Estimating Indoor TVOCs in Response to Varying Humidity Regimes in Vernacular and Conventional Dwellings

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Abstract

Indoor environment quality (IEQ) has emerged as a crucial factor after the COVID-19 pandemic determining the health, well-being and productivity of occupants. The current research aims to examine the buildings' ability to regulate indoor air quality, specifically looking at indoor moisture and toxicity characterised in terms of total volatile organic compounds (TVOCs). According to the United States Environmental Protection Agency (USEPA), the concentration of these compounds is two to five times greater indoors as compared to outdoors. Building materials and indoor surfaces such as paints, synthetic floorings, carpets, etc., constantly emit TVOCs. The dependence of TVOC on varying moisture regimes has been examined in this study. The climatic response of these dwellings has been examined through indoor comfort and air quality parameters. The indoor temperature, humidity and TVOC levels in conventional and vernacular residential dwellings have been examined for the warm and humid climatic zone. Concurrently, these dwellings have also been modelled (and validated with real-time data for temperature and relative humidity levels) using Design Builder. This study examines indoor moisture and toxicity (TVOCs) levels in vernacular and conventional buildings for three climate-change scenarios. Simulation studies gave an insight into how the indoor temperature, indoor humidity and indoor TVOC levels, attributed to fresh paints, could increase over the years as per different climate change scenarios. The ageing of the wall paints has been examined further to compare how power decay affects the emissions in the future. The naturally derived materials do not have any harmful chemicals and, hence, emit less TVOCs as compared to the conventional building materials, thereby, maintaining better indoor air quality for the occupants.

1. Introduction and Motivation

Climate change is leading to rising temperatures in an intensified manner as compared to the expected levels. The recent report by Intergovernmental Panel on Climate Change (IPCC) reports that the warming of the earth will reach 4.5 °C by the end of this century. Studies show that regional temperature changes can be more extreme than the global average. In a world with a +2 °C global temperature increase, a local area might experience a 3 °C change, which is 1°C higher than the global average. If the global temperature increase reaches +4 °C, that same local area could see a 7.5 °C change, exceeding the global average by 3.5 °C (New, 2011).

Several countries across the globe have recorded their highest temperatures in the past nine months (Pandey, 2024). In March 2024, record-breaking temperatures have been reported for Columbia, South Africa, Gabon, Kenya and South Sudan. On the other hand, in South Sudan, extreme temperatures exceeding 43 °C are usually recorded in the summer months, but this year, 41 °C was reported on March 19 in the capital city Juba. South Africa is experiencing an unusual heatwave. Rio in Brazil has experienced a record-setting heatwave since March 17, 2024, the highest in a decade. The high heat that is predicted to persist in 2024 due to both climate change and the naturally existing El Nino is confirmed by these record-breaking temperatures that occurred on March 18 and 19, 2024. Heatwave regions often experience two heat waves in a season that last five to seven days each. However, as a result of global warming, heatwave frequency, length, and maximum duration are all increasing. Over the past 30 years, the average length of heat waves in India's hotspot regions has increased by almost 2.5

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days (Rajeevan et al., 2023). According to India Meteorological Department (IMD) data, India also had a 34% increase in heat-related mortality in the last decade. The number of states and union territories experiencing heatwaves in March 2023 was three, whereas, in April 2023, it rose to eleven. Many Indian cities have recorded the highest temperatures in 2023 and 2024 till now. March to May 2023 observed the highest recorded temperatures in Delhi (46.2 °C; T_{mean} = 40.1 °C), Mumbai (39 °C; T_{mean} = 32 °C) and Bankura (43.7 °C; T_{mean} = 40.1 °C; T_{mean} = 38.8 °C).

As the outdoor temperature rises, the indoor temperature also rises correspondingly. A climate change model predicts that an increase in outdoor temperature of 1 °C during the summer will result in an increase of 0.41 °C in indoor temperature (Asumadu-Sakyi et al., 2019). Recent research has also revealed the role of the building material in passively regulating indoor moisture in response to external climatic conditions for occupants' wellness in naturally ventilated buildings (Priyadarshani et al., 2023). Besides, building materials constantly emit TVOCs through walls, ceilings and roofing in the case of modern buildings (D'Amico et al., 2020). VOCs are affected by the temperature and relative humidity conditions (Zhou et al., 2017). Indoor temperature, moisture, and VOCs are important factors influencing indoor air quality (Mannan and Al-Ghamdi, 2021). This can potentially deteriorate the indoor air quality and cause risks to human health and productivity. Therefore, it is crucial to examine the interplay of indoor moisture and VOCs in naturally ventilated dwellings, extended to account for possible climate change scenarios.

The present study aims to examine:

(a) indoor temperature, humidity and TVOCs in naturally ventilated vernacular and conventional dwellings
(b) impact of climate change on indoor air quality in terms of indoor TVOCs.

2. Methodology

There are three main segments in which the study has been conducted: real-time monitoring, simulation studies using Meteonorm and Design Builder, and estimation of TVOC levels indoors based on changing humidity levels based on earlier studies (Fang et al., 1999) and IA-Quest, an indoor air quality emission simulation tool. Data monitoring for temperature and relative humidity was done to validate the design-builder models. TVOCs were monitored in the conventional and vernacular dwellings to compare the emissions from the building materials. The rooms selected were similar in occupancy and activity patterns.

2.1 Real-Time Data Monitoring

For real-time data monitoring, one vernacular and one conventional residential dwelling have been identified in the rural village of Sugganahalli, located about 90 km from Bangalore, India. As per the National Building Code of India, the village falls under the warm and humid climatic zone. These buildings have been selected based on different building materials used. The walls of the vernacular dwelling are made up of stones and coated with mud or lime plaster as shown in Fig. 1. However, the walls of the conventional dwelling are made up of brick, mortar, cement plaster and painted with commercially available paints as shown in Fig. 2. The conventional dwelling is twelve years old, whereas the vernacular dwelling is ninety years old. The sensors have been placed outdoors and in the bedrooms of both dwellings, which have a bed and shelves.

The data for temperature and relative humidity, both outdoors and indoors has been monitored real-time using Supco LTH sensors (range: T = -40 °C to 65 °C, RH = 0 to 99.9%; accuracy: T = ±1 °C). The indoor TVOC levels have been monitored using the Temtop LKC1000S+ 2nd generation device. This device measures the TVOC values (range: 0-5 mg/m^3; resolution: 0.01 mg/m^3). The frequency of the data collected is every ten minutes for one month.

Fig. 1 – Vernacular dwelling in Sugganahalli

Fig. 2 – Conventional dwelling in Sugganahalli

2.2 Simulation-Based Study

The selected dwellings were modelled in Design Builder v4.5. These models were calibrated using the field data for temperature and relative humidity parameters. Three climate change scenarios that are being examined as per the reports of IPCC are IPCC AR4 (Fourth Assessment Report) B1 (structured economic growth and adoption of clean and resource-efficient technologies), IPCC AR4 A1B (rapid economic growth fuelled by balanced fossil/non-fossil energy use), and IPCC AR4 A2 (regionally sensitive economic development). Since India is a developing nation where growth in rural and urban areas is dynamic, all three climate change scenarios based on the nature of future growth have been simulated. As per the different scenarios (AR4 A1B, AR4 A2 and AR4 B1), weather files for Sugganahalli were exported for the years 2020 and 2040 from Meteonorm v7. This data was integrated into the design-builder model to examine the building's climatic response using simulation. The varying humidity levels for the years 2020 and 2040 for the warm and humid climatic zone have been analysed and used for the estimation of indoor TVOC levels. The ventilation rates while running the simulations were kept to a minimum equal to infiltration rates (0.5 h^{-1}), as observed on the field because the door and windows were kept closed. The design-builder simulations were run for the years 2020 and 2040 for all three climate change scenarios. The results for indoor temperature and indoor relative humidity levels were further used to estimate the indoor TVOC levels for freshly painted surfaces as explained in Section 2.3.

2.3 Estimation of TVOC Levels

The TVOC levels have been estimated for the indoor temperature and humidity conditions for the conventional dwelling for three different climate change scenarios for the years 2020 and 2040 as shown in Fig. 3. Data from Meteonorm can be obtained at ten-year intervals, hence, data from 2020 has been used as the base year. The emission factors for various building materials used in a conventional dwelling were taken from a controlled experimental study (Fang et al., 1999). This study discussed emissions from floor varnish, PVC flooring, sealant, carpet and wall paint. However, in the context of this study, the conventional dwelling used commercially available paint. The emission factors from the paint are considered for the estimation. The temperatures taken for the controlled experiment were 18 °C, 23 °C and 28 °C. The relative humidity levels taken for the same were 30%, 50% and 70%. It was observed from the controlled experiments that wall paint was a major contributor to the TVOC levels (Fang et al., 1999). This study primarily investigates whether temperature and relative humidity affect the TVOC emission concentration from the wall paint. Paints are considered the major contributors to indoor TVOCs (Mai et al., 2024; Mo et al., 2020). Testing of emission factors is complex, requiring controlled environment studies. There were no recent studies to refer to the emission factors of various building materials, therefore, study by Fang et al. is considered to estimate the impact of temperature and relative humidity on TVOC emissions. The specifications of the paint used in the study by Fang et al. might be different from the paint that is being used in the dwellings taken as case studies. But the trends of emission decay would be similar. The relation of dependency of TVOC values on absolute humidity (Equation 1) has been taken as a basis for the projection of TVOC values for climate change scenarios by best curve fitting the TVOC concentration levels at different temperatures and relative humidity values. This equation is used to estimate the TVOC concentration in milligrams per cubic metre using the humidity ratio values, where x represents the value of humidity ratio in grams of water vapour per kg of dry air (g_{wv}/kg_{da}). Values from Equation 1 depict the initial TVOC emissions from the wall paint at different moisture content levels in the air.

$$TVOC = -7.3456x^2 + 277.11x - 414.86 \quad (1)$$

Temperature and relative humidity have been taken on an hourly basis for the entire year to estimate indoor TVOC levels. This has been further analysed to study the seasonal variation of the TVOC concentration for freshly painted surfaces. The simulation has been done for the present and future scenarios in the case of the conventional dwelling. The initial maximum emission factor is calculated using Equation (1). The power decay law is then used to calculate the emissions from the painted surfaces over years, provided the surfaces are not re-painted in between the duration. The coefficient values for the decay of emissions from wall paints have been taken from the material database of IA-QUEST software. It calculates the emission factors according to Equations 2a, 2b, and 2c (Sander et al., 2006) with the age of the building material. EF is the emission factor in mg m^{-2} h^{-1}, t is time in hours, and a, b and x_0 are constants.

Power law decay model:

$$EF = a * t\hat{}b \quad (2a)$$

Peak model:

$$EF = a * \exp\{-0.5\,[\frac{\ln(\frac{t}{x_0})}{b}]\} \quad (2b)$$

Constant model:

$$EF = a \quad (2c)$$

The power decay function is applied to TVOC emissions calculated from a freshly painted surface at a certain moisture content. The TVOC exposure values are extrapolated from the equations used by the IA-QUEST software and presented in Table 1. However, no significant difference between exposure values has been observed in different climate change scenarios as these values lie in the constant emission range.

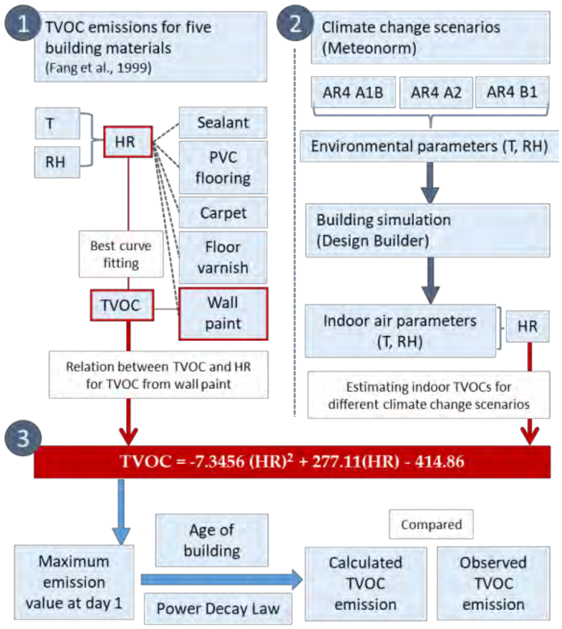

Fig. 3 – Study methodology

2.4 Results and Discussions

2.4.1 Estimation of TVOCs as per various humidity regimes

TVOCs have been estimated based on humidity ratio values for all three climate change scenarios for freshly painted surfaces. It can be observed from Table 1 that the average indoor temperature from 2020 to 2040 is expected to increase from 27.95 °C, 27.92 °C, 27.94 °C to 28.41 °C, 28.35 °C, 28.27 °C, respectively for AR4 A1B, AR4 A2 and AR4 B1 scenarios. Similarly, the average indoor relative humidity is expected to increase from 74.67%, 74.58%, 74.67% to 75.41%, 75.32%, 74.99% respectively and humidity ratio is expected to increase from 15.21 g_{wv}/kg_{da}, 15.41 g_{wv}/kg_{da}, 15.20 g_{wv}/kg_{da} to 16.01 g_{wv}/kg_{da}, 15.91 g_{wv}/kg_{da}, 15.70 g_{wv}/kg_{da} respectively as per three climate change scenarios. The monthly average values for indoor temperature, indoor relative humidity, humidity ratio and estimated TVOC concentrations indoors for the years 2020 and 2040 as per various climate change scenarios have been summarised in Table 1. The increase in the humidity ratio is resulting in increased overall TVOC emissions.

The seasonal variation trends of estimated TVOCs for different climate change scenarios have been shown in Fig. 4. It can be observed from these

graphs that TVOC emissions are maximum in summer and monsoon seasons which means that an increase in either the temperature or the relative humidity can cause an increase in TVOC emissions.
Table 2 shows the maximum and minimum values of the TVOC emissions estimated for various seasons for three climate change scenarios. It can be observed from the table that the range of TVOC exposure values increases in the summer season due to an increase in temperature. This creates a higher possibility of sudden exposure to TVOCs for the occupants of the buildings.

Table 1 – Monthly average values of indoor temperature relative humidity and estimated initial and exposure levels of TVOCs as per various climate change scenarios

Climate change scenarios	Month	2020 T (°C)	2020 RH (%)	2020 HR (g wv/kg da)	2020 TVOC (mg/cu m)	2020 TVOC exposure levels (mg/cu m)	2040 T (°C)	2040 RH (%)	2040 HR (g wv/kg da)	2040 TVOC (mg/cu m)	2040 TVOC exposure levels (mg/cu m)
AR4 A1B	January	26.68	64.28	11.15	1.76	0.07	27.19	65.06	11.77	1.83	0.02
	February	27.94	66.38	12.81	1.93	0.07	28.48	67.17	13.57	1.99	0.02
	March	29.64	69.64	15.63	2.12	0.07	30.18	70.44	16.6	2.16	0.02
	April	31.1	74.6	19.51	2.2	0.07	31.63	75.48	20.79	2.17	0.02
	May	30.24	77.66	19.24	2.2	0.07	30.74	78.46	20.4	2.18	0.02
	June	27.59	77.04	15.25	2.1	0.07	28.03	77.88	16.04	2.14	0.02
	July	27.13	79.55	15.35	2.11	0.07	27.56	80.14	16.08	2.14	0.02
	August	26.8	80.62	15.23	2.1	0.07	27.21	81.18	15.91	2.13	0.02
	September	27.17	83.6	16.52	2.16	0.06	27.49	84.6	17.27	2.18	0.02
	October	27.73	79.34	16.07	2.14	0.06	28.1	79.91	16.74	2.17	0.02
	November	26.78	74.22	13.57	1.99	0.06	27.14	74.92	14.14	2.04	0.02
	December	26.57	69.11	12.14	1.87	0.06	27.11	69.72	12.82	1.93	0.02
	Average	27.95	74.67	15.21	2.06	0.07	28.41	75.41	16.01	2.09	0.02
AR4 A2	January	26.59	64.19	11.06	1.75	0.07	27.11	64.93	11.67	1.82	0.02
	February	27.93	66.42	12.81	1.93	0.07	28.39	67.05	13.45	1.98	0.02
	March	29.59	69.79	15.62	2.12	0.07	30.08	70.57	16.51	2.16	0.02
	April	31.04	74.45	19.35	2.2	0.07	31.54	75.19	20.5	2.18	0.02
	May	30.3	77	19.1	2.2	0.07	30.76	77.93	20.22	2.18	0.02
	June	27.52	77.3	15.23	2.1	0.07	28	77.91	16.01	2.14	0.02
	July	27.2	79.55	15.44	2.11	0.07	27.55	80.08	16.04	2.14	0.02
	August	26.78	80.68	15.22	2.1	0.07	27.09	81.47	15.83	2.13	0.02
	September	27.11	83.51	16.41	2.15	0.06	27.44	84.22	17.09	2.18	0.02
	October	27.69	78.99	15.92	2.13	0.06	28.1	80.07	16.79	2.17	0.02
	November	26.7	74.34	13.52	1.99	0.06	27.23	74.66	14.19	2.04	0.02
	December	26.53	68.72	12.02	1.85	0.06	26.96	69.8	12.68	1.92	0.02
	Average	27.92	74.58	15.14	2.05	0.07	28.35	75.32	15.91	2.09	0.02
AR4 B1	January	26.77	64.37	11.25	1.77	0.07	27.1	64.87	11.64	1.82	0.02
	February	27.94	66.41	12.81	1.93	0.07	28.28	66.78	13.25	1.97	0.02
	March	29.71	69.76	15.77	2.13	0.07	30.07	70.1	16.34	2.15	0.02
	April	31.13	74.55	19.52	2.2	0.07	31.56	74.85	20.4	2.18	0.02
	May	30.29	77.45	19.25	2.2	0.07	30.69	77.66	20.01	2.19	0.02
	June	27.57	77.2	15.26	2.1	0.07	27.88	77.22	15.67	2.12	0.02
	July	27.07	79.37	15.23	2.1	0.07	27.41	79.92	15.81	2.13	0.02
	August	26.77	80.66	15.2	2.1	0.07	26.9	81.31	15.53	2.12	0.02
	September	27.15	83.76	16.54	2.16	0.06	27.46	83.76	16.98	2.17	0.02
	October	27.7	79.03	15.94	2.14	0.06	27.9	79.7	16.41	2.15	0.02
	November	26.65	74.47	13.5	1.99	0.06	27.04	74.52	13.93	2.02	0.02
	December	26.57	69	12.12	1.86	0.06	26.92	69.14	12.49	1.9	0.02
	Average	27.94	74.67	15.2	2.06	0.07	28.27	74.99	15.7	2.08	0.02

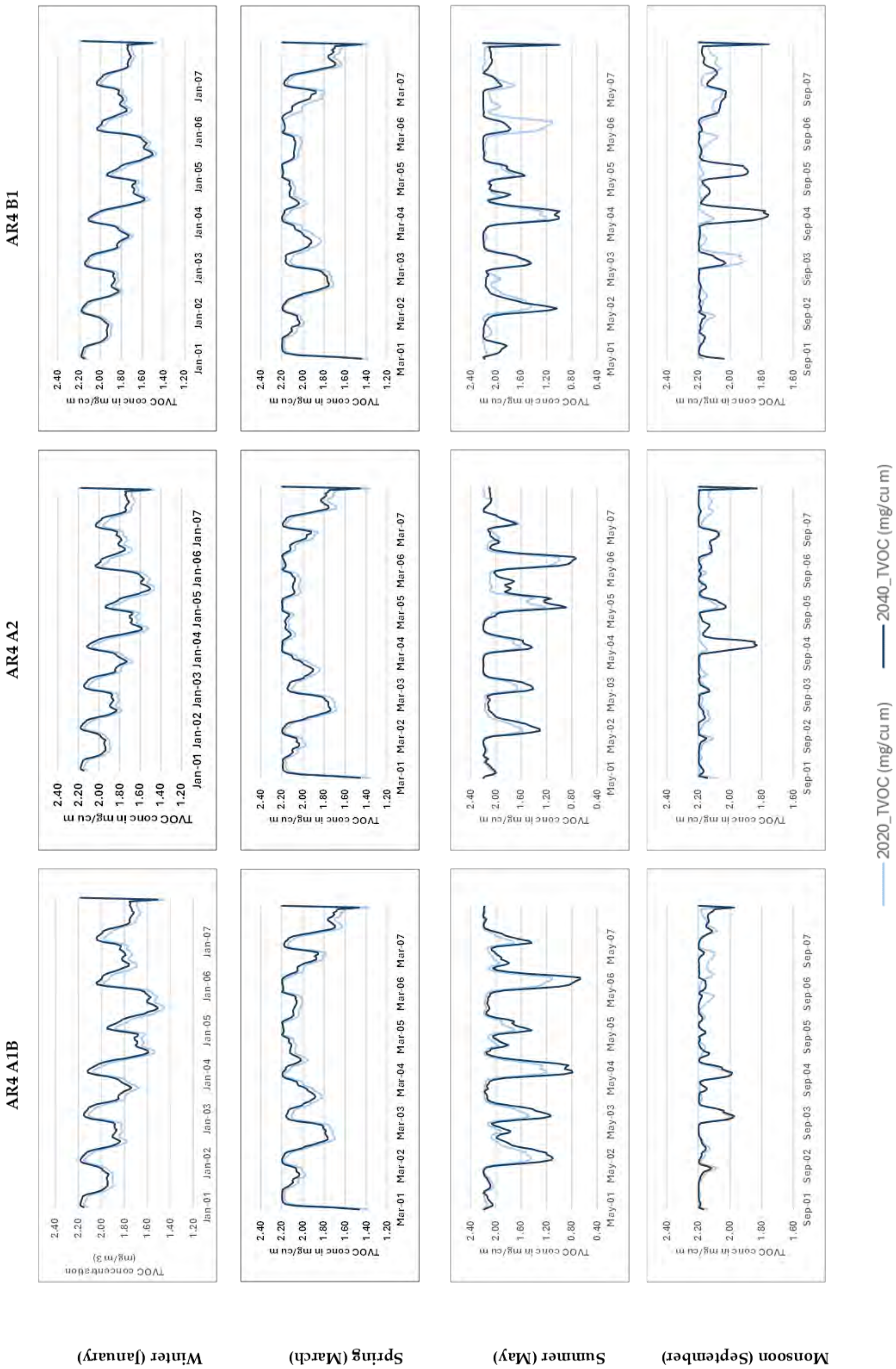

Fig. 4 – Seasonal variation of estimated initial monthly average TVOC concentration as per various climate change scenarios

Table 2 – Minimum and maximum values of estimated TVOCs as per various seasons and climate change scenarios

Estimated TVOC levels for different years (milligrams per cubic metre)							
Climate change scenario		**AR4 A1B**		**AR4 A2**		**AR4 B1**	
		2020	**2040**	**2020**	**2040**	**2020**	**2040**
Winter (January)	**Minimum**	1.45	1.51	1.46	1.50	1.46	1.50
	Maximum	2.15	2.18	2.15	2.18	2.16	2.18
Spring (March)	**Minimum**	1.38	1.47	1.37	1.46	1.39	1.44
	Maximum	2.20	2.20	2.20	2.20	2.20	2.20
Summer (May)	**Minimum**	1.11	0.67	0.99	0.74	1.11	0.99
	Maximum	2.20	2.20	2.20	2.20	2.20	2.20
Monsoon (September)	**Minimum**	2.00	1.98	2.06	1.83	1.91	1.76
	Maximum	2.20	2.20	2.20	2.20	2.20	2.20

2.4.2 Comparison of the estimated and the observed values in the conventional dwelling

The estimated values of TVOCs are the maximum initial emitted from the surface of wall paints. However, these values are further combined with the ageing effect to understand how the decay factor affects the emissions.

IA-Quest software is used to model the conventional dwelling and plot TVOC emission decay plots for the present and future scenarios. The simulated average TVOC emission value for the present comes out to be 0.063 mg/m³ (as shown in Fig. 5), however, the average value from the data monitored in the conventional dwelling is 0.046 mg/m³. These emissions are further expected to decrease as per simulation for the year 2040 to 0.02 mg/m³ (as shown in Fig. 6).

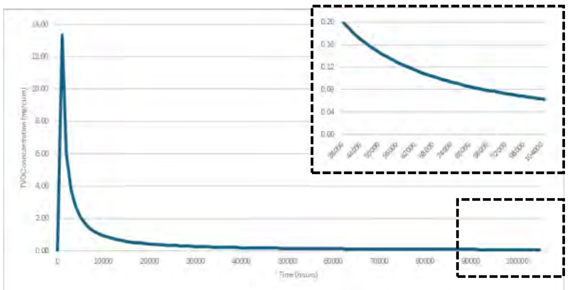

Fig. 5 – Simulation of TVOC in the conventional dwelling (2024)

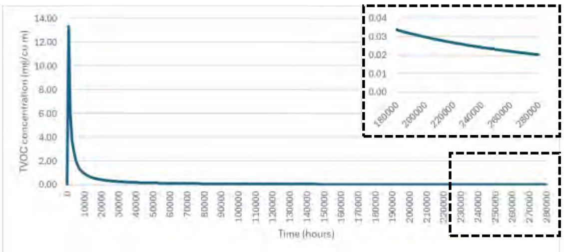

Fig. 6 – Simulation of TVOC in the conventional dwelling (2040)

Fig. 7 shows the average values simulated for the years 2024 and 2040 along with the monitored value of TVOC emissions on the field in the conventional dwelling. For the newly constructed buildings, the initial TVOC emissions would be higher. These emissions are expected to decrease as per the decay models as the painted surface gets old (according to Equations 2a, 2b, and 2c) unless it is re-painted in between which can cause a sudden increase in TVOC emissions. The emission values are in the permissible range, however, continuous exposure to volatile organic compounds can cause chronic health impacts for occupants of the dwelling.

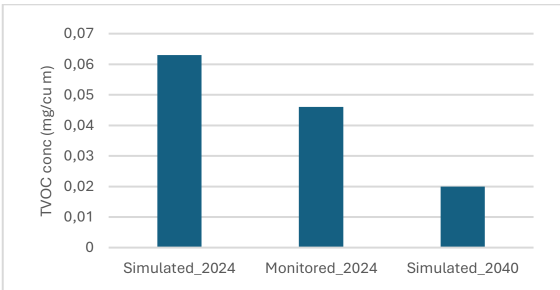

Fig. 7 – Comparison of simulated and monitored average TVOC values for 2024 and 2040

2.4.3 Comparison of the monitored values in the conventional and vernacular dwelling

The data for indoor temperature, indoor relative humidity and indoor TVOCs has been monitored in the case of conventional and vernacular dwellings as shown in Table 3.

Table 3 – Comparative indoor temperature, relative humidity and TVOCs for conventional and vernacular dwelling

	Conventional				Vernacular		
	T (°C)	RH (%)	TVOC (mg/m3)	Simulated TVOC (mg/m^3)	T (°C)	RH (%)	TVOC (mg/m3)
Min	26	35.1	0.01	-	25.9	44.1	0.01
Max	33	68.2	0.5	-	28.9	66	0.31
Avg	29.2	51.2	0.03	0.06	27.4	55.8	0.02

TVOC concentration in the vernacular dwelling is lesser as compared to that in conventional dwelling as shown in Fig. 8. The peaks which are observed in the case of vernacular dwelling is because of burning incense stick inside the room, as reported by the residents of house, representing minimal emissions from the building material. This indicates that the naturally occurring materials do not significantly contribute to TVOCs as compared to modern building materials. It also highlights better indoor air quality in vernacular dwellings as compared to conventional counterparts.

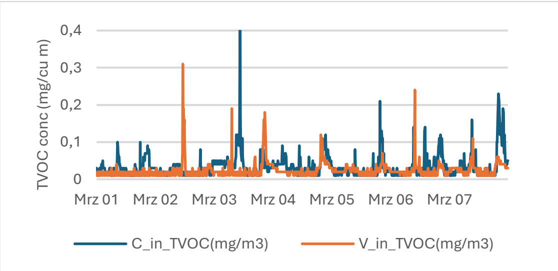

Fig. 8 – TVOC in a conventional and vernacular dwelling for a typical week in March 2024

3. Conclusion

The study examines indoor moisture and air quality, characterised in terms of TVOCs. As the temperature is expected to rise over the years according to recent IPCC reports, VOCs from building materials are also expected to increase which can deteriorate the indoor air quality. This study focused on naturally ventilated buildings, taking the case of one conventional and vernacular dwelling in warm and humid climatic zone of India. The simulation results, for all three climate change scenarios, indicate that the initial concentrations of TVOCs would increase.

The simulations also indicate that the maximum average concentrations of TVOCs are found in the months of summer (May) and monsoon (September). In summers, the temperature increases and in monsoon, the humidity levels increase which results in increased values of TVOC. This suggests that higher levels of either temperature or relative humidity result in higher TVOC emissions. The emissions are expected to significantly decrease with increasing age of the paints, however, re-painting the surfaces can exponentially increase the emissions which can be harmful to the occupants of the dwelling. The vernacular dwellings are made up of earth-based materials and don't have paint coatings, hence, have lower TVOC emissions as compared to conventional dwellings. This suggests that naturally occurring materials can be used as building materials to improve indoor air quality. The emission factors used in this study are taken from the literature. However, experimental studies are envisaged to be taken up to calculate the emission factors for the presently available surface finishes including wall paints.

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Nomenclature

Symbol	Description
RH	Relative Humidity (%)
T	Temperature ($°C$)
TVOC	Total Volatile Organic Compounds

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