

Original Article

Impact of Courtyards on Climatic and Spatial Attributes in a Vernacular House: Case of Kumbakonam in Tamil Nadu, India

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Abstract - Residential courtyards have existed across many civilizations. The thermal performance of the courtyard is researched to enhance the microclimate of indoor spaces. The microclimate of an indoor space can be defined as the climate inside a room or a building. This study evaluates the effect of the courtyard within a vernacular house in the warm, humid climate of Kumbakonam. Firstly, the spatial layout was documented through on-site observations. Further, the climatic and spatial relationship of the courtyard and its surrounding spaces was analyzed through a matrix of attributes. A statistical analysis was done to evaluate the correlation between all the attributes considered. Finally, a simulation using DesignBuilder was carried out to analyze the variation in climatic attributes between the semi-open courtyard and the closed courtyard. The study revealed that the area and openings of a space are significantly related to the temperature and humidity. Illumination levels and wind speed are closely linked to the enclosure of a space. An open courtyard within the dwelling helps to reduce the temperature by 4°C during the summer season. This study highlights the significance of a semi-open courtyard in modern residences for enhanced microclimate conditions. The findings of this study contribute to the expanding research on courtyard design. Furthermore, it will aid architects and designers in planning modern residences.

Keywords - Arc GIS, Behaviour, Courtyard, Microclimate, Climatic Design, Spatial analysis, Vernacular, India.

1. Introduction

In the Indian context, courtyards play a significant role in residential design. With varying climates across the country, courtyards have been incorporated in the design of residences to optimize thermal comfort. Existing research focused on courtyards' various advantages, like thermal performance, natural ventilation, daylighting, typological variations, cultural significance, regulation of urban microclimate, etc. There remains a notable gap in comprehending the impact of courtyards on climatic and spatial characteristics within the house and the corresponding behavioural adaptations of the occupants of the house. However, this study aims to address this gap and promote understanding of the impact of incorporating courtyards in residential design. Designing with courtyards can be a sustainable approach that influences buildings' microclimate and energy consumption. [1] In the warm, humid climate of Colima, Mexico, lower heat gain was observed in courtyards with their long axis in an east-west direction. [2] Shading provided by various roof coverings in the courtyard is observed to be significant in providing better thermal conditions for buildings in hot, humid climates. [3]

Simulation results in a tropical terrace house in Penang, Malaysia, suggested that the semi-enclosed courtyard feature and a shading device can provide optimal environmental conditions of the courtyard space in a hot, humid climate. [4] Incorporating an internal courtyard in terrace houses of Malaysia helped in enhancing the natural ventilation and thermal comfort in spaces that have openings to the external environment.

In hot, humid areas of Hainan Island, China, internal courtyards covered by semi-open roofs prevented direct solar radiation and heat penetration[5]. [6] Research investigation in the 3-section courtyard traditional house in Northeast Sichuan, China, revealed that the courtyard model was highly reliable. Under the same outdoor conditions, the simulation results of air temperature in bedrooms and living rooms were found to be consistent with the measured results. [7] In the tropical climate of Kafanchan, Africa, the microclimatic performance of a fully enclosed courtyard building was found to be better than that of a non-courtyard residential building. The study found that the air temperature difference was



between 2°C and 4°C and 2% to 6% relative humidity variation. [8] A field survey of vernacular houses in Jammu City revealed that the courtyard system in traditional buildings aided ventilation even during calm outdoor conditions. The temperature of the courtyard was found to be 2 to 3°C higher during late afternoons and 2 to 3°C lower during early mornings when compared to the indoor room temperatures. [9]. Research on the open spaces in low-rise residences in India found that the courtyard spaces in rural areas exhibited 3°C lower temperature, better illumination during the day, cross ventilation, and multifunctionality compared to their urban counterparts. [10].

In the warm, humid climate of Kerala, the internal courtyard provided in traditional buildings helped in inducing internal air movement through the building to achieve thermal comfort even when air conditioning still exists outdoors. [11]. When the thermal performance of the courtyard was analyzed in the row house of Edalakudy in Nagercoil, Tamil Nadu, the results emphasized that an efficient courtyard could reduce the temperature from 2°C to 4°C. [12] Research carried out in Chinese traditional siheyuan through space syntax revealed that even the way of everyday life on the social organization of traditional structure can be explored in research [13]. A comparative study of traditional courtyard houses of Cairo revealed that an increase in enclosure ratio and the extent of facade projections aid in the decrease of direct solar radiation received [14].

Irrespective of its size, the courtyard helps in providing natural diffused daylight to the dwelling, thereby reducing energy consumption. The size and location of the courtyard are major parameters based on which thermal conditions can be assessed inside the dwelling. The courtyard's size acts as the deciding factor for the nature of activities carried out within this space and its surroundings in the Thanjavur region, Tamil Nadu. [15]. The courtyard house is one of the general typologies of house forms in Tamil Nadu. Though variations in built form can be found in many regions, rectangular courtyards are found to be constant. [16] Simulation research in the warm humid climate of Tiruchirappalli city, India, revealed that rectilinear and dual courtyard forms were found to have more desirable temperature and air flow [17].

In the hot humid climates of Kuala Lumpur, Malaysia, Courtyards that face North and East have 0.5°C lower temperatures, especially between 10 am and 5 pm. These courtyards were found to have high levels of humidity when compared to other courtyards. The highest temperatures were recorded in the west-facing courtyard due to the lowest level of wind speed in this orientation. Simulation results for the same show that an increase in the height of wall enclosures in courtyards leads to a decrease in the air temperature. The courtyard with the highest level of wall enclosure receives significantly lower direct solar radiation from 11 am to 5 pm. [18] Results from the study of the tropical courtyard house in

Colombo, Sri Lanka, revealed that the envelope openings act as a positive pressure zone and the courtyard's sky roof openings act as a negative pressure zone. Thus, a differential pressure was created, inducing air movement within the house. [19] A study on the behavioural use of courtyards by a Nupe community in central Nigeria proved that native people have evolved clever use of courtyards based on sun movement and building shade. A courtyard is a space where people shape their behaviour to meet the functional needs as a place and bioclimatic functions. [20] Research in the contemporary courtyard housing in Ahmedabad found that the courtyard acted as a private space rather than a community space [21]. Courtyard house research in Kuwait revealed that the internal courtyard plays a role in lowering the stress among the members of the house. This typology of houses improved the psychological well-being of inhabitants [22].

In recent years, Vernacular houses have undergone rapid transformations. Open spaces within these houses, like courtyards, are the most transformed spaces despite their various advantages. This is because there is still a lack of understanding of the effect of the internal courtyard on the occupants of the house. There has been substantial research on the relationship between climatic aspects and the spatial use of the courtyard in vernacular houses.

However, studies that explore the behavioural aspects of residents concerning the courtyard, along with the climatic and spatial aspects in a vernacular courtyard house, are rare. Existing research findings revealed that the courtyard has the potential to solve many problems of the present day. Therefore, the novelty in this research is that it focuses on investigating the relevance of the internal courtyard in the present scenario and the interrelationships between the climatic and spatial factors with the spatio-temporal activities carried out within a transformed vernacular house in warm, humid climates.

2. Kumbakonam: The Study Context

Kumbakonam, a temple city located in Thanjavur district in Tamil Nadu, India, was chosen for study. It is located at 10.97°N and 79.42°E. The city is noteworthy for its numerous temples and silk weaving. It has a tropical, warm, humid climate, which is suitable for weaving activities. Silk weaving was carried out primarily by the Sourashtrian community (an Indo- Aryan ethno-linguistic Hindu Brahmin community of South India) in Kumbakonam. The courtyard was the major spatial element in their houses.

This study investigates a transformed courtyard house of the Sourashtrian community in Nadana Gopal Street near Ramasamy temple. The street has many vernacular courtyard houses, which are culturally significant and undergoing transformations. Three large courtyard houses were analyzed in this street as part of ongoing research. However, this paper elaborates on one of the oldest (84 years old) and largest houses within the precinct, which has 4 courtyards. Figure 1 shows the location of the study area.

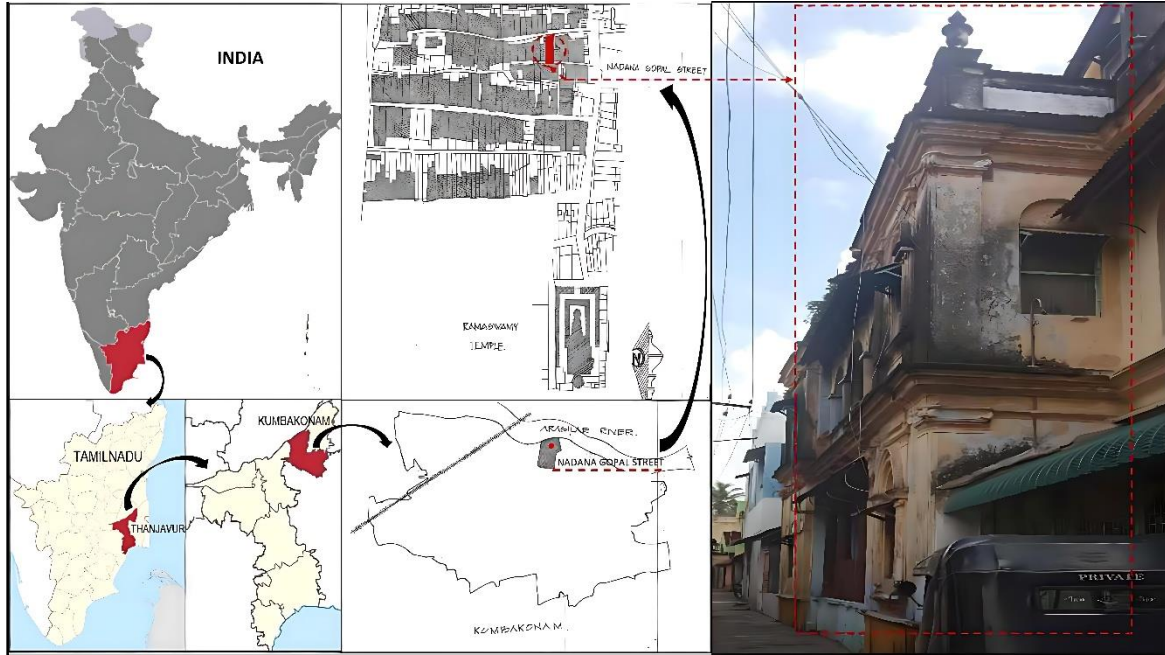


Fig. 1 Location of the site area



Fig. 2 Floor plan of the house

Figure 2 shows the plan of the selected vernacular courtyard house. The house, which was initially occupied by a single joint family, is now divided into 2 dwelling units due to a family dispute. The house has four courtyards: a first courtyard, a second courtyard, a rear courtyard and a kitchen courtyard. The main and rear entrances of the house are aligned on an axis that passes through the first, second, and rear courtyards. Later, the ownership of the house was transferred due to economic reasons to a family whose major occupation was agriculture. At present, the residents have shifted to other temporary job opportunities in the locality, which has reduced the occupation-based activities in the

second courtyard. However, the front, rear and kitchen courtyards are used regularly even in the transformed house.

3. Materials and Methods

The hypothesis of the study is, “the presence of an internal courtyard in residences contributes towards enhancing the microclimate conditions”. The study investigated the relationship between the behavioural, climatic and spatial characteristics of the courtyard in a semi-open-transformed courtyard house with ground and first floor. Only the ground floor is considered for the present study since it is the major activity space. The first floor is not used by the residents as it is entirely dilapidated. Firstly, the spatial layout of the selected

vernacular house was documented through on-site observations. Unstructured interviews were conducted with informed consent from the residents to understand the behavioural characteristics from the residents' perspective. The identity and data of the participants were kept anonymous

throughout the research. Further, the climatic and spatial relationship of the courtyard and its surrounding spaces were analyzed through a matrix of relevant attributes identified through literature [1-22]. Figure 3 shows the methodology of the study.

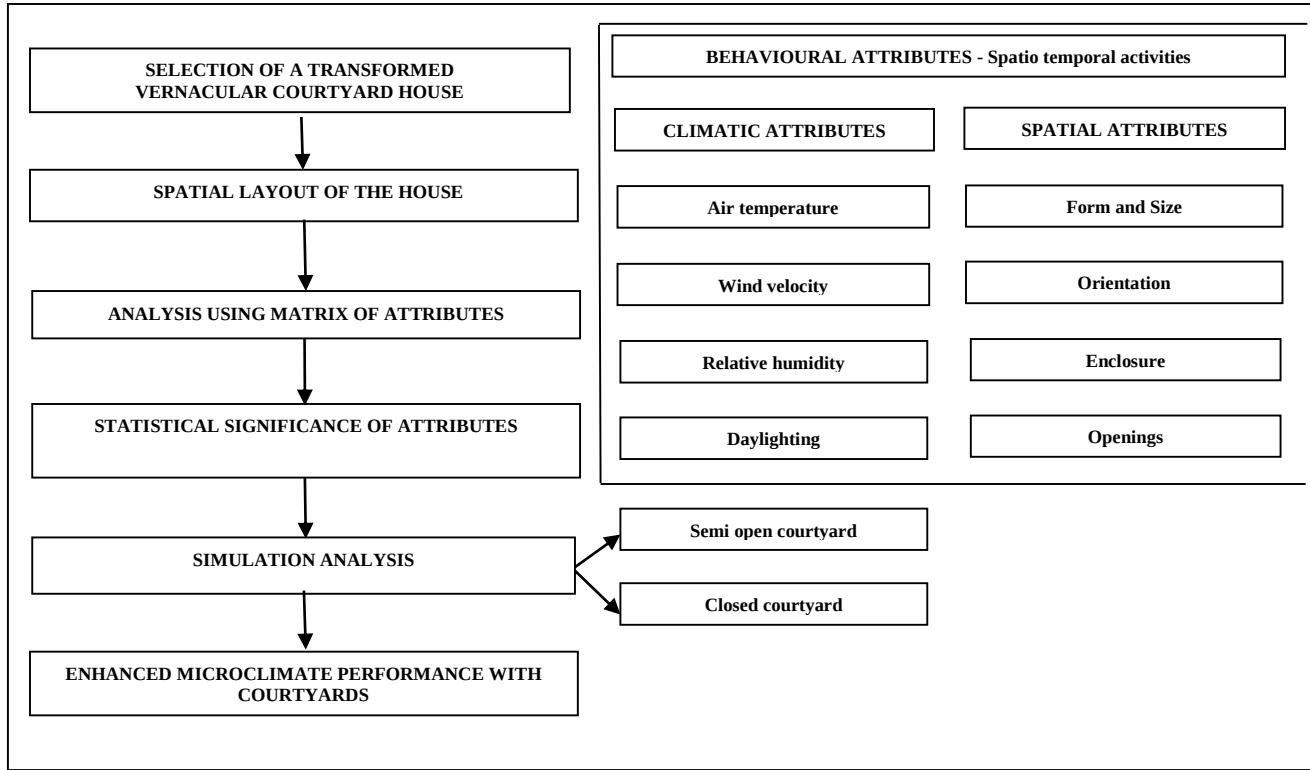


Fig. 3 Research methodology process

The data on climatic attributes were collected through in-situ measurements recorded between 7 am and 7 pm at an interval of two hours for one week in December 2021 (winter) and May 2022 (summer). The measurements were recorded manually. For activities at the standing level and sitting level, the measurements were taken at a height of 1.1m and 0.6m, respectively.

All measurements were taken at the centre of every space. In the case of direct sunlight, measurements were taken at the nearest shaded area. Figure 2 shows the measurement location of the dwelling.

Instruments used to measure climatic parameters:

Air Temperature and Humidity HTC instrument digital indoor hygrometer thermometer with clock.

(Model no: 103 – CTH); (Temperature: Measuring range: -50°C to +70°C; Accuracy: +0.5°C (0°C to 40°C) or +1%); (Humidity: Measuring range: 10% to 99% RH; Accuracy: +3% RH (50% to 80%) or +5%)

Illumination levels - HTC instrument – 1989 LX-101 A – Light meter; (Measuring range: 0 to 2,00,000 LUX; Accuracy: +5% of reading receiving light)

Wind speed - Ace instruments Testo 405i thermal anemometer with smartphone operation for measuring wind speed; (Measuring range: 0 to 30 m/s Accuracy: $\pm (0.1 \text{ m/s} + 5\% \text{ of mv})$)

Assessment of spatial attributes was done through spatio-temporal mapping of activities to investigate the impact of activity patterns within the spatial organization of spaces within the dwelling. A statistical analysis was carried out using a spatial lag model through ArcGIS software to evaluate the correlation between all the considered attributes. Further, a simulation analysis was carried out using DesignBuilder software for the existing semi-open courtyard and the closed courtyard condition. The temperature and humidity isopleths were derived using ArcGIS software for the typical summer and winter seasons for semi-open and closed courtyards. The thermal performance between the two scenarios was compared to identify the significance of the courtyard for enhanced microclimate in a residential environment. The study is limited to the ground floor of the selected dwelling. The upper floors are not considered due to the restriction of access by the owners of the house. For simulation analysis, a block model of the same is used. Only the activities that take place most of the time are considered. Activities that happen between 7 pm and 7 am are not considered due to permission issues.

Table 1. Spatio-temporal activities within the dwelling

Timing	Category	Activity	Space used
7 am - 9 am	Female (Unit -2)	Brushing, Bathing Cooking Breakfast	Rear Courtyard Kitchen Ancillary space near the Kitchen
	Male (Unit -2)	Brushing, Bathing Breakfast	Rear Courtyard Ancillary space near the Kitchen
	Female (Unit -1)	Brushing, Bathing Breakfast cooking and Dinner	Rear Courtyard
9 am -11 am	Female (Unit -2)	Rest Sweeping Cleaning vessels Drying food items Talking to neighbors	Living space 2 Entire house First courtyard First courtyard, Kitchen Courtyard and Entrance
	Male (Unit -2)	Cleaning activities Washing clothes Drying clothes	Entire house Rear courtyard Second courtyard
	Female (Unit -1)	Watching TV, Rest	Bedroom 1
11 am - 1 pm	Female (Unit -2)	Cooking	Kitchen
	Male (Unit -2)	Work Preparatory activities - cooking	Outside the house Living space 2
	Female (Unit -1)	Lunch cooking and dining	Living space 1
1 pm - 3 pm	Female (Unit -2)	Lunch Watching TV, Sleeping Drying grains	Ancillary space near the Kitchen Living space 2 First courtyard
	Male (Unit -2)	Lunch Watching TV, Sleeping Leisure	Ancillary space near the Kitchen Living space 2 First courtyard
	Female (Unit -1)	Watching TV, Rest	Bedroom 1
3 pm - 5 pm	Female (Unit -2)	Tea Cleaning vessels Talking on the phone Drawing kolam	Ancillary space near the Kitchen Rear courtyard First courtyard Street
	Male (Unit -2)	Talking over the phone Watching TV Talking to neighbors	First courtyard Living space 2 Street
	Female (Unit -1)	Talking to neighbors	Street
5 pm - 7 pm	Female (Unit -2) Male (Unit -2)	Watching TV	Living space 2
	Female (Unit -1)	Watching TV	Bedroom 1

4. Results and Discussion

4.1. Functioning of the Vernacular Courtyard House

The functioning of the courtyard house was documented through on-site observations by the researcher, and the data were analyzed from the residents' perspective through unstructured interviews. Inferences were drawn based on the analysis in the research. Daily activities take place in the courtyards during mornings, especially in the rear courtyard. Courtyards are the primary open spaces within the house. Due

to its large size and increased privacy, the rear courtyard is found to be comfortable for users in the early morning. Hence, activities like brushing, bathing, washing and drying clothes and vessels are carried out in the rear courtyard.

Cooking activities are performed in the Kitchen while preparatory activities happen in the living space of unit 2, located adjacent to the front courtyard. This space, being a semi-enclosed space, is also used for resting, watching

television, and sleeping in the afternoons. This might be due to the diffused light and shading received in this space due to its proximity to the courtyard.

The ancillary space near the kitchen is used as a dining area owing to privacy needs. Unit 1 is used by a female member only. The bedroom of unit 1 is used for taking a rest and watching television. The living space of unit 1 is mainly used for cooking and dining. During the night, both the living space of unit 2 and the bedroom of unit 1 is used for dining and sleeping. There is no difference in the preference for space for any activity during summer and winter in either of the units within the dwelling. Table 1 lists the spatio-temporal activities that are carried out within the dwelling.

From Table 1, it is observed that, in Unit 1, the bedroom is the most used space. It is not connected to the semi-open first

courtyard visually or physically. This preference is due to the need for privacy. It is noted that, in Unit 2, the space that holds the maximum number of activities is the first courtyard. Activities like cleaning vessels, drying food items, drying grains, leisure and talking on the phone are carried out in this space. It is used for 6 hours. The second most used spaces are the living space of unit 2 and the rear courtyard. The living space of unit 2 is located adjacent to the semi-open first courtyard, which is used for 8 hours. Activities like resting, doing preparatory activities for cooking, watching TV, and sleeping are carried out in this space. The rear courtyard is used for 6 hours. In this courtyard, activities like brushing, bathing, washing clothes and cleaning vessels are carried out. The second and the kitchen courtyard are used for only one activity each. The first, second and the rear courtyard are used throughout the day as a walkway. Figure 4 shows the views of the courtyard and its activities.

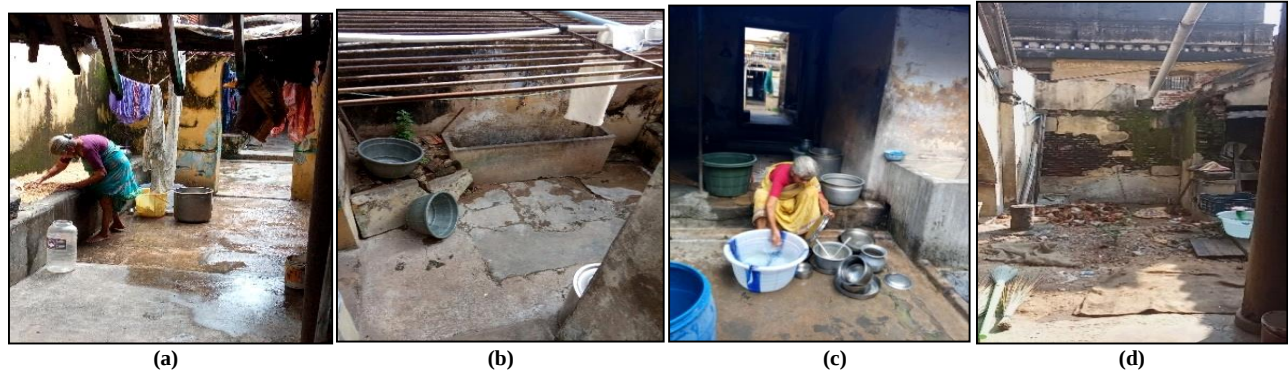
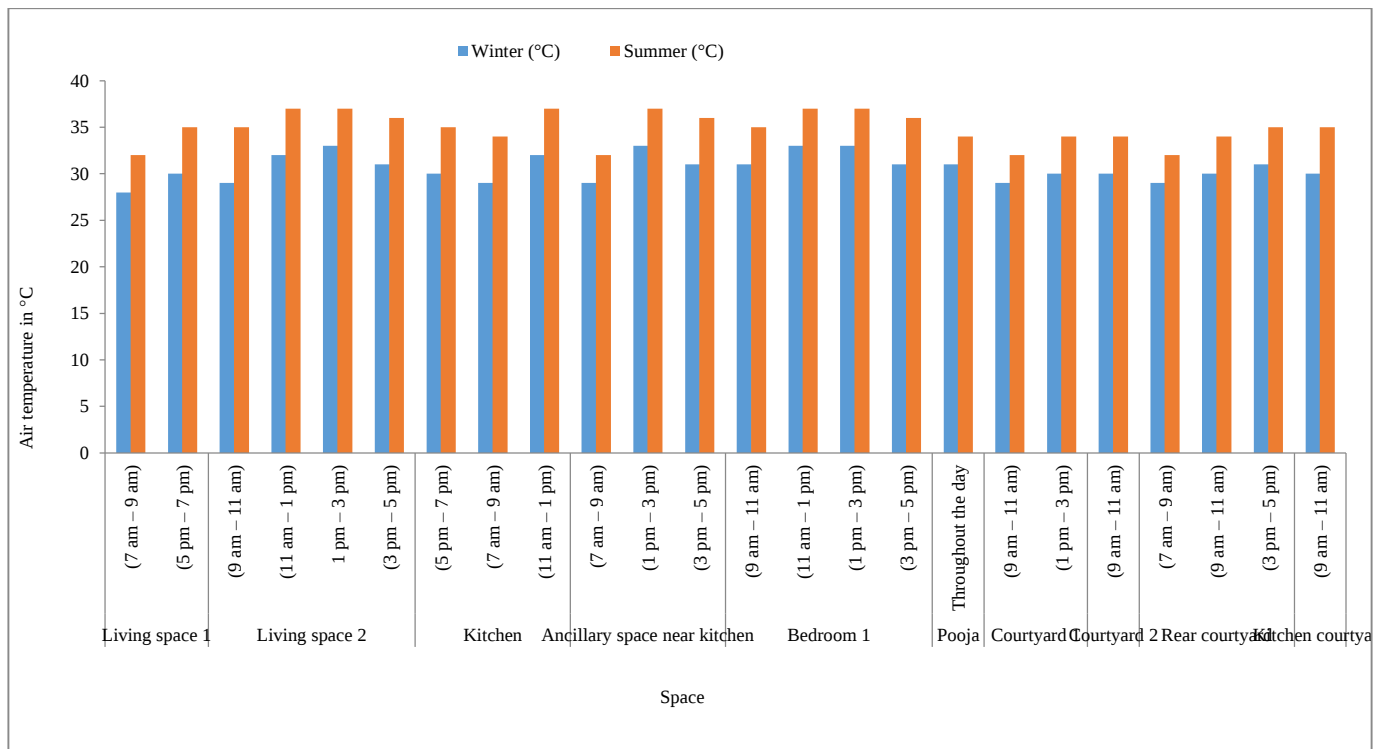
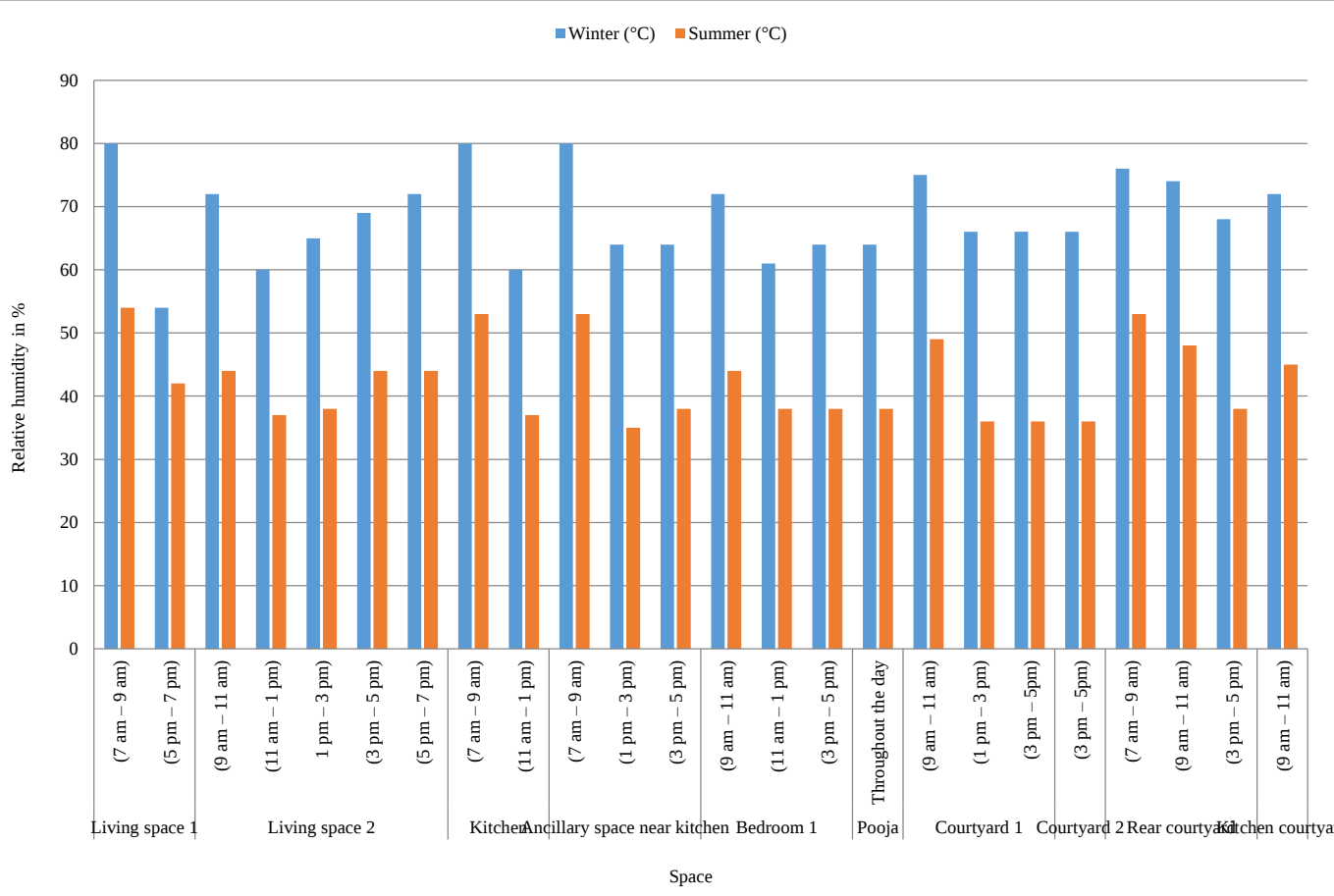


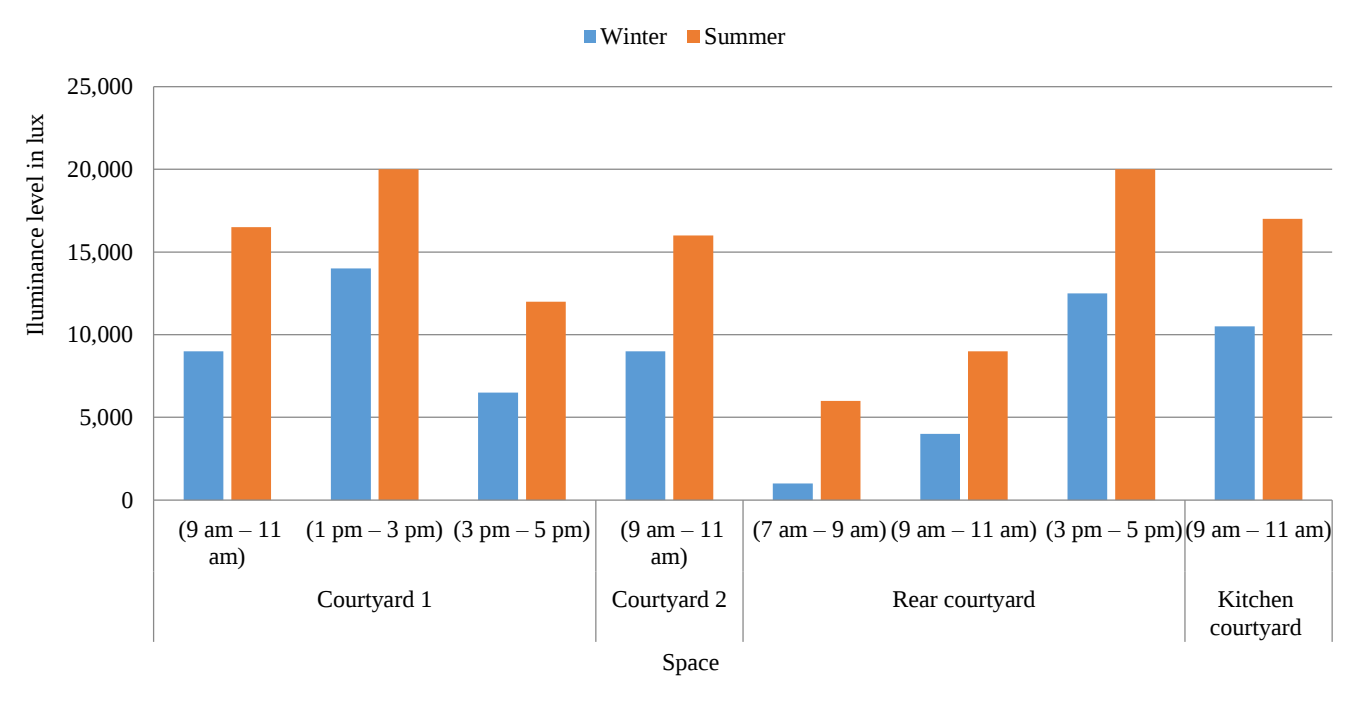
Fig. 4 Views of the courtyard and activity: (a) First courtyard, (b) Second courtyard, (c) Rear courtyard, and (d) Kitchen courtyard.



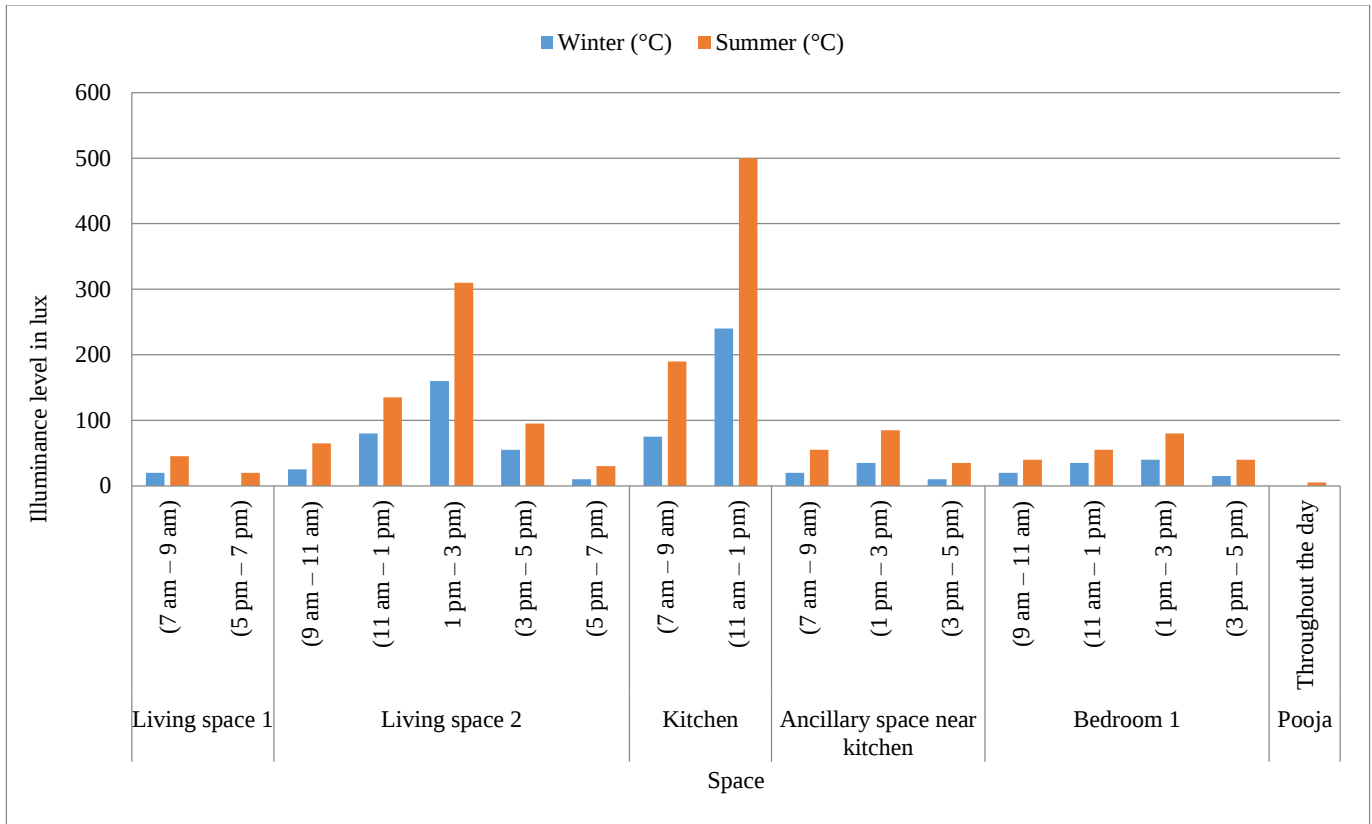
(a) Air temperature measurement



(b) Relative humidity measurements



(c) Illumination levels in courtyards



(d) Illumination levels in rooms
 Fig. 5 In Situ microclimatic observations within the dwelling

4.1.1. Residents' Perspective

The surrounding spaces of the first courtyard are found to be thermally comfortable by the residents throughout the day, during summer and winter. The living space of unit 2 is found to have a lower temperature. Often, a fan is required to maintain thermal comfort. An external light source is required during the day for spaces away from the courtyard, especially in unit 1, due to a minimal number of windows that face the street. At times, for private reasons, these windows are kept closed, which creates thermal discomfort. Since unit 1 is smaller in size as compared to unit 2, the resident felt that a larger space with its openings oriented to the courtyard would aid in better thermal conditions within the dwelling.

4.2. Analysis of Attributes within the Dwelling

4.2.1. Climatic Attributes

Courtyards adapt to changing microclimatic conditions and serve as a place to perform a lot of daily activities within vernacular dwellings. Residents' behavior is closely associated to the prevailing comfort conditions within the dwelling. Figure 5 shows the in-situ microclimatic observations recorded within the dwelling.

Figure 5 shows that during any activity, the average indoor temperature varies between 32 and 37°C in summer and 28 to 33°C in winter. The average indoor humidity varies

between 35% to 55% in summer and 54% to 81% in winter. Lower humidity can be found in the first, second, and rear courtyards compared to other living spaces within the dwelling. Wind speed is found to vary between 0 and 0.04 m/s. In most of the interior spaces, air conditioning still exists during the summer and winter seasons. The unusually low wind speed and still air experienced in the interior spaces (especially within rooms) are due to a lack of cross ventilation. Also, vegetation is absent from the entire neighborhood surrounding the selected house. This leads to poor air quality and an increase in temperature indoors.

However, air conditioners were not used by the residents, and they adapted to spaces in and around the courtyard for their daily routine. The living space of unit 1 and the living space of unit 2 lack sufficient illumination during early morning hours till 9 am and from late afternoons after 3 pm. Courtyards are a major source of illumination in these vernacular dwellings. The analysis of Tables 1 and 2 revealed that poor illumination levels existed throughout the day in the bedroom of Unit 1 and the living space of Unit 1, especially during winter.

Artificial lighting is needed to carry out daily activities in these spaces, as these spaces are located away from the courtyard. In unit 2, the living space, which is the primary

activity space, has ample illumination level, mainly due to the better microclimate that prevailed in the courtyard and surrounding spaces. Residents experience thermal discomfort in spaces away from the courtyard.

4.2.2. Spatial Attributes

The spatial use and pattern of the activities within the dwelling changed with the change in the ownership of the house. The form of the dwelling or courtyard was not transformed further in this dwelling. For the division of units between the family members, only a temporary solution was sought. A saree is used as a screen that divides the living spaces. Hence, there was no major change in the microclimatic conditions within the dwelling. The kitchen courtyard had a large water tank that traditionally catered to the needs of resident weavers. It was demolished later since the residents thought it was no longer needed for their use.

The form and size of the courtyard are major deciding factors in the behavior of the users. The living space of unit 2 has the largest area. It is the most used space in Unit 2. It is followed by the Living space of unit 1. All the spaces within

the house are Rectangular and compact in form. It is also observed that when the major living space is designed in proximity to the courtyard and oriented towards the same, better visual and thermal comfort is achieved. It also helps with carrying out the daily activities very efficiently within the dwelling. In unit 2, daytime activities in the front courtyard and its surrounding spaces are carried out as usual since there is no major transformation. Due to the division of units within the dwelling, in unit 1, the daytime activities are more confined to the internal space. This also happens due to reduced size, need for privacy and increased dependency on electrical and mechanical devices like light and fan for thermal and visual comfort. Enclosed spaces that are located away from the courtyard tend to affect the physical and mental well-being of the residents. Table 2 lists the spatial attributes of the dwelling. The openings of the living spaces are oriented either towards the courtyard spaces or the passage connecting the courtyard. The openings in the courtyard are on the east and west sides. Most of the spaces within the dwelling are semi-enclosed spaces. Enclosed spaces are very minimal in number. These enclosed spaces have their openings facing the street.

Table 2. Spatial attributes of the dwelling

S. No.	Space	Length (m)	Width (m)	Height (m)	Ratio (H/D)	Area (m ²)	Orientation	Openings	Enclosure type
1	Living space 1	4.19	4.57	3.65	0.8	19.14	N - S	Open to the passage connecting the first courtyard	Semi-enclosed
2	Living space 2	7.08	4.62	3.65	0.8	32.7	E - W	Open to the courtyard	Semi-enclosed
3	Kitchen	2.69	4.01	3.65	0.91	10.78	N - S	Open to the kitchen courtyard	Semi-enclosed
4	Ancillary space near the kitchen	5.84	2.71	3.65	1.34	15.82	E - W	Door – East side Opening – North side	Semi-enclosed
5	Bedroom 1	3.73	2.43	3.65	1.5	9.06	E - W	Door – North side	Enclosed
6	Pooja	2.13	2.43	3.65	1.5	5.17	N - S	Door – North side	Enclosed
7	Courtyard 1	5.63	2.05	2.28	1.1	11.54	E - W	Openings – East, West and South side	Semi-enclosed
8	Courtyard 2	3.65	2.05	2.28	1.1	7.48	E - W	Openings – East and West sides	Semi-enclosed
9	Rear courtyard	3.3	2.05	Open to the sky	Open to the sky	6.76	E - W	Openings – East and West sides	Open to the sky
10	Kitchen courtyard	3.27	2.33	Open to the sky	Open to the sky	7.61	E - W	Openings – East and South side	Open to the sky

4.3. Links between Climatic and Spatial Attributes

The residents use different spaces within the dwelling according to the comfortable microclimate and spatial requirements. The reduction in the size of unit 1 led to a reduction in the comfort of the users within the dwelling. The division of units led to a limited illumination level and air circulation from the first courtyard in the living space of unit 1. This is due to the fact that the windows in this space that face the street are kept closed for want of privacy.

Hence, it may be said that a change in the spatial attribute has led to a change in the microclimatic condition. This, in turn, led to a change in the behavior of the residents. To evaluate the relationship between the climatic and spatial attributes further, a statistical analysis was carried out using ArcGIS software. In this study, the spatial lag regression model was used. Primary data from Tables 1 and 2, along with Figure 5, were used to conduct the spatial regression analysis. Tables 3 to 10 show the numerical results of the spatial lag model.

Table 3. Temperature vs Spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Temperature	-0.50	0.36	-1.38	0.16
Constant	56.08	13.65	4.10	0.00
H/D Ratio	-0.04	0.02	-1.68	0.09
Area in m ²	0.00	0.001	3.20	0.00
Orientation	-0.03	0.03	-0.98	0.32
Enclosure	-0.06	0.03	-2.29	0.02
Openings	-0.04	0.01	-2.18	0.02

Table 4. Humidity vs Spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Humidity	-0.50	0.36	-1.38	0.16
Constant	56.08	13.65	4.10	0.00
H/D Ratio	-0.04	0.02	-1.68	0.09
Area in m ²	0.00	0.001	3.20	0.00
Orientation	-0.03	0.03	-0.98	0.32
Enclosure	-0.06	0.03	-2.29	0.02
Openings	-0.04	0.01	-2.18	0.02

Table 5. Illumination level vs. Spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Illumination level	-0.36	0.367	-1.00	0.31
Constant	655.93	3114.61	0.21	0.83
H/D Ratio	-9.37.58	1526.73	-0.61	0.53
Area in m ²	-316.15	104.41	-3.02	0.00
Orientation	5617.05	1778.9	3.15	0.00
Enclosure	9197.55	2624.45	3.50	0.00
Openings	1157.2	1141.75	1.01	0.31

Table 6. Wind vs Spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Wind	-0.68	0.38	-1.75	0.07
Constant	0.01	0.005	1.94	0.05
H/D Ratio	-0.002	0.002	-0.96	0.33
Area in m ²	0.0002	0.0001	1.48	0.13
Orientation	0.00	0.003	0.57	0.56
Enclosure	-0.01	0.003	-3.60	0.00
Openings	-0.0006	0.002	-0.29	0.76

Table 7. Male gender vs Spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Male	-0.45	0.39	-1.14	0.25
Constant	0.87	0.64	1.36	0.17
H/D Ratio	0.04	0.27	0.17	0.86
Area in m ²	-0.00	0.01	-0.19	0.84
Orientation	-0.42	0.31	-1.34	0.17
Enclosure	-0.41	0.33	-1.22	0.22
Openings	0.51	0.20	2.49	0.01

Table 8. Female gender vs. spatial attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Female	-0.16	0.31	-0.51	0.60
Constant	1.29	0.24	5.35	0.00
H/D Ratio	-0.15	0.10	-1.40	0.15
Area in m ²	0.00	0.00	0.06	0.95
Orientation	0.23	0.13	1.81	0.06
Enclosure	-0.70	0.14	-4.72	0.00
Openings	-0.38	0.08	-4.72	0.00

Table 9. Male gender vs Climatic attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Male	-0.37	0.39	-0.93	0.34
Constant	-823.63	405.64	-2.03	0.04
Temperature	25.20	12.19	2.06	0.03
Humidity	-1.36	0.59	-2.29	0.02
Light	-0.00	6.69	-2.64	0.00
Wind speed	-94.72	39.33	-2.40	0.01

Table 10. Female gender vs. Climatic attributes

Variable	Coefficient	Std. error	Z - Value	Probability
Female	0.00	0.20	0.00	0.99
Constant	-35.09	140.83	-0.24	0.80
Temperature	0.43	4.21	0.10	0.91
Humidity	0.25	0.20	1.26	0.20
Illumination level	7.45	2.30	3.24	0.00
Wind speed	-13.23	13.83	-0.95	0.33

From tables 3 to 10, it can be observed that temperature is significantly related to the considered parameters in the order of area, openings, enclosure, H/D ratio, and Orientation. Area is more significant than other factors. Temperature is directly proportional to Area. Temperature is inversely proportional to H/D Ratio, Openings, Orientation, and Enclosure. Humidity is significantly related to the parameters considered in the order of area, openings, enclosure, orientation, and H/D ratio. Area, Openings and Enclosure are more significant than other factors. Humidity is directly proportional to Area.

Humidity is inversely proportional to Orientation, Enclosure, H/D Ratio, and Openings. Light is significantly related to the parameters considered in the order of Enclosure, Orientation, Area, Openings, and H/D ratio. Enclosure, Orientation, and Area are more significant than other factors.

Illumination level is directly proportional to Enclosure, Openings, and Orientation. Illumination level is inversely proportional to H/D Ratio and Area. Wind is significantly related to the considered parameters in the order of enclosure, H/D Ratio, Orientation, and Openings. Enclosure is more significant than other factors. Wind speed is directly proportional to Orientation and Area. Wind speed is inversely proportional to Enclosure, Openings, and H/D Ratio.

Male gender, considering one male member in unit 2, is significantly related to the considered parameters in the order of illumination level, wind speed, humidity, and temperature. Light is more significant than other factors. Male presence is directly proportional to Temperature. Male presence is inversely proportional to Light, Wind and Humidity. Male gender is significantly related to the considered parameters in the order of Openings, Orientation, Enclosure, Area, and H/D

Ratio. Male presence is directly proportional to openings and the H/D ratio. Male presence is inversely proportional to Enclosure, Orientation, and Area. Female gender, considering 1 member each in unit 1 and unit 2, is significantly related to the considered parameters in the order of light, humidity, wind, and temperature. Light is more significant than other factors. Female presence is directly proportional to Light, Humidity, Temperature. Female presence is inversely proportional to Wind. Female gender is significantly related to the parameters considered in the order of Enclosure, Openings, Orientation, H/D Ratio, and Area.

4.4. Simulation Analysis using Design Builder

Based on the primary data collected from the in-situ study, DesignBuilder software is used to model the courtyard

residence. Figure 6 shows the simulated model of the residence. Table 11 shows the parameters considered for simulation. Simulation has been carried out under two conditions: the semi-open courtyard condition and the closed courtyard condition.

In the closed courtyard condition, the courtyard is covered with a glass curtain system. For the open roof, the model was built with a flat roof and an external hole was added to the flat roof. For the closed roof type, basic infiltration through the material, through the sides, and through the built type was considered. The flow network model was not used for natural ventilation. In both the courtyard conditions, the climatic effects during winter and summer are simulated.

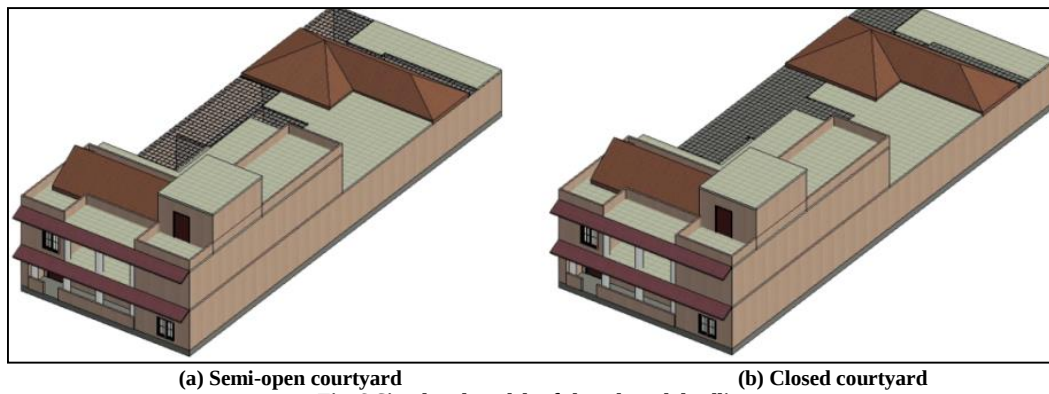


Fig. 6 Simulated models of the selected dwelling

Table 11. Simulation input parameters

Location	Kumbakonam (10°97' N, 79°38' E)
Building typology	Residential
Number of occupants	3 (Male – 1; Female – 2)
Outdoor temperature	26.4° C
Relative humidity	64%
Wind speed	2.5 m/s
Metabolic rate	1.0
Clothing thermal resistance	1.0
Wall material	350mm brick wall (external); (R-value: 0.50 m2 K/W) 175mm brick wall (internal) (R-value:0.20 m2 K/W)
Door and Window material	Wood (R-value: 0.8 W/m2 K)
Floor material	Plain cement concrete R-value: 0.47 m2 K/W)
Roof material	Part pitched roof with clay tiles (R-value: 0.15 m2 K/W) Part 200mm slab
Ventilation	Natural ventilation and mechanical ventilation(fans only), Air conditioning (HVAC) – No
Lighting control	No
Roof opening	90% for semi–open courtyard 5% for closed courtyard
Shading	0.5m overhang
Percentage of opening	40%

4.5. Comparison between in Situ and Simulated Data

The in-situ data measured during summer for the considered dwelling was taken as input into the DesignBuilder software to simulate the indoor air temperature (dry bulb) for all the courtyards and rooms within the dwelling. Figure 7 depicts the comparison between in situ data and simulated

data. From Figures 7(a) and 7(b), it is found that the average value of R-squared is 0.9. This shows the high level of correlation between the in-situ measurements and simulated measurements. This confirms that the model of the vernacular courtyard house is greatly reliable.

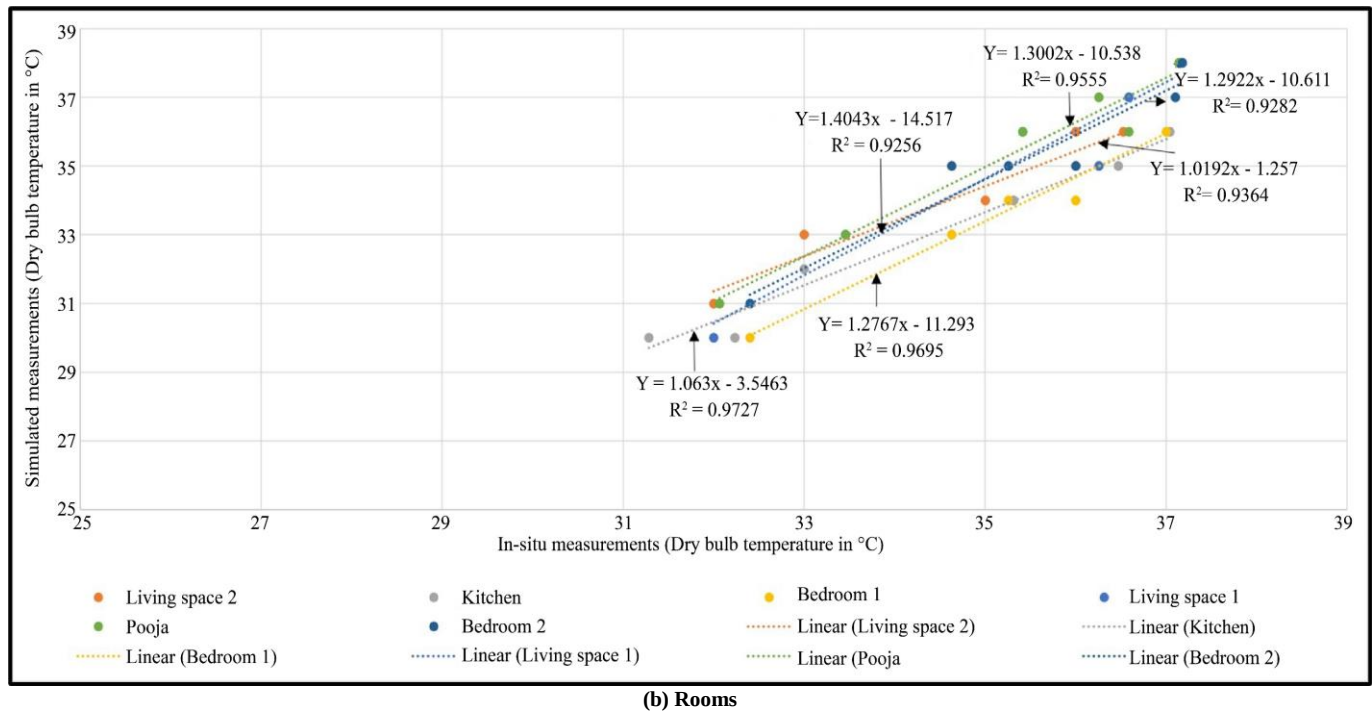
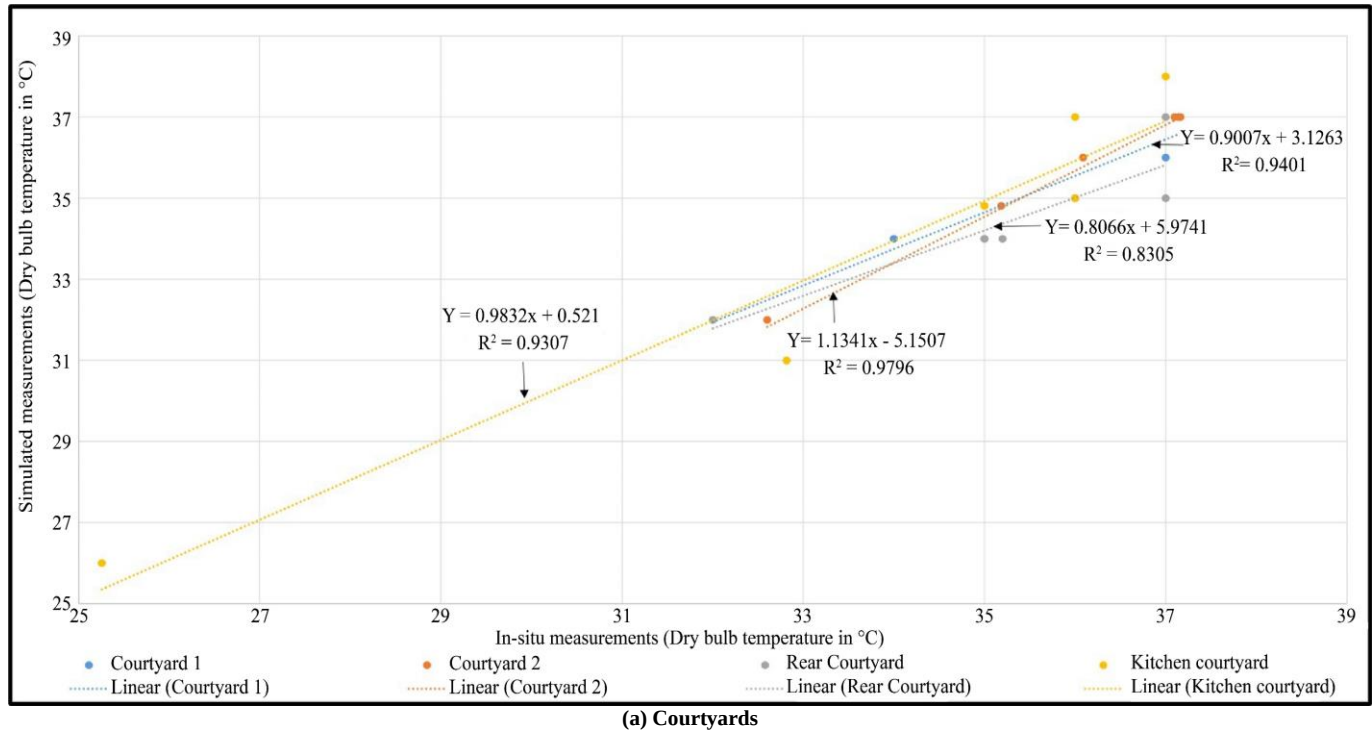


Fig. 7 Comparison between the measured and the simulated data within the dwelling

4.6. Analysis of the Temperature and Humidity Isoleths

To further understand the behavior of the courtyard and the internal spaces, with the average temperatures of the simulated semi-open courtyard and the simulated closed courtyard, temperature and humidity isopleths are derived

using ArcGIS software for both summer and winter seasons. Figures 8 and 9 depict the temperature and humidity isopleths for the summer season. Figures 10 and 11 depict the temperature and humidity isopleths for the winter season.

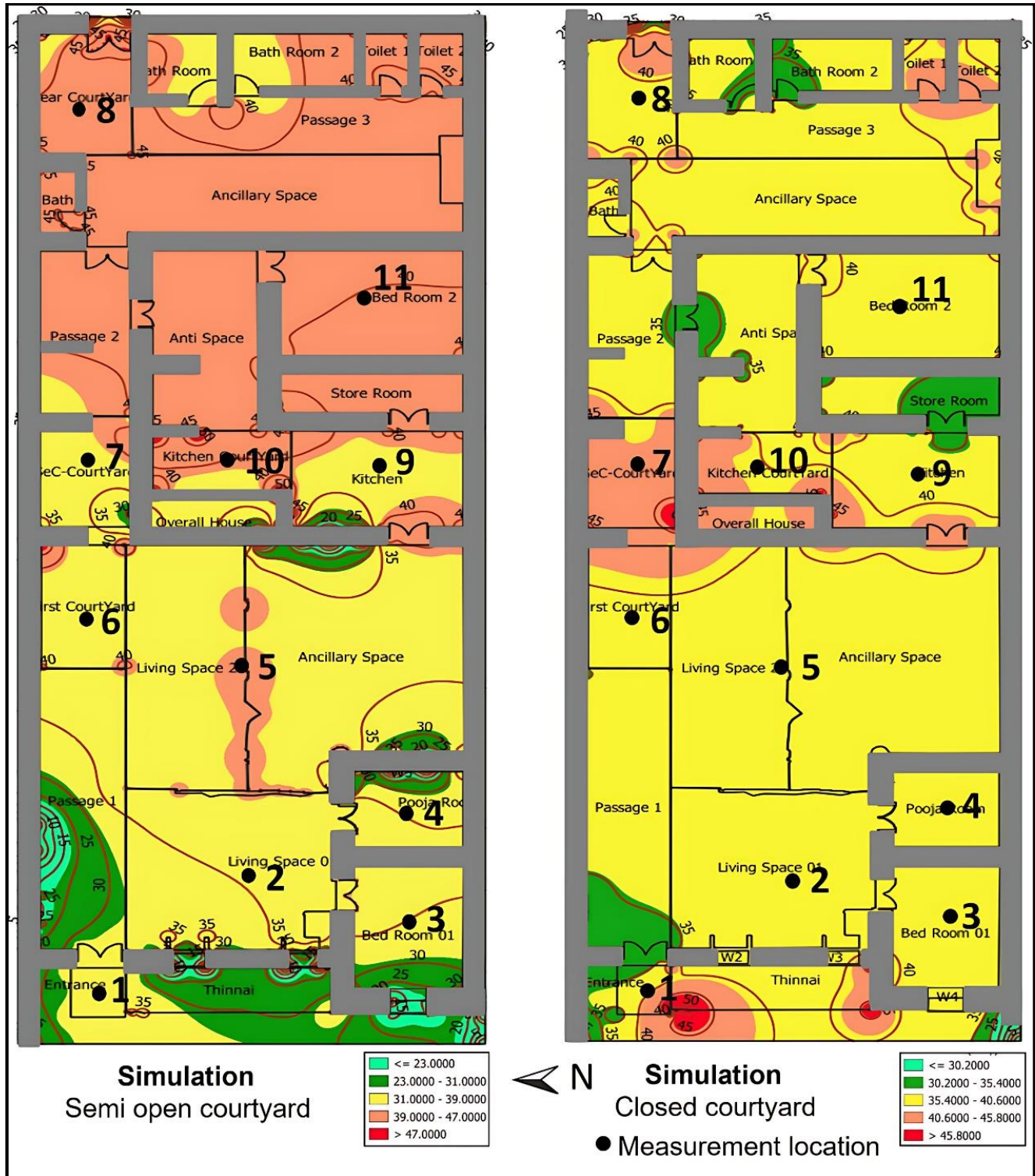


Fig. 8 Temperature isopleths within the dwelling during summer

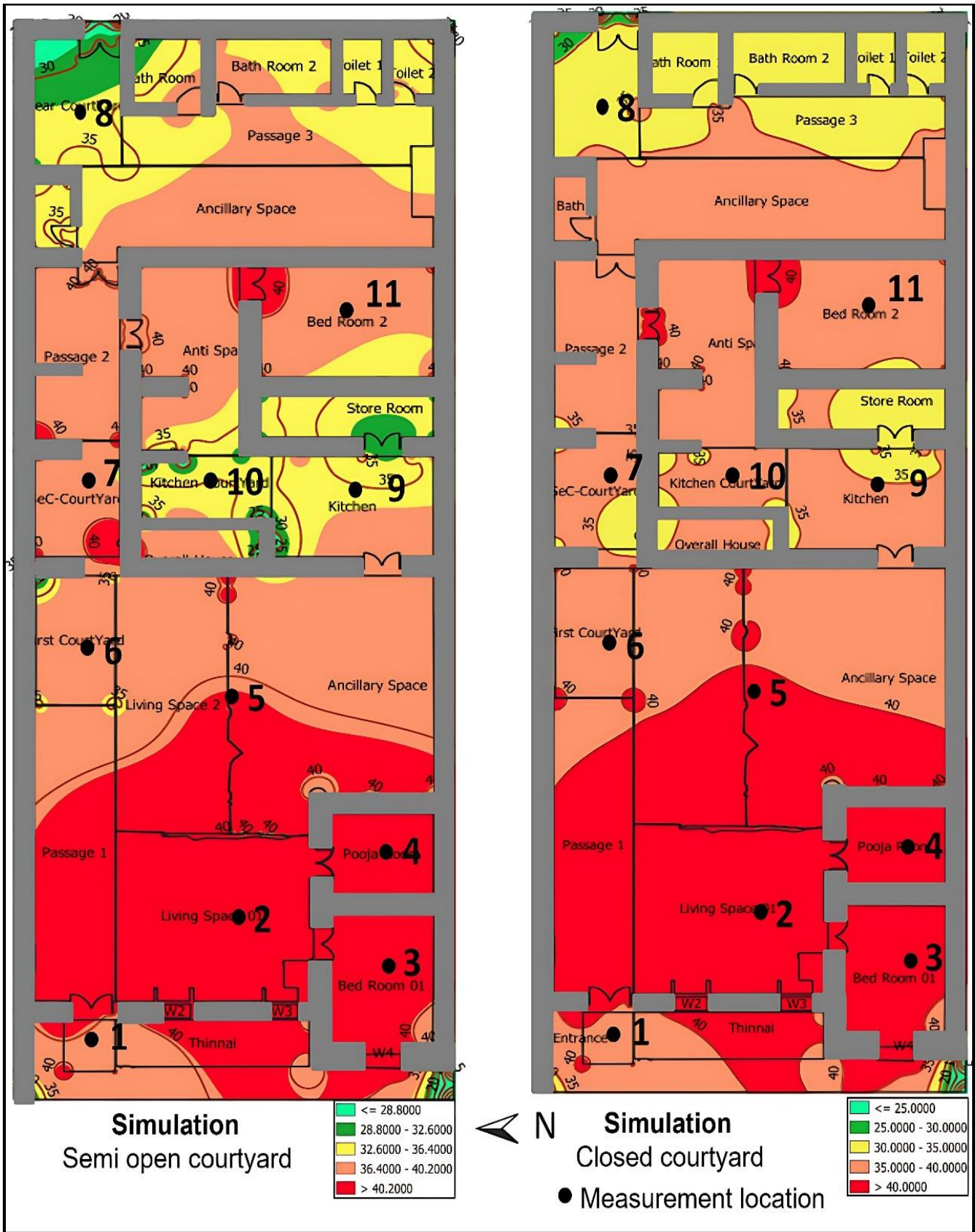


Fig. 9 Humidity isopleths within the dwelling during summer

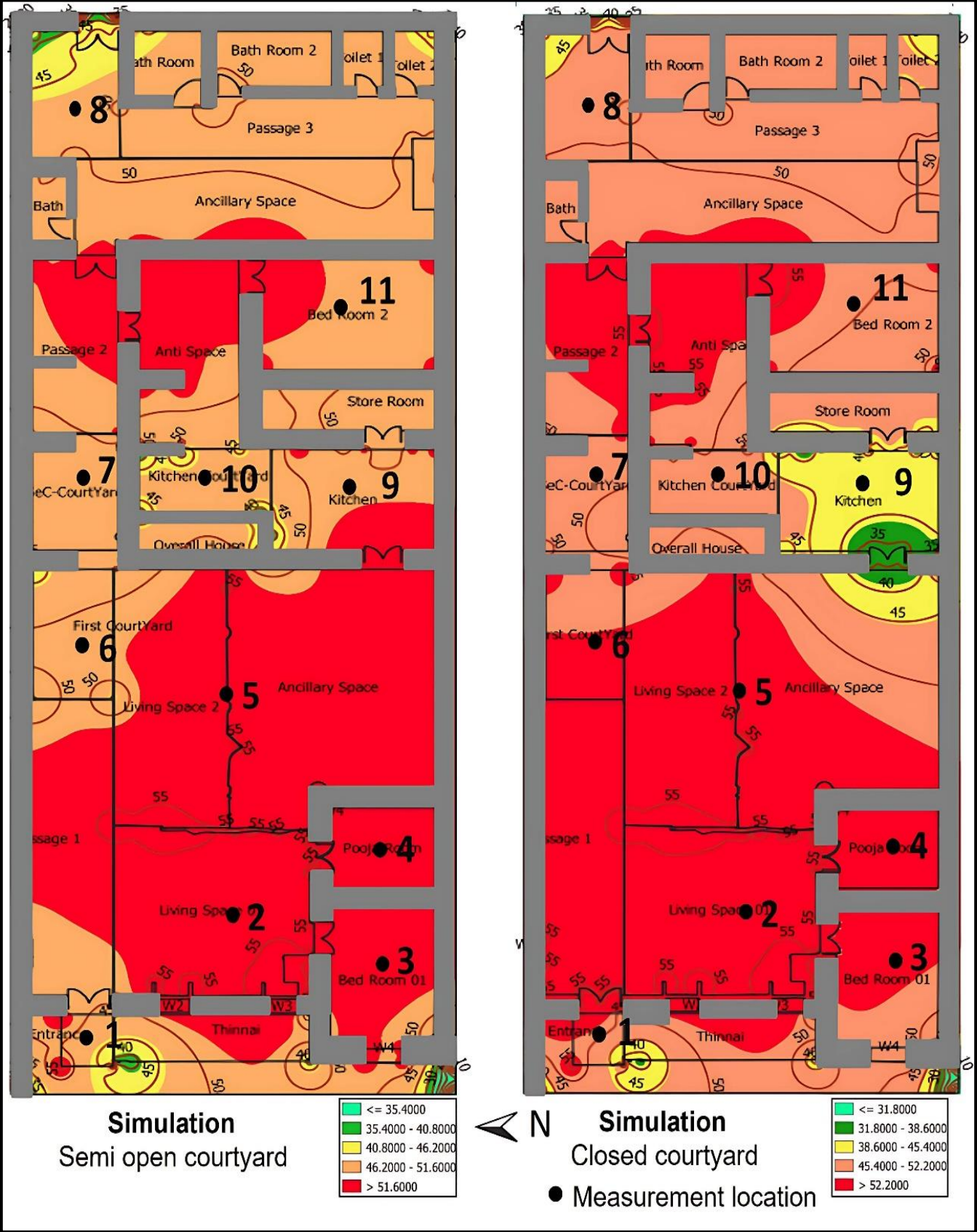


Fig. 11 Humidity isopleths within the dwelling during winter

Figures 8, 9, 10, and 11, the following results can be observed:

4.6.1. Isopleths during the Summer Season

During the summer season, in the simulated semi-open courtyard condition, the eastern part of the dwelling is found to have a very high temperature ranging between 39° C and 47° C and the western part of the dwelling is found to have a temperature ranging between 31° C and 39° C. During Summer, in semi-open courtyard conditions, a temperature ranging between 23°C and 31°C can be found in areas like the entrance, passage 1, thinnai and some parts of the bedroom and pooja. Major activity spaces like living spaces 1 and 2, First and second courtyard, ancillary space, some parts of passage 1 and kitchen are found to have a temperature ranging between 31°C and 39°C. Spaces like passage 2, anti-space, bedroom 2, storeroom, and kitchen courtyard experience a temperature ranging between 39°C and 47°C. In the closed courtyard condition, very few areas of entrance, passage 1 and storeroom are found to have a temperature between 30.2°C and 35.4°C. The majority of the spaces within the house are found to be in a higher temperature range between 35.4°C and 40.6°C. Areas like the second courtyard and some parts of the entrance are found to have temperatures greater than 45°C in summer under these conditions.

In the simulated semi-open courtyard condition and closed courtyard condition, more spaces that include passage 1, living space of unit 1, pooja room, bedroom of unit 1, some parts of the living space of unit 2 and ancillary space have humidity higher than 40.2%. The rear courtyard and kitchen courtyard have less humidity, ranging between 32.6% and 36.4%. The first courtyard, second courtyard, passage 2 and ancillary spaces have humidity levels ranging between 36.4% and 40.2%. During summer, in the simulated closed courtyard condition, most parts of the house are found to have a temperature ranging between 35.4° C and 40.6° C.

4.6.2. Isopleths during the Winter Season

During winter, in simulated semi-open courtyard conditions, the spaces on the western side of the house are found to be cooler with a temperature ranging between 24.4° C and 28.8° C. All the courtyards and their surrounding spaces are found to have temperatures ranging between 28.8° C and 33.2° C. It is observed that comparatively very few areas, especially spaces away from the courtyard, have a higher humidity of 51.6% and above. The courtyard and its surrounding spaces have a comparatively lower humidity range between 46.2% and 51.6% respectively.

During Winter, in semi-open courtyard conditions, most parts of the house, like living spaces 1 and 2, all the courtyards, kitchen, anti-space, bedroom 2, ancillary space and passage 3 have a temperature ranging between 28.8°C and 33.2°C. In the closed courtyard condition, the majority of the spaces, like passage 1, first courtyard, kitchen, passage 2, bedroom 2, anti-space and some parts of the rear courtyard, living space 1 and 2, bedroom and pooja, ancillary space, and kitchen courtyard, have a temperature ranging between 26.4°C and 29.6°C.

In simulated closed courtyard conditions, huge temperature variations are found between the interior spaces, with the temperature ranging between 23.2° C and 32.8° C. It is observed that a few parts of the interior spaces have a high humidity of 52.2%. All the courtyards are found to have a humidity range between 45.4% and 52.2%.

Out of the two courtyard conditions considered for the study, the semi-open courtyard model is found to have a comparatively lower temperature during summer. The semi-open courtyard model has a 4°C lower temperature than a closed courtyard model. During winter, the temperature difference between the two courtyard conditions was only 1°C. In a closed courtyard condition, all the internal courtyards are found to have a comparatively lower humidity range between 45.4% and 52.2%. During winter, the closed courtyard has 15.4% lower humidity when compared to the semi-open courtyard condition.

5. Findings and Discussion

This research focused on exploring the relevance and impact of the courtyard's climatic, spatial and behavioural aspects in a vernacular house. It was found that the courtyard, as an internal space, is still relevant in the present scenario. The highlight of this study is that the daily activities of the residents were recorded in detail with respect to both space and time. Furthermore, the microclimatic conditions and spatial characteristics of the activity spaces were assessed to identify the most used space within the house and the reason for such preference. The courtyard and its surrounding spaces were found to be primarily used for increased illumination levels when compared to other parts of the house. To understand the significance of the relation between the climatic and spatial attributes accurately, statistical analysis was carried out. The quality of the processed data was ensured at all stages of the research to achieve better results.

Additionally, a detailed comparative analysis of the simulated semi-open and closed courtyard models was carried out to conclude on the advantages of designing with courtyards in modern residences. It is believed that the unique findings of this research will aid engineers, architects, designers, and policy makers in rethinking the relevance of the implementation and use of courtyards in residential design. The implications of the findings of this research underscore the need to revive existing courtyards to cater to residents' changing needs and reinvent various ways to use courtyards efficiently. It highlights the need to improve thermal and spatial comfort to create resilient buildings.

6. Conclusion

This study evaluated the correlation between the climatic and spatial attributes within a vernacular house to enhance the thermal comfort of the occupants. It assessed the effect of a semi-open courtyard within the house. Statistical analysis was used to find the correlation between climatic and spatial attributes. Simulation was carried out using Design Builder to analyze the variation in the climatic attributes. Temperature and humidity isopleths were derived from ArcGIS software to

further understand the behavior of internal courtyards. From the statistical results, it is concluded that the area and openings of an internal space are significantly related to temperature and humidity values within the dwelling. The illumination level in a space is closely related to the degree of enclosure, openings and orientation of the space. The wind speed is primarily governed by the degree of enclosure of a space. Both male and female genders use a space with a higher illumination level for their daily activity. Results from Design Builder simulation and ArcGIS outputs reveal that the semi-open courtyard offers a reduced temperature of 4°C during summer compared to a closed courtyard. The procedure and data collected in this research can be extended to other similar vernacular structures in warm, humid climates to assess and understand the significance of the internal courtyard and its related attributes. In addition, in situ measurements can be recorded during nighttime wherever possible. From this research, it is evident that the semi-open courtyard helps in regulating the temperature efficiently within vernacular residences, especially during summer.

This research explored 4 courtyards, namely, the first courtyard, second courtyard, rear courtyard and kitchen courtyard. It analyzed the purpose of each of the courtyards and how they have been part of the everyday life of any Sourashtrian house, especially in Kumbakonam. Courtyards are rarely introduced in the design of modern houses. They can be integrated within residences by combining traditional

benefits with contemporary design. Instead of designing houses with multiple courtyards, a single courtyard having multiple uses can be designed, considering the space constraint in residences nowadays. Courtyards can connect indoors to outdoors, bring in natural light and airflow, give privacy and security, provide recreation and relaxation, and act as an exclusive family get-together space with an outdoor kitchen and dining in the home. It can act as a personalized outdoor space within homes to minimize the stress encountered in everyday life, especially in situations like the COVID-19 pandemic. It can cater to the needs of all age groups by being a peaceful retreat, promoting mental well-being. The courtyard's roof can be made flexible to be kept open or closed according to the requirements of the user. Green walls and living walls may be introduced as part of the courtyard for their numerous benefits. In addition, courtyards can be integrated into the whole house to collect rainwater and grey water, which can be reused. Low-maintenance and cost-effective techniques like permeable pavers, solar-powered lights, simple hard landscaping, rain gardens with native plants, and shade structures made of simple household items can be explored in the design of courtyards. Hence, by pondering these advantages, it is recommended that the semi-open courtyard be included in the design of modern residences to create a more sustainable and resilient built environment with improved thermal performance.

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