Passive Design Strategies and Thermal Performance of Vernacular Temples in the Warm-Humid Climatic Zone of South India

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Abstract

Religious beliefs, traditional wisdom, rituals, and cultural practices all play an important part in the protection of biodiversity and the environment. In fact, vernacular architecture of India has long demonstrated cultural ethics that contribute to the conservation of environment and the natural resources. The Indian Temple architecture is noteworthy and is a manifestation of these socio-cultural-environmental values, conceptualized and constructed in unique ways integrating passive features which keeps on educating and inspiring generations after generations. These timeless temples through their passive architectural elements and harmonic aesthetic qualities enable the communities to perceive themselves as part of a spiritual network and to connect them to their biophysical surroundings. Given this, this research explores the passive architectural features and thermal performance of the naturally ventilated south Indian Temples, located in warm and humid climate zones. It examines how these passive features can be implemented in the contemporary buildings to achieve thermal comfort.

The research employs a qualitative descriptive comparative method. It examines case studies of two temples located in Kerala, having a warm-humid climate, and investigates the passive architectural features and thermal performance. Data was collected through field visits to the two Temples: Iringole Kaavu Bhagavathy Temple (old) and Thottuva Temple (new). Environmental data was also collected during the field-surveys.

The study concludes that the adaptation of passive architectural features, in response to the local climatic conditions contribute immensely to improve the thermal performance of the structures and thermal comfort of the users. Hence, it is argued that the passive climate-responsive architectural features of the South Indian Temples, suitable to the local geoclimatic and cultural conditions, can continue to be followed in the present and future construction of buildings.

Keywords: Temple architecture, Passive techniques, Warm-humid climate, Architectural characteristics, Thermal performance, Air movement.

Introduction

From time immemorial, Indian Hindu Temples, located in hot and warm-humid regions, have been conceptualized, designed, and constructed to achieve comfortable indoor ambient conditions relying only on passive cooling via natural ventilation and use of suitable building envelope materials. However, due to the high moisture content in the air today, passive cooling design solutions are difficult to be implemented in warm-humid locations. For this reason, in warm-humid conditions, passive cooling systems need to be incorporated in the early stages of building-design while taking informed decisions regarding their siting, alignment, spatial zoning and planning, material-selection, fenestration design, ventilation, as well as effective facility planning and administration.

Many researchers have highlighted the salient architectural features of the South Indian temples and their architectural detailing (Brown, 1982; Hardy, 2001; Hardy, 2002; Grover, 2010; NCERT, 2024), such as the use of natural light to create a divine and holy ambience (Mukherji, 2001), measurements and proportion systems (Meister, 1985), and the use of iconography and symbolism (Cummings, 2014). In this connection, Noble (1981) and Freeman (1999) have discussed the significance of the Kerala temples in terms of their physical sitings, cultural and environmental settings, and their spatial, sculptural, and artistic organizations. All of these holistic qualities have culminated in the past into the creation of a timeless masterpieces and marvelous architecture. Nevertheless, no such study has been done producing any comparative assessment of the architectural features and thermal performance of the old and new Kerala Temples located in the warm-humid climate zone.

In this context, this research examines the passive design strategies used in the traditional temple architecture of Kerala. It’s intention is to find out, whether or not the temple architecture offer suitable passive strategies that can be incorporated in present day’s naturally ventilated buildings located in the warm-humid climatic zone of India. The scope of the study includes the exploration of the selected Kerala temples, that have retained the original design footprint, located in the warm-humid climatic zone. South Indian temples which are using complete and hybrid mechanical heating, ventilation, and air-conditioning (HVAC) systems are not investigated in this study.

Therefore, the aim of this study is to investigate the passive design strategies found in the traditional Kerala temple architecture and their thermal performance. In so doing, it intends to develop optimum architectural passive design strategies that can be incorporated in the naturally-ventilated buildings constructed in similar climatic zones today. The objectives of the study are as follows:

a) To identify the passive design strategies of naturally-ventilated temples in Kerala, India.
b) To assess the thermal performance and airflow characteristics of selected temples and
c) To propose passive design strategies suitable for the naturally conditioned buildings located in warm-humid climatic zone of India, based on the findings.

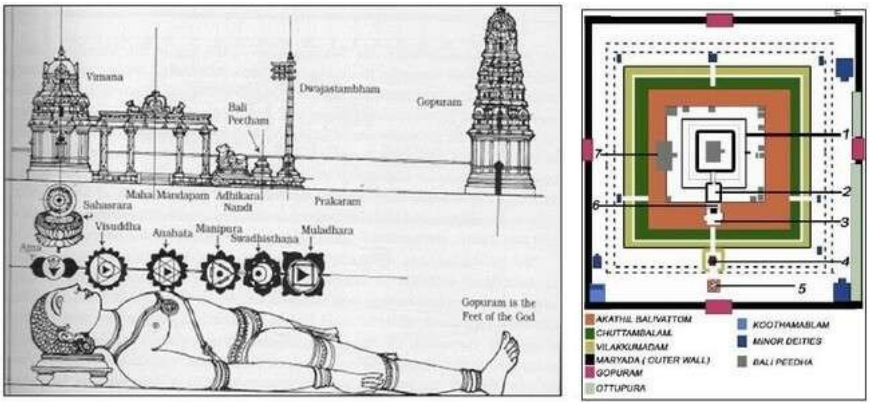
Historical Background

It is well known that Hindu Temples in India have evolved overtime. Early tribal communities have conceived the idea of God as an entity based on Nature and environment which could protect as well as destroy them. This thought has led them to worship elements of Nature such as Sun, Rain, Fire, Animals and Plants, etc. However, gradual evolutions have occurred in the modes of worship as time passed. Indeed, the society has had a slight shift towards spirituality, Indian mythology, and people, who attained divinity.

According to Oijevaar (2007), there is no written evidence regarding the origin of temples in Kerala. Even though it is believed that temples of Kerala have existed before the Christian era, records of temples date back to the 8th century onwards.

The survey of the Archeology Department of the Kerala government divides temples into three distinct phases of construction. They are Early Period (800-1000AD), Medieval Period (1001-1300AD), and Late Period (1301-1800AD).

According to Chaudhary (2017), temples in Kerala are not confined to the purpose of worship but have been centers of art, culture, and have also preserved a diverse responsibility towards Nature. Interestingly, these temples, like others, are designed based on the principles of 'Vaastu Purusha Mandala', based on five natural elements: water (Jal), air (Vaayu), fire (Agni), earth (Prithvi), and space (Vyom) as well as their positioning. This shows how the built environment (Temple) is designed and built in harmony with the surrounding natural environment. Fig. 1 shows the various components of the Temple architecture of Kerala.



(a) Hindu Temple and the structure symbolism of the human body
(b) General layout of a Kerala Temple

Fig. 1: Detailed components of Temples in Kerala
Source: https://journal.unpar.ac.id/

Temples of Kerala are classified into five different types as follows:
(1) Village temples ("Grama Kshetram") that exist in every village;
(2) A "Desa Kshetram" located in every "Desam" within a village;
(3) Family-owned temples, where a family deity is worshiped;
(4) Sacred groves ("Kaavu"); and
(5) Transplanted deity temples ("Kudiyiruthukal").

Kerala is located in the warm-humid climate zone of India ((NBC, 2016), characterized by high temperature and high humidity levels throughout the year due to their proximity to the equator and the sea-coast. This region also receives high annual rainfall which further increases the moisture content in the air and the corresponding humidity level, which is responsible for the thermal discomfort along with the intense solar radiation.

Theoretical Framework

Thermal comfort is a basic human need in order to be present in any environment to be engaged in any activity related to living and working. In fact, it the degree to which a person feels both physically and psychologically at rest in response to the temperature of the surrounding environment, that enables the person to be not disturbed by the temperature of the surrounding. Wong et al. (2020) argue that one of the most important passive features to maintain thermal comfort of an occupant is the utilization of natural ventilation, both wind and buoyancy driven, in the design of buildings located in hot and warm humid climate.

Passive architectural features are defined as those structural strategies which are employed in buildings to improve their thermal performance during extreme climatic conditions, by reducing heat gain in summer and heat loss in winter months, to keep them thermally comfortable by utilizing natural means only without using any mechanical system. According to Hyde (2008), Koenigsberger et al. (2013) BEEP (2016) and Kolokotsa, Yang and Pantazaras (2020), passive architectural strategies for buildings located in hot and warm humid climate are as follows:

(1) Avoiding direct sunlight and heat through (a) shading devices and projections to protect indoor areas from the direct sun, (b) low thermal mass to minimize heat storage, (c) minimum fenestrations due east and west facades;
(2) Maximize natural ventilation through (a) large openings on north/south facades, (b) open plans- spatial arrangement to aid cross-ventilation, (c) elevated construction to improve exposure to wind, (d) double banking of rooms to be avoided, (e) sufficient spacing of built units for fresh air and access, (f) whole house ventilation is enabled to dissipate indoor heat;
(3) Orientation in response to both wind and sun;
(4) Pitched roof to facilitate water drainage;
(5) Use of reflective roof, ventilated air space and insulated ceilings; and
(6) Use of courtyards and air-well to encourage ventilation and day light.

In fact, these theoretical ideas and principles have immense value in understanding the thermal comfort of a person in any setting.

Review of Literature

Many have examined the issue of thermal comfort emanating from both the natural environments and built-environments. For example, in terms of built-environments, and temple architecture in particular, Oijevaar (2007) and Kim (2014) argue that the principles of the Vaastu Sastra and Silpa Sastra have been followed in the design and construction of the holy Hindu Temples that have produced excellent levels of thermal comfort while also create a timeless eternal heavenly ambience in and around the temple complexes.

Pongomathi et al. (2021) enumerate the salient features of the south Indian Temple architecture highlighting the climate-responsive design features adopted in the Hindu Temple construction methods as per the geoclimatic locations utilizing natural daylight and ventilation. Similarly, Nguyen et al., (2011) and Beccali et al. (2018) emphasize the role of bioclimatic climate-responsive architectural design approaches found in the vernacular construction practices to maintain indoor thermal comfort conditions in hot and humid climatic condition. In contrast, Sreshthaputra et al. (2004) and Vella et al. (2021) have conducted field surveys to assess the thermal performance of the passive architectural features and comfort conditions found in the naturally ventilated religious architecture in different parts of the world. In fact, they have developed design guidelines for naturally ventilated buildings in the present-day context.

Research Methodology

The research employs case studies as a methodology within which a field-survey is conducted. Thus, it examines two Hindu Temples in Kerala: one ancient and another new, in order to conduct a comparative assessment of their passive architectural features and thermal performance. The old and the new temple are selected from the same geographic location: Perumbavoor, Ernakulam, Kerala. These case studies represent vernacular style south Indian temples located in Kerala and are naturally ventilated temples. They are selected on the basis of their architectural characteristics that represent the region.

The research investigates their passive architectural features and thermal performance to bring out their importance and relevance in present day architectural practices. It unravels the strategies employed in them to derive passive design strategies for present day naturally ventilated buildings located in the warm-humid climatic zone.

Data was collected through field-surveys of these two temples recording their architectural design characteristics, construction techniques including the materials used, passive design strategies, shading analysis, air-flow conditions, use of courtyards, and spatial arrangement. Further, measurements of environmental parameters were also carried out using calibrated scientific instruments to assess the thermal performance in terms of indoor thermal comfort. An unstructured thermal comfort perception survey was carried out during the visits to the temples with the 'pujaris' and the other visitors.

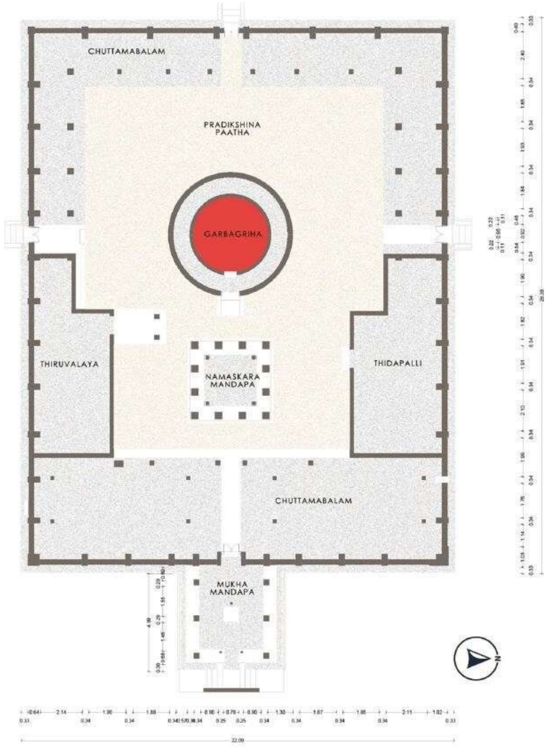
It employs a descriptive qualitative analysis, which ascertains whether there are any significant differences in the architectural design and construction of the new temples built during the last 15-20 years compared to the older temples constructed at least a century ago.

Introduction to Case Studies:
Description of the Study Area

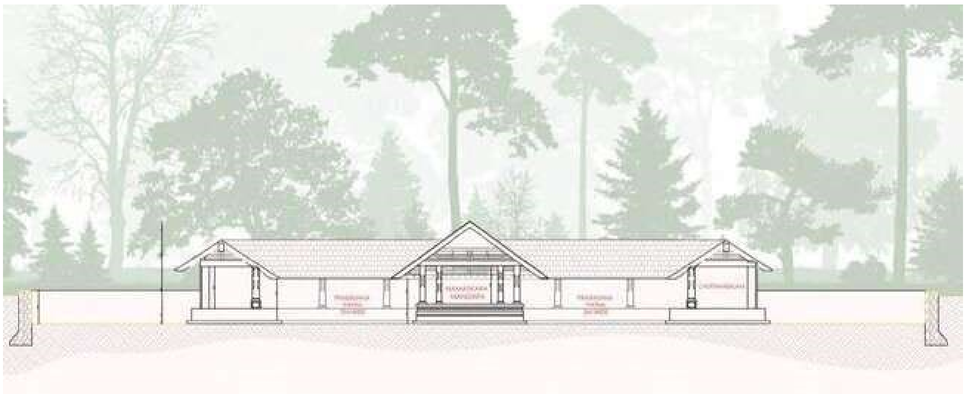
The study area is located in Kochi which is a cosmopolitan city in Kerala that has risen to prominence due to its spice riches. Two temples have been chosen for the study. Both are located in Perumbavoor, Ernakulam, Kerala. Since one of the research objectives is to study two temples in warm-humid climate at a particular location with vast age difference, the selection criteria of the Case study temples are: age difference, proximity, and construction style. Both the selected temples are Vimana style Dravidian temples with difference only in the shape of Garbagriha, where the shrine is kept.

Case Study 01: Architectural Details of the Old Temple - Iringole Kaavu

The architectural details of the selected old temple - Iringole Kaavu, in terms of plan, section, elevations, and view, are presented in the Fig. 3, which demonstrates the salient architectural details of this sacred temple. One of the main highlights of this temple is the presence of a circular shrine/ Garbagriha.



(a)



(b)

(c)

(d)

(e)

Fig. 3: Iringole Kaavu Temple - (a) Sardara Vimana - circular Dravida Kerala shrine plan; (b) Section through Garbagriha; (c) Front/ east elevation; (d) South elevation; (e) Perspective view - Source: Authors

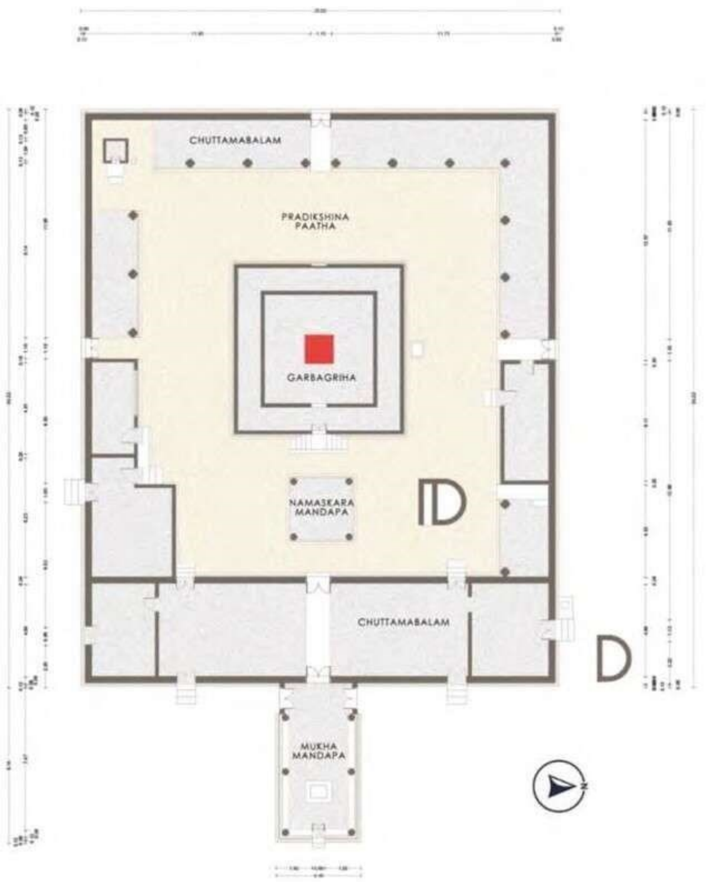
Case Study 02: Details of Selected New Temple – Thottuva Temple

Fig. 4: Views of selected Thottuva Temple
Source: Google Maps and Kerala Tourism

The selected new temple Thottuva Sree Dhanwanthari Moorthi temple (hereafter called Thottuva), is also located in Perumbavoor, Ernakulam, Kerala (10.17°N Lat., 76.49°E Long.). It is approximately 25 years old and has a built-up area of 497.09m^2 (Fig. 4). Thottuva temple is located one km. from the Thottuva junction in Koovapady panchayat of Ernakulam district, on the Perumbavoor- Kodanad highway. It is 15 km from the Cochin International Airport and the Angamaly Railway Station. A tiny creek runs along the southern flank of the temple and travels eastward. It is customary to bathe in this brook before entering the temple for Darshan.

Architectural Details of the New Temple - Thottuva temple

The architectural details of the selected new temple - Thottuva temple, in terms of plan, section, elevations, and view are presented in the Fig. 5 which shows the spatial arrangement.



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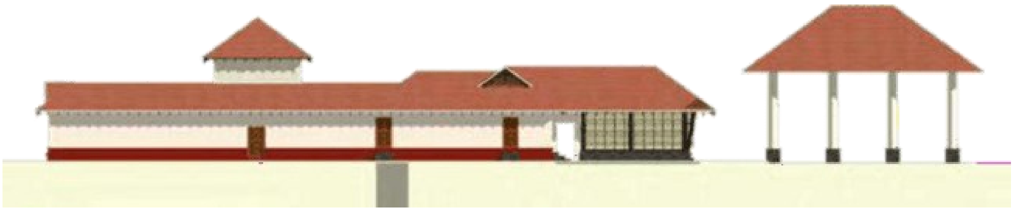
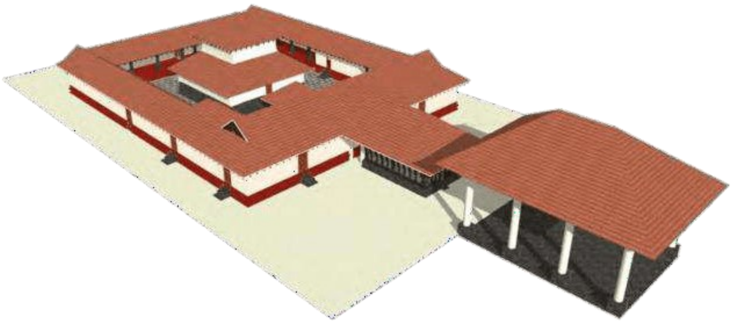


(c)



(d)

Fig. 5: Thottuva Temple - (a) Dwithala Vimana - square Dravida Kerala shrine plan; (b) Front / east elevation; (c) South elevation; (d) Perspective view
Source: Authors

Climatic Data of Kochi

Kochi experiences warm-humid climate (NBC, 2016). As per the climatic data (IMD, 2022), the annual average dry-bulb temperature is 28ºC; the average maximum air temperatures are between 31°C – 35ºC and the average minimum air temperature is 20ºC – 25ºC; the diurnal temperature range is approximately 7°C – 11ºC; the annual average relative humidity (RH) value is 74%, with a maximum range of 90 - 94% during humid monsoon periods and minimum range of 53 - 70% during cooler months; the annual average precipitation is approximately 3000 - 3200 mm. During the winter months, the wind blows maximum from the North-East, and in the summer months, the wind blows maximum from the South-West.

Thermal Performance Measurements

To assess the thermal performance of the selected old and new temples, on-field measurements are taken during the field visits about the environmental parameters such as indoor air temperature (dry-bulb and wet-bulb temperatures), RH, and air-flow, as well as reference outdoor air temperature, RH, air-flow and wind-direction. For measurements of dry- bulb temperature and RH digital thermo-hygrometer instrument is used; wet-bulb temperature is measured with hand- held sling psychrometer; air-flow and wind-direction are measured with a digital handheld anemometer. RH is also calculated using a psychrometric chart, using the on-field data regarding dry-bulb and wet-bulb temperatures.

For both the selected old and new temples, environmental data of two days in the summer month of March, 2022 from morning 7.00am to evening 7.00pm has been measured and recorded. The findings are presented and discussed in the following sections.

Findings
Passive Design Strategies
Case Study 01: Iringole Kaavu Temple (Old Temple)

(a) Site selection

The temple is placed at the center of a conserved forest, at the highest contour at the particular location of around 1.6 km in radius and has public roads of about 0.8 to 1.2 km from the temple. The trees around are from 50 to 70 meters in height and are pretty thick and most age more than the temple itself, so that it is creating a microclimate inside itself. Due to the presence of this thick forest cover around, the wind movements recorded on field was pretty less (Fig. 6).

It has been observed during the field visits that, as there is a significant wind movement above the trees, the air of the temple complex moves up, creating a positive pressure zone and leaving a low-pressure zone on the lower level, thus reducing temperature within the temple significantly about 4 to 5 degrees Celsius than the actual temperature on the particular location on that particular day, and creating a microclimate within.

Fig. 6: Site plan - Iringole Kaavu Temple
Source: Authors

(b) Orientation

The old temple is oriented along east to west where its front is facing east (Fig. 7.a). It is found from the literature survey and field-observation that, every temple built in Kerala Dravidian style is oriented towards cardinal directions, with respect to 'Vaastu'. All temples built in the style of Dravidian Kerala shrines are built similarly. In this temple, where lamps are used as major light-source, it is necessary to make use of natural daylight. In order to let the daylight in the Garbagriha during morning, which doesn't have any fenestrations other than only the door opening to the front, the orientation is done to face east. Hence, the idols are placed on higher pedestals on the western side facing east so that the idol's face is lit by the eastern sun. The resultant shining and sparkling effect change diurnally and temporally creating a spiritual ambience inside the temple to enchant the visitors to perform their holistic rituals.

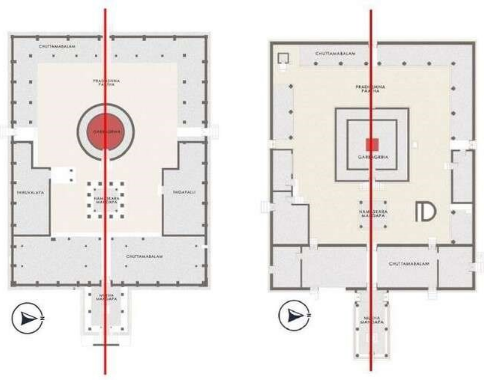


Fig. 7: Temple orientation (a) Iringole Kaavu, (b) Thottuva Temple
Source: Authors

(c) Shape and Form

The old temple is rectangular in shape with 1:1.2 ratio between its north-south and east- west sides, almost forming a square, which is considered to be ideal after circular form in terms of reducing heat-gain during hot months. The Iringole Kaavu - the old temple follows 'Sardara Vimana shrine', which meant to be circular in shape (Fig. 8.a).

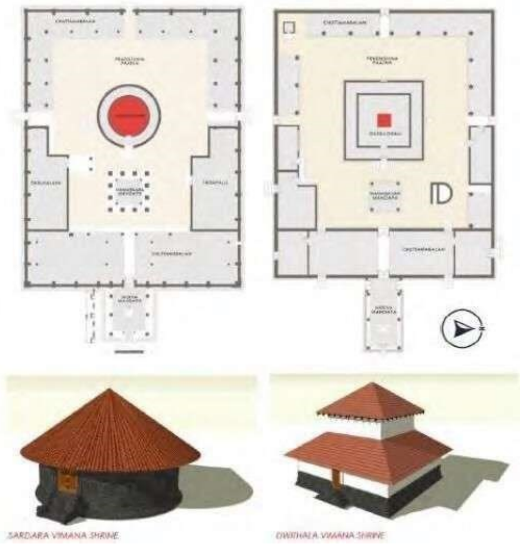


Fig. 8: Shrine types and forms (a) Iringole Kaavu, (b) Thottuva Temple
Source: Authors

But as the shrine is a standalone structure within, it gets direct radiation as it is placed in the center of the courtyard. The shrine also lacks proper ventilation, as the only opening is the front door. Also, there are many oil-lamps being used inside the shrine, which further increase the temperature inside the shrine/Garbagriha when lighted.

The old temple has the shrine or Garbagriha in circular shape, which is considered as the most efficient built form in terms of reducing radiation intake (Fig. 8.a). The temple shrine is constructed with double walls as a passive design strategy, which also helps in reducing heat gain from direct solar radiation (Fig. 8.a). Even though these strategies help in reduction of direct solar heat gain, the heat generated within the Garbagriha from the lamps as well as the occupants/ pujaris' bodies, still need solution within. Upon interviewing, the pujaris of the temple have mentioned about the hotness within the Garbagriha.

As the temple plan is semi-open, there is no point in considering the surface-to-volume (S/V) ratio of the particular structure. Also, as the climate is warm-humid, it needs breathing spaces within the structure by designing and spreading the surface area optimally. In terms of perimeter/area (P/A) ratio, for the old Iringole Kaavu, P/A = 0.16, which signifies its compact design to prevent heat gains.

(d) Construction Materials

The character of local resources and available materials typically affect the shape of the structures created by the vernacular builders who employ all their wisdom vigorously to make the structure respond to the socio-cultural-economic-environmental need as well as resilient enough to withstand the test of time. Kerala architecture developed a hybrid method of building as a result of material limitations.

According to the field visits, stone work is up to the plinth; walls are of laterite; and tiles cover the timber roof framework. The calculated physical and thermal properties of the construction materials used in the selected old temple are shown in the table-1.

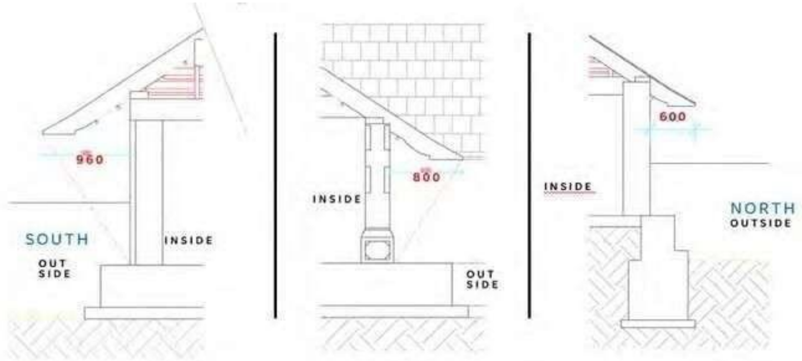
Table 1: Properties of Construction Materials - Iringole Kaavu Temple
Source: Authors as per BIS, 1978; Koenigsberger et al., 2013

		Physical Properties		Thermal Properties			
Elements	**Material**	**Dimension (mm)**	**Density (Kg/m^3)**	**Specific heat (kJ/kgK)**	**Conductivity (W/mK)**	**U-value (W/m^2K)**	**Time-lag (hours)**
Foundation	Granite	-	2961	0.76	1.6	-	-
External walls	Laterite	250	1778.5	0.49	1.07	2.3	5.8
	Lime plaster	25mm on outside and inside	1646	0.88	0.73		
Internal walls	Laterite	150	1778.5	0.49	1.07	3.02	4.1
	Lime plaster	18mm on outside and inside	1646	0.88	0.73		
Roof	Wood (teak, jackfruit, rosewood) rafters and purlins	150mm thick rafters and 500mm thick purlins	720	1.68	0.144	2.01	2.5
	Mangalore tiles	400 x 250	1220	0.92	0.71		
	Copper shingles	100 x 150	8930	0.38	2.01	-	-
Flooring	Oxide (black ochre, red ochre)	17	-	-	-	-	-
	Granite paving	60	2691	0.76	1.6	-	-
Pillars	Teak wood	300 x 300	720	1.68	0.144	-	-
	Granite	380 x 380	2691	0.76	1.6	-	-
Windows and doors shutters	Teak wood	30	720	1.68	0.144	2.8	-

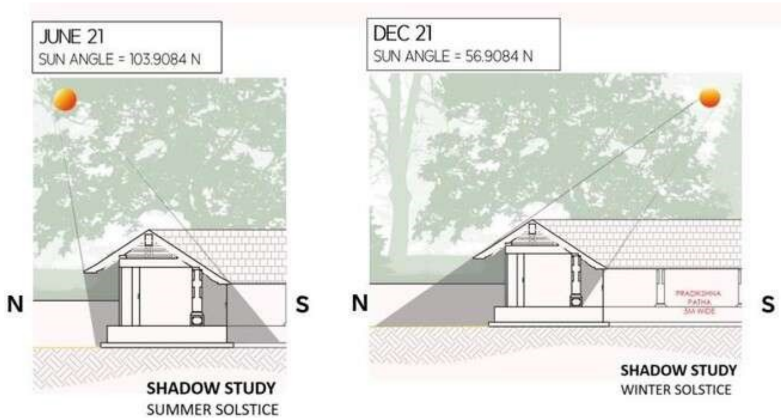
(a) Shading Analysis

As per the data collected from the field-surveys, the temple is occupied from morning 05:00 to 11:30 am and between 04:30 to 07:15 pm during evenings. Other than this during the annual festivals the temple is occupied during the whole day for almost 2 weeks. For the old temple, it happens during the summer, usually from the third week of March. Hence, shading strategies play a vital role to keep the building interior and exterior surfaces cooler to create comfortable indoor and outdoor conditions for the devotees.

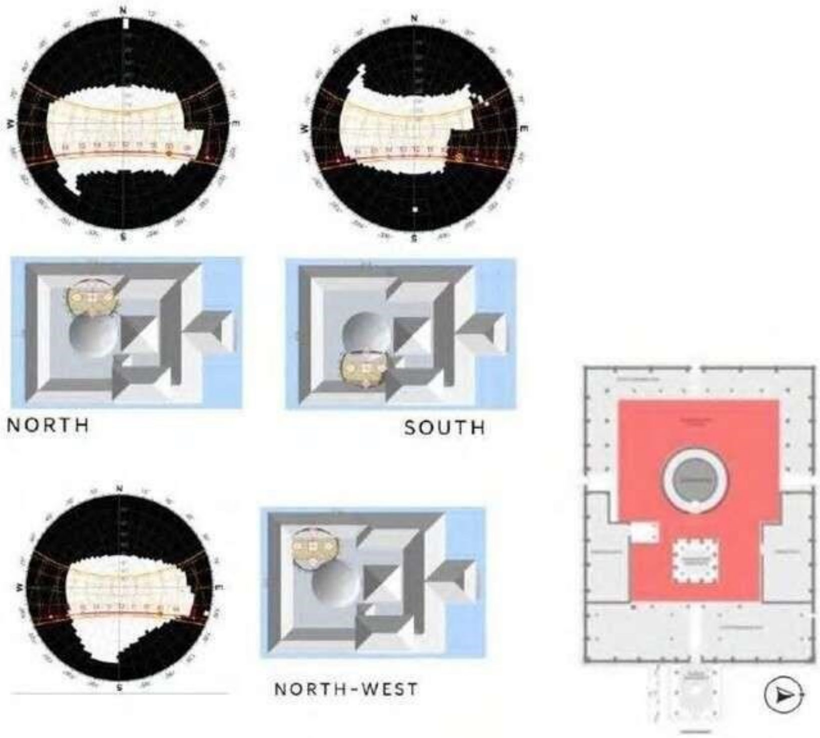
It is observed that the old temple employs sensible shading strategies at different directions with respect to sun angles, where it covers the walls from being exposed to direct solar radiation as well as rain (Fig. 9.a and Fig. 9.b). The analysis of shading mask for the old temple is shown in Fig. 9.c. The results show good coverage of the external wall surfaces, verandahs, and indoor spaces in the temple through the design of shading devices in the form of roof-projections. Although, the shadow analysis shows that the open-to-sky courtyards of the temple are unprotected against the solar radiation during the sufficient length of the days, especially noon-time throughout the whole year, which can cause overheating due to the effect of sol-air temperature. Hence, temporary shading of the open spaces is required for the thermal comfort of the visitors and devotees without obstructing the air-flow.



(a) Varying chajja shading angles in the old temple - Iringole Kaavu



(b) Shadow study and sunshade, Iringole Kaavu



(c) Shading mask of Iringole Kaavu courtyard

Fig. 9: Details of shading strategies and shading mask for the old temple
Source: Authors

It was reported by the pujaris of the temple during field-visit that the granite stone paving was installed in the old temple recently in the year 2016. The shadow angle studies show that the courtyards of the temple are exposed to direct solar radiation almost throughout the whole year, on major parts of the day. Upon interviewing, the pujari of the old temple has explained briefly about the temperature change experienced upon installing the granite-paving, which is on the higher side. Hence, extensive hard-paving should be avoided and more soft- paving need to be incorporated in the design of the open spaces for outdoor thermal comfort.

(e) Air-flow and Ventilation Analysis

It is found from the field-observation that the forest cover around the old temple is thick and high, and so there is no significant movement of air at lower sections of the temple campus. So, even during the field-measurement, the maximum air-speed in the campus recorded is 0.4m/s. Due to this lack of air movement, there isn't any significant effect on ventilation in the old temple. But the wind moving above over the 50-70m high trees creates a negative pressure zone above and so the hot air inside rises up, which reduces the heat (Fig. 10.a).

In terms of openings, the old temple lacks windows, but does have doors on all cardinal directions to allow natural ventilation and daylight to the interior spaces.

Most of the rooms are placed towards the eastern side of the temple in order to get sunlight directly during the working hours in the morning (Fig. 3.a). The designers and builders have avoided placing any rooms on the western side, which will actually be warmer during the late evenings. According to Vaastu, even in residential buildings, the most preferable buildings will face east as to let in sunlight during mornings. The 'Thirvalaya', considered as the temple kitchen, is placed on the south-east corner according to Vaastu, with provision for natural ventilation to send the smoke out (Fig. 10.b).

(a) (b)

Fig. 10: (a) Air movement due to the pressure difference created in the forest near old temple, (b) Stack ventilation in kitchen, Iringole Kaavu – the old temple
Source: Authors

Case Study 02: Thottuva Danwanthari Temple (New Temple)

(a) Site selection

The temple is placed on flat land but is placed according to the particular branch of river Periyar taking a turn on the southeast corner of the temple. So, the temple is placed with minimal displacement after offset from the river turn, in order to maximize the intake of potential wind generating at that particular water body pivot.

On seeing the wind pattern, analyzed on-field by anemometer also, it is quite clear that the wind from that particular south-east corner is greatly washing through the interiors as well as exteriors of the temple and is creating a unique microclimate for the temple and thus greatly influencing the ventilation within the structure (Fig. 11).

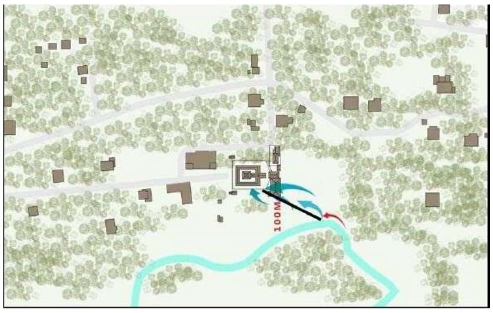


Fig. 11: Site plan - Thottuva Temple
Source: Authors

(b) Orientation

Like the old temple, the new temple is also oriented along east-west axis where its front is facing east (Fig. 7.b), following the principles of 'Vaastu'. Hence, the idols are placed on higher pedestals on the western side facing east so that the idol's face is lit by the eastern sun, entering to the Garbagriha through the door opening.

(c) Shape and Form

The temple is rectangle in shape with 1:1.2 ratio between its north-south and east-west sides, almost forming a square. The new Thottuva temple follows 'Dwithala Vimana shrine', which is of square shape (Fig. 8.b). The new temple has used an attic double height space above the square shrine, which also has a wooden ceiling placed within it, in order to reduce the direct radiation (Fig. 8.b).

The new temple shrine also uses double walls as a passive design strategy, which also helps in reducing heat gain from direct solar radiation (Fig. 8.b). In terms of perimeter/area (P/A) ratio, for the new Thottuva temple, P/A = 0.14, which is less than the value for the old temple and is helping in reducing the heat gain due to its compactness.

(d) Construction Materials

The calculated physical and thermal properties of the construction materials, which are found appropriate for the local climatic conditions, used in the selected new temple is presented in table-2.

Table 2: Material properties - Thottuva Dhanwanthari temple
Source: Authors as per BIS, 1978; Koenigsberger et al., 2013

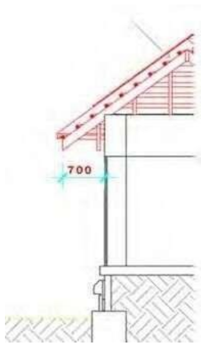
		Physical Properties		Thermal Properties			
Elements	**Material**	**Dimension (mm)**	**Density (Kg/m^3)**	**Specific heat (kJ/kgK)**	**Conductivity (W/mK)**	**U-value (W/m^2K)**	**Time-lag (hours)**
Foundation	Granite	-	2961	0.76	1.6	-	-
External walls	Laterite	300	1778.5	0.49	1.07	2.1	5.8
	Cement plaster	25mm on outside and inside	2162	0.87	1.9		
Internal walls	Laterite	150	1778.5	0.49	1.07	3.02	4.1
	Cement plaster	12mm on outside and inside	2162	0.87	1.9		

Roof	Wood (teak, jackfruit, rosewood) rafters and purlins	150mm thick rafters and 500mm thick purlins	720	1.68	0.144	2.01	2.5
	Mangalore tiles	400 x 250	1220	0.92	0.71		
Flooring	Oxide (black ochre, red ochre)	17	-	-	-	-	-
	Granite paving	60	2691	0.76	1.6	-	-
Pillars	Granite	380 x 380	2691	0.76	1.6	-	-
Windows and doors shutters	Teak wood	30	720	1.68	0.144	2.8	-

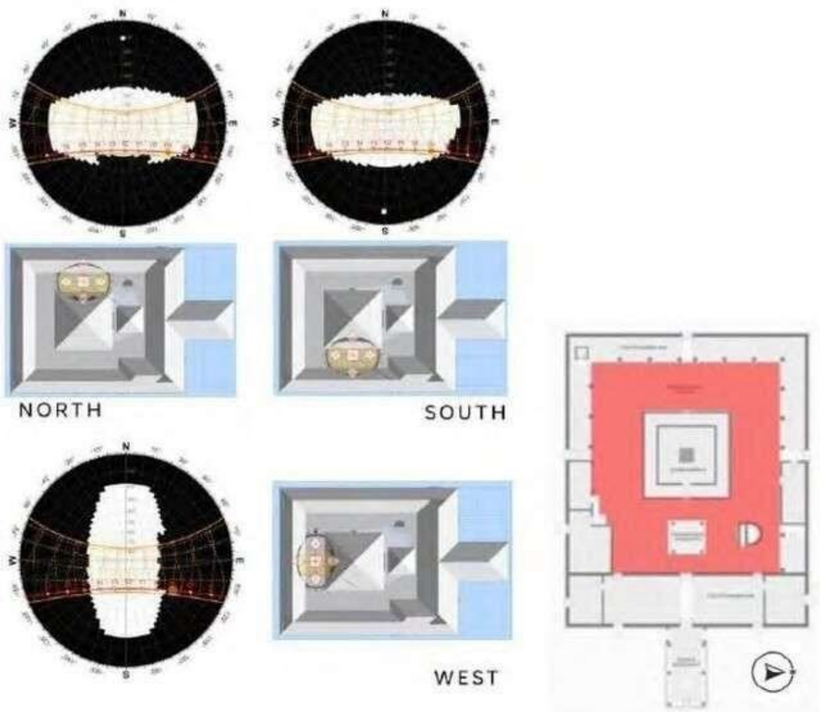
(a) Shading Analysis

Like the old temple, the new temple is also occupied from morning 05:00 to 11:30am and between 04:30 to 07:15pm during evenings. Other than this during the annual festivals the temple is occupied during the whole day for almost 2 weeks. This festival happens for the new temple in winter, from third week of December. Additional to this annual festival, the new temple celebrates another festival called, 'Dasavathara', during the third week of November, for 10 days, when too the temple is occupied throughout with almost more than 50 times of normal visitors in number. Hence, in all case scenarios shading strategies play a vital role to keep the building interior and exterior surfaces cooler to create comfortable indoor and outdoor conditions for the devotees.

The new temple follows uniform shading projection of 700mm from the vertical walls at all directions (Fig. 12.a). The analysis of shading mask for the new temple is shown in Fig. 12.b. The result shows good coverage of the external wall surfaces, verandahs, and indoor spaces in the temple through the design of shading devices in the form of roof-projections. Although, similar to the old temple, the shadow analysis shows that the open-to-sky courtyards of the new temple is unprotected against the solar radiation during the sufficient length of the days, especially noon-time, throughout the whole year which can cause overheating due to the effect of sol-air temperature.



(a) Uniform Chajja projection in the new Thottuva temple



(b) Shading mask of the Thottuva temple courtyard
Fig. 12: Details of shading strategies and shading masks of the selected temples
Source: Authors

(e) Air-flow and Ventilation Analysis

In case of the new temple, it is observed during site visits that the ventilation pattern is pretty much contrasting with the air-flow pattern observed in the selected old temple as the temple's air-changes per hour (ACH) is influenced by the turn taken by the river on south-east corner, which is pretty good. The courtyard does helps collecting the hot air from the rooms and spaces around.

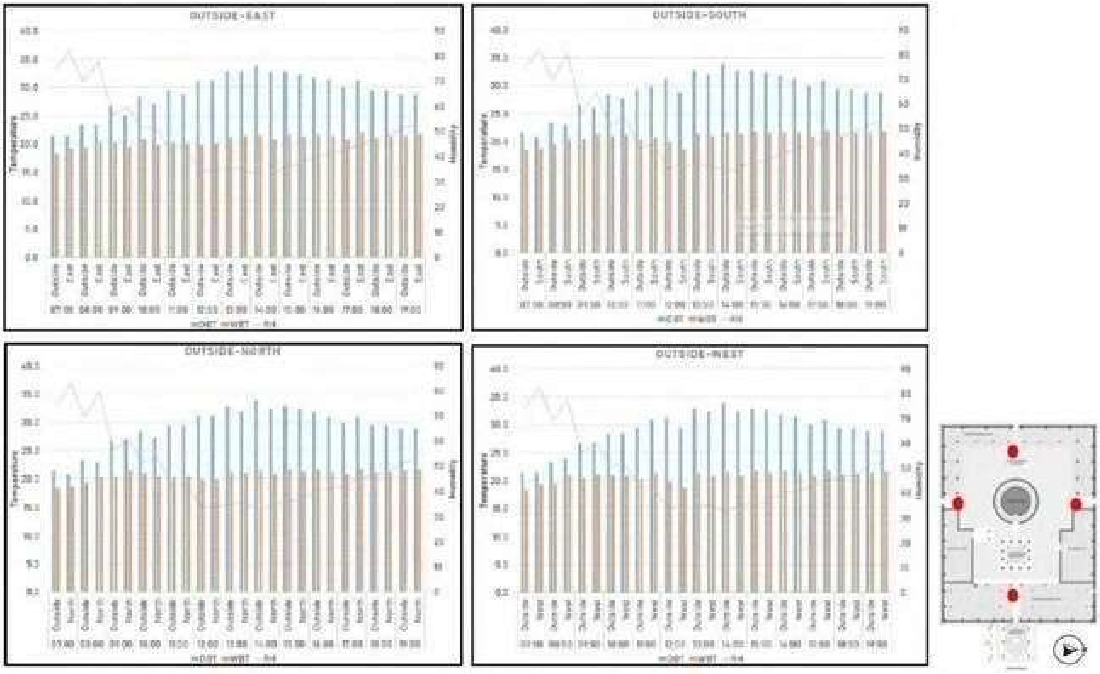
In terms of openings, the new temple also lacks windows, but does have doors on all cardinal directions to allow natural ventilation and daylight inside the spaces. The new temple has additional doors on its east end rooms, used as an exit from each room.

Thermal Performance

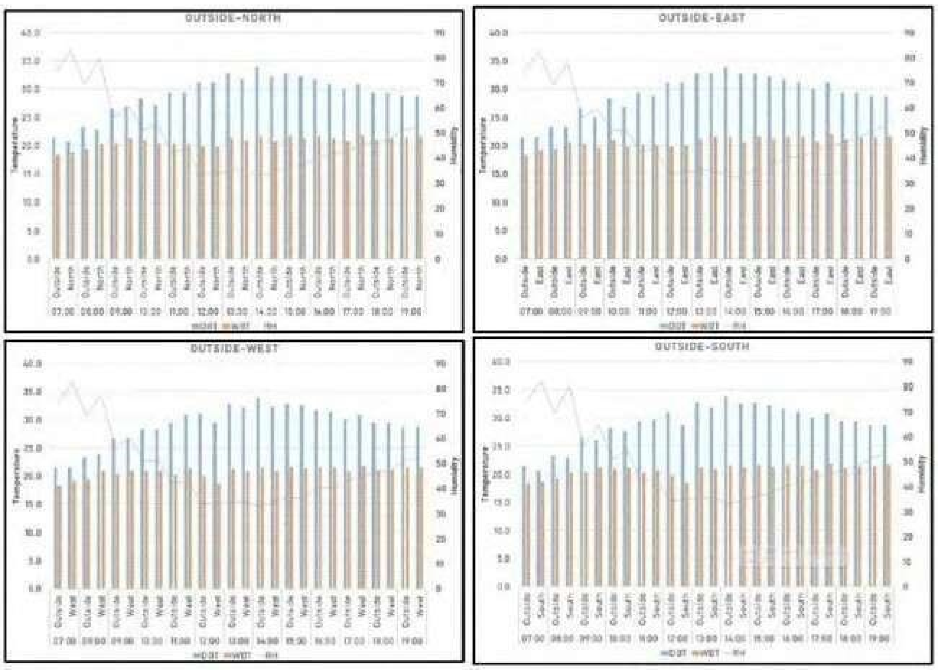
From the on-site measurements information are collected from both the old temple and the new temple regarding the environmental parameters such as outdoor temperature, indoor dry-bulb temperature, wet-bulb temperature, RH, wind speed, and wind direction during the hot summer month of March, 2022. The temperature readings during the hot summer month of March show that the indoor spaces are mostly comfortable and acceptable throughout the days. Due to resource constraints information could not be collected for the other seasons and months in the present study, which may be done in future studies. The findings from the analysis of on- field measurement data are discussed in following sections.

Iringole Kaavu Bhagavathy Temple (Old Temple)

Regarding the old temple complex, it can be seen from Fig. 10 that during the survey-days in March between morning 7.00am to evening 7.00pm, the outside temperature range isn 21.7ºC – 28.6ºC with maximum of 32.6ºC during 1.00 - 3.00pm; inside temperature range is 21.7ºC – 28.6ºC with maximum of 32.5ºC during 2.00 - 3.00pm, with RH values ranging between 35% (during day and noon time) to 81% (during early morning time); indoor air velocity is varying between 0 – 0.6m/s. The indoor thermal environment is mostly comfortable as per the standards (NBC, 2016) and acceptable by the users.



(a) Day 01 - Graphs of on-field environmental data, Iringole Kaavu (old temple)

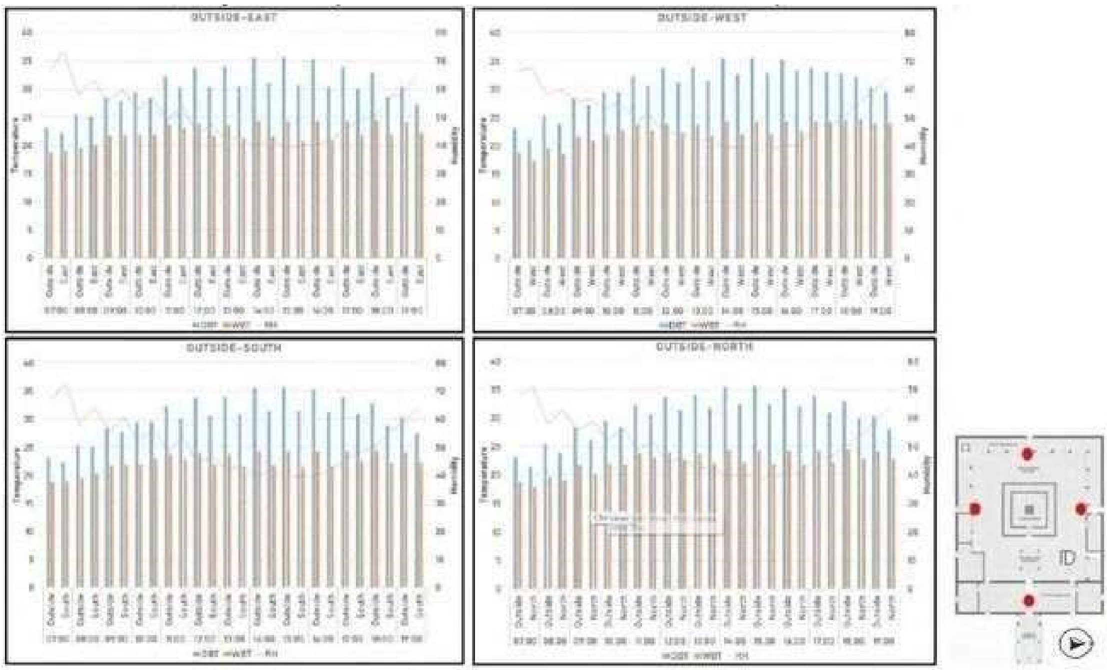


(b) Day 02 - Graphs of on-field environmental data, Iringole Kaavu (old temple)

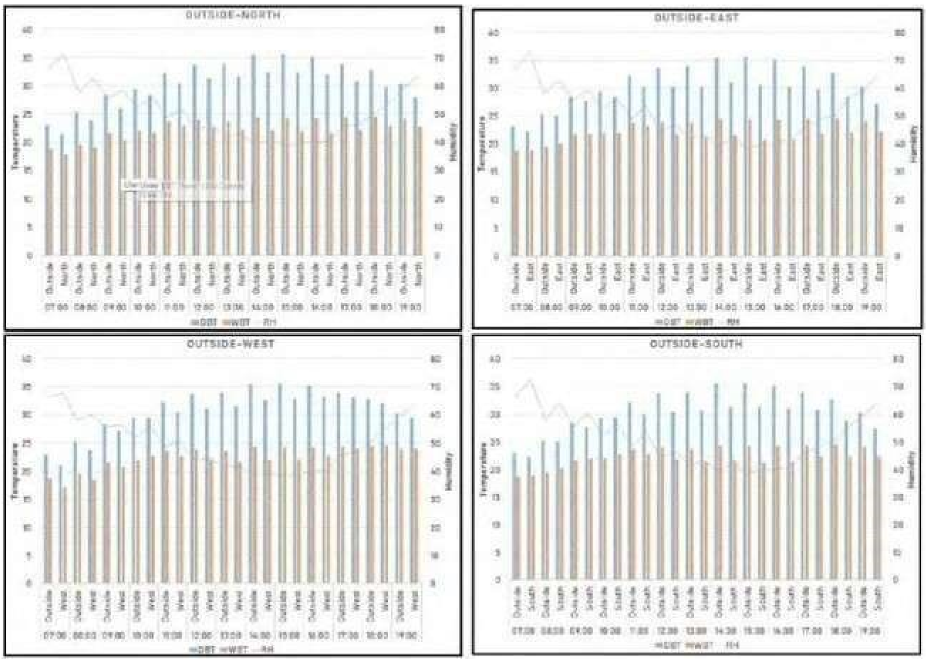
Fig. 13: Graphs of on-field environmental data of the old Temple Source: Authors

Thottuva Danwanthari Temple (New Temple)

It can be seen from Fig. 14 that during the survey- days in March between morning 7.00am to evening 7.00pm, the outside temperature range is 22.8°C – 30.1°C with maximum of 35.4°C during 1.00 - 4.00pm; inside temperature range is 21.4°C – 29.2°C with maximum of 32.7°C during 2.00 - 5.00pm, with RH values ranging between 38% (during day and noon time) to 70% (during early morning time); indoor air velocity is varying between 0 – 1.6m/s. This shows that the indoor thermal performance of the new temple, constructed recently following the principles of Vaastu Sastra and Silpa Sastra by using similar construction materials, is comfortable as per the standards (NBC, 2016) and reported satisfactory by the users. Indoor air velocity is more in the new temple due to the variation in site conditions.



(a) Day 01 - Graphs of on-field environmental data, Thottuva temple (new)



(a) Day 02 - Graphs of on-field environmental data, Thottuva temple (new)

Fig. 14: Graphs of on-field environmental data of the new temple

Source: Authors

Impact of Internal Courtyards – in both the Temples

It is observed during the field-surveys that the large open courtyards and shaded verandahs played a positive role in both the old and new temples, acting as 'microclimate modifiers' suitable for warm-humid climates, to achieve passive cooling for the internal and external spaces. The courtyards have formed better microclimate than surrounding open regions, by creating positive impact in elevating the enclosing building volume's internal comfort conditions. A pool of relatively cool air is preserved in the courtyard because the cool air is heavier than the surrounding hot air. During day-time, the top layer of air in the courtyard warms up and becomes lighter, forcing the air to rise (Fig. 10.a). As a result, a low pressure develops in the courtyard, causing air to flow in from the outside and into the surrounding areas.

In addition to thermal induction, the interior courtyards have also aided in the induction of air movement through the pressure effect in the case of high-velocity external wind blowing over the structure. The wind movement lowers the pressure in the air column's top layer, creating a suction effect over the little courtyard. This causes an upward movement in the courtyard's top layer of air, drawing air towards the court through the surrounding areas, resulting in air circulation in those places.

Spatial Planning - in both the Temples

It can be seen from Fig. 3.a and Fig. 5.a, that most of the rooms are placed towards the eastern side in both the old and new temples in order to get sunlight directly during the working hours in the morning. The designers and builders avoided placing any rooms on the western side, which can become warmer and uncomfortable during the late evenings, as a response to local hot and warm-humid climatic conditions. The 'Thirvalaya', considered as the temple kitchen, is placed on the south-east corner according to Vaastu.

Comparative Analysis of Old and New Temples

Based on the results of the analysis from the field-survey data presented above, the passive design strategies for buildings located in warm-humid climatic zone are presented in table-3, derived from the comparative analysis of the old and new naturally ventilated temples located in the similar climatic zone.

Table 3: Passive design strategies from the analysis of the selected naturally ventilated temples
Source: Authors

Parameters	**Iringole Kaavu (The old temple)**	**Thottuva Temple (The new temple)**	**Inferences - Passive design strategies**
Site Selection	Placed at the center of the forest, at the highest contour at the particular location of around 1 mile in radius.	Placed on flat land with minimum displacement to the particular branch of river Periyar taking a turn on the Southeast corner of the temple.	Site should be selected with respect to what the site surroundings offer, so that it's maximum potential can be utilized.
Orientation	Oriented east to west where its front facing east, with respect to Vaastu, to make maximum use of morning sun.	Oriented East to West where its front facing the East, with respect to Vaastu, to make maximum use of morning sun.	Orientation according to local climatic condition maximizes the use of daylight during morning occupied hours and rooms are protected from direct west radiation during evenings.
Shape and Form	Garbagriha in circular shape, which is considered as the most efficient built form in terms of radiation intake.	Attic double height space above the square Garbagriha, which also have a wooden ceiling placed within it, in order to reduce the direct radiation.	Both square or circular forms are efficient if they are designed and constructed judiciously to reduce the heat gain.
Materials	250mm laterite walls with 25mm lime plaster on either side, Mangalore tiles over wooden truss, oxide flooring and granite foundation.	300mm laterite walls with 25mm cement plaster on either side, Mangalore tiles over wooden truss, oxide flooring and granite foundation.	Similar optimum contemporary materials can be selected which will be performing good in terms of providing thermal comfort.
Shading	Sensible shading angles at different directions with	Same shading angles at all directions. Courtyard paving	Sensible shading angles at different directions with

	respect to sun angles. Courtyard paving is exposed to direct radiation.	is exposed to direct radiation.	respect to sun angles to be designed. Avoiding paving or shading it properly can reduce temperature inside and can create cooling effect.
Ventilation	Due to this lack of air movement, there isn't any significance of ventilation in the old temple. Use of double height stack ventilator.	Ventilation (ACH) is influenced by the turn taken by the river on south-east corner, which is pretty good.	Use of courtyards and stack ventilators can effectively reduce the temperature inside, utilizing the prevailing wind direction.
Spatial Planning	Most rooms are placed on the east wings of the temple, facing east to let in early morning sun wash its interiors.	Most rooms are placed on the east wings of the temple, facing east to let in early morning sun wash its interiors.	The planning according to local climatic conditions make maximum use of morning sun and also reduces the intake of evening solar radiation.
Thermal Performance	The temperature readings from two days on the hottest month shows the indoor spaces are comfortable throughout the day.	The temperature readings from two days on the hottest month shows the indoor spaces are comfortable throughout the day.	Building with respect to local climatic conditions and traditional wisdom, regarding dimension and proportion system, in the architectural projects create comfortable indoor spaces with none to minimum use of mechanical means.

Discussion

Findings have shown that the south Indian Kerala Temple architecture, in case of both Iringole Kaavu Bhagavathy Temple (old) and Thottuva Temple (new), has deployed many time-tested passive strategies in terms of their site-selections, orientations, shapes and forms, building component construction materials, shading techniques, use of daylight, utilization of natural ventilation processes for passive cooling, design of courtyards, and spatial planning, for indoor thermal comfort of the users, in response to the local warm-humid climatic condition to maintain the acceptable comfort condition. Similar kind of results are also reported by the other researchers Pongomathi et al. (2021).

Further, the results of the thermal performance analysis of the selected old and new Kerala Temples, through on-site measurement, have buttressed the fact that both the temples are able to maintain the acceptable thermal comfort condition by applying the above-mentioned passive strategies which are having deep rooted precedence in the vernacular architecture and construction practices of this warm-humid region. These findings in essence corroborates the conclusions emphasized by the other researchers Sreshthaputra et al. (2004) and Vella et al. (2021) that the thermal performance of the passive architectural features to maintain comfort conditions found in the naturally ventilated religious architecture is an important inspiration to develop optimum design guidelines for naturally ventilated buildings in the present-day context for the similar climatic conditions.

Conclusion

From the case studies of the Iringole Kaavu Bhagavathy Temple (old) and Thottuva Temple (new) located in Kerala Temples, based on the analysis of the data and synthesis of the results, many useful and contextual passive design strategies and their thermal performances to maintain indoor thermal comfort conditions are enumerated, which should be adopted and integrated in the design and construction process of present day naturally ventilated buildings located in the warm-humid climatic zone to achieve thermal comfort without relying on the costly mechanical cooling and ventilation systems.

This knowledge and wisdom, derived from this study of the traditional sacred Kerala Temples, will be inspirational to the present day architects, building designers, and other professionals associated with the built environment, They can utilize and integrate climate-responsive suitable passive strategies in the design and construction of present day buildings to achieve acceptable comfort level for the occupants by maintaining an optimum holistic balance between the built environment and surrounding natural environment.

Therefore, it is concluded that the selected Iringole Kaavu Bhagavathy Temple (old) and Thottuva Temple (new), as representative of South Indian Kerala style temple architecture, are not only acting as an embodiment of art-forms, aesthetics, symbolism, and spirituality with their ominous existence, but also acting as a beacon in the field of architecture. They follow and inspire the future generation to carry on the rich heritage and legacy of vernacular design and construction practices which are socio-culturally acceptable and climatically suitable.

Future studies should be conducted for monitoring the thermal performance of the temples found in warm-humid region for the whole year. Also, the modern building energy simulation tools can be used to assess the annual thermal performance of the temples and computational fluid mechanics (CFD) tools can be used to assess the performance of the air-movement and ventilation in and around the temple complex including the courtyards.

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