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Authors: Vismaya Paralkar[1], Rashmin Damle[1]
Affiliations: faculty of technology, cept university, ahmedabad, india[1]
Orcid ids: 0000-0003-2688-6826[1]
Contact e-mail: architectvismaya@gmail.com

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Moisture Buffering and Mold Growth Characteristics of Naturally Ventilated Lime Plastered Houses.

Vismaya Paralkar[a], Dr.Rashmin Damle[a]

a CEPT University, Ahmedabad, India

Abstract

Lime plaster is a sustainable building material that can be an effective passive cooling strategy. The moisture buffering quality of lime causes adsorption and desorption of moisture which moderates the indoor relative humidity. Its vapour permeability is also influential in moisture transfer across the building envelope. Lime plaster also has a self-healing quality which prevents the formation of inner cracks. Moreover, its strength increases with time leading to a longer life span. In old structures, an important function is the breathability of the ceiling and walls. Hence, it is essentially used in conservation projects vastly adding to the appearance and durability of old buildings. Often organic additives employed to impart certain qualities to the lime mortar/plaster led to mold growth. Mold growth degrades indoor air quality, and the occupant health is compromised. To avoid mold-related problems, it is necessary to understand the behaviour of lime plaster with respect to the indoor relative humidity and surface moisture content. This work focuses on the hygrothermal performance of lime plaster in naturally ventilated residential spaces. Surveys are carried out in 45 traditional buildings of Ahmedabad in India with measurements of ambient variables, such as temperature, relative humidity, wall moisture content, etc.The mold growth patterns of these spaces are related to the measured variables and wall characteristics. Hygrothermal simulations of some spaces are also carried out to observe the moisture buffering of lime plaster. Experimental observations are then compared to simulation results to see if the predictions of the hygrothermal models are realistic.

Keywords: Lime plaster; Hygrothermal simulations; mold growth; surface relative humidity conditions.

Nomenclature

T_a – Ambient Temperature inside a space.

T_o – Outside Dry Bulb Temperature.

GT_o – Outside Globe Temperature.

GT_i - Inside Globe Temperature.

μ - Moisture Content of the walls.

RH_o – Outside Relative Humidity.

RHi – Inside Relative Humidity.

Ts_O – Outside Surface Temperature.

Ts_i - Inside Surface Temperature.

RH_s – Inside Surface Relative Humidity

v_a – air velocity at the level of the globe thermometer.

MRTo – Outside Mean Radiant Temperature.

MRTi – Inside Mean Radiant Temperature.

EMPD – Effective Moisture Penetration Depth

HAMT – Heat and Moisture Transport

MBV – Moisture Buffering Value

1 Introduction

The relative humidity of air in a building determines its energy performance, comfort, and indoor air quality (1). Moisture buffering characteristics of wall materials can modulate indoor humidity by absorbing/desorbing the moisture present in the indoor air. (2) demonstrated that the use of hygroscopic materials in the envelope and a well-controlled HVAC system could reduce the cooling and heating energy consumption by 5% and 30% respectively. (2) achieved energy efficiency in buildings by combining moisture buffering with relative humidity-sensitive ventilation. By employing hygroscopic gypsum and wood fibre materials, the energy saving potential of 25 – 30 % for temperate and semi-arid climates was observed by (3). The hygroscopic interaction between the wall surface and room air affected the air temperature by 2 to 3 °C (4). Due to moisture buffering, up to 20 % reduction in heating energy was observed in different climate zones of India (5).

Apart from the energy aspect, relative humidity also affects the concentration of noxious gases in the air as it alters the rate of off-gassing in the building materials. Due to microbial interactions, odorous and irritant substances or allergens are emitted from damp materials. The presence of moisture is a cause of deterioration inside buildings (6) while affecting the latent and sensible conduction loads (7). Relative humidity coupled with high temperature has direct adverse effects such as thermal discomfort like heat stroke, exhaustion and can possibly prove to be fatal. It's indirect effect on human health can lead to allergic incidences and respiratory diseases (8). Several health issues like asthma and respiratory disorders are associated with the dampness in buildings.

The fungal growth on building surfaces is highly influenced by the relative humidity of indoor air. 21 different types of building materials were studied (9) to understand the influence of temperature and relative humidity on the metabolism and growth of eight different micro-fungi. Under constant temperature conditions, with relative humidity up to 95% and water activity at 0.95, Penicillium, Aspergillus, and Eurotium overgrew other indoor fungi. The minimum water activity for fungal growth in materials susceptible to mold growth is 0.78 – 0.8 (9) . For the same water activity, favourable conditions for mold occur at 10℃ under 80 – 90% relative humidity and at 5℃ for relative humidity more than 90%. The four sources of dampness and moisture in the building are leakage of rain and snow into the building construction or moisture from the ground; moisture from occupants and their indoor activities; and water leakage (10) Moreover, the problem of even small water leaks has a significant impact if the moisture buffering capacity of the material is low. Therefore, the moisture transfer/buffering capacity of building materials plays a vital role in regulating the indoor relative humidity by moisture transfer through the building envelope.

Lime is an environment-friendly material that has been forgotten in contemporary construction practices. Before the advent of Portland cement lime mortar and lime plaster were widely used as binder and finishing materials. The use of lime plaster in the caves of Ellora (11) and baked brick walls at Karvan (12) in India dates back to the 6th century AD. Lime plaster mixed with hemp, dolomite, or cannabis was applied in different layers for longevity (13). Lime has lower embodied energy (14) and excellent moisture buffering capacity (15). (16) reported a reduction in humidification and dehumidification energy requirements with lime-stabilized bentonite clay. In comparison to cement mortars, lime-based mortars had three times more moisture buffering capacity (17). Post occupancy analysis of lime-plastered spaces in a warm & humid climate zone showed 5-15% variation in indoor humidity levels than the outdoor humidity levels for a studied spaces under lime plastered dome and a vault (1). Lime plaster is also vapor-permeable i.e., useful in 'breathing wall' construction (18). It is recyclable, involves nontoxic chemicals for manufacturing, and its production can be downscaled as needed. When used as an internal render, it improves indoor air quality by absorbing low amounts of carbon dioxide (19) and regulating indoor relative humidity for a prolonged period (20). Lime avoids problems of decay and dampness by allowing the building envelope to breathe and unlike several modern nonporous materials (21)The rain exposure impact is low on hygrothermal performance of a capillary closed material like mineral plaster. But the impact is significant on mold index for a lime plaster assembly (22). Material like lime plaster has higher capillary action and its moisture content is vastly dependent on its exposure to driving rain (23).

Variations in the location of humidity sources and room ventilation rates give rise to pockets of high relative humidity. The average relative humidity throughout the building should be maintained between 40 % to 60 %.

The main objective of this work is to study the mold growth propensity of naturally ventilated lime-plastered spaces. To this end a three-tier methodology has been employed:

1. Survey of Naturally Ventilated Residential Spaces in order to correlate the observed mold growth in terms of the building characteristics like coatings on the wall, ventilation, the level of water activity inside the space, and the function of the space, sunlight, and clutter near the walls.

2. Hygrothermal simulations to assess the capability of the EMPD (Effective Moisture Penetration Depth) model (30) using EnergyPlus (31) and (3) experiments to study the onset of mold growth in lime plaster samples kept at different relative humidity levels.

2 Survey of naturally ventilated residential spaces

Two different types of naturally ventilated lime-plastered houses were surveyed in the city of Ahmedabad. Ahmedabad falls in the hot-dry climate zone of India. The heritage city of Ahmedabad includes thousands of Pols, a dense cluster of residences belonging to people of the same caste, religion, and occupation. For more than 300 years, these neighbourhoods are popularly known as Pol houses (24).

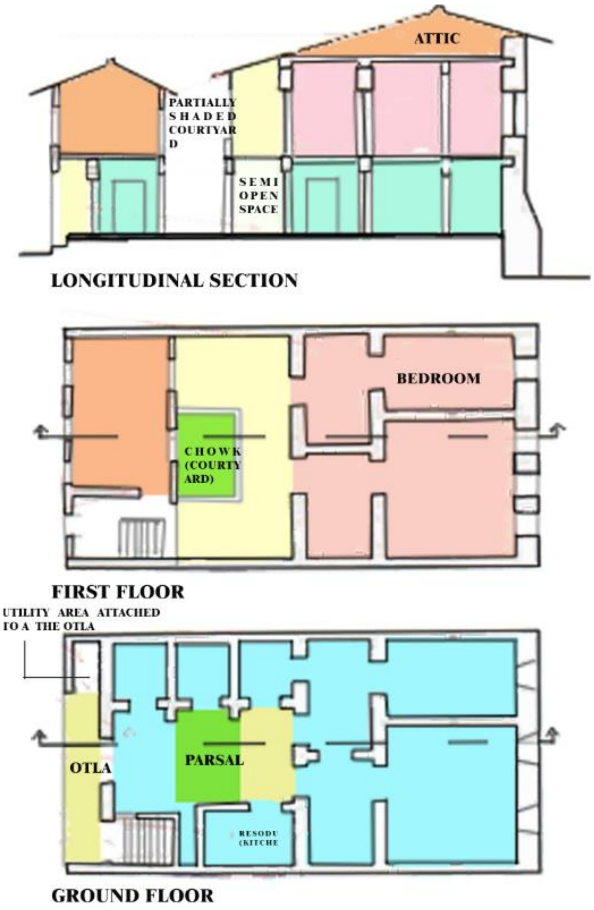


Figure 1 Details of a Pol House, Ahmedabad (Source : (25))

Figure 1 above, shows the passive strategies in the design of Pols are prominent: protecting the inside spaces from direct heat gains include mutual shading, thick walls, long shared walls, central courtyard, multi-story structure, narrow lanes, dense clusters, etc. The otla (26) outside the house is the open space that usually used to dry clothes in some houses. Attached to the otla is a small, dedicated space for washing utensils and toilets. The construction of the house is of timber framework, brick masonry, and wall surface finish of lime plaster. Forty-five spaces were surveyed in Pols which had lime plaster as the rendering material with characteristics mentioned in **Error! Reference source not found.**. The selection of these spaces was based on the on the type of wall finishes used (either lime plaster or plastic paint (waterproof paint)), typology of the house, and accessibility.

Figure 2 Pol Houses

Detached lime-plastered residences were also studied and are shown in Figure 3. Girikunj Residence Figure 3a) is a residential bungalow (27), designed using passive design strategies and traditional materials and methods. The ventilation system is well designed using glass exhaust shafts on the periphery. These shafts collect hot air from the small grill outlets in the spaces when the windows are closed. Air vents attached to it exhaust this air to the outside. Lime is employed for plastering, wall wash, and mortar. It consists of additives like Gur (jaggery), Gugal (Commiphora wightii)(28) , and Methi (fenugreek) for improving binding and waterproofing.

The RSR Residence (Figure 3b), a bungalow designed by Abhikram Architects (27), is constructed using lime mortar and lime plaster. The type of lime plaster used is Marmarino lime plaster which gives a marble-like finish. The walls were not coated with paint. Mechanical ventilation is provided with the help of exhaust fans and air vents throughout the space.

Figure 3 (a) Girikunj Residence (*Source: Abhikram Architects*); (b) RSR Residence

For the selected spaces, the function of and typical activities within each space were also noted. A layout of the space was created considering the wall thickness, opening area, and adjacent spaces. Detailed architectural plans were drafted which showed the wall thickness, openings and adjacent spaces for each house.The volume is calculated from the measurements taken for floor plans. Surveys were carried out in the afternoon from 2:00 pm to 4:00 pm when the outdoor temperatures were relatively high. Measurements were taken on every other day from the 25th of December 2019 to 16th March 2020. This resulted in around 85-90 readings for each space over the measurement period with a total of 3800 data points. Point in time measurements (Figure 4) included outdoor air temperature, relative humidity, globe temperature for calculating MRT, and air velocity were noted for each space. Similarly, inside air temperature, relative humidity, globe temperature, and air velocity at the centre of the space were measured. For measuring the inside surface temperatures of all the walls, the emissivity of the thermal gun was set to 0.95 which is the typically value of emissivity of lime plaster. The surface temperature of the ceiling and floor was also noted.

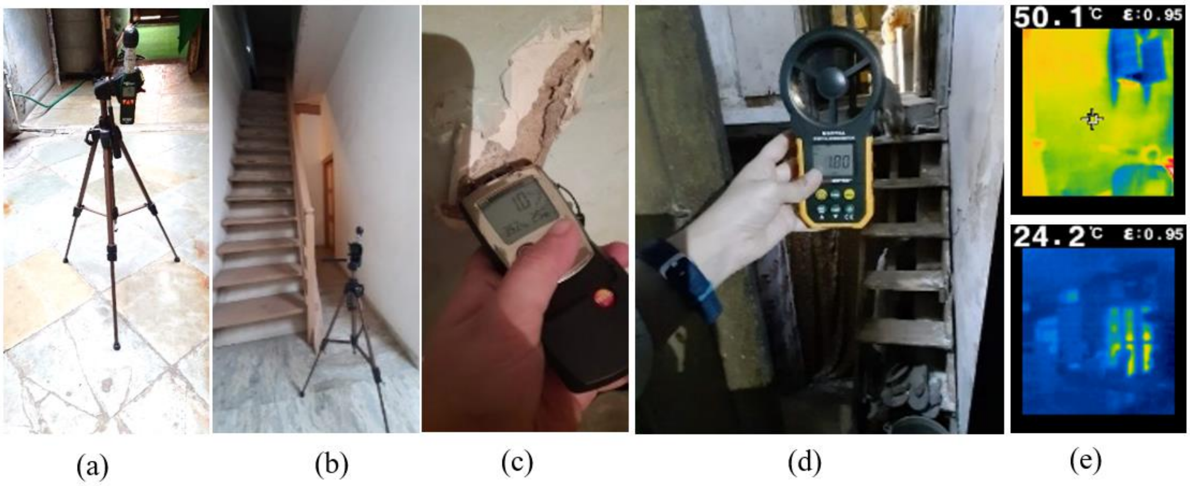


Figure 4 Site Measurements using several instruments

The details of the instruments employed for measurements in Figure 4 are the following:

(a)

Table 1 gives the details the measured parameters, their location, and the respective instruments.

Table 1 List of instruments and their measured parameters

Instrument used	Parameter measured	Measurement location	Specifications
Heat Stress WBGT Meter (Extech HT30) Figure 4 (a)	Outside air temperature, relative humidity, Black Globe Temperature	Outside the survey space at a height of 1100 mm from the ground	Measuring Range - Wet bulb globe temp - 32 to 122°F (0 to 50°C) Humidity - 0 to 100%RH Accuracy - Wet bulb globe temp - ±4°F/2°C Humidity - ±3%RH
Heat Stress WBGT Meter (Extech HT30) Figure 4 (a)	Inside air temperature, relative humidity, Black Globe Temperature	At the center of the survey space at a height of 1100 mm from the Floor Finish Level.	
Vane Anemometer (PEAKMETER MS6252A). Figure 4 (d)	Air velocity	1. Near the globe thermometer, perpendicular to three planer axes. 2. Perpendicular to the vertical plane of the openings inside a space.	Measuring Range - 0.40~30.0 m/s Accuracy - ±(2.0% reading+50)
Thermal Gun (FLIR TG165) Figure 4 (e)	Surface temperature.	Inside and outside exposed surfaces of all the walls surrounding the space (including the ceiling and floor).	Measuring Range - 0.40~30.0 m/s Accuracy - ±(2.0% reading+50)
Testo 606-2 Moisture Meter (38767439/711) Figure 4 (c)	Moisture content and surface relative humidity.	Moisture content inside lime plaster and surface relative humidity near it.	Measuring Range - -10 to +50 °C 0 to 100 %RH Accuracy - ±0.5 °C / 0.1 °C ±2.5 %RH (5 to 95 %RH)
HOBO U10 Temperature and Humidity Logger Figure 8	Temperature and RH logger	Inside the experiment jars where the RH was kept constant	Measuring Range - Temperature - 20° to 70°C (-4° to 158°F) Humidity - 25% to 95% RH Accuracy – Temperature - ± 0.53°C from 0° to 50°C (± 0.95°F from 32° to 122°F) Humidity - ± 3.5% from 25% to 85% over the range of 15° to 45°C (59° to 113°F) ± 5% from 25% to 95% over the range of 5° to 55°C (41° to 131°F)

Simulating the studied spaces with the EMPD model.

Before simulating the surveyed spaces, preliminary simulations are worked out with the Building Energy Simulation Test (BESTEST) geometry (29). These simulations are carried out with both the EMPD (Effective Moisture Penetration Depth) (30) and thermal-only i.e. the conduction transfer function (CTF) models of Energy Plus (31). The EMPD model considers the moisture absorption and desorption at wall surfaces, while the thermal-only model ignores it completely. The purpose of employing these two models is to check whether moisture absorption and desorption at the wall surfaces are captured by the EMPD model. Several authors (3,30,32,33) have employed the BESTEST geometry in their hygrothermal studies. Figure 5 shows the BESTEST geometry which is a single-zone space of 8m x 6m x 2.7m. The space has a moisture source of 500 g/h from 9 a.m. to 5 p.m. and a constant air change rate of 0.5 air changes per hour for Ahmedabad weather (29) . The walls are assumed to be made of 230 mm thick brick masonry . For the inner wall surfaces finishing materials such as gypsum plasterboard, plywood, and lime plaster are considered. The properties of these materials were considered from the energy plus data base (34).

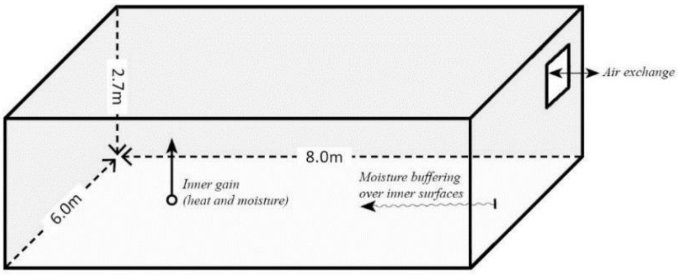


Figure 5 BESTEST Geometry (Source: (29))

EMPD is a simplified model which considers the moisture absorption and desorption at wall surfaces. It assumes a thin layer of air near the wall surface which is dynamic and exchanges moisture in the air in cyclic pulses of air moisture. EMPD gives a reasonable approximation of reality for short periods when there is no net moisture storage (35). EMPD model is employed in this work because it needs lesser information on hygric properties of materials in comparison to the detailed HAMT (Combined Heat and Moisture Transfer) model of EnergyPlus (31).

It is a challenge to derive a universal sorption curve for lime plaster as its composition is site-specific and varies from region to region. The sorption curve was derived from the moisture content values of building materials available in the literature (36). The sorption coefficients were then derived through these moisture content values by a close-fitting curve as shown in Figure 6. The difference observed between the curves is very minuscule with a maximum difference of 0.002 µ(kg/kg). These values were then fed into the EMPD model to carry out simulations. After carrying out hygrothermal simulations for BESTEST geometry, a sample surveyed space is simulated with the EMPD model. The change in mean radiant temperature (MRT), relative humidity, and surface temperatures were observed through simulations. This further helped to predict the trend of the hygrothermal behaviour of lime plaster in that space throughout the year. The weather files for simulation are taken from Energy Plus weather data. (Ahmedabad weather data).

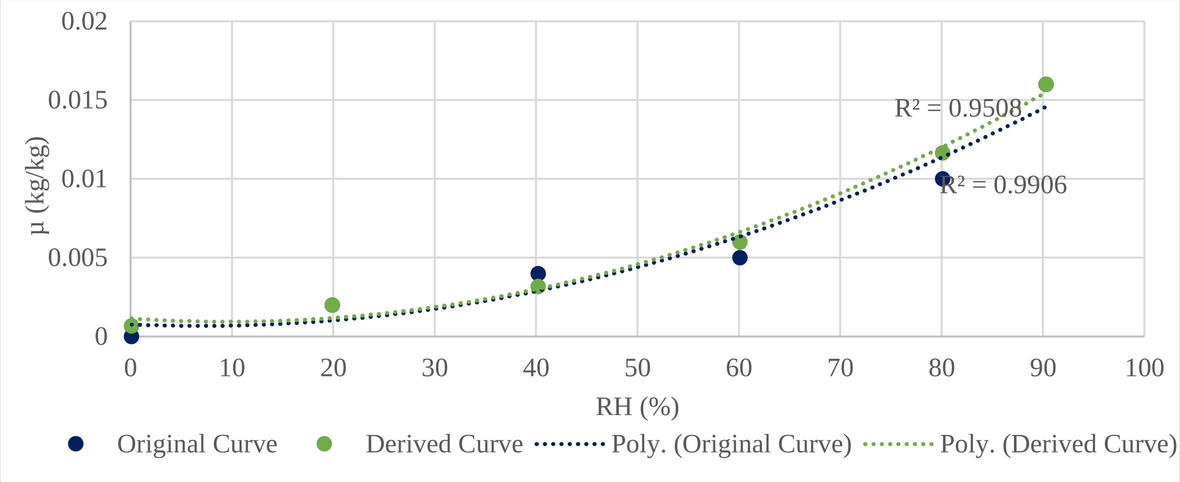


Figure 6 Best-fit sorption curve for lime plaster

Studying the onset of mold growth in lime plaster samples

To understand the onset of mold growth on lime plaster, an experiment similar to (37) was carried out. Different relative humidity levels were maintained in containers by different salt solutions. Table 2 shows the different salts and the quantity of salt and water to maintain the RH level inside the container. For this experiment, four plastic containers were filled with different salt solutions as shown inFigure 6. Preliminary trials were carried out by trial and error to fix the amount of salt and water to obtain the specific RH value. The temperature and relative humidity loggers (Hobo U10) were attached on the inner side of the lid of the jars to ensure constant relative humidity inside the containers.

Table 2 Relative humidity achieved for different salt compositions

Name of Salt	**Composition of Salts**	**RH Gained**	**Quantity (g)**	**Water Quantity (g)**
Sodium Chloride	NaCl	75%	53.33	27.283
Ammonium sulphate	$(NH_4)_2SO_4$	80%	53.33	30
Potassium Chloride	KCl	86%	30	10
Potassium sulphate	K2SO4	99%	53.33	18.19

Figure 8 Lime plaster samples used for experiment

Figure 7 Jars containing different salt solutions

The samples of lime plaster (see Figure 8) contained one part of lime one and a half parts Surkhi (burnt red-clay brick powder), and two parts of fine aggregate sand in the mixture. Additives such as e and Gugal (Commiphora wightii) water were also mixed to improve the water proofing qualities of the mixture. The jars were kept in space where temperature was between 25- 30 °C and the maintained RH levels were logged for four weeks at an interval of 5 mins. Once the desired RH levels were achieved, lime plaster samples of equal size (40mm x 40 mm x 10 mm), weight, and composition were introduced into the containers. The samples remained in closed containers at the respective RH value maintained by the specific salt solution. This experiment was carried out to identify the onset of mold growth. Results and Discussions

2.1 Simulation results with the BESTEST geometry

Figure 9 shows the relative humidity (RH) in the space with lime plaster as the finish material for inside surfaces. The contrast in the RH levels of thermal-only (CTF) and EMPD models is visible. In the case of the CTF model, the RH levels go up to 100 %. While with the EMPD model, the RH levels are maintained between 39% to 95%. Thus, the EMPD model (31) captures the moisture buffering effect of lime-plastered wall surfaces.

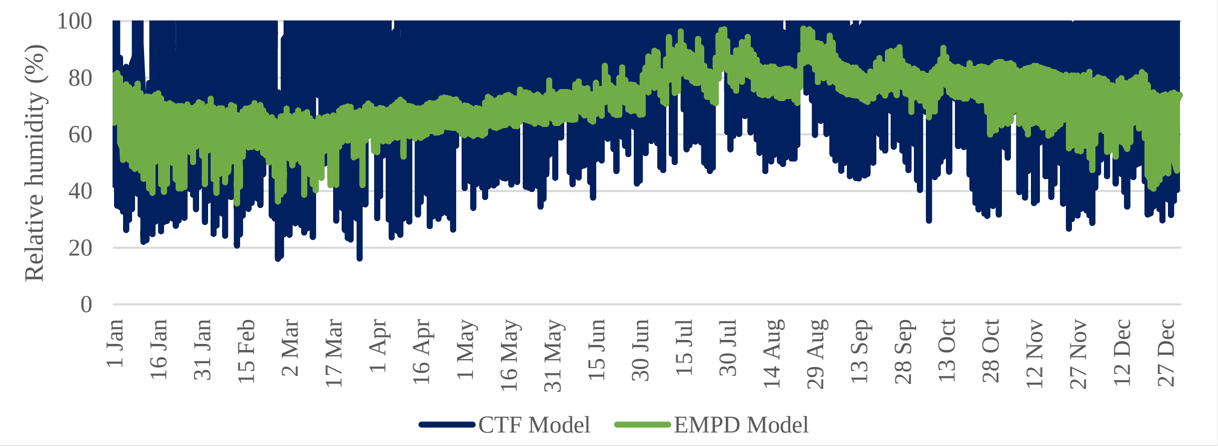


Figure 9 Relative Humidity of space with CTF and EMPD Models

Simulations with the EMPD were also carried out with gypsum plasterboard, and plywood as inner surface finishes. Figure 10 shows the box plot of RH values for the different cases. Amongst the different surface finish materials, lime plaster showed the least variation in RH levels and the least amplitude. In cases of gypsum plasterboard, plywood, and no plaster material the maximum RH is 99%. While the maximum RH with lime plaster was about 97 %. RH values with lime plaster and plasterboard don’t drop below 30% for the given conditions. Also, 50% of the time RH with lime plaster was in the range of 62% to 72%. The RH values were lower during moisture increase and higher during moisture reduction with lime plaster. The above confirms the better performance of lime plaster over the rest of the finish materials.

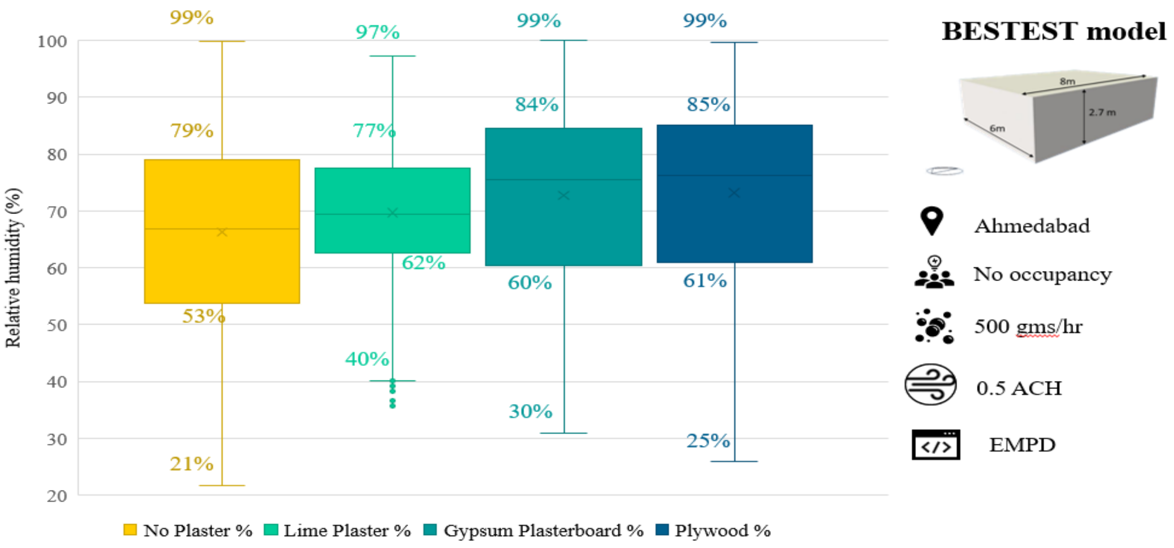


Figure 10 Indoor relative humidity in different materials

2.1.1 Simulation Results of Surveyed Sample Spaces

Annual hygrothermal simulations with the EPMD model were carried out for two spaces – PT_B and PS_A. The geometry of these spaces was recreated for the simulations. Physical parameters similar to the actual space were created except for the lime composition which was unknown. Spaces PT_B and PS_A had an occupancy of 1 & 3 respectively and there were no external source of the moisture. These spaces were selected because they showed substantial mold growth to check simulation predictions. The performance in terms of MRT and indoor RH were observed throughout the year.

Figure 11 shows the temperature variations observed from outdoor to indoor throughout the year for space PT_B. The outside DBT varied with a maximum diurnal variation of 20°C and a minimum variation of 7°C. The indoor air temperature variation is around 5°C. Similarly, the variation of the MRT inside the space was around 2°C and was maintained between 20 to 30°C for this space.

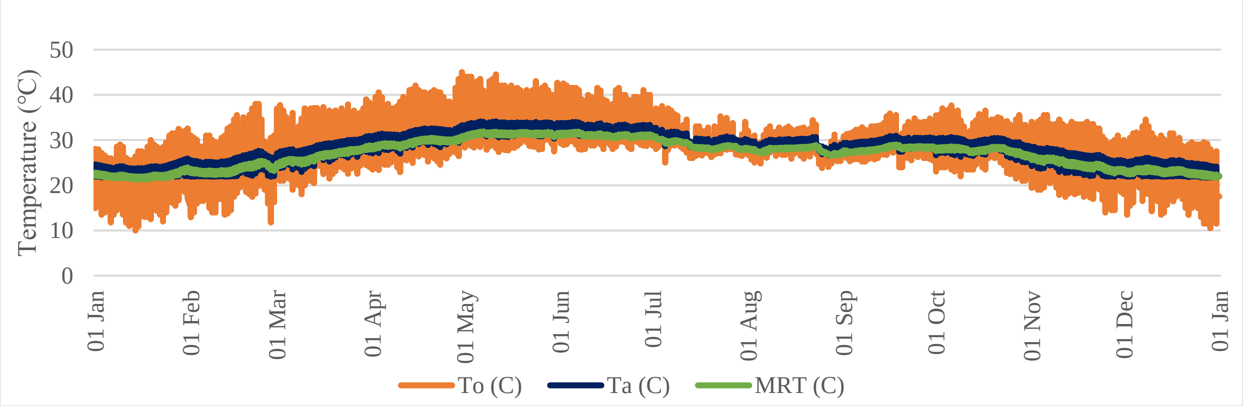


Figure 11 Outdoor, indoor, and mean radiant temperature in space PT_B

The relative humidity of outdoor, indoor and four wall surfaces of PT_B are shown in Figure 12. The outdoor maximum was 11.5 % higher than the indoor maximum and the outdoor minimum was 11% lower than the indoor minimum. Also, the difference between the first quartile and third quartile was 33% for outdoor RH and 24% for indoor RH. It was observed that the surface RH levels were higher than the indoor RH levels. The RHs maximum was higher by 3% while the RHs minimum was higher by 7% when compared to the maximum and minimum values of RHi. To prevent mold growth, ASHRAE suggests that it is necessary to keep the spaces below 60% RH (38). However, 25% of the surface RH values were more than 70% leading to mold risk.

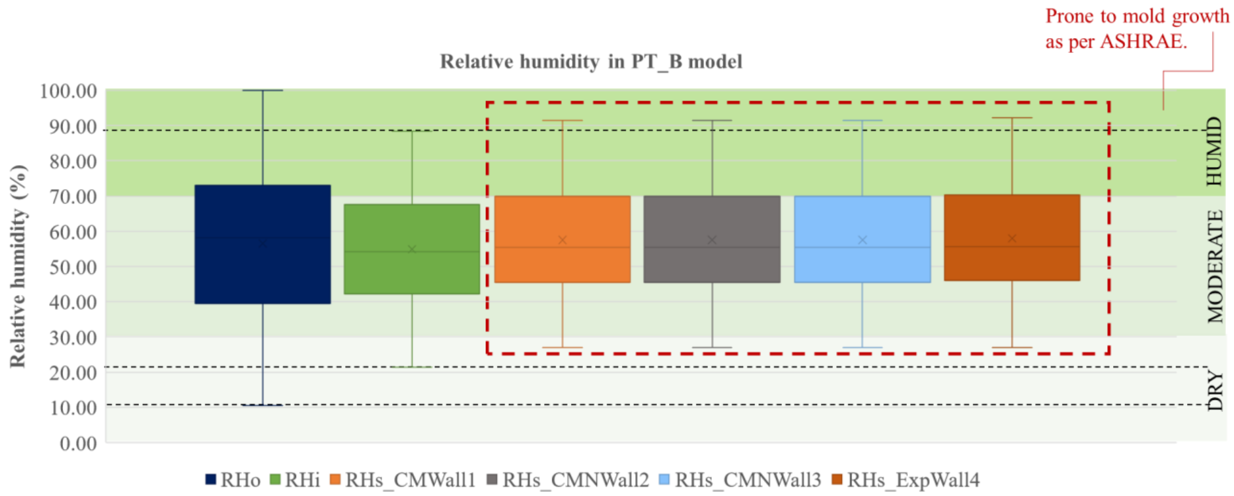


Figure 12 Indoor and surface relative humidity levels in PT_B

Figure 13 indicates varying RH levels over the year. During the monsoon months (from July – October), the indoor RH was always above 60%, while the surface RH of the walls was always above 68%. These are the months when the wall surfaces are highly prone to mold growth.

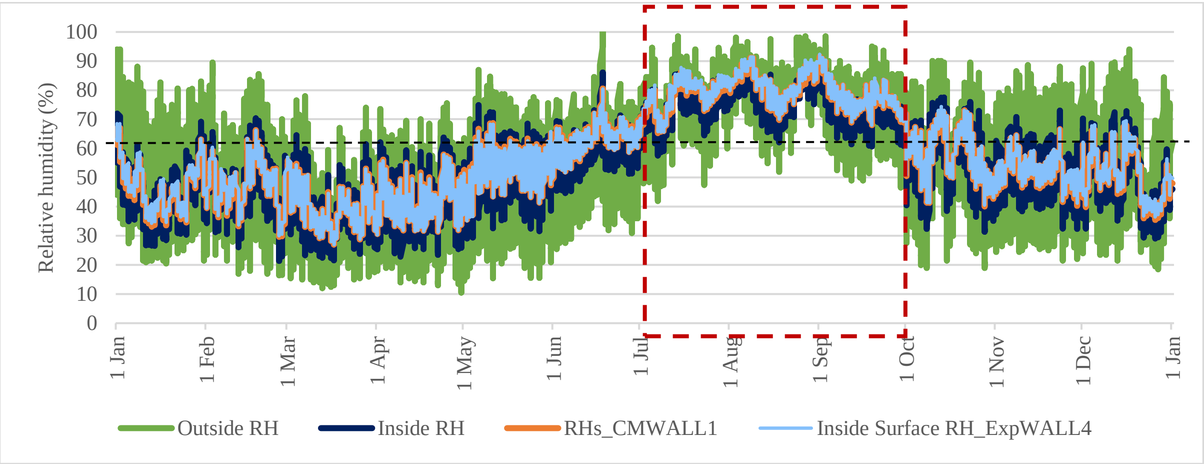


Figure 13 Relative humidity levels throughout the year in PT_B

The percentage of hours when RH levels were favourable for mold growth is shown in Figure 14. Out of 8760 hours, 32 to 54 hours were above 90% RH near the walls. 60% of the hours were between 60% - 90% RH resulting in a risk of mold growth. Even though the simulation results show an equal percentage of high RH near the walls, the percentage of mold growth observed on-site over each wall was different. This could be because of the varied placement of furniture, openings, and air velocity adjacent to each wall.

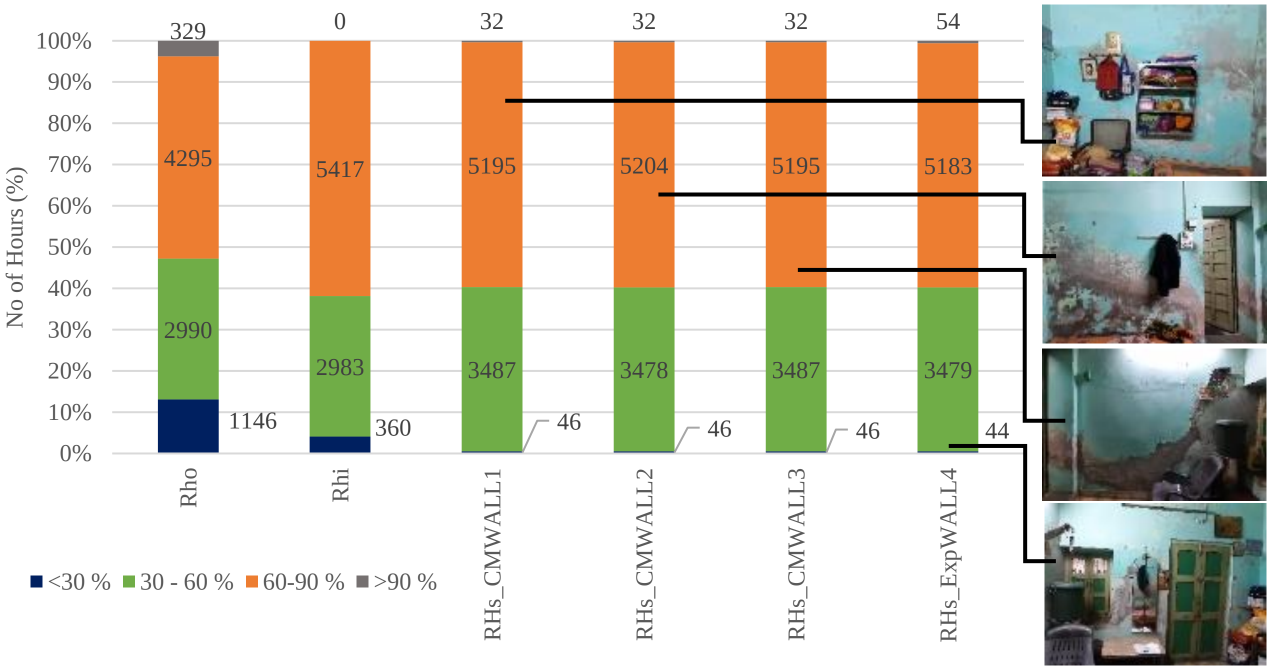


Figure 14 Hours corresponding to relative humidity ranges over the year for space PT_B

. Another space PS_A showing mold on the walls was also simulated to check the hygrothermal model. However, for brevity, only important results are included for this space. In this case, the indoor RH maximum was lower than the outdoor maximum RH by 17 %, and the maximum surface RH values were below 90 %. The surface RH near the walls varied from 60% to 80% in the monsoon months (July- October). This period is favourable for mold growth. Through simulations of PS_A, the moisture buffering and indoor MRT were observed. The indoor RH was moderated, and the MRT was lower in these spaces. Lime-plastered spaces maintain MRT between 20°C to 30°C. The indoor RH levels were lower than the outdoor RH by 9 -11 %. Overall, simulations helped to predict the duration for which the walls would be exposed to high RH levels (>70 %) that lead to mold growth. Thus, the EMPD model was able to predict conditions favourable for mold growth in the two surveyed spaces.

2.2 Survey Results:

The observations from the surveyed Pol houses and residences are discussed in this section.-The Table 3 below indicates the characteristics of the studies spaces as per the observations on site.

Table 3 Characteristics of studied spaces

Space Name	Wall Details	Mould growth observation	Function	Type of Coating over Plaster	Volume (cu.m)	Occupancy	Age of Buildings (Estimated)
KL_A	North and West Wall Exposed	No Visible Mould Growth	Living Area	Lime Wash	34.52	1	100 - 300 yrs
KL_B	South and West Wall Exposed	Outside exposed wall	Kitchen	Lime Wash	36.62	0	100 - 300 yrs
PS_A	North Wall Exposed	No Visible Mould Growth	Living Area	Lime Wash	69.01	3	100 - 300 yrs
PS_B	Open to sky	On 1 Common Wall	Kitchen	Lime Wash	120.06	0	100 - 300 yrs
PS_C	No Exposed Wall	On all Walls	Store Room	Lime Wash	21.09	0	100 - 300 yrs
BT_A	North Wall Exposed	No Visible Mould Growth	Bedroom	Lime Wash		4	100 - 300 yrs
PT_A	South and West Wall Exposed	Inside and Outside all Walls	Common area	Lime Wash	33.68	0	100 - 300 yrs
PT_B	North Wall Exposed	On all Walls	Bedroom	Lime Wash	23.32	1	100 - 300 yrs
PR_A	East Wall Exposed	On all Walls	Store Room	Lime Wash	72.90	0	100 - 300 yrs
PR_B	No Exposed Wall	On all Walls	Store Room	Lime Wash	25.80	0	100 - 300 yrs
MN_A	South Wall Exposed	On Common Walls	Living Area	Lime Wash		3	100 - 300 yrs
MN_B	North Wall Exposed	No Visible Mould Growth	Kitchen	Lime Wash		1	100 - 300 yrs
MZ_A	East Wall Exposed but shaded	No Visible Mould Growth	Small scale industry activity	Distemper	28.92	3	100 - 300 yrs
MZ_B	No Exposed Wall	On Both the Walls	Passage	No Coating	7.51	0	100 - 300 yrs
BH_A	West Wall Exposed	On East Wall	Living Area	Plastic Paint	41.10	3	100 - 300 yrs
BH_B	North and West Wall Exposed	On East Wall	Kitchen	Plastic Paint	31.50	1	100 - 300 yrs
RM_A	East Wall Exposed	No Visible Mould Growth	Living Area	Distemper	39.30	4	100 - 300 yrs
RM_B	North Wall Exposed	No Visible Mould Growth	Bedroom	Distemper	32.10	1	100 - 300 yrs
JG_A	North and East Wall Exposed	On all Walls	Common area	Plastic Paint	72.00	0	100 - 300 yrs
JG_B	No Exposed Wall	On all Walls	Store Room	Plastic Paint	45.00	0	100 - 300 yrs
CH_A	North Wall Exposed	No Visible Mould Growth	Kitchen	Lime Wash	26.19	1	100 - 300 yrs
CH_B	No Exposed Wall	No Visible Mould Growth	Bedroom	Lime Wash	52.96	1	100 - 300 yrs
CH_C	No Exposed Wall	No Visible Mould Growth	Store Room	Lime Wash	6.28	0	100 - 300 yrs
GRD2_A	East Wall Exposed	No Visible Mould Growth	Dining Area	Lime Wash	37.92	0	100 - 300 yrs
GED2_B	West Wall Exposed	No Visible Mould Growth	Store Room	Lime Wash	18.79	0	100 - 300 yrs
GRD2_C	East Wall Exposed	No Visible Mould Growth	Store Room	Lime Wash	22.75	0	100 - 300 yrs
PZ_A	South and West Wall Exposed	No Visible Mould Growth	Living Area	Lime Wash	210.77	0	50-80 yrs
PZ_B	South and West Wall Exposed	No Visible Mould Growth	Bedroom	Lime Wash	44.21	0	50-80 yrs
PZ_C	South and West Wall Exposed	On Common Walls	Basement Store Room	Lime Wash	45.26	0	50-80 yrs
PZ_D	South and West Wall Exposed	No Visible Mould Growth	Basement Store Room	Lime Wash	110.52	0	50-80 yrs
PZ_E	South and West Wall Exposed	On 2 Common Walls	Basement Store Room	Lime Wash	94.33	0	50-80 yrs
PZ_F	South and West Wall Exposed	No Visible Mould Growth	Common area	Lime Wash	107.28	0	50-80 yrs
PZ_G	South and West Wall Exposed	No Visible Mould Growth	Bedroom	Lime Wash	49.50	0	50-80 yrs
PZ_H	South and West Wall Exposed	No Visible Mould Growth	Bedroom	Lime Wash	113.83	0	50-80 yrs
PZ_I	South and West Wall Exposed	On Exposed Walls	Terrace Common area	Lime Wash		0	50-80 yrs
RJ_A	South and West Wall Exposed	No Visible Mould Growth	Living Area	No Coating	196.00	0	10-15 yrs
RJ_B	South and West Wall Exposed	No Visible Mould Growth	Dining Area	No Coating	126.60	2	10-15 yrs
RJ_D	South and West Wall Exposed	No Visible Mould Growth	Living Area	No Coating	189.00	2	10-15 yrs
RJ_E	South and West Wall Exposed	No Visible Mould Growth	Bedroom	No Coating	69.60	0	10-15 yrs
RJ_F	South and West Wall Exposed	No Visible Mould Growth	Store Room	No Coating	33.60	0	10-15 yrs
RJ_G	South and West Wall Exposed	No Visible Mould Growth	Store Room	No Coating	105.00	0	10-15 yrs
RJ_H	South and West Wall Exposed	No Visible Mould Growth	Store Room	No Coating	47.20	0	10-15 yrs
RJ_I	South and West Wall Exposed	No Visible Mould Growth	Living Area	No Coating	183.41	1	10-15 yrs
RJ_I	South and West Wall Exposed	No Visible Mould Growth	Entrance Lobby	No Coating	17.92	0	10-15 yrs
RJ_K	South and West Wall Exposed	Inside and Outside Exposed Walls	Living Area	No Coating	73.41	1	10-15 yrs

2.2.1 Pol Houses

The surveyed Pol houses were categorized according to the coatings used over lime plaster. During the study period (December to March) the RH levels varied between 10 % - 55 % inside the studied spaces. The indoor minimum values of RH were higher by 2.1% and 1% in the case of lime-washed and non-porous painted walls. Slightly higher indoor RH levels could be due to indoor occupancy and moisture generation. To further examine the simulation observations for sample space PT_B, the onsite readings were analyzed. In Figure 15, the outdoor relative humidity is compared with the indoor and surface RH levels from January to March.

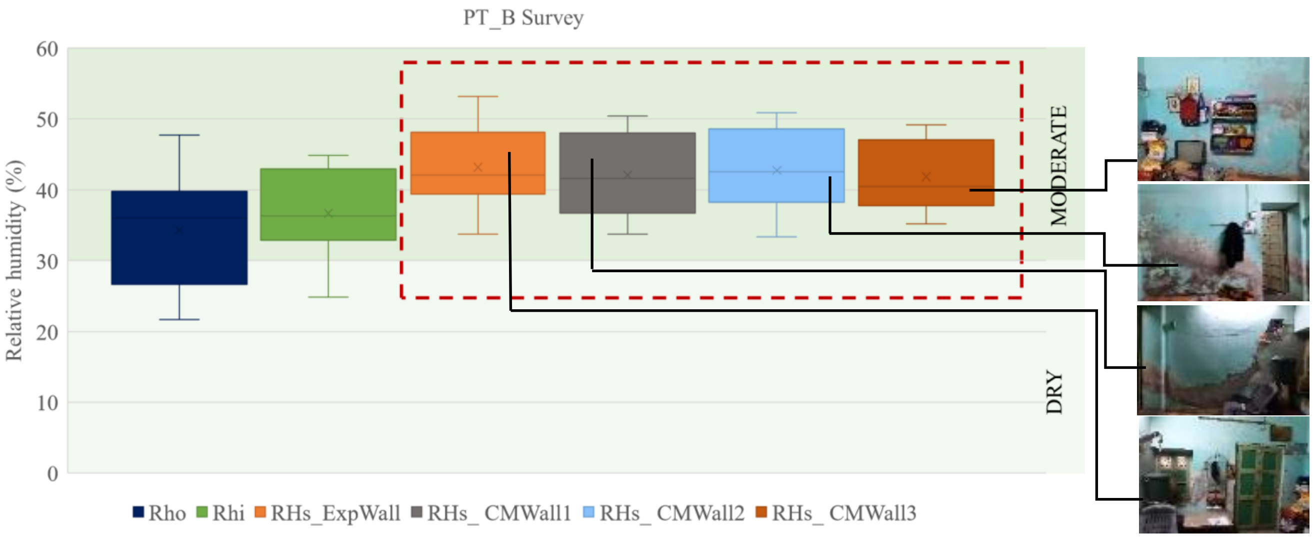


Figure 15 Onsite relative humidity levels inside PT_B

Similar to the simulation results (refer Figure 12), surface RH levels were higher than the indoor RH levels. 50% of the indoor readings were higher than outdoor indicating a humid indoor environment. The minimum values of surface RH were 9.8% to 12.4% higher than the minimum indoor RH. The maximum surface RH is 4.3% to 8.3% higher than the maximum indoor RH. If the above pattern is followed throughout the year, whenever the space RH goes above 60%, the surface RH will be around 65 to 70 % RH. In the monsoon period, when the outside RH levels are in the range of 80-95%, the surface RH of the walls could reach 95 to 97%. These RH levels are favourable for mold growth unless the moisture is removed from the surface.

2.2.2 Girikunj Residence and RSR Residence

For Girikunj Residence, the surveyed spaces included a basement and topmost rooms exposed to the sun. Figure 16a shows the relative humidity in the study period of March. The outdoor RH near Girikunj varied between 14.6% to 40%. The RH in indoor spaces varied between 18.2% to 37.4%. A difference of 3% to 4% was observed between the high and low values from outdoor to indoor. No water activity or occupancy (excluding the surveyor) was observed inside any of these spaces.

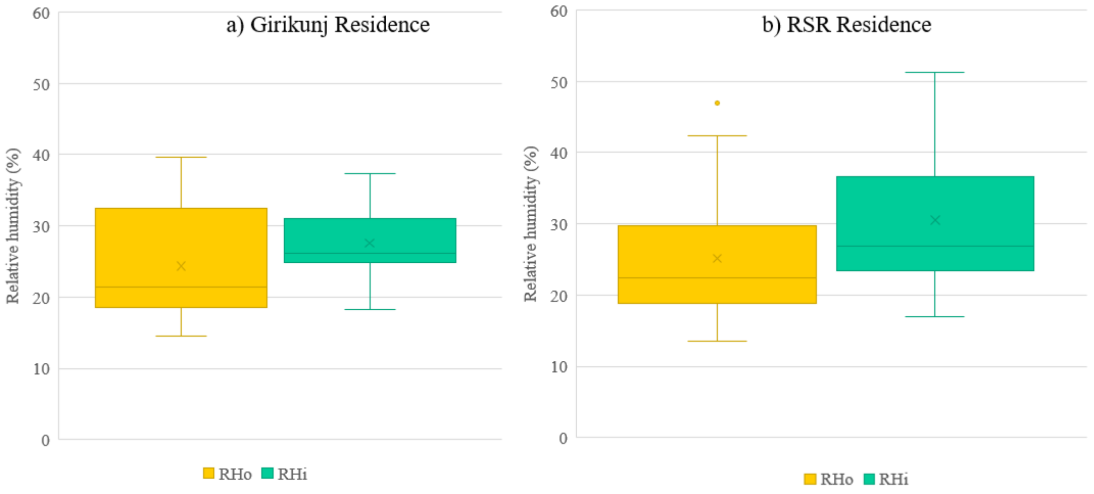


Figure 16 Indoor relative humidity of different spaces

The topmost coating in RSR residence is that of Venetian lime plaster which is a smooth marble-like lime plaster that does not require any paint. Thirteen spaces on the ground floor were surveyed in the month of March. Figure 16b shows the indoor and outdoor RH levels. The mean of indoor RH was higher than that of outdoor by 4.7%. Mold growth was observed in one of the spaces (RJ_K). In this space, the indoor RH was higher by 8% to 14% and a maximum difference of 18% was observed between the surface RH and indoor RH. An adjacent space, RJ_J, was found to be free of mould. The indoor RH in RJ_J space was higher by 1% to 5% while the surface RH was higher than indoor RH by 5% to 9%. Thus, the correlation between higher surface RH and mold growth was observed through on-site surveys.

2.2.3 MRT observations

Figure 17 shows the difference between outdoor and indoor MRT for all the studied spaces. The MRT of space was calculated as per the formula given in (39). With increasing outdoor temperatures, the difference increases for all the spaces except those having a nonporous coating over lime plaster. A positive difference shows that the indoor MRT is lower than the outdoor MRT. The differences were highest (indicated by a steeper trendline) for RSR residence where lime plaster was exposed. The differences for Girikunj were lower than RSR residence and least for Pol houses with limewash.

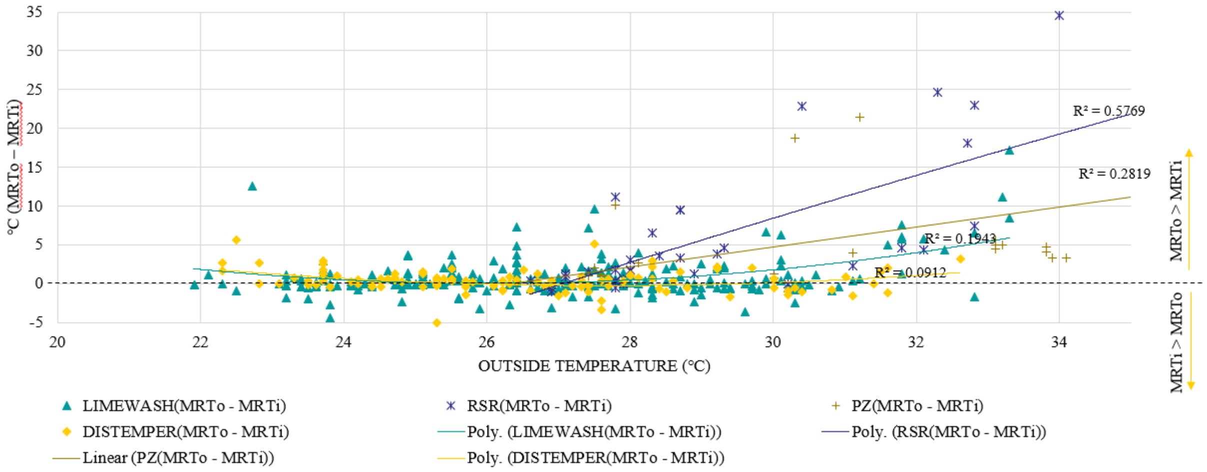


Figure 17 MRT Variation with outdoor temperature for different spaces

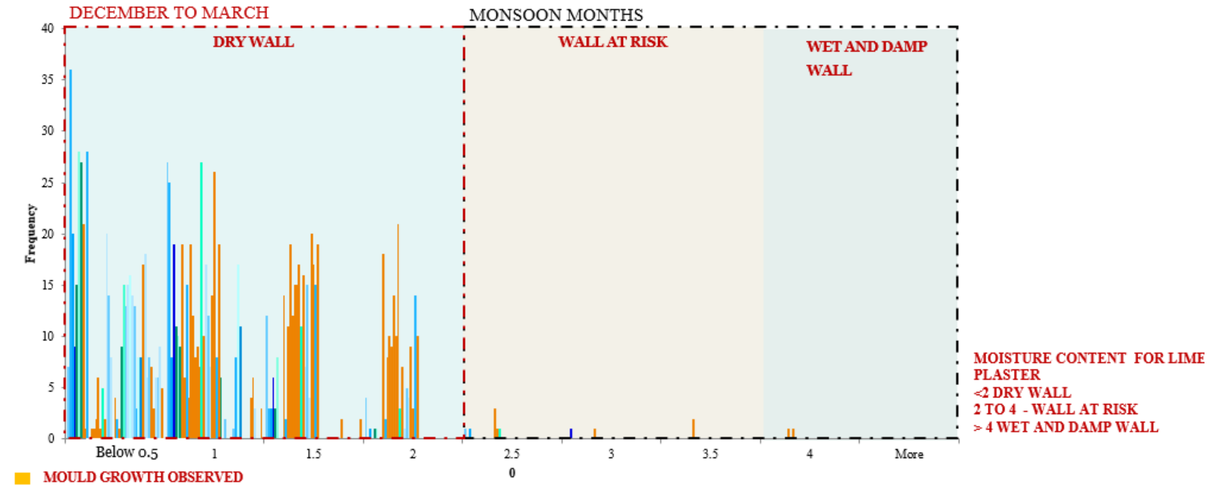
The indoor was considered to be comfortable when inside MRT (MRTi) was found to be lower than the outside MRT (MRTo). Based on above criteria, it was observed that the spaces with non-porous paint were hot 30 % of the time. Limewashed spaces in Pol houses remained hot for 18.5 %, while RSR and Girikunj residences stayed hot for 8.6 % and 7.4 % respectively. Thus, RSR and Girikunj Residences were comfortable for more than 90% of the time. Pol houses with limewash were comfortable for 81% of the time in March. These differences could be more in hotter months and need to be studied further by year around measurements.

2.2.4 Mold Risk Observations

From the surveys, it was observed that the hygrothermal behaviour of spaces varied with their characteristics. The spaces were identified based on the topmost finish of the wall surface layer, air velocity inside the space, occupancy, storage, the sunlight received and the type of activity happening in that space. Figure 18 shows photos of different spaces with visible mold growth.

Figure 18 Onsite photos of different locations with mold growth.

For further analysis, the moisture content of the walls was recorded and is shown in Figure 19. The walls of the spaces where mold growth is observed are marked in orange. During the study period from December to March, all the walls were dry and showed low moisture content below 2%. However, mold growth was still observed on these walls. The mold would have grown during the past monsoon season from July-October when the RH levels were in excess of 90 % for sustained periods. Factors like damaged construction, presence of water pipelines, low ventilation, etc., were other reasons for mold.



Moisture content

	0.5	1	1.5	2	2.5	3	3.5	4	More
■ KL_A	7	27	12	4	1	0	0	0	0
■ KL_B	36	25	3	0	0	0	0	0	0
■ CH_A	20	8	3	1	1	0	0	0	0
■ CH_B	9	19	6	0	0	1	0	0	0
■ CH_C	15	11	3	1	0	0	0	0	0
■ RM_A	28	10	8	1	0	0	0	0	0
■ RM_B	27	9	0	0	0	0	0	0	0
■ BH_B	21	19	0	0	0	0	0	0	0
■ MN_A	1	6	14	18	0	0	0	0	0
■ MZ_A	28	15	2	2	0	0	0	0	0
■ MZ_B	0	4	11	8	0	0	0	0	0
■ PT_A	1	19	19	10	0	0	0	0	0
■ JG_A	1	12	12	9	0	0	0	1	0
■ PT_B	2	8	15	14	0	0	0	0	0

	0.5	1	1.5	2	2.5	3	3.5	4	More
■ PS_B	6	9	15	10	3	1	2	1	0
■ PS_C	1	7	17	21	1	0	0	0	0
■ PS_A	5	27	11	3	1	0	0	0	0
■ JG_B	2	10	16	7	0	0	0	0	0
■ BH_A	20	17	7	1	0	0	0	0	0
■ MN_B	14	12	15	5	0	0	0	0	0
■ BT_A	8	7	4	4	0	0	0	0	0
■ PR_B	0	14	20	9	0	0	0	0	0
■ PR_A	4	26	17	3	0	0	0	0	0
■ PT_B	2	8	15	14	0	0	0	0	0
■ PT_A	1	19	19	10	0	0	0	0	0
■ GRD2_A	9	6	0	0	0	0	0	0	0
■ GRD2_B	15	0	0	0	0	0	0	0	0
■ GRD2_C	13	2	0	0	0	0	0	0	0
■ RJ_A	15	0	0	0	0	0	0	0	0
■ RJ_B	16	0	0	0	0	0	0	0	0
■ RJ_D	14	0	0	0	0	0	0	0	0

Figure 19 Moisture content of all walls surveyed between December2019 and March2020

Since the study was conducted in drier months there were hardly any walls having a moisture content of more than 2%. Nonetheless, mold was present on these walls which can further be analyzed by understanding the correlation of moisture content with the surface relative humidity. In Figure 20, the wall moisture content is plotted against the indoor surface relative humidity. The points marked in orange, ochre, red, and maroon represent the readings of walls having mold. The rest of the points are shown in blue colour. The graph is divided into six sections by referring to the characteristic curve of lime mortar in the moisture meter (40). For surface humidity above 60% and moisture content above 2%, there are definite chances of mold. For relative humidity below 30% and 1.5 moisture content, the conditions are dry enough to restrict mold. Walls with mold showed moisture content greater than 0.5%.

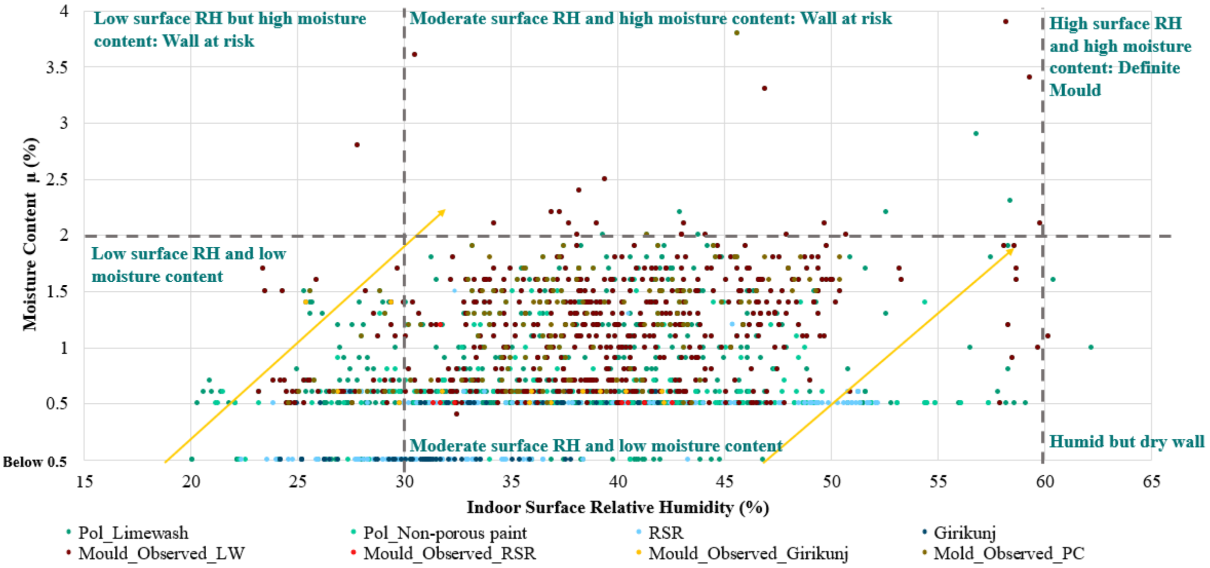


Figure 20 Moisture Content vs surface relative humidity

In case of Pol houses, most of the readings in Figure 20 are populated in the section of moderate humidity and drywall. These also include walls affected by mold due to the predated wet monsoon season. Thus, the poor performance of the building during monsoons or due to specific damage is evident. Points lying below 60% surface humidity and above 2% moisture content suggest mold growth due to the trapped moisture in the walls. Points in bright red are of RSR residence, where the reason for the presence of mold was the existence of a water pipeline and high moisture source (pool) outside the space. In Girikunj residence (marked in dark blue) the mold was observed in the basement and space attached to the terrace. Due to leakage near the slab of the terrace during rain, the walls might have been damaged. There are numerous blue points observed towards the right of the graph indicating well-ventilated and undamaged walls. Overall, a gradual shift towards the right is observed with the increase in indoor surface relative humidity. This indicates the increase in moisture content with the increase in the indoor surface relative humidity.

Figure 21 shows the mold scenario of each space with respect to its characteristics. It helps in identifying the strongest and most common factors that affect mold growth as observed and measured during the multiple site visits. The spaces highlighted in black are indicative of mold growth. All the spaces were further categorized and color-coded as per the following characteristics:

- Plaster paint: coating used over the plaster-like lime wash paint, distemper paint (cement paint) (41), plastic emulsion paint, or not coated. If the topmost coating is nonporous, the moisture is trapped inside, resulting in mold growth.
- Ventilation: if the wall surfaces are not properly ventilated, the moisture inside the pores of the finishing layer doesn’t evaporate ad leads to mold growth.
- Sunlight: Sunlight plays a role in killing bacteria and keeping highly humid surfaces dry.
- Water Activity: high water activity i.e., activities like washing, cleaning, etc., result in higher moisture inside the space.
- Clutter near the wall (storage): more stuffed spaces create humid pockets inside the space. Clutter is considered low, moderate, and high if the furniture and other items are blocking the walls by 30%, 60%, or 70%. This was based on just visual observations.

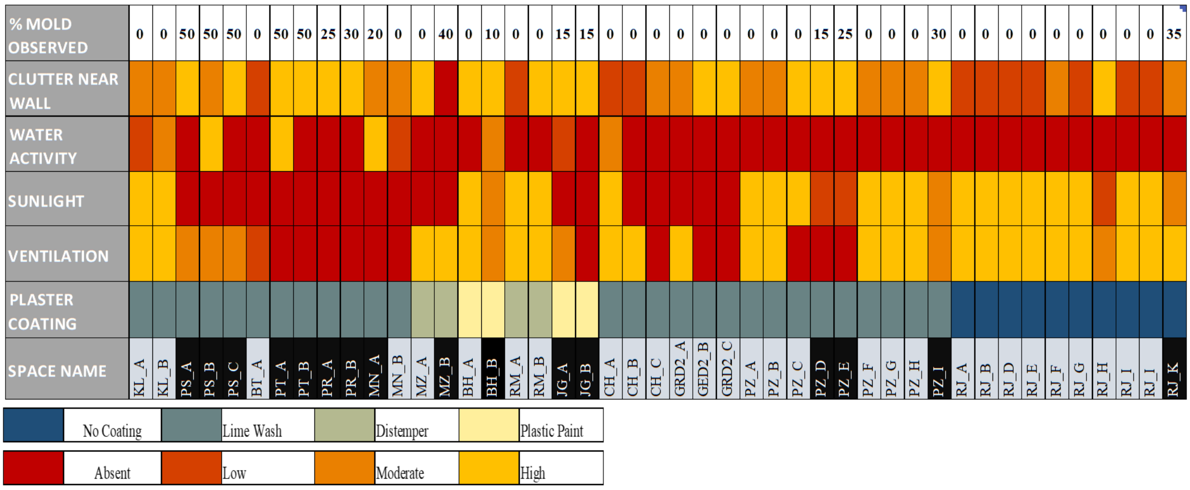


Figure 21 Space characteristics and mold growth relationship

The best and worst combination for predicting mold risk can be inferred from Figure 21. For example, the worst-case scenario was observed in spaces PT_B and PT_A. More than 50% of the walls were densely covered with mold. PT_B has a good scope of ventilation, but the openings were always closed. So, it can be marked as not ventilated, with no sunlight, low water activity, moderate storage near walls, and a limewash coating on the wall. Even though there was no water activity, other factors were dominating. The PT_A space was characterized by closed openings, no sunlight, high water activity, moderate storage near the walls, and lime wash. In both cases, it was observed that due to lack of ventilation and no sunlight the moisture was trapped inside the space which led to mold growth. The best combination is where lime plaster is not coated or coated with limewash, and the spaces were well ventilated and sunlit. The surveys suggest that mold growth in lime plaster was observed if the moisture transfer is obstructed. Therefore, if lime-plastered surfaces are allowed to breathe in ventilated spaces mold growth can be avoided.

The number of studied spaces/rooms in Pols accounted to 57% and the spaces/rooms in the in the individual residences accounted to 43% , . In comparison to the Pol houses, the individual residences had better strategies such as air vents, daylight spaces, and periodic maintenance. In the hotter month of March, they show better hygrothermal performance and were comfortable for more than 90% of the time. The indoors were cooler than the outdoor by 1 ℃ to 5 ℃. The walls were drier and were recorded to be mostly below 0.5% of moisture content. The exposed lime plaster helped in moderating the indoor RH levels. The major issue observed in lime-plastered Pol houses was the lack of proper ventilation, sunlight, and maintenance.

2.2.5 Mold observation under the microscope

Samples were collected from the site to verify the presence of mold on the walls. The most common type of mold that is formed over lime plaster was observed. Figure 22 shows the collected samples as observed under a 40x simple microscope. In Figure 22a and Figure 22b, the tread-like filaments are the hyphae of the mold structure. The small granules are likely to be spores. Figure 22c and Figure 22d, show a sample scrapped from a gap between a wooden door frame and a lime plaster wall. This type of mold is different from the one observed on the walls having lime plaster. Observation under a high-resolution compound microscope will be required to identify the type of mold.

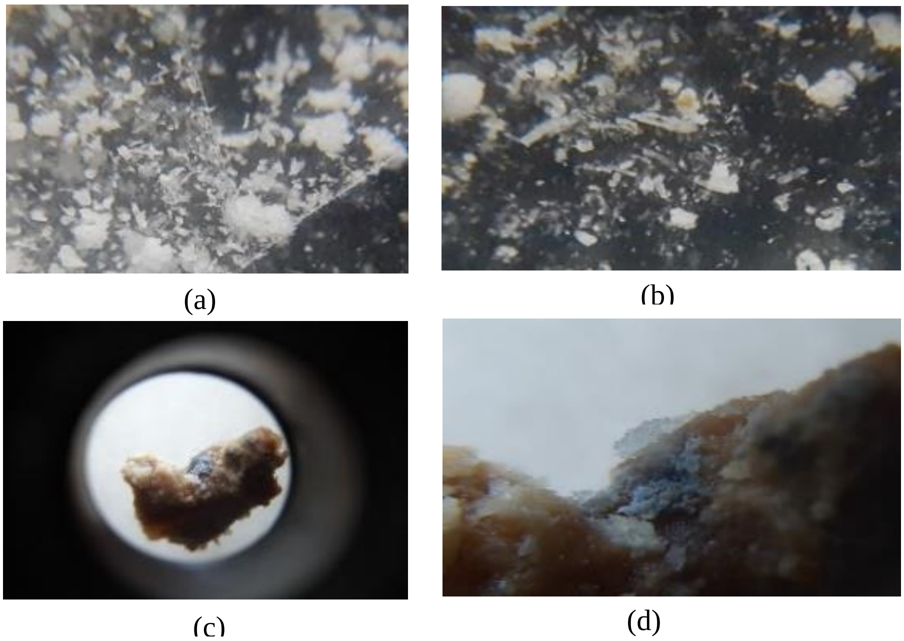

(a)
(b)
(c)
(d)

Figure 22 Mold sample under the 40x simple microscope

2.2.6 Studying the onset of mold growth on lime plaster samples

All the samples of lime plaster weighed 20 grams and had an initial moisture content of 0.6 %. Of the four containers, the one containing potassium sulphate (96 % RH) had early signs of mold growth. The other three containers (having RH of 75%, 80%, and 86%) showed no visible mold growth until the third week. However, at 96% RH mold growth was visibly seen on the lime plaster sample within three weeks (see Figure 23). Thus, a favourable environment for mold growth is created if the surface relative humidity in the space is more than 95%. This observation can be related to the conditions on site where mould is observed on the walls considering that the humidity near those walls has been consistently high for some time.

Figure 23 Mold growth observed under 96% relative humidity

3 Conclusion

In this work, the hygrothermal performance of lime plaster in naturally ventilated spaces is studied and co-related with mold risk. The survey of the lime-plastered spaces was carried out between December 2019 to March 2020. In relatively dry weather conditions, surface RH levels of the studied spaces were higher than the outdoor RH. The indoor RH levels are expected to rise further in the wet monsoon period and therefore prone to mold growth. The mold growth wasn't observed in spaces that were well maintained (uncluttered), well-ventilated and sunlit. Non-porous coatings on plastered surfaces led to mold growth. Thus, it is important to maintain a breathable wall assembly and adequate ventilation to facilitate moisture transfer across the building envelope. Spaces finished with a lime wash and exposed lime plaster also showed lower indoor MRT than spaces with non-porous coatings.

Hygrothermal simulations with the EMPD model were able to capture moisture buffering in different materials. Hygrothermal simulations carried out with the EMPD model were able to predict the indoor conditions which might result in mold formation. Thus, mold growth risk on different wall surfaces can be identified. However, more numerical analysis with hygrothermal properties of typical lime plaster used in India needs to be carried out for realistic predictions. Walls with high surface RH were susceptible to mold risk if exposed to indoor RH levels greater than 60 % for more than four weeks. Experiments with lime plaster samples showed visible mold growth in 3 weeks under an environment with a relative humidity of around 95 %. By combining the above observation with the simulations, the chances of mold growth in a space can be predicted. The performance gap between a simulation and an actual case can also be narrowed down for better predictions if the simulations are carried out in collaboration with survey observations.

Overall, lime plaster is a sustainable and low embodied energy material with good moisture buffering capacity. It can moderate indoor RH levels and lead to lower MRT. Although it is prone to mold growth in high humidity conditions, avoiding non-porous coatings and maintaining adequate ventilation can reduce mold risk. Especially suited for historic buildings, lime plaster should also be considered in contemporary building practices.

Future work on identifying the composition of lime plaster composition to relate it to mold growth is necessary. Hygric property characterization is also required for carrying out detailed hygrothermal simulations for predicting mold formation. Finally, a year around study will give a comprehensive picture of the interrelated parameters responsible for mold growth.

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5 Declarations and conflicts of interest

5.1 Conflicts of Interest

All authors declare no possible conflicts of interest.

5.2 Research ethics statement

Ethics approval is not needed.

5.3 Consent for publication statement

Authors have secured informed consent to participate in the study and to publication before submitting it to the journal

5.4 Open data and materials availability

No further data was used in addition to referenced works.

5.5 Authorship contribution

Rashmin Damle has been the guiding faculty in this study and Vismaya Paralkar has carried out data compilation, assessments, and reporting.

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