	0.65	0.53	0.53	0.53	0.09	3.06	0.03	0.49	0.09	0.10	0.09
	Min	27.31	69.31	0.07	23.07	27.14	27.02	27.16	27.66	63.37	0.06	22.51	27.56	27.50	27.60
	Max	28.65	74.01	0.10	24.95	28.46	28.35	28.49	27.91	70.99	0.15	23.68	27.79	27.78	27.83
Station 2	Mean	28.03	75.18	0.07	24.56	27.85	27.77	27.88	29.57	66.59	0.06	25.06	29.46	29.34	29.44
	SD	0.35	2.01	0.02	0.39	0.31	0.29	0.30	0.81	1.78	0.02	0.68	0.82	0.82	0.81
	Min	27.65	72.87	0.03	23.90	27.51	27.45	27.55	28.94	64.29	0.04	24.65	28.85	28.74	28.82
	Max	28.65	77.34	0.08	25.03	28.38	28.25	28.39	30.76	68.61	0.07	26.08	30.67	30.55	30.64
Station 3	Mean	26.86	79.89	0.04	24.16	26.64	26.53	26.66	28.96	61.90	0.08	24.58	28.79	28.71	28.82
	SD	0.58	3.10	0.01	0.79	0.57	0.56	0.56	0.41	4.74	0.03	0.44	0.42	0.45	0.43
	Min	25.93	75.22	0.03	23.12	25.75	25.64	25.77	28.20	55.43	0.06	24.06	28.01	27.90	28.03
	Max	27.52	82.84	0.05	25.19	27.29	27.16	27.30	29.31	67.60	0.13	25.19	29.17	29.14	29.21
Station 4	Mean	25.99	77.00	0.23	22.92	25.94	25.96	25.98	27.58	59.09	0.08	21.33	27.44	27.34	27.45
	SD	0.83	3.64	0.03	0.89	0.79	0.74	0.79	0.55	4.48	0.01	0.63	0.55	0.55	0.55
	Min	24.51	72.29	0.15	21.87	24.53	24.67	24.57	26.92	54.35	0.06	20.31	26.77	26.68	26.79
	Max	27.22	81.13	0.25	24.23	27.11	27.06	27.15	28.22	65.03	0.10	22.01	28.06	27.97	28.09
Station 5	Mean	35.01	60.10	0.34	28.25	34.81	34.52	34.84	30.11	62.59	0.35	24.26	29.92	29.68	29.95
	SD	0.53	3.64	0.04	0.73	0.52	0.50	0.52	1.37	2.67	0.10	1.18	1.36	1.34	1.35
	Min	34.17	52.83	0.29	27.09	34.02	33.77	34.03	28.18	60.29	0.24	22.62	27.99	27.77	28.04
	Max	35.53	63.94	0.38	29.22	35.32	34.99	35.34	31.41	66.31	0.46	25.33	31.20	30.90	31.21
Station 6	Mean	27.49	64.41	0.17	22.41	27.36	27.24	27.38	25.86	64.67	0.17	21.01	25.74	25.65	25.77
	SD	0.58	2.06	0.02	0.44	0.56	0.56	0.57	0.74	1.91	0.02	0.63	0.71	0.69	0.71
	Min	26.89	61.73	0.13	21.67	26.78	26.66	26.79	24.95	62.10	0.15	20.00	24.85	24.74	24.86
	Max	28.65	66.99	0.19	23.11	28.48	28.37	28.52	27.24	67.49	0.20	21.83	27.06	26.92	27.10
Station 7	Mean	31.74	62.26	0.16	25.79	31.68	31.73	31.74	28.79	66.54	0.22	23.89	28.69	28.58	28.70
	SD	0.40	3.32	0.03	0.41	0.37	0.36	0.38	0.14	2.96	0.04	0.47	0.13	0.14	0.13
	Min	31.18	55.82	0.11	25.13	31.11	31.13	31.16	28.65	63.61	0.18	23.34	28.56	28.46	28.57
	Max	32.32	65.68	0.19	26.33	32.20	32.24	32.28	28.95	71.31	0.29	24.52	28.86	28.76	28.87

in the range of 2.7–6.76 °C. *Tw* values fall within the range of ASHRAE-55 standard recommendations for room air temperature except in Station 5 in summer. This indicates that lower temperature can be achieved with evaporative cooling of air. *Tg* represents the combined effect of radiation, *Ta*, and V_A. A minimal difference is observed between the mean *Ta* and *Tg* in the range of 0.05–0.21 °C. Table 5 presents the descriptive summary of thermal indices calculated from environmental parameters.

The WBGT thermal stress index range in Chennai metro stations is 23.83–30.24 °C in summer and 22.44–26.39 °C in winter. The WBGT index value is considered for combined sitting and walking operations and assuming that passengers are non-acclimatized to the heat. The mean thermal stress index values in the studied metro stations are well within the regulatory limits except in station 5 in the summer season. The PMV and PPD index values in all metro stations surpassed the stipulated regulations of acceptable PMV and PPD (Table 3). The PPD range in selected metro stations is 36.70–98.76% and 38.20–80.72% in the summer and winter, respectively. In some metro stations, PPD values are approached to 100%. The PPD range is higher in summer than winter, and it has a strong relation with *Ta* and T_O. Station 5 has the highest mean T_O (34.84 °C). Thus, it has the highest mean PPD of 98.76%. Further, it is observed that a high T_O is maintained in UG metro stations to save energy costs. The metro stations having low-density passenger travel are maintained with high-temperature levels (in the range of 28.7–34.8 °C) followed by medium-density passenger travel stations (in the range of 26.0–29.4 °C) and then high-density passenger travel stations (in the range of 25.7–27.8 °C) (Table 4). The percentage of passengers' dissatisfaction ranges are 60.9–98.2%, 36.7–67.1%, and 30.2–55.3% for low-density, medium-density, and high-density passengers travel stations, respectively (Table 5). Thus, the thermal conditions in UG metro stations are maintained based on station usage to save energy costs which leads to environmental quality deterioration. It might cause short-term health consequences to passengers.

Thermal prediction and acceptability

Thermal parameters and predicted mean vote

The high values of thermal parameters impact the thermal acceptability of an environment. PMV and PPD indices define the thermal acceptability of an environment. Fig. 4 presents the variation of PMV against thermal parameters. The linear relationship between PMV and thermal parameters represents the influence of thermal parameters on thermal sensation; *Ta* and PMV ($R^2 = 0.97$ and $r = 0.99$, Fig. 4a), RH and PMV ($R^2 = 0.14$ and $r = -0.38$, Fig. 4b), V_A and PMV ($R^2 = 0.22$ and $r = 0.47$, Fig. 4c), and T_O and PMV ($R^2 = 0.97$ and $r = 0.98$, Fig. 4d). Here, R^2 represents the coefficient of linear relationship or dependency of PMV on thermal parameters, and *r* represents the strength of the relationship between PMV and thermal parameters. The data correlated is taken as a daily average for both seasons, collected from the studied metro stations.

Fig. 4a reveals that when *Ta* is higher than 34.2 °C, the PMV is higher than 3. When *Ta* is less than 25 °C, the PMV is lesser than 0.85. It indicates that *Ta* has a significant influence on PMV. A temperature of 25 °C needs to be maintained to meet the acceptable PMV limit. Fig. 4b shows the weak dependency of PMV on RH and a weak negative correlation. Fig. 4c depicts the weak dependency of PMV on V_A and a moderate positive correlation. It indicates that RH and V_A do not significantly impact PMV. Also, the linear relationship between PMV and T_O is plotted. T_O takes into account the effect of *Ta*, *Tr*, and V_A. Fig. 4d shows that when T_O is higher than 34.16 °C, the PMV is higher than 3. When T_O is less than 24.8 °C, the PMV is lesser than 0.85. Similar to *Ta*, T_O has a substantial influence on PMV. A T_O of 24.8 °C needs to be maintained to meet the acceptable PMV limit. No significant impact of airflow and solar radiation is observed on the thermal sensation of passengers in the UG metro stations. The room air temperature is a dominant parameter. Thus, no significant difference is observed between *Ta* and T_O.

Table 5
Descriptive statistic summary of thermal indices calculated from environmental parameters.

Stations	Statistic Variables	Summer			Winter		
		WBGT (°C)	PMV	PPD	WBGT (°C)	PMV	PPD
Station 1 LUG	Mean	23.98	1.31	41.84	23.35	1.25	38.20
	SD	0.25	0.04	1.69	0.79	0.10	4.88
	Min	23.62	1.23	39.05	22.58	1.13	32.81
	Max	24.25	1.35	43.90	24.39	1.39	44.96
Station 1 UUG	Mean	25.10	1.59	55.29	24.38	1.50	51.08
	SD	0.60	0.14	6.64	0.34	0.04	2.15
	Min	24.31	1.41	46.86	24.06	1.46	48.75
	Max	26.02	1.77	64.40	24.92	1.58	55.09
Station 2	Mean	25.56	1.64	58.01	26.39	1.81	67.08
	SD	0.35	0.09	4.29	0.72	0.18	8.68
	Min	25.00	1.53	53.05	26.02	1.65	59.06
	Max	26.06	1.80	65.90	27.47	2.06	79.40
Station 3	Mean	24.92	1.42	47.71	25.86	1.64	58.31
	SD	0.70	0.15	6.78	0.36	0.23	12.25
	Min	24.04	1.21	38.54	25.42	1.38	44.45
	Max	25.84	1.60	56.02	26.38	1.95	74.45
Station 4	Mean	23.83	1.06	36.70	23.18	1.31	45.02
	SD	0.83	0.22	7.90	0.60	0.07	3.24
	Min	22.86	0.71	25.85	22.28	1.24	41.54
	Max	25.10	1.42	50.88	23.79	1.39	47.95
Station 5	Mean	30.24	3.21	98.76	25.97	2.11	80.72
	SD	0.59	0.14	2.20	1.22	0.22	8.88
	Min	29.47	2.99	93.80	24.25	1.95	74.44
	Max	30.99	3.34	99.80	27.10	2.26	86.99
Station 6	Mean	23.91	1.36	43.71	22.44	0.97	30.23
	SD	0.45	0.13	6.42	0.64	0.18	7.18
	Min	23.30	1.24	37.79	21.46	0.73	21.25
	Max	24.74	1.63	57.12	23.42	1.29	43.34
Station 7	Mean	27.56	2.42	88.49	25.34	1.69	60.89
	SD	0.29	0.07	2.26	0.33	0.04	2.05
	Min	27.26	2.31	83.99	24.92	1.64	58.59
	Max	28.07	2.52	90.95	25.74	1.74	63.05

Thermal parameters and percentage of passengers dissatisfied

Fig. 5 presents the linear relationship between PPD and the thermal parameters. The R^2 coefficients for Ta, RH, V_A, and T_O are 0.93, 0.12, 0.18, and 0.93, respectively. The correlations (r) are 0.96, −0.35, 0.42, and 0.96, respectively. RH and V_A do not significantly influence PMV. Ta and T_O are the dominant parameters. As per ASHRAE-55 and ISO 7730 regulations, the PPD should be less than 20%. In order to achieve the 20% PPD under prevalent thermal conditions, the operative temperature of 23.6 °C needs to be maintained (Fig. 5). However, there are no specific standards available for transport microenvironments. As the residence time of passengers in UG metro stations is of short duration, a higher PPD in metro stations can be acceptable. Also, as per ASHRAE-55, the room air temperature of 26.1 °C (upper limit) is acceptable in an indoor environment. Fig. 5a and d show that at the Ta and T_O of 26.1 °C, a PPD of up to 39% is acceptable.

Comfort perceptions of passengers in UG metro stations

Characteristics of subjects

During the subjective assessment, 457 subjects participated in the questionnaire survey. Fig. 6 (a-e) shows the characteristics of surveyed samples.

The percentage participation of males and females is 77.68% and 22.32%, respectively (Fig. 6a). The majority of passengers travelling through the metro are service persons (32.8%) and students (30.2%) (Fig. 6b). The maximum number of passengers (47.48%) responded that they travel through the subway regularly (Fig. 6c). The travel time spent by the substantial number of passengers (62.26%) during a one-way journey is less than 30 min, while 33.7% of passengers responded with their travel time range of 30 min - 1 h (Fig. 6d). The majority of subjects who participated in the survey are aged 20–30 years (61.49%) (Fig. 6e).

Perceptions of environmental parameters

Passengers' perceptions concerning basic thermal parameters: comfort state with temperature, humidity, airflow, and overall air quality in terms of sense of stuffiness or odor are recorded. Table 6 presents the thermal sensation scales used for recording passengers' perceptions concerning thermal parameters. Fig. 7 shows the perceptions of thermal parameters (temperature, Fig. 7a; humidity, Fig. 7b; airflow, Fig. 7c; and air quality, Fig. 7d) against in-field measured mean levels.

The thermal dissatisfaction is higher in metro stations having high mean temperature levels. The dissatisfaction rate with prevailing thermal conditions reaches up to 100% in stations with the room air temperature above 30 °C (Fig. 7a). It is identified that few passengers rated the environment as cool because they were standing directly beneath the HVAC supply air duct. Due to improper/ineffective airflow distribution, the overall thermal conditions are unsatisfactory in metro stations. The passengers' perception of humidity and the actual humidity level do not follow a similar trend (Fig. 7b). This is attributed to the fact that the sense of humidity depends on passengers' physical condition, such as perspiration, dryness of throat, dryness of eyes, etc. About 32.4–55% of passengers responded by stating their discomfort with the humid environment, while the responses of 39.5–47.6% passengers showed neutrality. Similarly, airflow perception and actual room air velocity do not follow the same trend (Fig. 7c). About 48.4–69.6% of passengers reported a sense of low airflow, while 30.4–51.6% of passengers reported neutral airflow. Differences in passengers' opinions regarding airflow are due to the ineffective distribution of air. Passengers standing beneath the supply air duct responded to low airflow, while others standing away responded with no airflow. Moreover, a higher perception of poor air quality is reported in stations having high TVOC levels (Fig. 7d). An average of 68% of passengers responded with a perception of neutral or good air quality, while 32% of passengers responded with a perception of bad indoor air quality. High-temperature maintenance to save the energy cost results in off-gassing of high levels of volatile organic compounds (VOCs). This leads to deterioration of IAQ.

Thermal sensation response and unacceptability

Based on the thermal sensation scale, responses are collected from the passengers. The collected responses are plotted against the passenger numbers. Fig. 8A presents the PMV responses in the studied metro stations. In the figure, the horizontal axis represents thermal sensation votes, and the vertical axis represents the number of respondents. From the collected responses, weighted average thermal sensation votes and percentage of unacceptability are calculated. Fig. 8B presents the percentage of unacceptability against thermal sensation votes.

It can be observed that in all selected metro stations, the thermal sensation votes lie in the warm discomfort state (Fig. 8A). The percentage of unacceptability values have surpassed the ASHRAE-55 guideline of 20% in all metro stations (Fig. 8B). In comparison to the different selected stations, it can be observed that stations 5 and 7 (low-density passenger travel stations) are rated highest percentage of passengers' unacceptability followed by stations 2 and 3 (medium-density passenger travel stations) and then stations 1 and 6 (high-density passenger travel stations). As already stated in the previous section, based on the ASHRAE recommendations of T_O, a PPD of 39% (~40%) can be acceptable in metro stations. Thus, from Fig. 7B, it is observed that corresponding to 40% unacceptability, a thermal sensation vote of '~1.3' can be acceptable in a metro station environment.

Immediate health effects associated with exposure to the metro environment

A record is made of the short-term health effects regularly experienced by passengers after they enter the metro space and get relieved

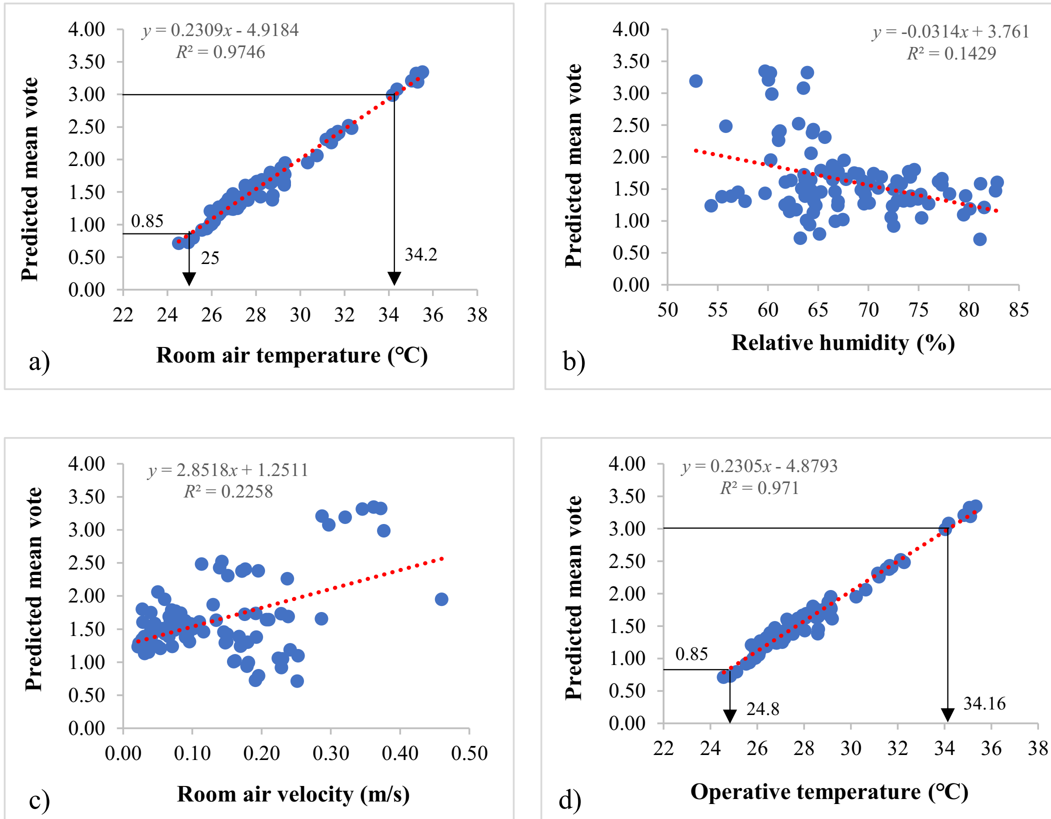

Fig. 4. Variation of predicted mean vote against thermal parameters a) room air temperature b) relative humidity c) room air velocity d) operative temperature.

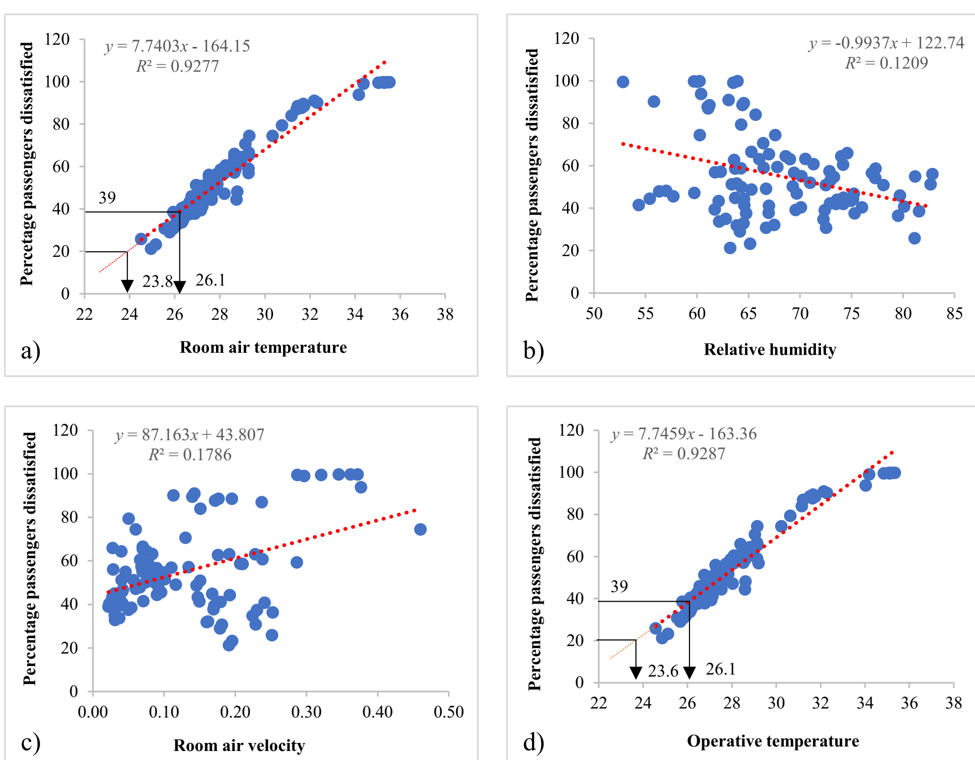

Fig. 5. Variation of percentage passengers dissatisfied against the thermal parameters a) room air temperature b) relative humidity c) room air velocity d) operative temperature.

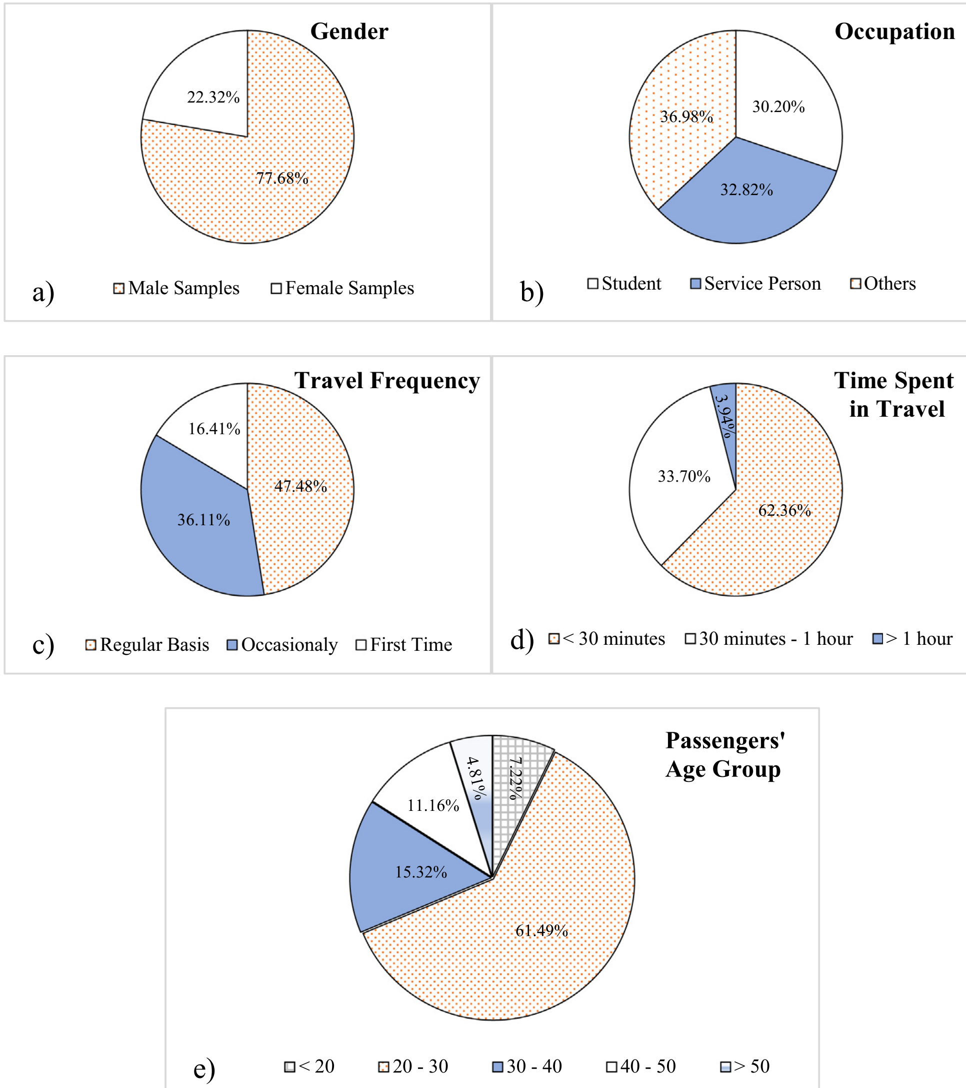

Fig. 6. Characteristics of subjects a) Gender b) Occupation of subjects c) Travel frequency d) Time spent in travel e) Passengers' age group.

after they exit the metro premises. Fig. 9 presents the percentage prevalence of short-term health effects.

The percentage prevalence of short-term health effects reported by passengers is less. A majority of passengers reported no side effects. Among the passengers who reported health issues, a maximum number of passengers had difficulty breathing (14.44%). The percentage prevalence of health effects is below 20%, which is within the acceptable range (as per ASHRAE-55).

Table 6
Thermal sensation scales used for recording passengers' perceptions concerning thermal parameters.

S. No.	Scale	Temperature Sensation	Humidity Sensation	Airflow Sensation	Air Quality Sensation
1	−3	Very Cold	Very Dry	–	Worst
2	−2	Cold	Dry	No air movement	Worse
3	−1	Slightly Cold	Slightly Dry	Low	Bad
4	0	Neutral	Neutral	Neutral	Neutral
5	+1	Slightly Hot	Slightly Humid	High	Good
6	+2	Hot	Humid	–	Better
7	+3	Very Hot	Very Humid	–	Best

Relationship between environmental parameters and passenger perceptions in selected metro stations

Agreement of thermal comfort investigation and passengers' perception

A good agreement is observed between thermal sensation votes (subjective survey) and predicted mean votes (measured with a thermal comfort meter). Passengers' perception of thermal sensation is presented in Fig. 10. The subject responses are indicated in the figure corresponding to a measured PMV index for each studied metro station.

It can be observed from Fig. 10 that the average PMV indices calculated through environmental parameters (instrument PMV) and the weighted average PMV responses calculated through the subject votes are overlapping or have a minimal difference in the range of 0.01–0.32. Thus, the actual thermal sensation votes obtained from passengers' responses are in agreement with calculated PMV indices. This indicates the efficiency of the instrument used and the accuracy of inputs applied before data collection. Further, a one-way ANOVA test is performed to find the correlation between PMV indices and subject responses with a significance level (α) of 0.05. The calculated *p*-value is

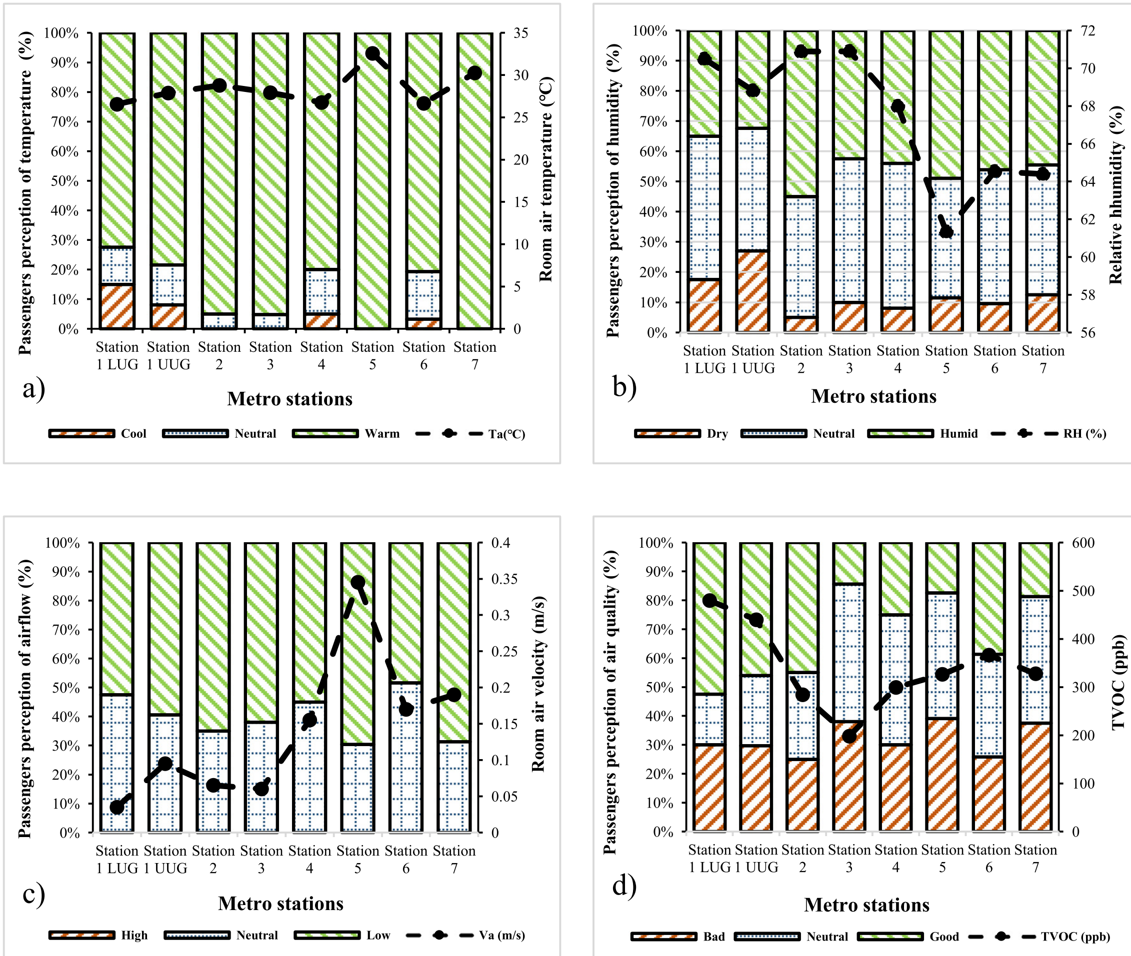

Fig. 7. Passenger perception of environmental parameters in subway stations against in-field measured mean levels a) temperature perception b) humidity perception c) airflow perception d) air quality perception.

0.84 (p-value > alpha). Thus, it is evident that there is no significant difference. This indicates a very close agreement between PMV indices and subject responses.

Correlation of thermal parameters among selected metro stations

A one-way ANOVA test is performed to check the correlations of existing environmental conditions among the studied metro stations. The significance level (α) = 0.05 is considered. The p-value is calculated to be $7.98*10^{-13}$ (p-value < α).

Thus, a significant difference is observed in the environmental conditions of the studied metro stations. Further, to check the significance of differences between each selected metro station, a post hoc test (t-test: two samples using equal variance) is performed. Table 7 presents the post hoc test statistic (if p-value < α, True else False). Here, true represents the significant difference, and false represents the not significant difference.

Along metro line 1, Station 1 LUG platform (high-density passenger travel station) differs significantly in environmental conditions than Stations 2 and 7 (medium and low-density passenger travel stations). Also, Station 7 is a terminal station (Fig. 1). The environmental conditions of Station 7 are substantially different from other stations. Further, Station 3 is a medium-density passenger travel station. There is not much difference observed when compared to other selected stations except Station 7. Along metro line 2, Station 1 UUG platform (high-density passenger travel station) differs significantly from Stations 6 and 4. Station 5 is a low-density passenger travel station. There is not much difference observed when compared to other selected stations except Station 4. Furthermore, a significant difference in environmental conditions is observed between Station 1 LUG (−28 m) and Station 1 UUG (−17.2 m) platforms located at different depths.

Thermal conditions inside metro trains

Thermal comfort assessment is done inside the metro trains during different times of the day, namely morning, afternoon, and evening. The total travel time in metro train for each trip is 36 min. Table 8 summarizes the thermal parameters and indices measured inside metro trains during different times of the day in the summer and winter seasons.

The thermal conditions inside the metro trains are similar in the summer and winter seasons. The values of thermal parameters are in the optimum range inside metro trains. The percentage of passengers dissatisfied with the thermal comfort is less than 12%. This shows the efficiency of the in-train air-conditioning systems. Fig. 11 presents the variation of the PMV against thermal parameters inside metro trains. The overall comfort conditions inside the metro trains are excellent. The linear relationships between PMV and thermal parameters are: *Ta* and PMV (R^2 = 0.71 and r = 0.85, Fig. 11a), RH and PMV (R^2 = 0.082 and r = −0.29, Fig. 11b), V_A and PMV (R^2 = 0.15 and r = −0.38, Fig. 11c), and T_O and PMV (R^2 = 0.75 and r = 0.86, Fig. 11d).

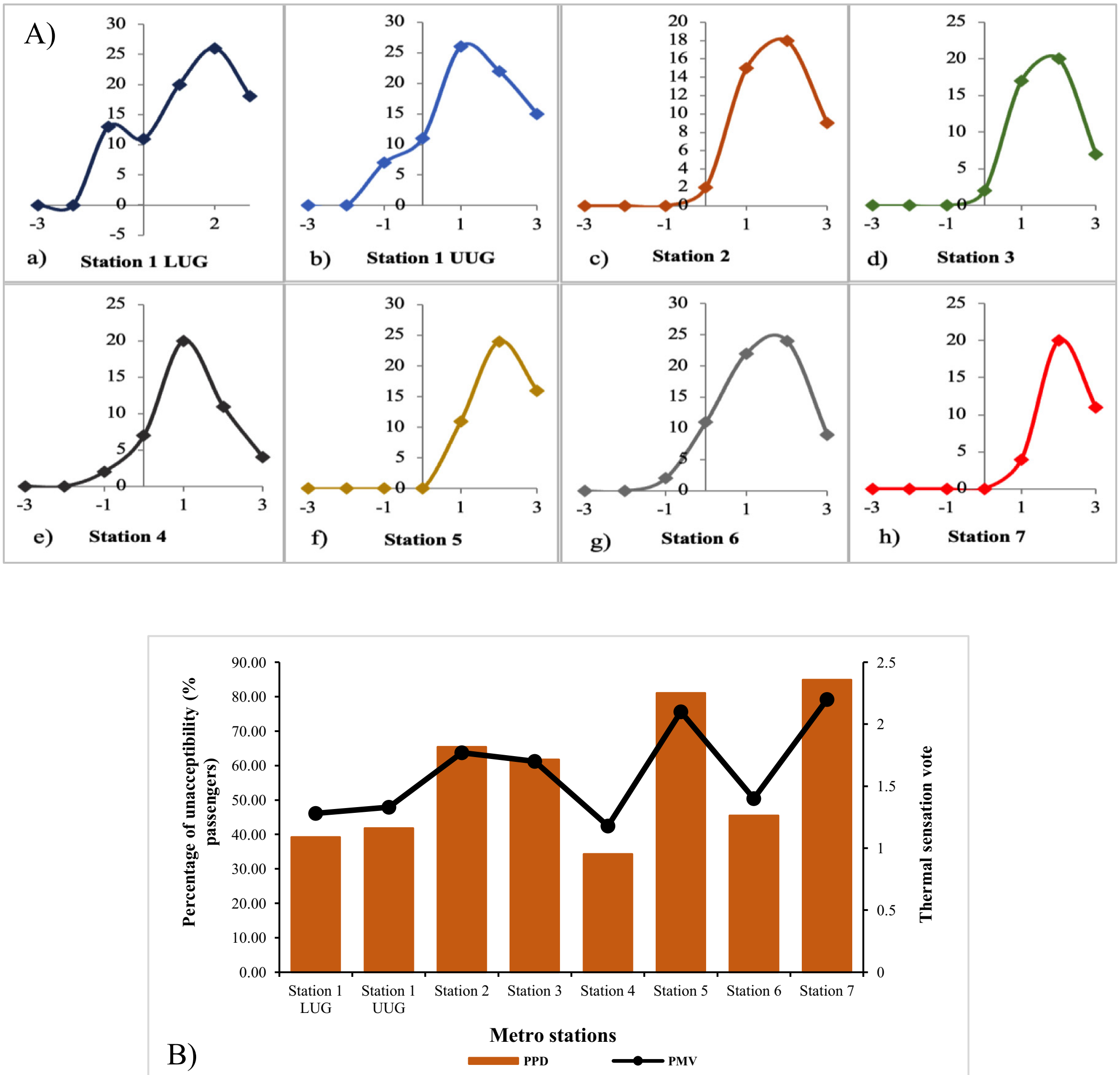

Fig. 8. Thermal sensation responses A) trend of thermal sensation responses in selected metro stations B) percentage of unacceptable thermal comfort against total thermal sensation votes.

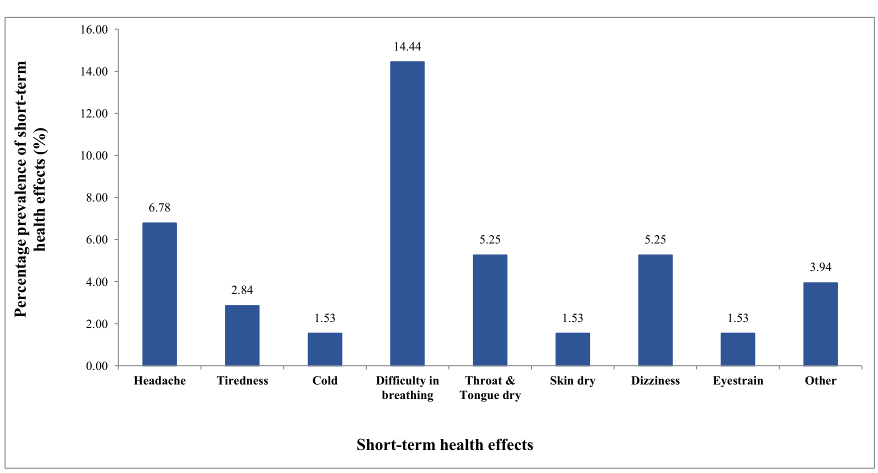

Fig. 9. Percentage prevalence of short-term health effects.

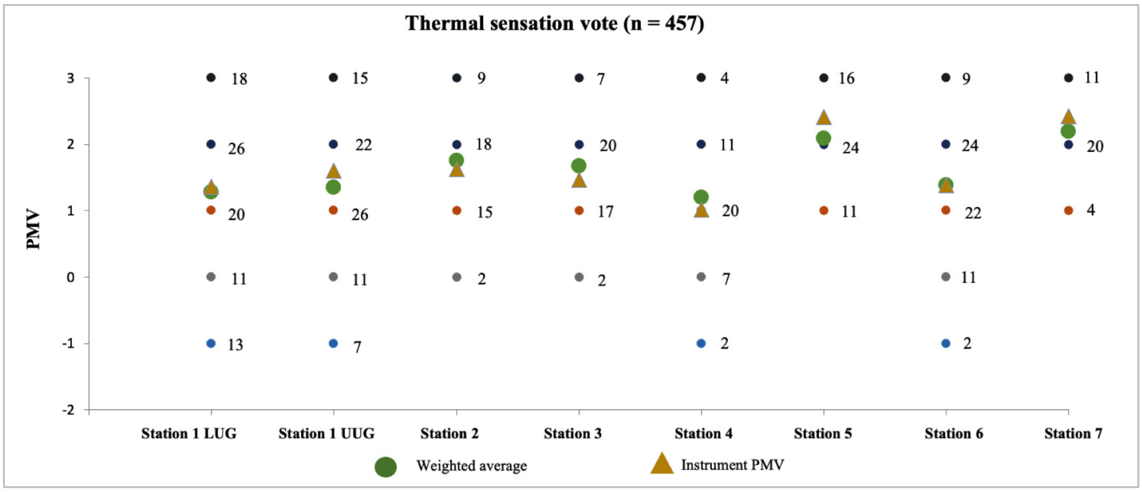

Fig. 10. Agreement between thermal sensation and predicted mean vote.

From Fig. 11a, it is noted that the maximum value of *Ta* inside metro trains is 25.7 °C. The corresponding PMV value is 0.75. The average train's cabin *Ta* is 24 °C. At this temperature, the PMV value is 0.37. Thus, a very strong relationship exists between *Ta* and PMV. Therefore, cabin *Ta* has a significant impact on PMV. In metro trains, *Ta* values are within the limits of ASHRAE-55. Thus, PMV values are also within the stipulated limit. Fig. 11b shows the weak dependency of PMV on RH and a weak negative correlation. Fig. 11c shows the weak dependency of PMV on V_A and a moderate negative correlation. It indicates that RH and V_A do not significantly impact PMV. The linear relationship between PMV and T_O is also plotted because T_O counts the effect of *Ta*, *Tr*, and V_A. Fig. 11d shows that the maximum value of T_O inside metro trains is 26.3 °C. The corresponding PMV value is 0.92. The average T_O is 23.85 °C. At this temperature, the PMV value is 0.36. Thus, a very strong relationship also exists between T_O and PMV. Further, it can be observed that inside metro trains, the mean T_O values are higher than *Ta* due to the effect of solar radiation (Table 8). This is because, in the Chennai metro, train tracks are laid in a partially elevated and partially UG manner. Solar radiations have a direct impact on travelling during travel along the elevated portion of the metro line. Thus, the corresponding PMV value is higher than the stipulated limit.

Impact of outdoor thermal conditions

The indoor thermal conditions of the subways are compared with outdoor thermal conditions to identify the impact of the outdoor

Table 7
Correlation of thermal parameters among selected metro stations.

Metro Line	Metro Stations	1				2			
		Station 2	Station 3	Station 1 LUG	Station 7	Station 6	Station 5	Station 4	Station 1 UUG
1	Station 2	1	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE
	Station 3	FALSE	1	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE
	Station 1 LUG	TRUE	FALSE	1	TRUE	FALSE	FALSE	FALSE	TRUE
	Station 7	TRUE	TRUE	TRUE	1	TRUE	FALSE	TRUE	TRUE
2	Station 6	TRUE	FALSE	FALSE	TRUE	1	FALSE	TRUE	TRUE
	Station 5	FALSE	FALSE	FALSE	FALSE	FALSE	1	TRUE	FALSE
	Station 4	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	1	TRUE
	Station 1 UUG	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	1

Table 8
Summary of thermal parameters and indices measured inside metro trains.

Parameters	Summer			Winter		
	Morning	Afternoon	Evening	Morning	Afternoon	Evening
Ta	22.34 ± 0.90	24.78 ± 0.32	24.23 ± 0.37	24.52 ± 0.43	24.09 ± 0.98	23.74 ± 0.41
RH	65.61 ± 6.67	55.86 ± 3.31	59.12 ± 3.92	67.31 ± 3	78.16 ± 4.08	68.41 ± 4.12
VA	0.43 ± 0.14	0.41 ± 0.22	0.24 ± 0.13	0.33 ± 0.14	0.38 ± 0.21	0.35 ± 0.13
Tw	17.97 ± 0.74	18.72 ± 0.57	18.73 ± 0.58	20.20 ± 0.64	21.31 ± 1.11	19.64 ± 0.85
Tg	22.88 ± 1.38	24.88 ± 0.50	24.26 ± 0.56	23.94 ± 0.51	23.52 ± 0.92	23.61 ± 0.33
Tr	24.10 ± 2.64	25.20 ± 1.18	24.32 ± 0.96	22.89 ± 0.92	22.36 ± 0.87	23.39 ± 0.66
T_O	22.91 ± 1.42	24.89 ± 0.51	24.26 ± 0.56	23.93 ± 0.52	23.50 ± 0.90	23.61 ± 0.33
WBGT	19.39 ± 0.70	20.56 ± 0.44	20.38 ± 0.44	21.38 ± 0.56	22.03 ± 1.03	20.84 ± 0.67
PMV	0.05 ± 0.33	0.54 ± 0.13	0.51 ± 0.16	0.42 ± 0.19	0.36 ± 0.24	0.32 ± 0.12
PPD	7.28 ± 3.57	11.46 ± 2.84	10.88 ± 3.56	9.42 ± 3.42	8.94 ± 4.87	7.39 ± 1.67

environment on the indoor environment. The outdoor data for temperature, RH, and air velocity is obtained from the website of the Central Pollution Control Board (cpcb.nic.in). Fig. 12 presents the variation in indoor and outdoor thermal conditions during the summer and winter. It can be observed from Fig. 12a that mean outdoor temperature values are higher than indoor values in the summer season. In the winter season, mean indoor temperature values are higher than outdoor values. This shows that the metro stations have their own sources of heat generation, such as the operation of metro trains, the functioning of metro stations, and the density of passengers. Further, in the summer season, mean indoor RH values are higher than outdoor values (Fig. 12b). In the winter season, mean outdoor RH values are higher than indoor values. There is a negative relationship between temperature and RH due to variation in evaporative cooling. In both seasons, the indoor air velocity values are much lower than outdoor values (Fig. 12c). This indicates the lesser exchange of mechanical air from the outdoor environment.

Recommendations to maintain good environmental quality in metro stations

The thermal parameters play a crucial role in maintaining good environmental quality in metro stations. The regulatory guidelines stipulated by ASHRAE-55, ASHRAE 62.1, and ISO 7730 (Table 3) should be followed strictly. It is identified that based on the

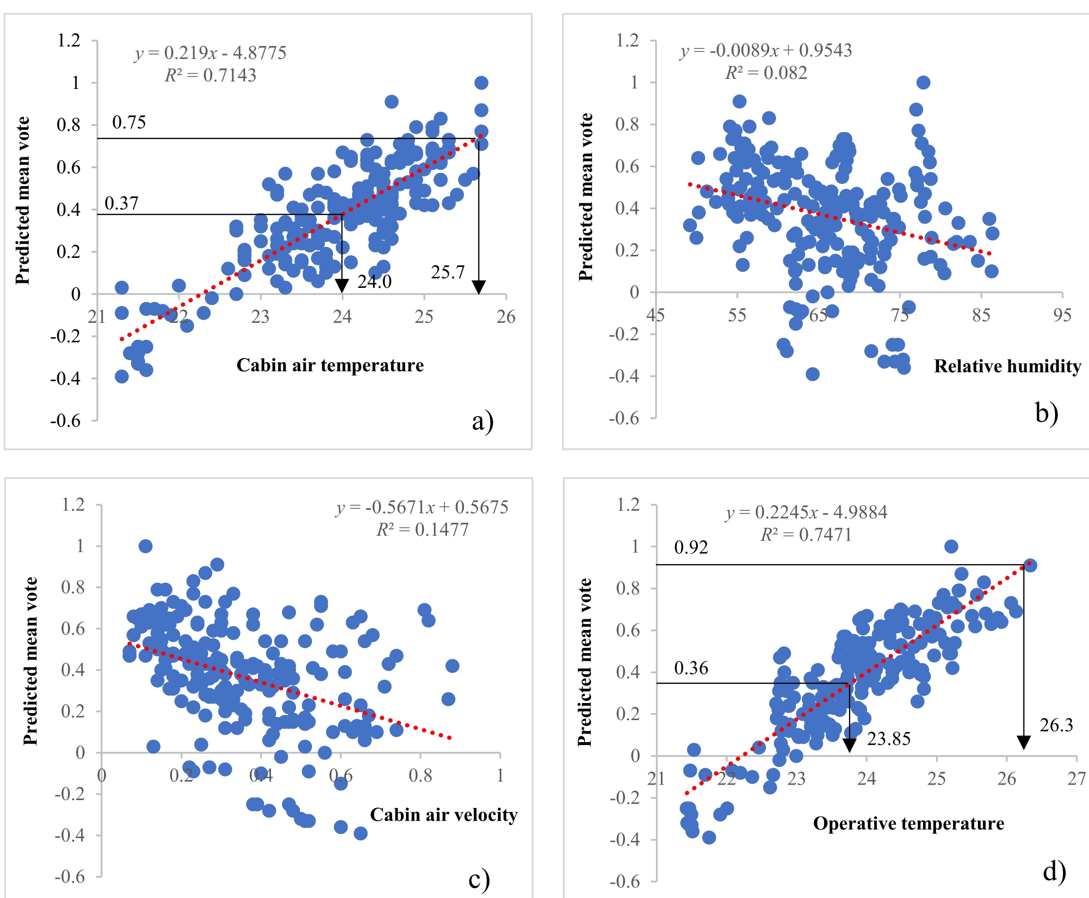

Fig. 11. Variation of the predicted mean vote against thermal parameters a) cabin air temperature b) relative humidity c) cabin air velocity d) operative temperature.

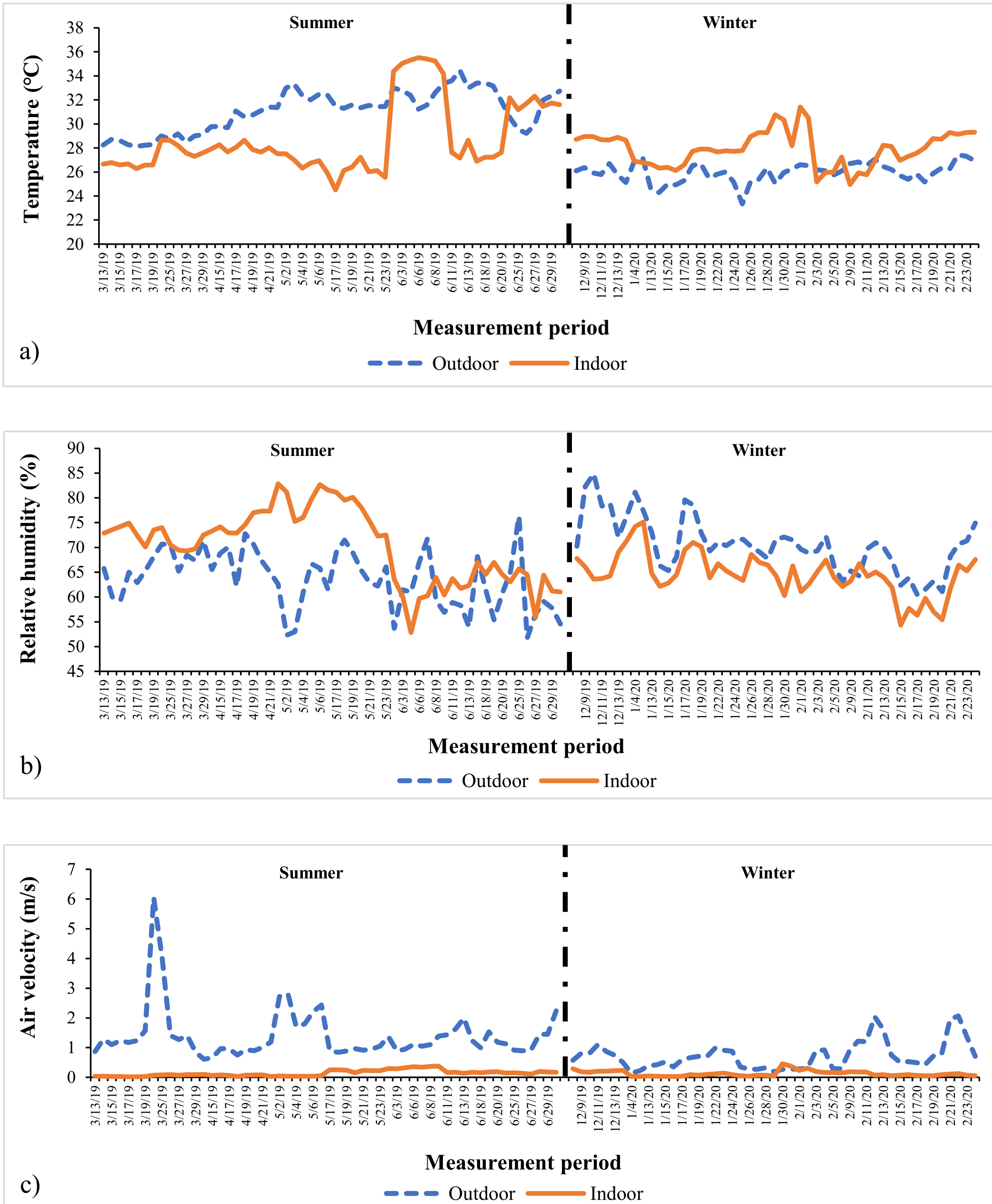

Fig. 12. Variations in the indoor and outdoor thermal conditions of metro stations.

ASHRAE-55 recommendations of T_O, a PPD of 40% could be acceptable in metro stations. Thus, to maintain this PPD, the subway T_O should be maintained at 26.1 °C. This study identified that stations with low-density passenger travel have worse thermal conditions than high-density passenger travel stations. Thermal conditions in all metro stations should be maintained uniformly to enhance subway environmental quality. Further, thermal conditions in metro trains are excellent while in metro platforms are worst. Thus, there is a need to maintain uniform thermal conditions in metro trains and platforms to avoid thermal shocks to subway passengers. Also, ASHRAE 62 (1989) recommends that an air supply of 8 L/s/person should be maintained in vehicles, public transportation platforms, and passenger waiting rooms (Eddy et al., 2017).

The metro stations should be designed with a full-length platform screen door (PSD) system. The PSD system acts as a barrier between the tunnel and the platform. It may reduce the transfer of heat and polluted air during metro operations and enhance environmental quality. Further, access to UG metro platforms should be provided at metro train entry points to improve the air exchange from the AG area. It results in advection purification of metro stations (Moreno et al., 2014), especially in the area where passengers gather. The installation of ventilation fans at natural ventilation points inside a metro tunnel could bring more fresh air from outdoor and enhance environmental quality in subway stations (Kim et al., 2016). The fresh air intake and station entrance should be away from the pollution source. Also, adopting a wider tunnel (tunnel with two rail tracks) in the station design might cause more fresh air exchange (Passi et al., 2021a). Furthermore, improper maintenance of the HVAC system deteriorates overall environmental quality. The HVAC system should be maintained regularly. Also, subway cleaning and internal hygiene should be adequately sustained.

Conclusions

The thermal comfort levels of passengers have been investigated in this study to assess their comfort perceptions in the context of Chennai UG metro stations. The thermal conditions in the metro stations are found to be similar in both the summer and winter seasons. The overall comfort conditions in both seasons surpassed the ASHRAE-55 and ISO 7730 guidelines for maintaining optimum comfort inside the subway environment. The average values of *Tr* and T_O are found to be higher in all selected metro stations (> 26.1 °C, ASHRAE-55). A high temperature is maintained to save energy costs, which results in IAQ deterioration. The mean thermal stress index (WBGT) values in the studied metro stations are well within the regulatory limits (26 °C, ISO 7243). The low *Tw* range (22.92–25.79 °C) indicates that lower temperatures can be achieved through evaporative air cooling in the metro stations. The thermal sensation votes (passengers' perception of PMV) are in the range of 1.18–2.2. The PPD with thermal comfort is higher than 20% in all the studied metro stations. The dissatisfaction rate with the prevailing thermal environment reaches up to 100% in stations with the room air temperature above 30 °C. The thermal conditions in metro stations are maintained based on station usage. The stations having low-density passenger travel are maintained with the highest operative temperature followed by medium-density and then high-density passenger travel stations. The T_O and PPD show a strong linear relationship, while there is a poor correlation between RH and airflow. To achieve the 20% PPD under prevalent thermal conditions, the T_O of 23.6 °C needs to be maintained. The percentage prevalence of short-term health effects due to exposure of passengers to the metro environment is less than 20%. Based on the prevailing thermal conditions and ASHRAE recommendations of T_O (26.1 °C, upper limit), a PPD value of up to 40% could be deemed as a thermal comfort metric that can be acceptable in the UG metro stations.

The correlation analysis of weighted average PMV indices calculated through thermal comfort investigation and passengers' perception indicate that both are in close agreement. This clearly shows the accuracy of the sample collection and the reliability of the field survey. The ANOVA statistical test reveals that there is no significant difference between PMV values of both assessments ($\alpha = 0.05$). Further, analysis of the results of the ANOVA statistical test conducted among the selected metro stations indicates a significant difference between the thermal conditions of the different metro stations. The thermal conditions inside metro trains are found to be excellent, with passengers' dissatisfaction rate less than 12%. Furthermore, the impact of outdoor thermal conditions on the indoor subway environment is deemed insignificant. Thus, it is inferred that internal factors such as the functioning of stations, operation of metro trains, and high density of passengers contribute significantly to indoor heat generation. There was not much attention paid to the thermal conditions in subway metro stations. The thermal conditions are one of the prime factors in influencing indoor environmental quality. The energy cost is a foremost issue to maintain good thermal conditions in subway metro stations. Thus, future research needs to work on the provision of natural sources of ventilation in UG metro stations, such as train piston force (train induced wind) and HVAC integrated multilayer air filtration systems for real-world applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Passenger's comfort satisfaction questionaries' survey form

1. Gender
☐ Male ☐ Female

2. Age Group
☐ Below 20 Years ☐ 20-30 Years ☐ 30-40 Years ☐ 40-50 Years ☐ Above 50 Years

3. Frequency of Metro Service Usage
☐ Regular Basis ☐ Occasionally ☐ First Time

4. Occupation
☐ Student ☐ Service Person ☐ other

5. Approximate Journey time spent by passenger in metro train and metro platform for wait.
☐ <30-minutes ☐ 30 minutes – 1 hour ☐ >1 hour

6. Rate the Satisfaction with Temperature in metro station. (Please Mark Tick)

-3	-2	-1	0	+1	+2	+3
Very Cold	Cold	Slightly Cold	Neutral	Slightly Hot	Hot	Very Hot

7. Rate the Satisfaction with air circulation or air flow in metro station.

+1	0	-1	-2
☐ High	☐ Neutral	☐ Low	☐ No air movement

8. Rate the Satisfaction with overall humidity inside metro station. (Please Mark Tick)

-3	-2	-1	0	+1	+2	+3
Very Dry	Dry	Slightly Dry	Neutral	Slightly Humid	Humid	Very Humid

9. Rate the Satisfaction with overall Air Quality in metro station (feeling any smell, air staleness, stuffiness etc.)

-3	-2	-1	0	+1	+2	+3
Worst	worse	Bad	Neutral	Good	Better	Best

10. Rate your overall Satisfaction with Comfort & Air quality in metro station.

-3	-2	-1	0	+1	+2	+3
Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slight Comfortable	Comfortable	Very Comfortable

11. Rate your Overall Satisfaction with Comfort and Air quality outside metro station area.

-3	-2	-1	0	+1	+2	+3
Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slight Comfortable	Comfortable	Very Comfortable

12. Are you experiencing any of the following short-term health effect while travelling in metro train or waiting in metro platform? (Please mark tick)
a.) Headache
b.) Tiredness
c.) Symptom of Cold
d.) Difficulty in breathing
e.) Throat and Tongue dry
f.) Skin dry
g.) Dizziness
h) Eye Strain
i.) Any other
j.) No symptoms

13. Are you experiencing any past health symptom/issue?
☐ Yes ☐ No ☐ Maybe

If yes, can you name it? ____

14. Rate your Satisfaction with Metro compared to other modes of transportation (e.g., bus, taxi, Auto etc.).

-3	-2	-1	0	+1	+2	+3
Very Uncomfortable	Uncomfortable	Slightly Uncomfortable	Neutral	Slight Comfortable	Comfortable	Very Comfortable

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