

SEASONAL TRANSITION DYNAMICS OF ROOF-INDUCED THERMAL BEHAVIOUR IN A WARM-HUMID TROPICAL CLIMATE: A FIELD-BASED ANALYSIS OF A NON-VENTILATED LIGHTWEIGHT HIP-ROOF SYSTEM IN OWERRI, NIGERIA

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Abstract

Lightweight residential roofs in warm-humid tropical climates are prone to roof-induced overheating from intense solar exposure and limited attic ventilation. This longitudinal field study monitored a non-ventilated lightweight multiple-hip roof assembly (stone-coated metal roofing over a plaster-of-Paris ceiling with sealed concrete fascia) in Owerri, Nigeria, to characterise how attic-indoor thermal coupling evolves across the dry-to-wet seasonal transition. Paired attic and indoor air temperatures were logged at 6-hour intervals from October 2024 to June 2025, yielding 1,052 synchronised observations. The mean attic-indoor temperature gradient fell from 0.663°C in the dry season (October–March) to 0.401°C at wet-season onset (April–June). Attic and indoor temperatures remained strongly coupled throughout (Pearson $r = 0.956$; OLS $R^2 = 0.913$; Indoor = $9.22 + 0.69 \times$ Attic, autocorrelation-robust 95% CI for slope [0.67, 0.70]), indicating that even under reduced wet-season solar loading, the sealed, non-ventilated attic continued to transmit a substantial share of absorbed heat indoors. Once corrected for a definitional inconsistency in the original calculation, the decrement factor was found to be essentially invariant across seasons (≈ 0.64), indicating that the effective dynamic attenuation between the monitored attic and indoor environments remained essentially stable across the two seasonal phases, while the magnitude of thermal excitation changed. Concurrent meteorological records available through April showed little change in mean daily solar radiation between the dry-season-dominant period and the initial month of wet-season onset, while relative humidity increased from approximately 70% to 80% and mean air temperature declined from 28.9°C to 28.2°C, indicating that the observed early-season thermal moderation cannot be explained by mean solar radiation alone. These findings underscore the need for attic ventilation, reflective roofing, or radiant barriers in tropical lightweight-roof design. As a single-building case study, findings characterise this specific assembly and should be extended cautiously to other roof configurations.

Keywords: Attic Temperature; Decrement Factor; Non-Ventilated Attic; Roof Thermal Performance; Seasonal Transition; Warm-Humid Climate

INTRODUCTION

Buildings in warm-humid tropical climates operate under persistent cooling stress, as intense solar radiation and high ambient temperatures coincide with elevated atmospheric moisture, while limited diurnal temperature variation and high night-time humidity constrain nocturnal heat dissipation and reduce the potential for passive cooling (Santamouris, 2015; Gupta & Deb, 2023). The thermal performance of the building envelope is therefore critical to indoor thermal conditions, occupant comfort, and cooling-energy demand. Roofs are especially significant among envelope components because they receive the greatest intensity of direct solar exposure and constitute the primary pathway for heat transfer into buildings (Akbari & Levinson, 2008; Santamouris, 2014), a fact widely reflected in research on roof reflectance, insulation, ventilation, and thermal mass (Akbari & Levinson, 2008; Gupta & Deb, 2023; Santamouris, 2016).

In southeastern Nigeria, lightweight roof systems dominate residential construction because of their affordability, ease of installation, and low structural load. Stone-coated metal roofing sheets, in particular, have gained increasing acceptance over conventional aluminium and corrugated sheets, reflecting a broader tropical-housing trend toward lightweight metallic roofing driven by cost efficiency and rapid construction (Oke, 1987; Akbari & Levinson, 2008; Gupta & Deb, 2023). These systems, however, exhibit high thermal conductivity and low thermal inertia, enabling rapid solar heat absorption and transmission into attic and indoor spaces. In the assembly investigated here, this behaviour is compounded by the limited thermal-buffering capacity of the plaster-of-Paris (POP) ceiling: where the attic cavity is poorly ventilated or sealed, heat removal by air exchange is restricted, and the attic instead functions as a semi-enclosed thermal reservoir capable of sustaining elevated temperatures well beyond peak solar hours.

Although lightweight metallic roofs are widely used in tropical residential construction, many remain poorly adapted to warm-humid conditions because of their limited thermal resistance, low thermal inertia, and inadequate attic ventilation — a combination that promotes rapid solar heat gain and indoor overheating (Santamouris, 2020; Gupta & Deb, 2023). Most existing evidence on roof thermal performance, however, comes from simulations, laboratory experiments, or short monitoring campaigns conducted under simplified or temporally stable conditions (Coakley et al., 2014; de Wilde, 2014), which limits insight into how attic–indoor thermal behaviour evolves as tropical environments transition from solar-forcing-dominated dry seasons to cloud- and rainfall-moderated wet seasons (Santamouris, 2015).

Long-term field-based evidence on non-ventilated lightweight roof systems within tropical African residential contexts remains particularly scarce, leaving it unclear whether seasonal reductions in indoor temperature reflect genuine improvement in roof-ceiling thermal performance or merely the temporary moderation of external climatic forcing. Resolving this distinction is necessary for developing climate-responsive roof-design strategies for warm-humid residential environments.

Aim and Objectives of the Study

The aim of this study is to investigate the seasonal transition dynamics of roof-induced thermal behaviour in a non-ventilated lightweight multiple-hip roof system in Owerri under warm-humid tropical climatic conditions, generating insights for climate-responsive residential roof design in warm-humid tropical environments. The objectives are to:

- i. characterize the monthly and seasonal evolution of attic and indoor temperatures, and quantify the associated attic–indoor temperature gradient, decrement factor, peak temperature difference, and time lag across the dry-to-wet seasonal transition;
- ii. examine the degree of thermal coupling between attic and indoor temperatures using regression analysis; and interpret the influence of the sealed fascia and non-ventilated attic condition on heat accumulation and delayed indoor heat transfer, distinguishing seasonal moderation driven by reduced solar forcing from genuine improvement in the intrinsic thermal performance of the roof–ceiling assembly.

Justification of the Study

The study is justified by the growing need for climate-responsive residential design strategies that reduce roof-induced overheating and improve indoor thermal comfort in warm-humid tropical environments. As lightweight metallic roofs continue to dominate residential construction across tropical regions for their affordability, low structural weight, and compatibility with rapid urban housing development, their contribution to indoor overheating under real climatic conditions is increasingly significant (Akbari & Levinson, 2008; Gupta & Deb, 2023; Santamouris, 2020). Understanding their dynamic thermal behaviour under real climatic exposure is therefore important for sustainable tropical housing development.

Study Area

The study was conducted in Owerri, southeastern Nigeria, which is characterised by a warm-humid tropical climate. Owerri lies between latitudes 5°24'1"N and 5°33'1"N and longitudes 6°58'1"E and 7°6'1"E. The area experiences high solar irradiance, particularly between January and May, alongside increasing relative humidity during the transition to the wet season. The climatic regime is predominantly cooling-dominated, with the primary building-performance challenge being the reduction of solar heat gain and indoor overheating (Santamouris, 2015). The analysis adopts a seasonal framing suited to the recorded period: October–March was treated as the dry-season-dominant monitoring phase, and April–June as the onset and establishment of wet-season conditions.

LITERATURE REVIEW

Theoretical Framework

This study is anchored in Systems Theory and supported by principles of building physics and dynamic thermal analysis. Systems Theory conceptualises buildings as open environmental systems that continuously interact with external climatic conditions through exchanges of heat, air, moisture, and radiation (von Bertalanffy, 1968; Hens, 2017). Within this perspective, the roof system functions as a major interface through which solar heat enters and shapes indoor thermal conditions, depending on the interaction between roofing materials, roof geometry, attic condition, ceiling system, and climatic exposure. In the present study, the stone-coated metal roof, enclosed attic cavity, POP ceiling, and indoor space are understood as components of a single interacting thermal system.

Because roof systems are exposed to cyclic solar loading rather than steady external conditions, their performance is better captured by dynamic thermal indicators — decrement factor, time lag, and attic–indoor temperature gradient — than by steady-state thermal resistance alone (Asan, 2006; Barrios et al., 2012). These indicators provide insight into heat attenuation, delayed heat transfer, and thermal coupling within the roof–ceiling assembly under changing seasonal conditions, and form the analytical basis for the present study.

Conceptual Review

Roof Thermal Performance in Warm-Humid Tropical Climates

Warm-humid tropical buildings are exposed to a combination of high air temperature, substantial solar heat gain and high atmospheric humidity, conditions that increase the importance of passive heat-control strategies in the building envelope. Recent reviews emphasise that envelope design in tropical climates must simultaneously control incident solar gains, limit conductive heat transfer and facilitate heat rejection rather than relying on material thermal resistance alone (Gupta & Deb, 2023; Kajjoba et al., 2025; Binarti & Kubota, 2026). Gupta and Deb’s review of low-energy building envelopes in tropical climates identifies roofs, shading, envelope thermal properties and natural ventilation among the principal determinants of cooling-energy performance, while Kajjoba et al. (2025) similarly emphasise solar exposure, air movement and material characteristics as important determinants of thermal conditions in low-income tropical buildings. More recently, Binarti and Kubota (2026), reviewing more than 70 passive-cooling applications across hot-humid climate classes, concluded that no single passive strategy is adequate across all such climates and that ventilation should be integrated with solar-control and heat-moderation measures.

Roofs are particularly important because their direct exposure to solar radiation can produce roof-surface and sub-roof temperatures substantially above ambient conditions. Lightweight metallic roofs respond rapidly to solar forcing because of their low thermal storage capacity, making their performance particularly sensitive to surface properties, ceiling construction, air cavities and ventilation. Recent tropical field research continues to demonstrate this dependence on the roof system rather than on roof-covering material alone. Aw et al. (2024),

for example, evaluated vegetative layers applied to metal roof systems under tropical dry and wet conditions, while Kindangen et al. (2022) demonstrated experimentally that both attic ventilation and radiant barriers reduced attic and indoor temperatures beneath galvanised metal roofs in a humid tropical climate.

Recent Nigerian evidence is particularly relevant. Taiwo and Dahunsi (2025) investigated stone-coated roofing sheets combined with different ceiling materials and roof inclinations using six months of field measurements in Ibadan. Their results demonstrate that thermal behaviour varies with roof inclination and ceiling configuration, confirming that stone-coated roofing cannot be evaluated independently of the wider roof–ceiling system. However, their study used purpose-built prototype models and focused primarily on roof angle and ceiling-material combinations rather than the seasonal attic–indoor behaviour of a full-scale occupied dwelling.

Attic Ventilation and Heat Accumulation

The attic constitutes an intermediate thermal zone between the externally exposed roof covering and the ceiling of the occupied space. Its thermal behaviour depends on solar heat transmission through the roof, long-wave and convective exchange within the cavity, air leakage, ventilation openings and heat transfer through the ceiling. In lightweight roof systems, restricted air exchange can allow heat accumulated beneath the roof covering to remain within the attic and increase the thermal load imposed on the ceiling.

Contemporary empirical evidence reinforces the importance of this boundary condition. Kindangen et al. (2022) compared ventilated and unventilated galvanised-metal-roof test cells in a humid tropical climate and found that attic ventilation reduced attic and indoor temperatures; at larger ventilation openings, its temperature-reduction effect exceeded that of the radiant barrier tested in the comparison. More recently, Moharrami et al. (2025) conducted simultaneous field measurements in tropical residential buildings and reported that hybrid attic ventilation reduced indoor temperature by approximately 1°C and relative humidity by approximately 7%, with simulated whole-building energy savings of about 10%. These studies support the interpretation of attic ventilation as an important heat-rejection mechanism rather than a secondary construction detail.

Nevertheless, these studies principally evaluate the benefit of ventilation interventions. They do not establish how attic–indoor thermal coupling in an already sealed lightweight residential attic changes naturally as climatic conditions move between seasons. This distinction is important because declining attic or indoor temperature during a wetter period cannot, by itself, be interpreted as improved roof performance: the apparent improvement may simply reflect changes in the climatic excitation acting on an otherwise unchanged roof–attic–ceiling system.

Dynamic Thermal Behaviour and Thermal Indicators

Roof systems in tropical environments operate under transient rather than purely steady-state boundary conditions because incident solar radiation, ambient air temperature, atmospheric

moisture, wind and cloud conditions vary over diurnal and seasonal timescales, producing time-dependent thermal loads on the building envelope (Hens, 2017; Gupta & Deb, 2023). Consequently, roof, attic and indoor temperatures do not necessarily respond simultaneously or with equal amplitudes to changes in external climatic forcing. The magnitude and timing of these responses depend on the thermophysical characteristics of the envelope, including thermal conductivity, heat capacity, density, thickness and the configuration of its component layers (Lu et al., 2024).

Steady-state parameters such as thermal conductivity, thermal resistance and U-value remain fundamental descriptors of envelope heat transfer, but they cannot by themselves fully characterise thermal behaviour under periodically varying environmental conditions. Dynamic thermal assessment therefore complements steady-state evaluation by considering the extent to which an imposed thermal fluctuation is attenuated and delayed as it propagates through the envelope (Juaristi & Krarti, 2024; Lu et al., 2024). Decrement factor and time lag are established indicators of this dynamic response: decrement factor expresses the attenuation of the thermal-wave amplitude, while time lag or phase shift represents the temporal delay between thermal excitation and the corresponding response (Asan, 2006; Lu et al., 2024). Recent analytical work continues to identify these parameters as important measures of dynamic envelope performance and demonstrates their dependence on material properties, thickness, thermal resistance, thermal diffusion and boundary conditions (Lu et al., 2024). In field-based roof studies, temperature amplitude, attic–indoor temperature difference and peak temperature difference can provide additional empirical measures of the magnitude of thermal excitation and its transmission between the roof cavity and occupied space. Taken together, these indicators provide a more temporally resolved characterisation of roof thermal behaviour than steady-state properties alone and are therefore appropriate for examining how an unchanged roof–attic–ceiling system responds to changing climatic forcing across a seasonal transition.

Decrement factor expresses the attenuation of a periodic temperature fluctuation between two thermal zones, while time lag describes the phase displacement between their temperature peaks. These concepts remain useful for comparing dynamic envelope behaviour, although their interpretation depends strongly on sampling resolution, boundary definition and the temperatures chosen as input and response variables. Earlier methodological work established these indicators for dynamic building-envelope analysis (Asan, 2006; Barrios et al., 2012), and more recent research continues to use dynamic measurements and temperature-amplitude suppression to evaluate roof interventions in tropical and warm climates. For example, contemporary studies have examined field-measured tropical metal-roof modifications (Aw et al., 2024), stone-coated roof–ceiling combinations in Nigeria (Taiwo & Dahunsi, 2025), and integrated high-reflectance and thermal-storage roof strategies under warm-humid exposure.

In the present study, these indicators are not used to assign a universal material property to the roof. Instead, they are used as system-level empirical measures describing the effective attenuation and temporal coupling between the monitored attic and occupied indoor space. This distinction is important because the measured response incorporates the combined

effects of the roof covering, attic boundary condition, ceiling construction and prevailing environmental forcing.

Seasonal Transition and Existing Knowledge Gap

Recent research has substantially improved understanding of tropical roof thermal performance, but the available evidence remains fragmented in ways that leave the seasonal behaviour of real residential attic systems insufficiently resolved. Studies have examined attic ventilation and radiant barriers in humid-tropical experimental buildings (Kindangen et al., 2022), tropical metal-roof modification strategies (Aw et al., 2024), stone-coated roof and ceiling combinations in Nigerian prototype buildings (Taiwo & Dahunsi, 2025), and hybrid attic ventilation in tropical residences (Moharrami et al., 2025). Recent reviews have likewise reinforced the importance of integrating ventilation, solar control and envelope design for thermally resilient hot-humid buildings (Gupta & Deb, 2023; Kajjoba et al., 2025; Binarti & Kubota, 2026).

Three related gaps nevertheless remain. First, much of the empirical roof literature evaluates alternative materials or deliberate interventions, such as ventilation, reflective layers, vegetation, insulation or ceiling configurations, rather than observing the unchanged roof–attic–ceiling system as climatic forcing varies naturally over time. Second, field evidence from full-scale residential buildings in warm-humid sub-Saharan Africa remains limited; recent Nigerian stone-coated-roof research has provided valuable experimental evidence, but predominantly through prototype configurations rather than longitudinal attic–indoor monitoring in an occupied building. Third, comparatively little attention has been given to whether seasonal reductions in attic and indoor temperatures represent a change in the effective thermal attenuation of the roof–ceiling assembly or simply a reduction or alteration in external climatic forcing.

The present study addresses these gaps through a nine-month longitudinal field investigation of a full-scale residential building in Owerri, Nigeria, incorporating a lightweight stone-coated metal multiple-hip roof, sealed fascia, non-ventilated attic and POP ceiling. Rather than comparing different roof materials or introducing an experimental retrofit, the study follows the same unchanged assembly across the dry-to-wet seasonal transition. It combines synchronised attic and indoor temperatures with local meteorological observations and evaluates seasonal changes using attic–indoor gradient, peak temperature difference, decrement factor, time lag and regression-based thermal coupling. This design makes it possible to distinguish changes in the magnitude of climatic excitation from changes in the effective dynamic attenuation of the roof–attic–ceiling system, thereby providing field evidence on a dimension of tropical roof performance that intervention-based and short-duration studies do not directly resolve.

METHODOLOGY

Research Design

This study adopted a longitudinal field-based monitoring design to investigate the seasonal transition dynamics of roof-induced thermal behaviour in a non-ventilated lightweight multiple-hip roof system. The design was considered appropriate because the study sought to observe actual attic and indoor thermal conditions under real warm-humid tropical climatic exposure rather than under simulated or laboratory-controlled conditions. The approach enabled the study to capture monthly and seasonal variations in attic–indoor temperature behaviour from the dry season to the onset of the wet season.

Description of the Investigated Building

The investigated building was a residential building located in Owerri, southeastern Nigeria. The roof system comprised a lightweight stone-coated metal multiple-hip roof installed over a plaster-of-Paris (POP) ceiling. The attic space was enclosed by sealed concrete fascia, with no effective soffit, ridge, or gable ventilation openings, making the building suitable for examining the thermal behaviour of a non-ventilated lightweight roof system under warm-humid tropical conditions. The roof–ceiling assembly was treated as a thermal system of four interacting components: the stone-coated metal roof covering, the enclosed attic cavity, the POP ceiling, and the indoor occupied space.

Instrumentation and Data Collection

Temperature measurements were obtained using calibrated Elitech RC-4 data loggers (compact), USB-enabled devices designed for continuous environmental monitoring — installed in the attic space and the indoor environment. The instruments operate within a temperature range of -30°C to $+60^{\circ}\text{C}$ (extendable to -40°C to $+85^{\circ}\text{C}$ with an external probe), a resolution of 0.1°C , and a manufacturer-stated accuracy of $\pm 0.6^{\circ}\text{C}$ within the standard range ($\pm 1.2^{\circ}\text{C}$ outside it). Each device is equipped with a high-sensitivity NTC thermistor sensor and a data storage capacity of up to 16,000 readings, allowing extended monitoring at configurable intervals from 10 seconds to 24 hours. Data retrieval was via USB, with export in PDF and spreadsheet formats for statistical analysis. The attic logger captured thermal conditions immediately beneath the roof covering, while the indoor logger, mounted at approximately 1.1 m above the suspended floor, recorded air temperature within the occupied space and was positioned to minimise conductive heat exchange with adjacent surfaces.

Data were recorded at 6-hour intervals from October 2024 to June 2025, selected to capture the major diurnal phases (early morning, late morning, afternoon, night-time), producing 1,052 paired attic and indoor observations. The monitoring period was divided into two seasonal phases: October–March as the dry-season-dominant phase, and April–June as the wet-season onset phase. Before analysis, attic and indoor records were synchronised so that only paired observations at corresponding timestamps were retained; incomplete or

unmatched observations were excluded. The data on daily recordings of solar radiation, humidity and air temperature were collected from a local meteorological station located at Imo State University, Owerri- IMSU-NIMET.

Variables of the Study

The primary measured variables were attic temperature and indoor temperature. From these, the study derived four dynamic thermal-performance indicators — attic–indoor temperature gradient, decrement factor, peak temperature difference, and observed time lag — used to interpret heat attenuation, delayed heat transfer, and thermal coupling between the attic and indoor environments.

Determination of Thermal-Performance Indicators

The attic–indoor temperature gradient was determined as the difference between attic and indoor temperature at each paired observation (Incropera et al., 2007; Hens, 2017):

$$\Delta T = T_{\text{attic}} - T_{\text{indoor}} \dots\dots\dots (\text{Eq. 1})$$

where ΔT is the attic–indoor temperature gradient, T_{attic} is attic temperature, and T_{indoor} is indoor temperature.

Decrement factor (DF) was determined as the ratio of the mean diurnal indoor temperature amplitude to the mean diurnal attic temperature amplitude, where the diurnal amplitude on a given day is the difference between that day's maximum and minimum temperature, averaged across all days within the relevant month or season (Asan, 2006; Barrios et al., 2012):

$$\text{DF} = \frac{A_{\text{indoor}}}{A_{\text{attic}}} \dots\dots\dots (\text{Eq.2})$$

where A_{indoor} and A_{attic} are the mean diurnal indoor and attic temperature amplitudes

Peak temperature difference was determined as the maximum observed difference between attic and indoor temperature within the relevant period:

$$\text{PTD} = T_{\text{attic}(\text{max})} - T_{\text{indoor}(\text{max})} \dots\dots\dots (\text{Eq. 3})$$

Observed time lag was determined as the difference between the time of peak attic temperature and the time of the corresponding peak indoor temperature:

$$\text{TL} = t_{\text{indoor}(\text{max})} - t_{\text{attic}(\text{max})} \dots\dots\dots (\text{Eq. 4}).$$

The monthly and seasonal time-lag values reported in Table 1 and Table 2 are the arithmetic mean of these day-level lags. Because each individual day's lag is necessarily a multiple of the 6-hour sampling interval (0, 6, 12, or 18 hours), the resulting monthly and seasonal means are small fractions of that interval.

Statistical Analysis

Temperature data were organized by date, time, month, and seasonal phase using Python (pandas and NumPy). Descriptive statistics (mean, minimum, maximum, standard deviation) were computed for attic and indoor temperatures, followed by monthly and seasonal summaries characterizing the dry-to-wet transition. The four derived thermal-performance indicators were computed on monthly and seasonal bases, and dry-season and wet-onset phases were compared to evaluate seasonal changes in roof-induced thermal behaviour.

Pearson product–moment correlation was used to examine the association between attic and indoor temperatures, and ordinary least squares (OLS) regression was used to evaluate the predictive influence of attic temperature on indoor temperature (Montgomery et al., 2021; Kutner et al., 2005):

$$T_{\text{indoor}} = \beta_0 + \beta_1 T_{\text{attic}} + \varepsilon \dots \dots \dots (\text{Eq. 5});$$

where T_{indoor} is indoor temperature, T_{attic} is attic temperature, β_0 is the intercept, β_1 is the regression coefficient, and ε is the error term. Because sequential 6-hourly readings from a single monitoring location are serially correlated through the diurnal cycle, regression diagnostics included the Durbin–Watson statistic to assess residual autocorrelation; given evidence of strong positive autocorrelation ($DW = 0.93$), heteroscedasticity- and autocorrelation-consistent (Newey–West) standard errors were used in place of naive OLS standard errors when computing confidence intervals and significance for β_0 and β_1 . As a robustness check, the regression was additionally estimated on daily-mean aggregates ($n = 264$ independent days) to reduce within-day dependence.

RESULTS

Dataset Overview

The final synchronized dataset contained 1,052 paired attic–indoor observations spanning 2 October 2024 to 22 June 2025. Across the full dataset, mean attic temperature was 31.15°C, mean indoor temperature was 30.57°C, and mean attic–indoor gradient was 0.58°C. Attic temperature ranged from 24.2°C to 39.0°C, while indoor temperature ranged from 24.5°C to 36.2°C.

Table 1: Monthly thermal performance indicators

Period	Mean attic (0C)	Mean indoor (0C)	Mean ΔT (0C)	Attic amp. (0C)	Indoor amp. (0C)	DF	Peak ΔT (0C)	Lag (h)
2024-10	28.878	28.610	0.268	5.227	3.157	0.604	1.663	1.20
2024-11	31.491	30.863	0.628	5.840	3.830	0.656	2.033	0.00
2024-12	31.025	29.998	1.027	6.974	4.497	0.645	2.497	0.00
2025-01	31.389	30.583	0.806	6.345	4.000	0.630	2.245	0.00
2025-02	32.859	32.221	0.637	6.350	4.011	0.632	2.111	0.21
2025-03	32.445	31.856	0.589	6.855	4.423	0.645	2.110	0.19
2025-04	31.237	30.790	0.447	5.723	3.693	0.645	1.623	0.60
2025-05	30.751	30.358	0.393	5.419	3.474	0.641	1.448	0.00
2025-06	29.943	29.595	0.348	4.686	2.868	0.612	1.395	0.55

Note. DF=decrement factor, computed as mean diurnal indoor amplitude $\div$ mean diurnal attic amplitude for each month; Peak ΔT = mean of each day's maximum simultaneous attic-indoor gradient; ΔT = attic-indoor temperature gradient.

Table 2: Seasonal comparison of dry-season and wet-onset dynamics

Season	Days	Mean attic (0C)	Mean indoor (0C)	Mean ΔT (0C)	Mean Peak ΔT (0C)	Attic amp. (0C)	Indoor amp. (0C)	DF	Lag (h)
Dry season (Oct-Mar)	180	31.342	30.679	0.663	2.113	6.272	3.991	0.636	0.27
Wet onset (Apr-Jun)	82	30.717	30.316	0.401	1.498	5.335	3.393	0.636	0.36

Note. Seasonal values are based on synchronised 6-hourly attic-indoor readings aggregated to daily and monthly bases. 181 and 83 calendar days fell in each season respectively; one partial day (2 of 4 readings) at each end of the deployment — 2 Oct 2024 and 22 Jun 2025 — is excluded from the day count shown here.

Table 3 presents the concurrent IMSU–NIMET meteorological record available from 1 October 2024 to 30 April 2025. Because meteorological observations were unavailable for May and June 2025, the climatic comparison is limited to the dry-season-dominant period (October–March) and April 2025, representing the initial month of wet-season onset. Accordingly, the meteorological data are used to contextualise, rather than directly replicate, the full April–June thermal comparison presented in Table 2.

Table 3: Table 3 presents the concurrent IMSU–NIMET meteorological record available from 1 October 2024 to 30 April 2025.

Period	Mean Solar Radiation (w/m2)	Mean Humidity (%)	Mean air temp (0C)
Dry season (Oct- Mar), n=182 days	85.9	69.6	28.9
April 2025 only, n=30 days	85.3	79.7	28.2

Monthly Evolution Across the Dry–Wet Transition

The monthly trend showed that attic and indoor temperatures increased from October into the hotter months, with the highest monthly mean attic temperature occurring in February (32.86°C). The attic–indoor gradient was strongest in December, when the mean gradient reached 1.03°C — coinciding with the driest, least humid conditions of the monitoring period. From April to June, both attic temperature and attic–indoor gradient declined progressively. This pattern indicates that wet-season onset moderated external roof heat input; however, it did not fully decouple indoor temperature from attic thermal behaviour. (Figure 1: Monthly evolution of attic temperature, indoor temperature, and attic–indoor gradient across the dry–wet seasonal transition.)

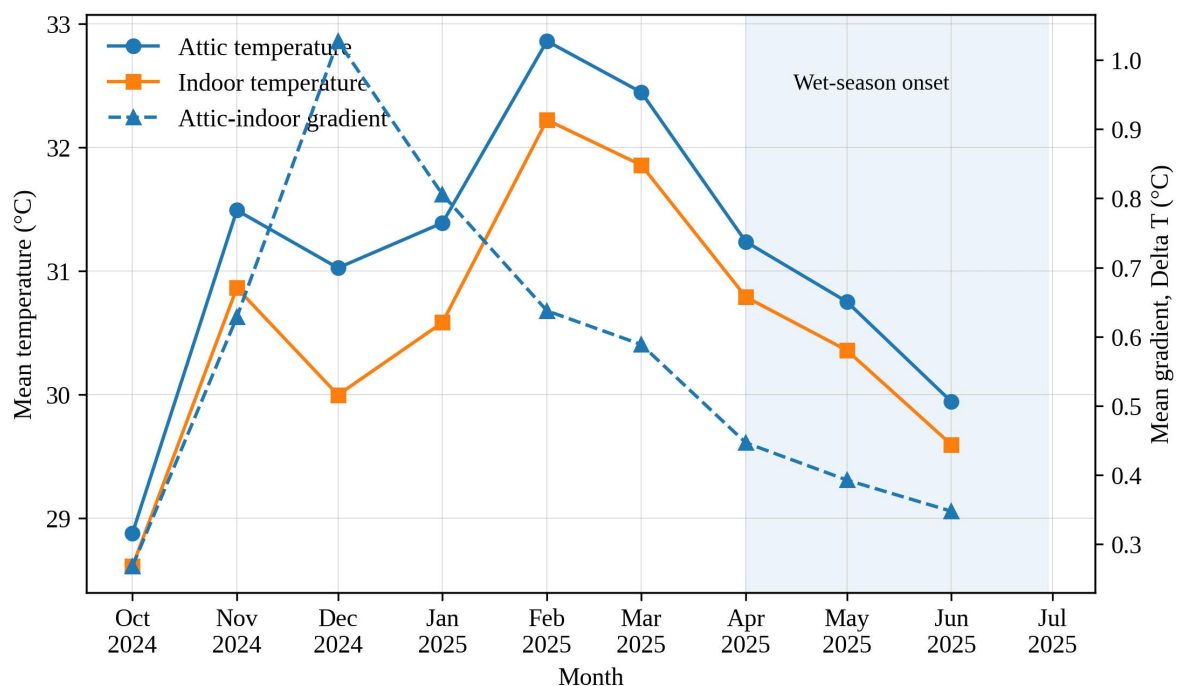


Figure 1: Monthly evolution of attic temperature, indoor temperature and attic-indoor gradient across the dry-wet seasonal transition

Source: Fieldwork (2026)

Diurnal Response and Heat Accumulation Pattern

The mean diurnal profile indicates that both seasonal periods followed a clear daily cycle, with the largest attic–indoor separation occurring at the 16:00 logging interval, reflecting afternoon heat accumulation within the attic cavity. During the dry season, mean attic temperature at 16:00 was 35.03°C, compared with 33.08°C indoors — a 1.95°C separation. During the wet-season onset, the corresponding means declined to 33.62°C and 32.24°C — a 1.38°C separation. At the 04:00 interval, indoor temperature exceeded attic temperature in both seasons (dry: 29.12°C indoor vs. 28.86°C attic; wet-onset: 28.99°C vs. 28.53°C), consistent with the attic cooling faster than the occupied space overnight once solar input

ceased. [Figure 2: Mean diurnal attic and indoor temperature profiles during the dry season and wet-season onset.]

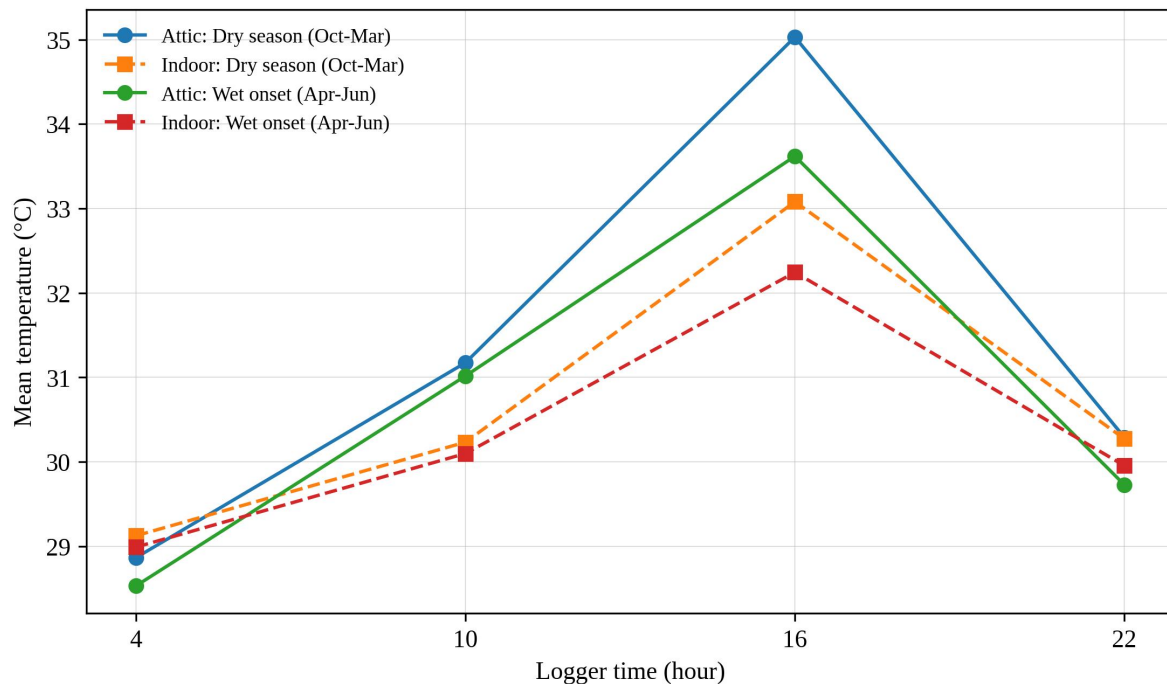


Figure 2: Mean diurnal attic and indoor temperature profiles during the dry season and wet-season onset

Source: Fieldwork (2026)

Regression-Based Attic–Indoor Thermal Coupling

The relationship between attic and indoor temperature was examined using ordinary least squares (OLS) regression: $T_{\text{indoor}} = \beta_0 + \beta_1 T_{\text{attic}} + \varepsilon \dots\dots$ (Eq. 6).

Table 4: Regression output

Parameter	Naïve OLS	Newey-West HAC
Intercept (β_0)	9.22 (SE 0.204)	9.22 (SE 0.265)
Slope (β_1)	0.686 (SE 0.0065)	0.686 (SE 0.0082)
95% CI for slope	[0.673, 0.698]	[0.669, 0.702]
R ²	0.913	—
Pearson's r	0.956	—
Durbin-Watson statistic	0.93	—
n	1,052	1,052

Note: The Durbin–Watson statistic (0.93, vs. 2.0 for no autocorrelation) indicates strong positive serial correlation in the residuals, expected given the diurnal structure of sequential 6-hourly readings from a single location. Newey–West standard errors are reported alongside the naive OLS standard errors for transparency; the substantive conclusion is unchanged. A re-estimation on 264 daily-mean aggregates

(reducing within-day dependence) gives $\text{Indoor} = 3.84 + 0.858 \times \text{Attic}$, $R^2 = 0.922$, $r = 0.960$, confirming the coupling is not an artefact of sampling frequency.

The resulting regression equation, $\text{Indoor} = 9.22 + 0.686 \times \text{Attic}$, indicates that each 1°C increase in attic temperature was associated with a 0.686°C increase in indoor temperature, and that 91.3% of the variance in indoor temperature was statistically associated with attic-temperature variation over the monitoring period. Because the underlying observations are serially correlated, this R^2 should be interpreted as a measure of association strength rather than as evidence of 1,052 independent confirmations of the relationship; the daily-aggregated and HAC-corrected estimates above show the coupling holds under both treatments. (Figure 3: Relationship between attic and indoor temperatures based on synchronised 6-hourly observations.)

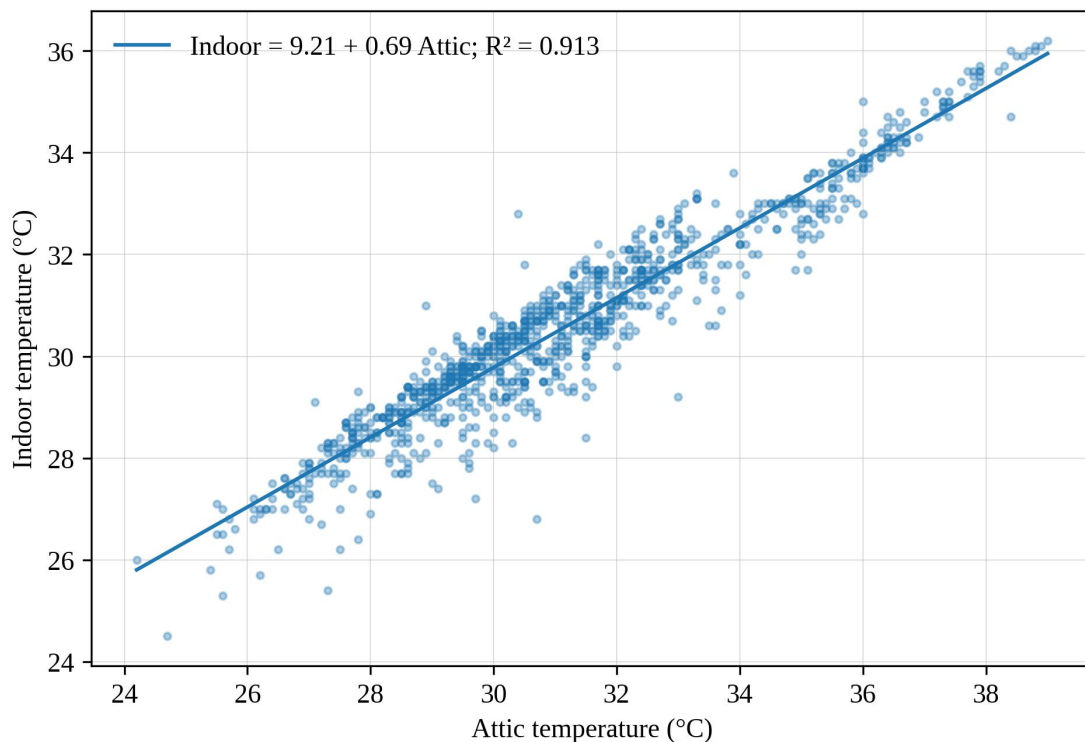


Figure 3: Relationship between attic and indoor temperatures based on synchronized 6-hourly observations

Source: Fieldwork (2026)

Physical Interpretation of the Non-Ventilated Attic Boundary Condition

The sealing of the concrete fascia restricted soffit-driven ventilation and effectively converted the attic into a quasi-enclosed air volume. Under solar loading, heat transmitted through the lightweight roof covering elevated attic air temperature, promoting buoyancy-driven stratification in which warmer, less dense air accumulated beneath the roof surface. In the absence of ventilation pathways, this thermally stratified air mass could not be displaced, resulting in sustained heat retention and increased thermal loading on the ceiling layer. This

behaviour is consistent with contemporary evidence on attic heat-transfer mechanisms, in which solar heat gain through the roof and buoyancy-driven air movement within the roof cavity influence attic temperature distribution and heat transfer to the occupied space (Kindangen et al., 2022).

Previous studies have similarly shown that inadequate attic ventilation intensifies heat accumulation and indoor heat gain in lightweight roofing systems under strong solar forcing (Akbari & Levinson, 2008; Barrios et al., 2012). Under dry-season conditions, the rate of heat input exceeded the limited convective dissipation available; under wet-season conditions, reduced net forcing lowered attic peaks, but the absence of ventilation meant the assembly remained dependent on conduction, radiative exchange, and limited air leakage for heat dissipation — consistent with the finding above that the assembly's intrinsic decrement factor did not change between seasons. (Figure 4: Conceptual model of heat accumulation in the non-ventilated attic cavity with sealed concrete fascia).

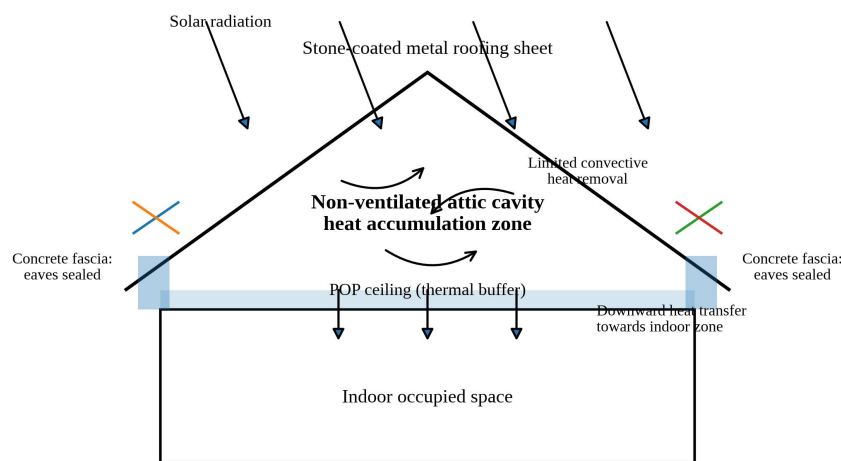


Figure 4: Conceptual model of heat accumulation in the non-ventilated attic cavity with sealed concrete fascia

Source: Fieldwork (2026)

DISCUSSION

Dry-Season Solar Forcing and Attic Heat Accumulation

The results showed pronounced attic temperature peaks and elevated attic–indoor temperature gradients during the dry season, consistent with solar irradiance acting as the dominant external thermal forcing on the roof system. Peak attic and indoor temperatures both occurred at the 16:00 logging interval, coinciding with maximum daytime solar exposure. Time lag was near zero in most months (Table 1) and did not exceed 1.2 hours in any month, indicating that attic and indoor peaks coincided almost simultaneously rather than showing the delayed response typical of higher-mass envelopes. Together with the low decrement factor variability discussed below, this near-instantaneous coupling reflects the low thermal

mass of the lightweight stone-coated metal roof and POP ceiling, which offer minimal capacity to buffer or delay the diurnal heat pulse before it reaches the occupied space — consistent with the physical mechanism detailed earlier, where the sealed, non-ventilated attic accumulates solar heat during the day and releases it into the indoor environment largely within the same 6-hour observation window. These findings align with previous studies on lightweight roofing systems under intense solar exposure (Asan, 2006; Barrios et al., 2012) and reinforce the importance of ventilation and solar heat-gain control in warm-humid roof design.

Seasonal Transition Dynamics

The transition from the dry season to the onset of the wet season was associated with a reduction in attic–indoor temperature gradients, with mean temperature difference declining from 0.663°C to 0.401°C. Once decrement factor is computed on a consistent diurnal basis, however, it is essentially unchanged across the two periods (0.636 in the dry season versus 0.636 at wet-season onset), directly demonstrating that this reduction did not reflect any change in the roof-ceiling assembly's intrinsic heat-attenuation capacity. Concurrent local meteorological records available from October 2024 to April 2025 provide partial climatic context for this seasonal transition. Mean daily solar radiation changed little between the dry-season-dominant period (October–March) and April, the initial month of wet-season onset (85.9 versus 85.3 W/m²), whereas mean relative humidity increased markedly from 69.6% to 79.7% and mean air temperature declined from 28.9°C to 28.2°C. These observations indicate that the initial moderation of roof thermal conditions cannot be attributed to a reduction in mean solar radiation alone. However, because the meteorological record does not extend through May and June, it cannot explain the climatic drivers of the entire April–June thermal transition.

These observations indicate that the initial seasonal moderation cannot be attributed to a decline in mean solar radiation alone. The concurrent increase in relative humidity and decrease in mean air temperature suggest that the changing atmospheric conditions associated with wet-season onset may also have contributed to the observed thermal response. However, because the meteorological record extends only through April and does not include direct measurements of cloud cover, rainfall, wind or long-wave radiative exchange, the individual contributions of these climatic factors cannot be resolved from the present data. The findings therefore support the broader interpretation that the reduction in attic–indoor thermal gradient reflects changing external climatic forcing rather than an improvement in the effective dynamic attenuation of the unchanged roof–attic–ceiling assembly.

Nocturnal Heat Retention and Atmospheric Moisture

Despite reduced daytime peak gradients during the wet-season onset, indoor temperatures at the 04:00 logging interval declined only modestly relative to the dry season (28.99°C versus 29.12°C), a much smaller change than the 1.4°C decline observed in the 16:00 daytime peak

(33.08°C to 32.24°C indoors). This asymmetry — daytime peaks moderating considerably more than night-time minima — is consistent with, though not directly confirmed by, the rise in atmospheric humidity documented over the same period, since higher moisture and cloud cover can reduce net long-wave radiative losses to the sky at night and narrow the diurnal temperature range. The IMSU-NIMET dataset used here reports daily-mean rather than night-specific humidity, so this mechanism should be regarded as a plausible contributing explanation rather than a confirmed one; concurrent night-time humidity or outgoing radiation measurements would be needed to test it directly. What the data do support is that thermal performance in this warm-humid setting is shaped by both daytime solar heat gain and night-time heat-release dynamics, and that the non-ventilated attic's role in prolonging indoor thermal stress after sunset does not appear to diminish appreciably at wet-season onset.

Influence of the Multiple-Hip Roof Geometry

A feature of the investigated assembly not yet addressed directly is its multiple-hip roof form, which comprises several differently oriented, differently insulated roof planes converging on a single attic volume. Because attic temperature was monitored at a single representative location beneath the roof, the reported values characterize that specific hip face and attic zone rather than the attic as a whole; roof planes facing away from the sun for longer portions of the day may experience a measurably different thermal regime, and the attic air itself may not be well-mixed across the full plan area given the low, converging geometry typical of hip roofs near the eaves. This is a limitation of the present single-point monitoring approach rather than a finding, but it is a design-relevant one: multiple-hip roofs may distribute solar heat gain unevenly across the attic in a way that simpler gable or mono-pitch geometries would not, and future work using multiple simultaneously logged attic locations would be needed to establish whether this asymmetry materially affects the indoor thermal response documented here.

Implications for Climate-Responsive Roof Design

The findings from this assembly demonstrate that a lightweight, non-ventilated roof-ceiling system of this type is susceptible to heat accumulation and prolonged indoor thermal loading in a warm-humid tropical setting. Effective thermal control in similar assemblies would plausibly require both reduction of solar heat gain and enhancement of attic heat removal, through measures such as high-reflectance roofing materials, radiant barriers, ceiling insulation, and soffit-ridge ventilation. The study also highlights that sealed concrete fascia, while architecturally common, may unintentionally suppress attic ventilation and compromise thermal performance, suggesting that fascia detailing warrants consideration as a thermal design parameter rather than only an aesthetic one. Because these findings derive from a single building, they should be read as generating testable design hypotheses for similar lightweight hip-roof assemblies in comparable climates, rather than as generalized conclusions about lightweight tropical roofs as a class; the results also underscore the value

of evaluating roof systems across seasonal transitions rather than relying solely on peak dry-season assessments.

Contribution to Building Physics and Environmental Assessment

The principal contribution of this study is not merely the documentation of elevated temperatures beneath a lightweight tropical roof, which has been established by previous researches, but the demonstration of how the thermal relationship between attic and occupied space changes—or remains stable—as climatic forcing changes across seasons in an unchanged roof–attic–ceiling system. Three specific contributions emerge.

Firstly, the study provides longitudinal field evidence that seasonal moderation of attic and indoor temperatures does not necessarily imply a corresponding improvement in the effective heat-attenuation behaviour of the roof–ceiling assembly. Although the mean attic–indoor gradient decreased from 0.663°C during the dry-season-dominant phase to 0.401°C at wet-season onset, the decrement factor remained approximately 0.636 in both periods. The important building-physics implication is therefore that thermal exposure and thermal attenuation are analytically distinct: an assembly can experience lower temperatures because climatic excitation has moderated while retaining essentially the same effective attenuation relationship between attic and indoor temperature fluctuations.

Secondly, the study quantifies the strength and persistence of attic–indoor coupling in a sealed lightweight tropical roof system. The high full-period correlation ($r = 0.956$), regression association ($R^2 = 0.913$) and corroborating daily-mean model demonstrate that indoor temperature variation remained closely associated with attic temperature despite the seasonal transition. This provides field-based evidence that the attic should be treated as an active component of the roof thermal pathway rather than merely as an unconditioned void separating roofing and ceiling.

Finally, the study introduces seasonal-transition analysis as a useful complement to conventional material- or intervention-based roof comparisons. By holding the physical roof system constant while observing changing climatic exposure, the research provides an empirical means of distinguishing climate-driven moderation from assembly-driven attenuation. This distinction is particularly relevant to field evaluation in warm-humid climates, where temperature reductions occurring during wetter periods might otherwise be incorrectly attributed to satisfactory roof performance.

CONCLUSION

This study investigated the seasonal transition dynamics of a lightweight stone-coated metal roof with a POP ceiling and non-ventilated attic in Owerri, using 1,052 synchronised attic–indoor temperature observations collected between October 2024 and June 2025. Dry-season conditions produced stronger attic heating and larger attic–indoor temperature gradients than the wet-season onset, with the mean gradient declining from 0.663°C to 0.401°C . Once

corrected to a consistent diurnal basis, however, the decrement factor governing this assembly's heat-attenuation behaviour was essentially unchanged across the two seasons (0.636 in both), indicating that the effective dynamic attenuation between the monitored attic and indoor environments remained essentially stable across the two seasonal phases, while the magnitude of thermal excitation changed. Concurrent local meteorological data showed that this forcing reduction was driven more by rising humidity and cloud cover than by a decline in solar radiation itself, which changed little between the dry season and wet-season onset. Attic and indoor temperatures remained strongly coupled throughout the monitoring period (Pearson $r = 0.956$; $R^2 = 0.913$, robust to serial autocorrelation), and near-zero time lags indicated that the assembly's low thermal mass provided little buffering of the diurnal heat pulse. Taken together, the findings show that seasonal reductions in attic and indoor temperatures should not automatically be interpreted as improved roof thermal performance. For the unchanged roof–attic–ceiling system investigated here, climatic exposure moderated across the seasonal transition while the effective decrement factor remained essentially stable and attic–indoor temperature coupling remained strong. The study therefore contributes a distinction between climate-driven moderation and assembly-level thermal attenuation, demonstrating that these two effects can be separated through longitudinal monitoring of the same roof system. The results further identify the sealed attic boundary as a plausible contributor to sustained attic–indoor coupling and provide an empirical basis for testing ventilation, reflective surfaces, radiant barriers and ceiling insulation in subsequent comparative studies. As evidence from a single building, the findings establish a field-based baseline for this roof configuration rather than a universal performance characteristic of lightweight tropical roofs.

LIMITATIONS AND FUTURE RESEARCH

This study is limited by its single-building case design, which restricts generalisability across roof configurations and residential contexts; findings should be read as generating testable hypotheses for similar lightweight, non-ventilated hip-roof assemblies rather than as conclusions about lightweight tropical roofs as a class. Attic temperature was monitored at a single location beneath a multiple-hip roof comprising several differently oriented planes, so the reported values characterize the monitored hip face and attic zone rather than the attic volume as a whole. Concurrent local meteorological data (solar radiation, air temperature, and humidity) were obtained and analyzed for part of the monitoring period (October 2024–April 2025) and helped refine the study's central claim about the drivers of seasonal moderation; however, this record did not extend through the full wet-season-onset period (May–June 2025), and wind, rainfall, roof-surface temperature, attic airflow, and night-specific humidity remained unmeasured throughout. Time lag estimates were derived from 6-hourly measurements and are therefore resolved only to multiples of that interval before averaging, limiting temporal precision and likely obscuring finer phase-shift behaviour within each day. Future studies should adopt multi-building comparative designs, incorporate higher-frequency thermal monitoring, extend meteorological records across the full seasonal cycle, and log attic temperature at multiple points beneath different roof faces to test whether hip-roof geometry produces spatially uneven heat accumulation. Such designs would better

resolve the conductive, radiative, and convective heat-transfer processes governing lightweight roof systems in warm-humid tropical climates.

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