# Discerning relative humidity trends in vernacular and conventional building typologies for occupant health

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**ABSTRACT**

The indoor built environment has a significant impact on the occupant's physiological, psychological, and behavioral health. Moisture is an important parameter that has a direct bearing on the quality of a built environment. Commonly referred to as water, moisture impacts nearly all dimensions of a building's functional performance, i.e., structural, durability, thermal, acoustics, indoor air quality, ventilation/freshness/odor, aesthetics, and also influences the health of occupants. Very high humidity can cause physical and chemical deterioration of materials, increased action of biological contaminants, and accelerate the spread of infections. However, low humidity can result in breathing difficulties, cough, irritation in the eye, wheeze, skin chapping, etc.

Building materials have an impact on indoor air quality. Vernacular building materials are often effective in regulating the thermal performance of a building, ensuring energy efficiency. Also, people residing in such dwellings have been found to have high resilience to withstand the adverse external conditions. This exploratory study aims to understand the performance of building materials for the regulation of indoor moisture and air quality for promoting the health and well-being of the building and the occupants. The study involves monitoring a conventional (brick, concrete) dwelling and vernacular dwellings (adobe construction, brick/lime construction) situated in India's Composite Climatic zone. The result suggests that dwelling constructed with earth (adobe) maintains the narrowest range of variation in indoor relative humidity. The indoor relative humidity variation range is widest in cement concrete construction.

The paper examines factors that regulate relative humidity in the indoor environment. Understanding the moisture buffering capacity of the building materials in indoor RH regulation for occupant health has also been discussed.

## INTRODUCTION

The built environment comprises the natural environment and the built environment comprising infrastructure facilities around us and articles used in

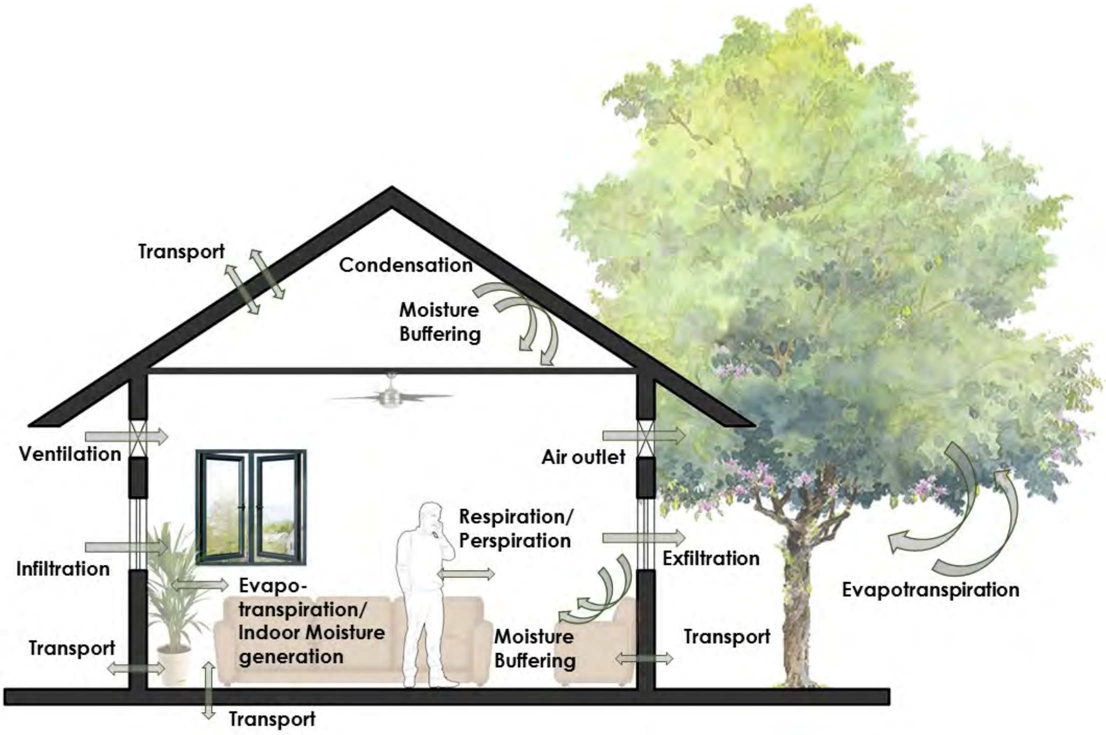


*Figure 1 Moisture transport within an enclosure*

everyday life. Buildings are shelters for human beings. (Klepeis et al.(2001)) reveal that 90% of our life is spent indoors. The indoor environmental quality is significantly responsible for occupants' physiological, psychological, and behavioral health (Andersen et al. (1973); Hutcheon (1964); McIntyre & Griffiths (1975); Jorn Toftum & Fanger (1999)). The aspects of comfort perception and composure: occupational, thermal, acoustic, illumination have been found to impact wellness perception in occupants and vice versa. People exposed to environmental conditions close to natural tend to have high resilience to withstand the adverse external conditions(al Tawayha et al. (2019); Mayer & Frantz (2004)). With the increasing range of building materials used globally, the vulnerability towards its ill effects leading to health consequences increases (John D. Spengler & Chen (2000); Straube (2014); Wolko (2018)). Several studies explain the hazardous effect caused by Volatile Organic Compounds and Endocrine disruptive chemicals emitted by the building materials on human health (Nehr et al (2017)). The outdoor environmental factors (temperature, humidity, wind, and radiation) in conjunction with these emissions cause temporal interactions leading to detrimental impacts.

Moisture/Humidity has been found to, directly and indirectly, impact human and building health(Höppe & Martinac (1998); John D. Spengler & Chen (2000); Seppänen & Kurnitski (2009); Wolkoff & Kjærgaard (2007)). The several physical processes leading to the occurrence of moisture in an indoor environment are explained in (Figure 1).In buildings, the occurrence of damp in cold climates, surface defects like flaking, efflorescence cause deterioration of buildings. Also, exposure to variation in humidity levels has been found to affect occupants' wellness. Direct health impacts due to prolonged exposure to improper moisture conditions include cold, cough, skin irritation, dryness in the nose and eyes, and upper respiratory problems. It has been found to cause illnesses like dermatitis, asthma, and reduced olfactory response (Seppänen & Kurnitski (2009)). Indirect impacts due to varied perceptions of moisture by occupants are discomfort, distress, and loss of productivity.

With emerging studies on the hygroscopicity of materials, physical understanding of moisture transport in buildings has improved (Hens (2017); Jerman & Černý (2012); Liu et al. (2017)). The phenomenon of moisture buffering has been understood through experimental and numerical studies in several building materials (Cascione et al. (2019); Osanyintola et al. (2006); Osanyintola & Simonson (2006); C. Rode (2005); Carsten Rode et al. (2009); Roels & Janssen (2004); Salonvaara et al. (2004)). It is predominantly responsible for maintaining hygroscopic equilibrium in an indoor environment by regulating relative humidity (or absolute moisture content/humidity ratio) and enhancing Indoor air quality. Implications of regulated relative humidity and moisture buffering in an indoor environment towards the thermal performance of a building and thermal comfort of occupants are evident from(Jerman & Černý (2012); Lozhechnikova et al. (2015); Osanyintola & Simonson (2006); Woloszyn et al. (2009); Zhang et al. (2017)).

In this paper, results obtained from monitoring conventional buildings (brick/concrete construction) and vernacular buildings (adobe construction) for three months in India's composite climate zone are presented. This ongoing study explains the phenomenon of regulation of relative humidity in both conventional and vernacular study blocks. Empirical relations developed by (Fang (1998b, 1998a); Jørn Toftum et al. (1998b, 1998a); Jorn Toftum & Fanger (1999)) have been used to understand the Percentage of Dissatisfied occupants for warm respiratory comfort and indoor air quality to compare the different building typologies for humidity related comfort offered to the occupants. Theoretical laws have been used to understand and explain the results in terms of humidity ratio (w) or absolute water vapor (kg-water vapor/kg-dry air). An attempt to understand the physical process of moisture buffering with the derived data for humidity ratio has been made.

## CASE STUDY: JAMGORIA CLUSTER

*Figure 2 The cluster of buildings around the courtyard as seen from the entrance (between C2 and C3)*

### Study Location

Jamgoria is located in Bokaro district, in the State of Jharkhand, situated in the eastern part of India (Composite Climate zone). Summers are generally warm and dry, with May being the warmest month (mean temperature is 31.5 degrees Celsius). The lowest averages are seen in January (mean temperature is 16.8 degrees Celsius). Most of the precipitation occurs from June to September. Situated at 214 meters above the mean sea level, this region is the lowest Chotanagpur plateau level, also called the Manbhum area. The region is surrounded by areas rich

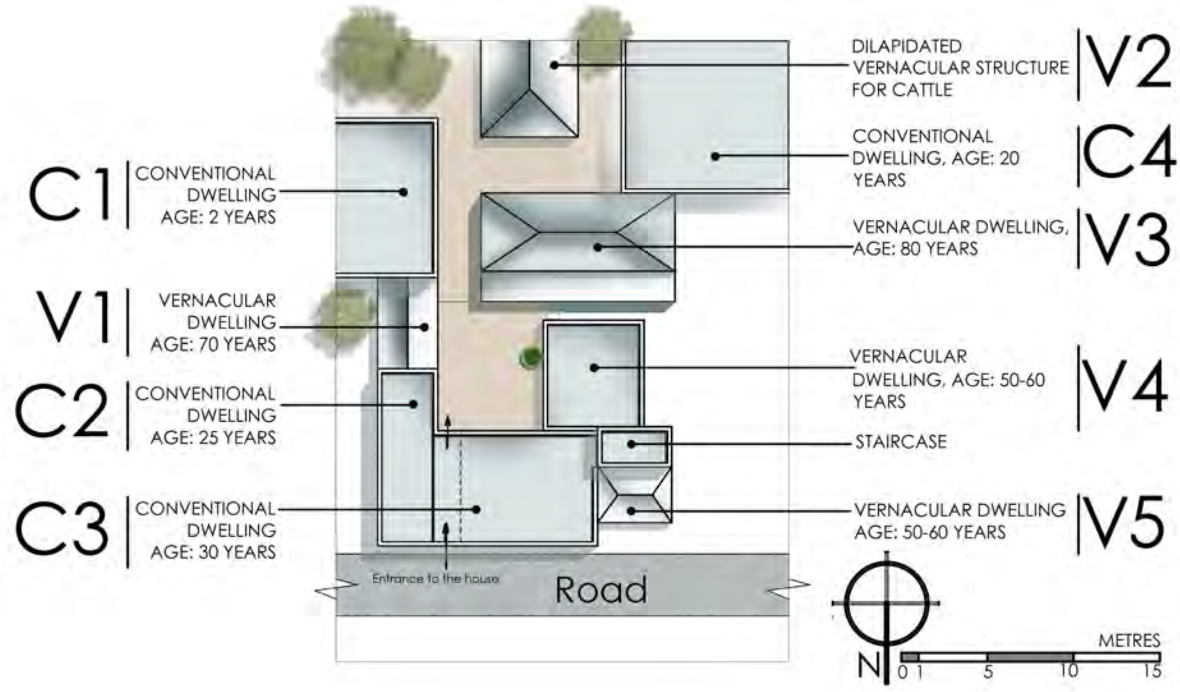


*Figure 3 Building Typologies in Jamgoria Cluster Case Study*

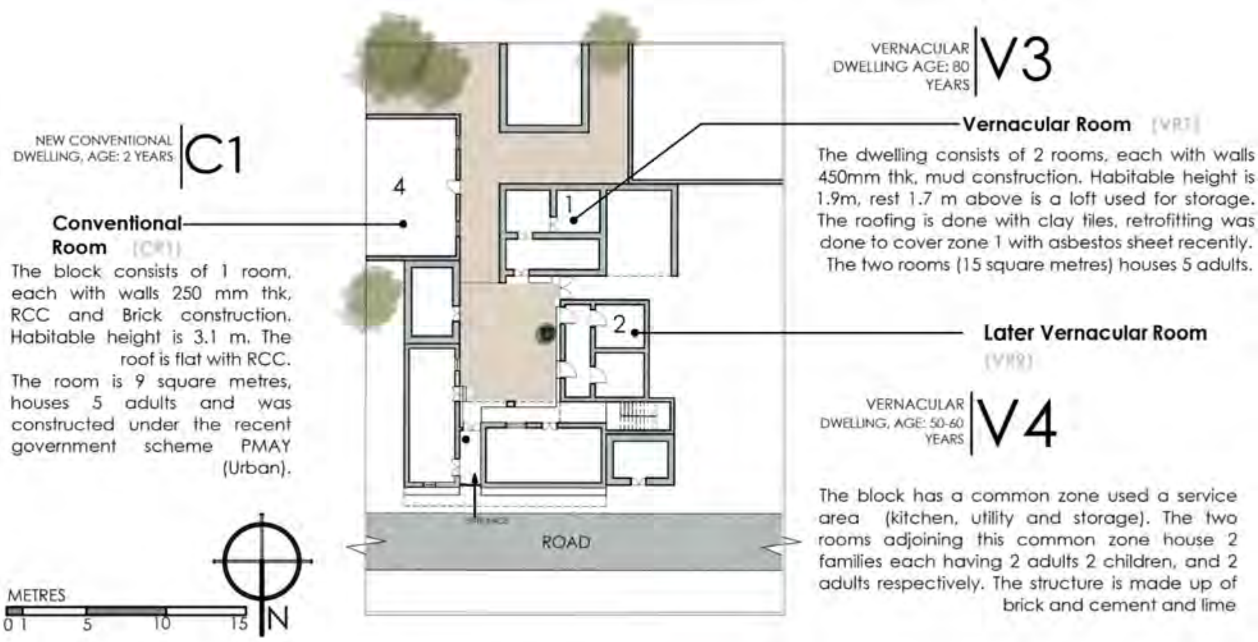


*Figure 4 Layout details of Selected Study Rooms in different blocks*

in mineral resources such as mica, bauxite, limestone, copper, iron ore, and coal. The agriculture and mining industry are the primary sources of income for livelihood. Predominant mining activities in the neighboring region have been a cause of environmental pollution causing affecting the health of residents of the area.

**Building details**

Earth construction was predominantly practiced in the region till the last decade, when a sudden surge in construction using standardized materials emerged. The building selected is a cluster surrounding a courtyard. Each block is owned by one household of the same family. The cluster consists of 3 building types as marked in (Figure 3) i.e.

1. Vernacular: Adobe Construction (V1, V2, V3)
2. Later Vernacular: Brick, Cement, Lime Construction (V4, C2, C3)
3. New Conventional Construction: RCC and Brick Construction (C1, C4)

The cluster was documented, and dataloggers were installed in each room to monitor indoor temperature and relative humidity. However, for the purpose of this study, where it was intended to compare the performance of building typologies, V3, C1, and V4 (bedroom 1 in each of the blocks) were selected as they have similar orientation, and occupational patterns. The selection of rooms was based on consistency in anthropogenic activities for better comparison. The details of the selected study rooms are shown in (Figure 4).

### Study Overview

The study was initiated during the lockdown due to the COVID-19 pandemic. All study building was documented by taking physical measurements on-site and documentation in the form of sketches and drawings. Also, this cluster was selected because of the presence of varied building typologies at one place, which was accessible for any instrument installation, data monitoring/download, and other necessary visits. With the limited instruments for data logging available, data loggers were installed in selected rooms to initiate the real-time monitoring. We are initiating logging in other rooms also and parameters causing the change in moisture levels at material and envelope levels will be investigated further taking the study forward. The analysis of the data presented in this paper intends to compare the building typologies for the ability to regulate indoor moisture levels based on empirical studies done in the past.

## STUDY METHODOLOGY

### Monitoring and Data Collection

The outdoor and indoor environmental variables measured were air Temperature (T in $^{0}$C) and relative Humidity (RH in %). For outdoor measurements, the temperature and humidity sensor "Tempnote-TH32 Datalogger" (accuracy ±0.5$^{o}$C, ±3%RH) was placed in a Stevenson screen and hung outdoors in the courtyard with the help of a projected bamboo from the roof of one of the Entrance block. It was installed at the height of 4.5 meters above the ground level, undisturbed by human activities in the area.

For indoor measurements, "Elitech RC-4HC datalogger" (accuracy ±0.5$^{o}$C, ±3%RH) was used. The sensors were hung from the roof to allow unhindered data logging. The study rooms had no windows; the sensors were placed away from the doors to avoid the effect of air movement. All the instruments used for data logging were pre-calibrated by the manufacturers.

### Data Interpretation and Analysis

For data interpretation and analysis, the elevation of Jamgoria $z$ is 214 m above the mean sea level. For calculations, the temperature at mean sea level is considered to be 15$^{o}$C. Total atmospheric pressure at height "$z$" was calculated using (Equation 1, Equation 2), where $\rho$ is the density of air [kg/m$^3$] and '$\alpha$' is the lapse rate [6.4997 $^{0}$ C/m].

$$\frac{dp}{dz} = -\rho g \quad (1)$$

$$\mathrm{T} = T_0 - \alpha z \quad (2)$$

$\phi$ is the relative humidity, or ratio of the partial pressure of water vapor $p_{wv}$ [Pa] in the air to the maximum partial pressure of water vapor (saturation pressure) $p_{wv,s}$ [Pa] at a given temperature $T$ [$^{o}$C]. Temperature and RH data collected from the field were used to determine the partial pressure of water vapor using (Equation 3). $p_{wv,s}$ is calculated using, Teten's

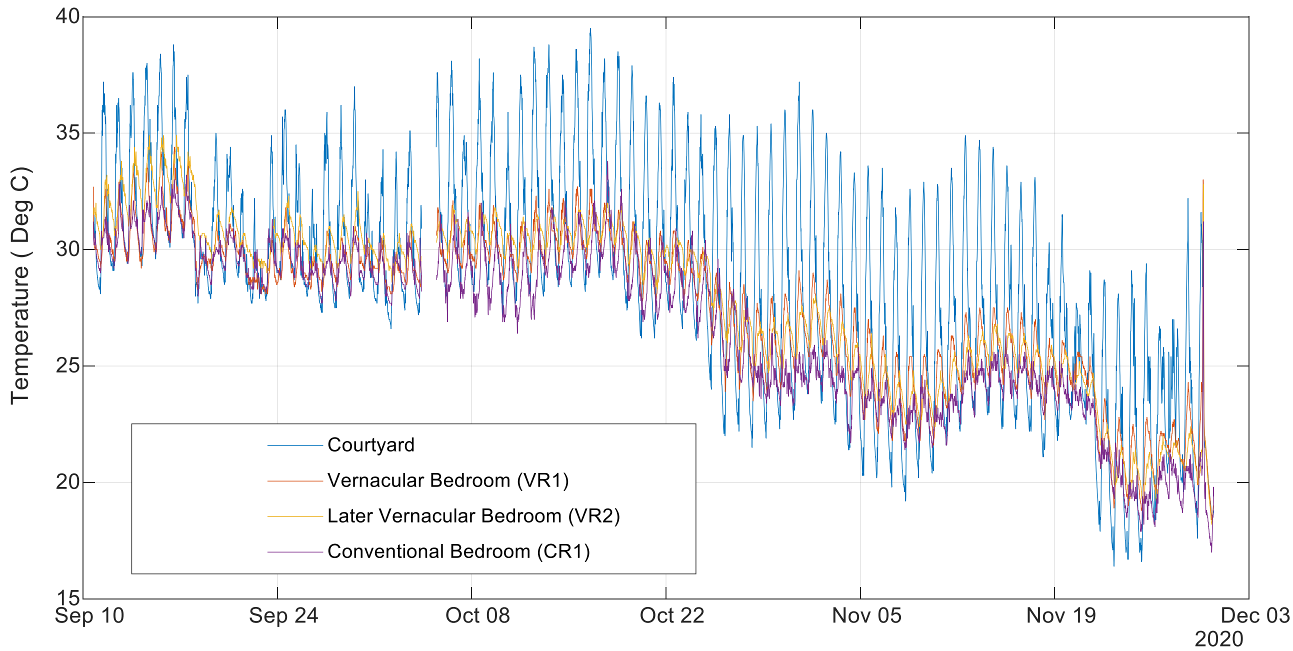


*Figure 5 Trend in change of temperature from 10th September to 30th November 2020 in different rooms*

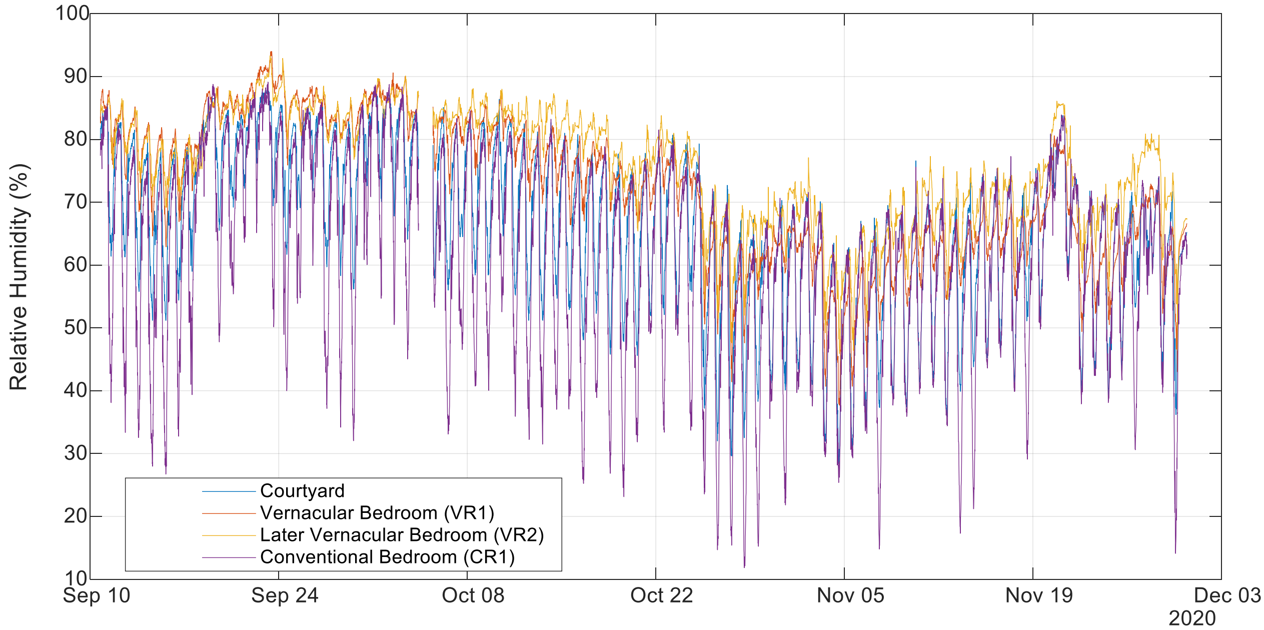


*Figure 6 Trend in change of relative humidity from 10th September to 30th November 2020 in different rooms*

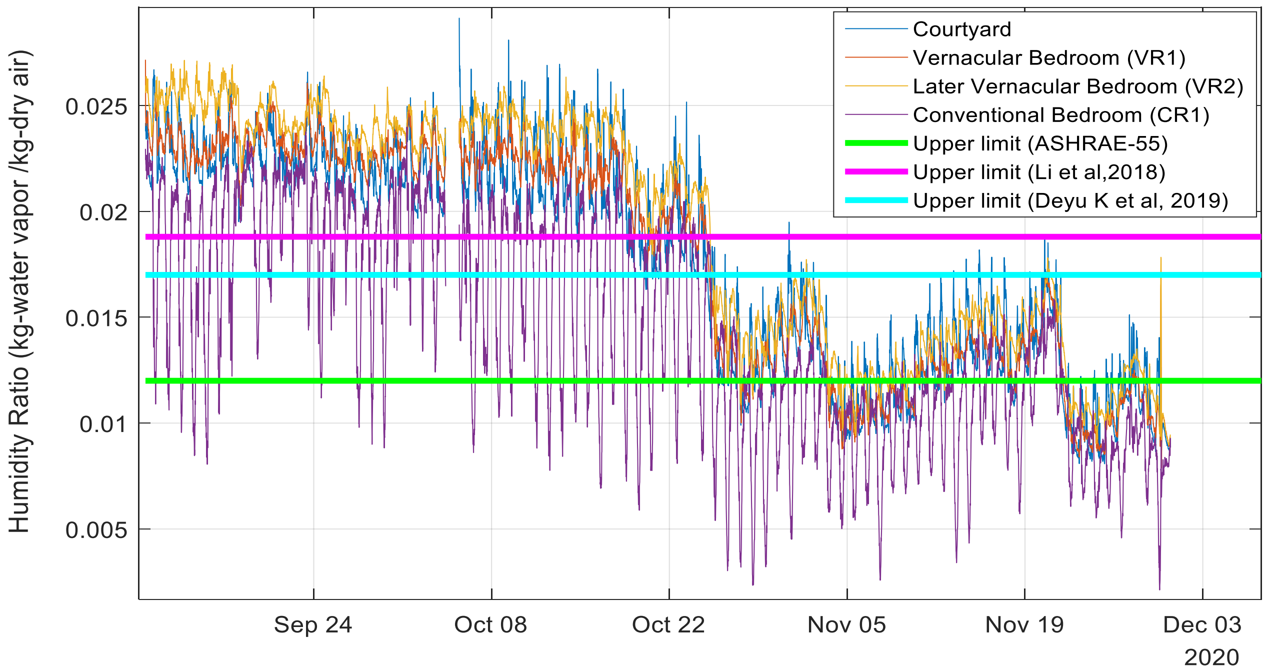


*Figure 7 Trend in change of humidity ratio from 10th September to 30th November 2020 in different rooms*

Relations (Equation 4) (Yang et al. (2012)) where B, C, and D are constants with B=7.5, C=237.3, D=0.21429 for Ts>0$^0$ C.

$$\phi = \frac{p_{wv}}{p_{wv,s}} \qquad (3)$$

$$log_{10}\, p_{wv,s} = \frac{BT_s}{C+Ts} - D \qquad (4)$$

For calculation of humidity ratio $w$ [kg-water vapor/kg-dry air], (Equation 5) has been used. Here, the molar mass of dry air $M_{da}$ is taken as 28.9645 [kg. K/mol] and the molar mass of water vapor $M_{wv}$ is taken as 18.01527 [kg.k/mol]. $p_t$ is the total atmospheric pressure in [Pa], $p_{wv}$ is the partial pressure of water vapor, and $p_{da}$ is the partial pressure of dry air.

$$w = \frac{M_{wv}}{M_{da}} \cdot \frac{p_{wv}}{p_{da}} = \frac{M_{wv}}{M_{da}} \cdot \frac{p_{wv}}{p_t - p_{wv}} \qquad (5)$$

An analysis of occupant comfort in the room, which is significantly affected by variations in RH levels, respiratory comfort, and perceived indoor air quality, is done using empirical relations(Fang (1998b, 1998a); Jørn Toftum et al. (1998b, 1998a)). Percentage Dissatisfied for warm respiratory comfort (PDwrc) is given by (Equation 6).

This relation is based on the result of the study conducted in (Jørn Toftum et al. (1998b)) that explains that too dry or too humid environment can cause warm respiratory comfort by causing insufficient evaporative and convective cooling of the mucous membranes in the upper respiratory tract leading to a perception of poor air quality.

Percentage Dissatisfied due to perceived indoor air quality (PDiaq) is assessed using (Equation 7), where H is the total enthalpy of air in kJ/kg. The equation is derived from the study conducted in (Fang (1998b)), and it considers only enthalpy of the air as a determinant of indoor air quality. Equation 6 and Equation 7 hold good, assuming that the indoor air is unpolluted or does not exceed the threshold limit for certain identified pollutants. The empirical relations from the studies mentioned above have been used for preliminary analysis. The determinants of comfort such as acclimatization to a particular climate zone, age, occupation, social and economic status of occupants are not the same in this case. Hence, the inferences drawn from the analysis need to be verified as we take the study forward.

$$PD_{wrc} = \frac{100}{1+\exp\left(-3.58+0.18(30-T)+0.14(42.5-0.01p_{wv})\right)} 100 \quad (6)$$

$$PD_{iaq} = \frac{\exp\left(-0.18-5.28(-0.33H+1.662)\right)}{1+\exp\left(-0.18-5.28(-0.33H+1.662)\right)} 100 \quad (7)$$

## RESULTS AND ANALYSIS

Temperature and Humidity data were monitored for 82 days, from September 10, 2020, to November 30, 2020, at an interval of 15 minutes. Loggers were turned off from October 4 (9:30 AM) to October 5 (10:00 AM) because of cleaning done in the test rooms on a local festival.

### Temperature and Relative Humidity

The temperature and Relative humidity data recorded shows the seasonal variation as the monthly mean temperature drops from 31.2 $^0$C to 25.3 $^0$C and monthly mean RH drops from 76.2 % to 59.1 % as given in (Table 1).

(Figure 5) shows the variation of temperature values in the courtyard, vernacular, later vernacular, and conventional room. During the study, the courtyard values reached a maximum of 39.5 degrees Celsius on October 16, 2020, at 1:11 PM and a minimum of 16.4 degrees Celsius on November 23 at 6:41 AM. The results show that conventional room temperature has a maximum range of diurnal variations, following which is the outdoor courtyard diurnal variation; however, the average conventional room temperature remains the lowest amongst the three.

Also, the diurnal variation range is the least in the vernacular rooms (lowest in adobe construction), offering a more consistent temperature throughout the whole day.

(Figure 6) shows the variation of relative humidity in the different rooms. Both the vernacular rooms always remain at a higher relative humidity than the conventional room and also offer a lower range of diurnal variation. The conventional room shows the highest variation in relative humidity during the day, where the values remain lower than the courtyard RH most of the time. The vernacular bedrooms have a higher RH than the courtyard; however, during November, the RH values have been observed to drop lower than the courtyard RH during the afternoon. The temperature and relative humidity are interdependent, and it becomes difficult to understand each of them explicitly. From the data, we see that as the temperature drops during November, the Relative humidity increases; however, the air is still dry in terms of humidity ratio. For quantification and analysis of moisture independently and in absolute terms, the quantity of "Humidity ratio" expressed in grams of water vapor per kg dry air (g-wv/kg-da) was used as discussed in the next section.

### Humidity Ratio

Humidity ratio values are used to understand the absolute moisture content in the air on dry air basis at a given temperature and relative humidity. (Figure 7) shows the variation of absolute moisture values (humidity ratio computed using (Equation 5). In all the selected rooms, windows were absent. Also, the effect of the wind was minimum in the vernacular rooms due to the presence of the common lobby, as shown in

*Table 1 Monthly mean values for different rooms*

| Monthly mean Values | Temperature ($^0$C) | | | Relative humidity (%) | | |
|---|---|---|---|---|---|---|
| | September | October | November | September | October | November |
| Courtyard | 31.2 | 30.7 | 25.3 | 76.2 | 67.3 | 59.1 |
| Vernacular | 30.1 | 29.1 | 24 | 83.1 | 74.4 | 62 |
| Later Vernacular | 31.2 | 29.5 | 23.8 | 82.7 | 78 | 68.7 |
| Conventional | 29.9 | 28.3 | 22.7 | 69 | 60.1 | 56.6 |

(Figure 3). The absence of any anthropogenic source of moisture and ventilation leading to change in HR levels, the variation of humidity ratio in the different building typologies might be attributed to their respective material's ability to regulate the indoor air moisture levels.

As seen in (Figure 7), the conventional room shows a very high range of diurnal variations in the humidity

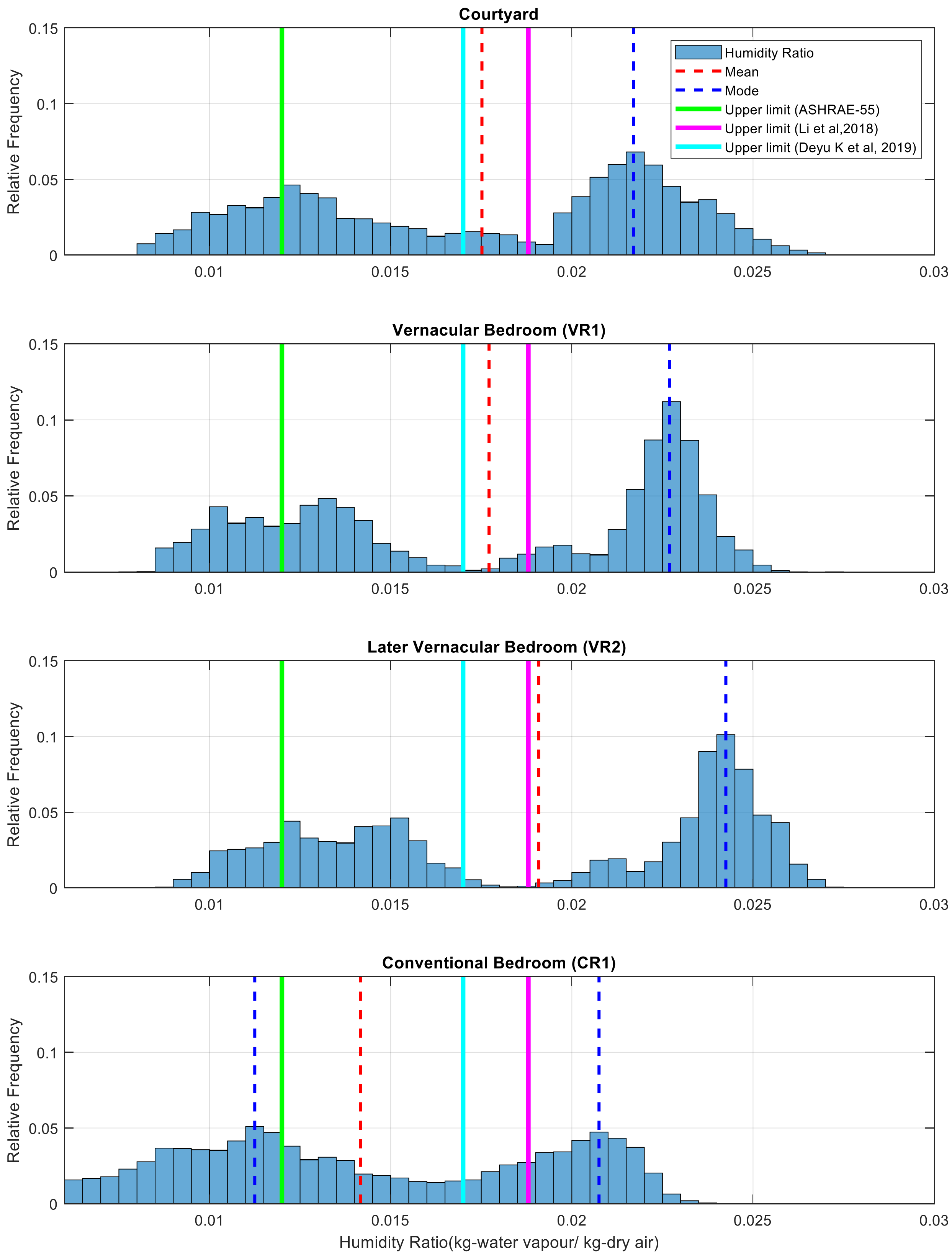


Figure 8 *Frequency Distribution of humidity ratio*

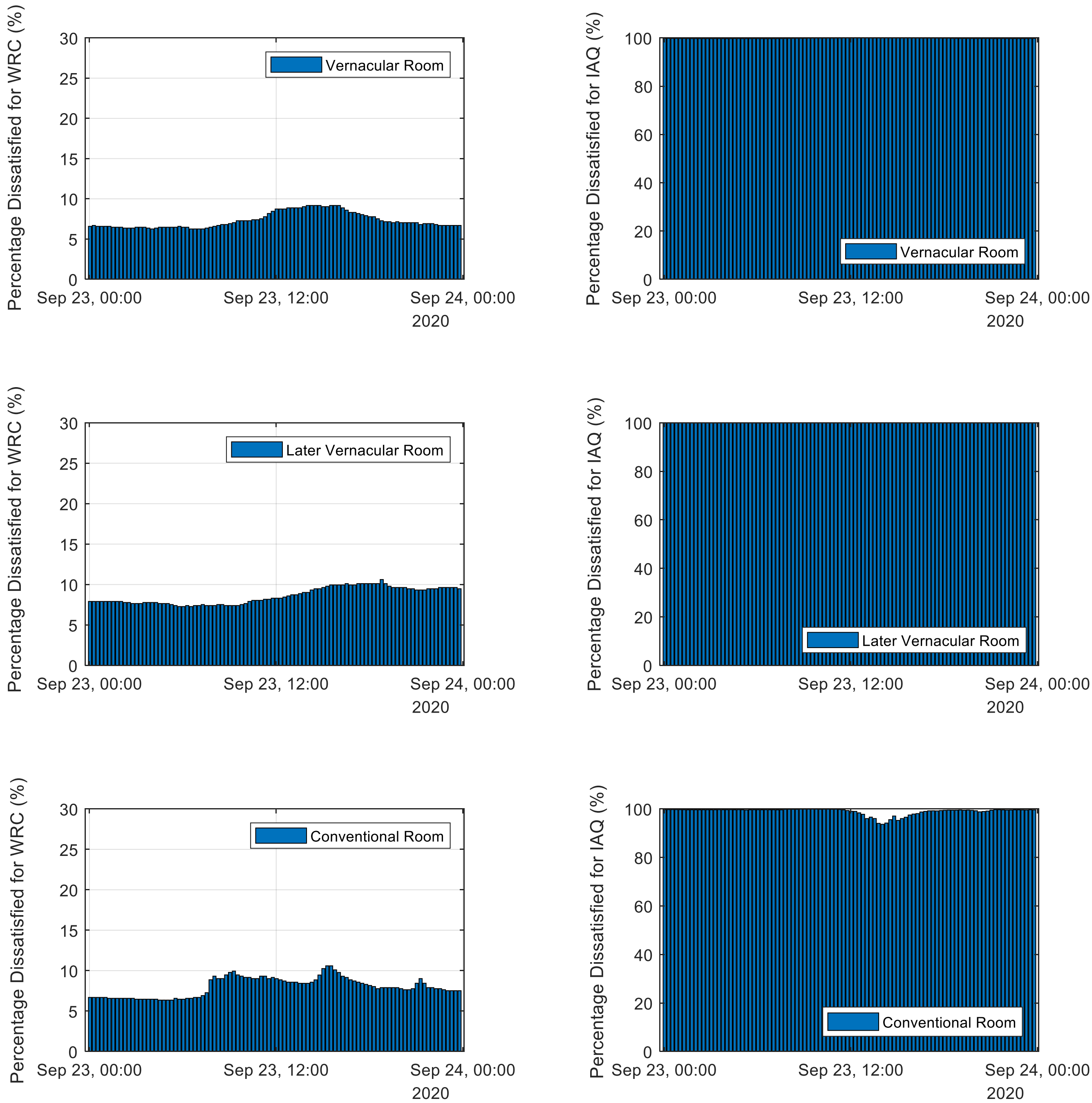


*Figure 9 Trend in change of Variation of Percentage dissatisfied for warm respiratory comfort and Indoor Air Quality on 23rd September 2020 (highest observed courtyard RH)*

ratio, which remain lower than the courtyard humidity ratio. In a study conducted by (Tran Le et al. (2010)), it was observed that more hygroscopic (hemp concrete) led to a higher value of air relative humidity at the same temperature compared to less hygroscopic (cellular concrete). In the present study, a similar phenomenon is observed. However, the humidity ratio levels in the conventional room drops below the courtyard, the reason for which needs to be investigated. (Ge et al. (2014)) have shown that moisture buffering is a surface phenomenon by virtue of which sorption of desorption of water vapor occurs in the material to maintain the relative humidity levels in an enclosure. The values depend upon the moisture absorption capacities of different materials; for example, plywood shows moisture absorption as high as 355 $g/m^2$, whereas Aerated Cellular Concrete block shows moisture absorption values as low as 41 $g/m^2$.

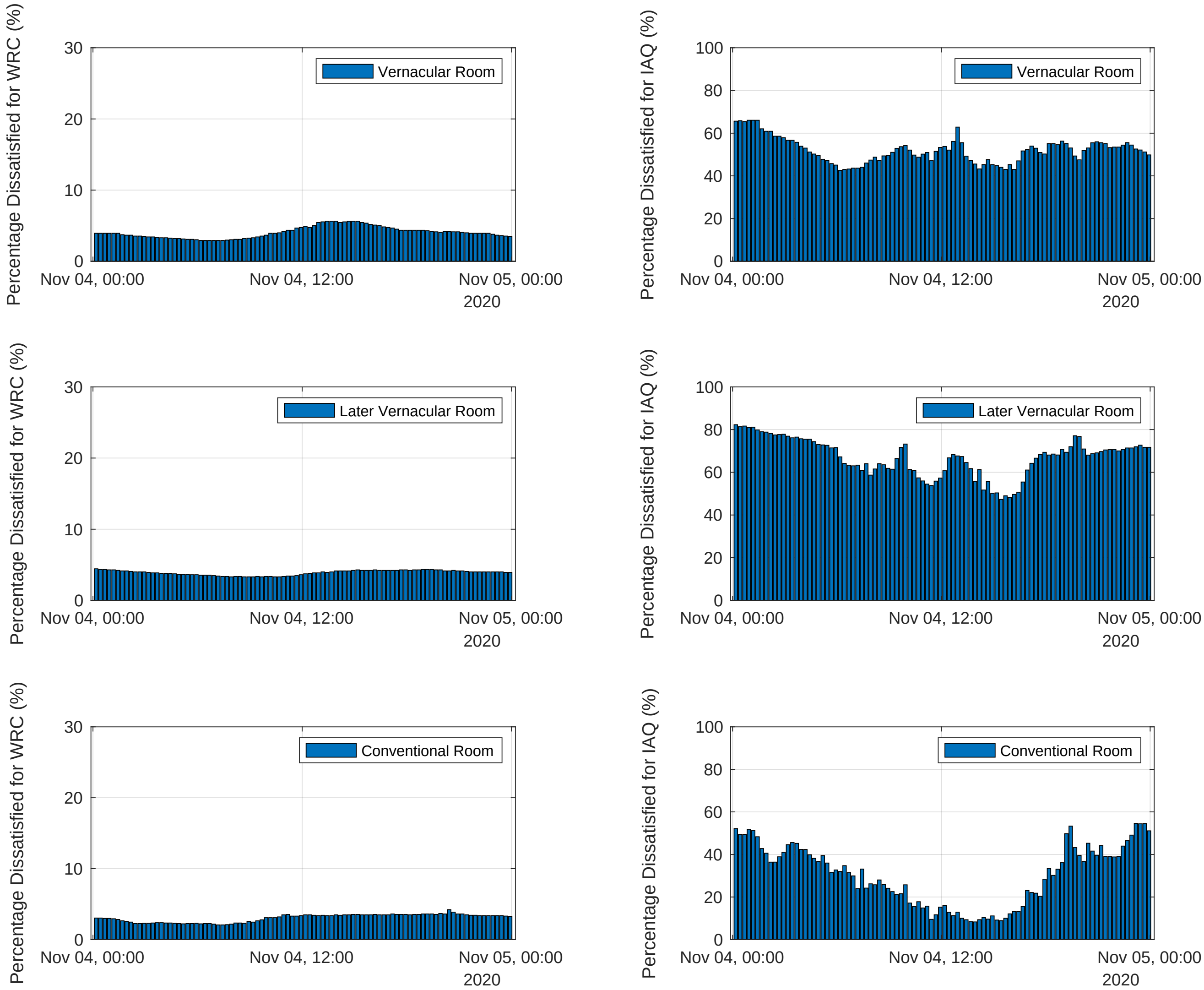


*Figure 10 Trend in change of Variation of Percentage dissatisfied for warm respiratory comfort and Indoor Air Quality on 4th November 2020 (lowest observed courtyard RH)*

The later vernacular room shows the highest recorded humidity ratio values, going even higher than the courtyard humidity ratio. Anthropogenic factors for moisture generation during the day can be ruled out in all three rooms as the residents are out for work during the daytime. However, the moisture retention by the articles housed in the rooms may be a reason for the higher humidity ratios observed (Yang et al. (2012)). The vernacular rooms have a narrow range (Adobe showed a narrower range than brick/Lime) of humidity ratio recorded with values lying within the

range of courtyard humidity ratio limits most of the time. The frequency distribution of humidity ratio is shown in (Figure 8), which shows that the courtyard values and very similar to that of the vernacular rooms. This observation hints at the ability of vernacular material envelopes to maintain an indoor environment very close to natural with respect to moisture in the air by offering a quick response to any change in the indoor moisture levels. The possibility of moisture accumulation in the three above-mentioned building typologies, the physical phenomenon of moisture transport from outside to inside, and its effect on building functional performance and occupant health needs to be further scrutinized.

Based on (ASHRAE, S. 55. (2004))standards, the comfort humidity ratio is 0.012kg-wv/kg-da, later, (Li et al. (2019)) proposed the revised value to be 0.0188 kg-wv/kg-da, and (Kong et al. (2019)) further revised it as 0.017 kg-wv/kg-da.

This implies that even though the vernacular rooms' humidity exposure is narrow in range, it is in consonance with exterior environmental conditions. However, there is a sudden change in the indoor humidity conditions in the conventional room, very different from the natural conditions. The diurnal variation in humidity ratio decreases significantly in November as the outside temperature drops. If this trend continues, the diurnal variation during the peak summer months will be very high, which needs to be observed and analyzed further.

### Percentage Dissatisfied for warm respiratory comfort and indoor air quality

The values obtained for Percentage Dissatisfied for warm respiratory comfort using (Equation 6) show that the humidity parameters are conducive and tend to have more acceptability than the outside temperature conditions in the conventional room. Trend of the comfort percentages is shown in (Figure 9 and Figure 10) show the percentage dissatisfied on the day with highest observed courtyard relative humidity and the lowest observed courtyard relative humidity respectively.

Especially during the winter month of November, when the air is drier, the accepted respiratory comfort inside the conventional rooms is always higher than that of the outside environment; however, during September, the later vernacular room (brick/lime construction) should be uncomfortable as per the relation than the outside environment during midnight. However, in the vernacular room (Adobe construction), though the variation of percentage acceptance is not very high, but it is consistently more comfortable and acceptable than the outside environment in all the study months.

The indoor air quality as accepted in the conventional room is the best as per the relation, however as the temperature drops in the month of November, acceptance in the vernacular rooms increases. However, the results obtained from the empirical studies are subject to acclimatization and other personal factors, which could carry characteristic responses unique to Indian conditions. The comfort levels in the dwellings have to be validated by obtaining responses from the occupants; deviation from present calculations can be used to understand the influence of climate, personal, cultural, and social factors.

## DISCUSSIONS

The observations made in the study reveals that absolute humidity conditions in vernacular rooms are closer to that of the external environmental conditions. Real-time measurement and inferences from earlier studies could vary where the physiological conditions and climate zones are different from the current study. Inconsistencies also might be present due to acclimatization, economic and social status, and occupation. The current study in future will try to verify the results.

The humidity levels in the conventional room (Cement/RCC construction) deviate from the outside conditions, the impacts of which on building structural performance needs to be investigated. Also, the Vernacular rooms show much higher humidity values. The ASHRAE-55 standards for human comfort suggest the maximum limit of humidity ratio to be 0.012 kg-wv/kg-da; however, the observed humidity ratio in the present study, most of the times, exceeds this limit. Recent studies, as discussed earlier, propose the values as 18.8 and 17 are much closer to the observed values in the present study. The courtyard has a mean humidity ratio of 0.0175 kg-wv/kg-da (min=0.0081, max= 0.0291 kg-wv/kg-da), vernacular room it is 0.0177 kg-wv/kg-da (min=0.0079, max= 0.0272 kg-wv/kg-da), for Later vernacular room it is 0.0142 kg-wv/kg-da (min= 0.0021, max= 0.0240 kg-wv/kg-da). Amongst all the rooms, the conventional room has the lowest values for humidity ratio of 0.0021 kg-wv/kg-da, and the highest is recorded in the recorded in the vernacular room, i.e., 0.0272 kg-wv/kg-da. With the data recorded, it can be said that the vernacular rooms (the envelope as well as the articles housed inside) are more hygroscopic in nature. It retains moisture better than the other rooms. Also, the narrower range of humidity ratio in the vernacular room reveals the tendency of the building typology to regulate moisture, maintaining a set humidity ratio level and preventing frequent fluctuations. The later vernacular room also shows a similar trend in humidity ratio. Therefore, this suggests that the response of building typologies to the moisture exposure with aging also needs to be investigated. The values obtained through the real-time monitoring of buildings also showed that the presently existing humidity ratio is much higher than the suggested upper limit for humidity ratio in the ASHRAE-55 standards. Earlier studies (Shastry et al. (2016)) have also questioned the adoptability of these codes for thermal comfort in vernacular buildings of tropical climate zones. Similar scrutiny needs to be done for adaptability and validity of the standards relating to comfort humidity levels in these dwellings, which will be taken up in the further course of this study.

Exposure of human beings to an optimum level of temperature moisture conditions is essential for physiological well-being. At a given temperature, the perception of moisture exposure variation is generally manifested through a change in temperature sensation. However, variation in moisture exposure (perceived/unperceived) at a given temperature can also be a cause of many health problems ranging from skin-related discomfort to breathing difficulties leading to asthma and impaired olfactory responses. With the seasonal variations and climatic acclimatization, the human body adjusts to the environmental conditions to cope with the extremities offered by nature. With respect to humidity conditions, Vernacular rooms (humidity ratio) remain very close to the outside environment, thereby not causing a sudden change in exposure when the occupant goes out of the room, however in the conventional room, the inside humidity conditions are very different from the outside environment, thereby causing a considerable range of variation in exposure. This study can be taken forward to understand the interdependent dynamics of temperature and relative humidity as it affects the occupant thermal and humidity perception in the different building typologies to understand better the possible health outcomes of habitation in these dwellings.

## CONCLUSION

Studies have emphasized the high adaptive resilience of people living in a traditional setup and vernacular buildings that offer a much stable indoor moisture range. The furniture, furnishings, number of people, and type of occupancy also play a role in regulating indoor RH and contribute to providing an optimum indoor condition to prevent health problems. Apart from this, personal factors like diet, attitude, personal habits also contribute directly to the indoor air moisture content as well as drive physiological health conditions. The results of the study reveal that the vernacular rooms maintain conditions closer to that of the outside environment than the conventional room with respect to moisture; however, the study needs to be extended to other climate zones for further clarity.

The acceptable range of humidity conditions is different for different occupational roles of a room. It differs with the age of people as well as the climatic conditions they are acclimatized to. More studies are required to be undertaken to establish the relation moisture in the environment and the comfort levels of different occupants. Many studies have shown that being close to nature and natural environmental conditions has a positive impact on physiological, psychological, and behavioral health. In the context of this study, it can be said that Vernacular construction, in comparison with conventional construction, keeps the indoor environmental conditions consistent and close to natural and may result in improved well-being for occupants.

## ACKNOWLEDGEMENT

Part of this research was supported by The British Academy's Well-being Achieved from Earthen Residence (WAFER) project (UWB190086), and partly through the Prime Minister's Research Fellowship, India at the Indian Institute of Science.

## REFERENCES

al Tawayha, F., Braganca, L. & Mateus, R. (2019). Contribution of the vernacular architecture to the sustainability: A comparative study between the contemporary areas and the old quarter of a Mediterranean city. *Sustainability (Switzerland)*, *11*(3). https://doi.org/10.3390/su11030896

Andersen, I., Lundquist, G. R. & Proctor, D. F. (1973). Human perception of humidity under four controlled conditions. *Archives of Environmental Health*, *26*(1), 22–27. https://doi.org/10.1080/00039896.1973.10666213

Cascione, V., Maskell, D., Shea, A. & Walker, P. (2019). A review of moisture buffering capacity: From laboratory testing to full-scale measurement. *Construction and Building Materials*, *200*, 333–343. https://doi.org/10.1016/j.conbuildmat.2018.12.094

Fang, L. (1998a). Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposures. *Indoor Air*, *8*(4), 276–284. https://doi.org/10.1111/j.1600-0668.1998.00008.x

Fang, L. (1998b). Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*, *8*(2), 80–90. https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x

Ge, H., Yang, X., Fazio, P. & Rao, J. (2014). Influence of moisture load profiles on moisture buffering potential and moisture residuals of three groups of hygroscopic materials. *Building and Environment*, *81*, 162–171. https://doi.org/10.1016/j.buildenv.2014.06.021

Hens, S. L. C. H. (2017). Building Physics - Heat, Air and Moisture 3e Fundamentals and Engineering Methods with Examples and Exercises. In *Building Physics - Heat, Air and Moisture 3e Fundamentals and Engineering Methods with Examples and Exercises*. https://doi.org/10.1002/9783433608548

Höppe, P. & Martinac, I. (1998). Indoor climate and air quality. Review of current and future topics in the field of ISB study group 10. *International Journal of Biometeorology*, *42*(1), 1–7. https://doi.org/10.1007/s004840050075

Hutcheon, N. B. (National R. council of C. (1964). *Humidity and Buildings_1964*.

Jerman, M. & Černý, R. (2012). Effect of moisture content on heat and moisture transport and storage properties of thermal insulation materials. *Energy and Buildings*, *53*, 39–46. https://doi.org/10.1016/j.enbuild.2012.07.002

John D. Spengler & Chen, Q. (Yan). (2000). Indoor Air Quality Factors in Designing a Healthy Building. *Annu. Rev. Energy Environ.*, *25*, 567–601.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. v., Hern, S. C. & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Kong, D., Liu, H., Wu, Y., Li, B., Wei, S. & Yuan, M. (2019). Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation. *Building and Environment*, *155*(March), 298–307. https://doi.org/10.1016/j.buildenv.2019.02.039

Li, C., Liu, H., Li, B. & Sheng, A. (2019). Seasonal effect of humidity on human comfort in a hot summer/cold winter zone in China. *Indoor and*

*Built Environment*, *28*(2), 264–277. https://doi.org/10.1177/1420326X17751594

Liu, F., Jia, B., Chen, B. & Geng, W. (2017). Moisture transfer in building envelope and influence on heat transfer. *Procedia Engineering*, *205*, 3654–3661. https://doi.org/10.1016/j.proeng.2017.10.229

Lozhechnikova, A., Vahtikari, K., Hughes, M. & Österberg, M. (2015). Toward energy efficiency through an optimized use of wood: The development of natural hydrophobic coatings that retain moisture-buffering ability. *Energy and Buildings*, *105*, 37–42. https://doi.org/10.1016/j.enbuild.2015.07.052

Mayer, F. S. & Frantz, C. M. P. (2004). The connectedness to nature scale: A measure of individuals' feeling in community with nature. *Journal of Environmental Psychology*, *24*(4), 503–515. https://doi.org/10.1016/j.jenvp.2004.10.001

McIntyre, D. A. & Griffiths, I. D. (1975). Subjective responses to atmospheric humidity. *Environmental Research*, *9*(1), 66–75. https://doi.org/10.1016/0013-9351(75)90050-X

Nehr, S., Hösen, E. & Tanabe, S. ichi. (2017). Emerging developments in the standardized chemical characterization of indoor air quality. *Environment International*, *98*, 233–237. https://doi.org/10.1016/j.envint.2016.09.020

Osanyintola, O. F. & Simonson, C. J. (2006). Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact. *Energy and Buildings*, *38*(10), 1270–1282. https://doi.org/10.1016/j.enbuild.2006.03.026

Osanyintola, O. F., Talukdar, P. & Simonson, C. J. (2006). Effect of initial conditions, boundary conditions and thickness on the moisture buffering capacity of spruce plywood. *Energy and Buildings*, *38*(10), 1283–1292. https://doi.org/10.1016/j.enbuild.2006.03.024

Rode, C. (2005). *Moisture Buffering of Building Materials Department of Civil Engineering Technical University of Denmark*.

Rode, Carsten, Peuhkuri, R., Time, B., Svennberg, K. & Ojanen, T. (2009). Moisture Buffer Value of Building Materials. *Heat-Air-Moisture Transport: Measurements on Building Materials*, *4*(5), 33-33–12. https://doi.org/10.1520/stp45403s

Roels, S. & Janssen, H. (2004). *Is the moisture buffer value a reliable material property to characterise the hygric buffering capacities of building materials ? June*.

Salonvaara, M., Holm, A. & D, P. (2004). Moisture Buffering Effects on Indoor Air Quality — Experimental and Simulation Results. *ASHRAE Journal*, *IX*, 11.

Seppänen, O. & Kurnitski, J. (2009). Moisture control and ventilation. *WHO Guidelines for Indoor Air Quality: Dampness and Mould*, 31–61.

Straube, J. (2014). *Indoor Air Quality and Hygroscopically Active Materials*. *January 2001*.

ASHRAE, S. 55., (2004).

Toftum, Jorn & Fanger, P. O. (1999). Air humidity requirements for human comfort. *ASHRAE Transactions*, *105*.

Toftum, Jørn, Jørgensen, A. S. & Fanger, P. O. (1998a). Upper limits for indoor air humidity to avoid uncomfortably humid skin. *Energy and Buildings*, *28*(1), 1–13. https://doi.org/10.1016/S0378-7788(97)00017-0

Toftum, Jørn, Jørgensen, A. S. & Fanger, P. O. (1998b). Upper limits of air humidity for preventing warm respiratory discomfort. *Energy and Buildings*, *28*(1), 15–23. https://doi.org/10.1016/S0378-7788(97)00018-2

Tran Le, A. D., Maalouf, C., Mai, T. H., Wurtz, E. & Collet, F. (2010). Transient hygrothermal behaviour of a hemp concrete building envelope. *Energy and Buildings*, *42*(10), 1797–1806. https://doi.org/10.1016/j.enbuild.2010.05.016

Wolko, P. (2018). *International Journal of Hygiene and Indoor air humidity , air quality , and health – An overview*. *221*(December 2017), 376–390. https://doi.org/10.1016/j.ijheh.2018.01.015

Wolkoff, P. & Kjærgaard, S. K. (2007). The dichotomy of relative humidity on indoor air quality. *Environment International*, *33*(6), 850–857. https://doi.org/10.1016/j.envint.2007.04.004

Woloszyn, M., Kalamees, T., Abadie, M. O., Steeman, M. & Sasic Kalagasidis, A. (2009). The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. *Building and Environment*, *44*(3), 515–524. https://doi.org/10.1016/j.buildenv.2008.04.017

Yang, X., Fazio, P., Ge, H. & Rao, J. (2012). Evaluation of moisture buffering capacity of interior surface materials and furniture in a full-scale experimental investigation. *Building and Environment*, *47*(1), 188–196. https://doi.org/10.1016/j.buildenv.2011.07.025

Zhang, M., Qin, M. & Chen, Z. (2017). Moisture Buffer Effect and its Impact on Indoor Environment. *Procedia Engineering*, *205*, 1123–1129. https://doi.org/10.1016/j.proeng.2017.10.417