

Passive cooling strategies for improving indoor thermal comfort of tropical school buildings

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ABSTRACT

In the context of increasing energy demand and thermal discomfort in the building sector, the assessment of thermal comfort and cooling energy consumption has become a key factor of research. This paper presents the passive cooling strategies performing in the tropical school building, including Phase Change Materials based on BioPCM, straw bale insulation covering fibers parallel and perpendicular to the heat flow, and building orientation. The study was conducted in two public elementary schools of Antsiranana, Madagascar, and focused on in-situ measurement using arduino recorder to highlight the outdoor and indoor environmental parameters and numerical approaches employing DesignBuilder as thermal simulation and building energy modeling software. As all the models are validated following ASHRAE Guideline 14 specification, the evaluation reveals that in the original configurations, both schools failed the comfort range during the rainy and the dry season spanning across the teaching period. Results demonstrate that straw bale insulation 40 cm with fibers oriented perpendicular to the heat flow exhibits the highest thermal performance and efficient payback period under 2 years for residential and business pricing scheme, followed by straw parallel configuration, Roof embedded PCM, and wall integrated PCM, and the north or south-facing. Since the electricity access remains very limited, this research focusing on the passive cooling principles provides relevant approaches in order to improve indoor thermal comfort, academic performance, and well-being of pupils.

1. Introduction

According to the OECD [1], Students will be exposed to more hot days at school by 2050. Bulgaria and Chile are projected to join Colombia, Costa Rica, and the United States on the list of countries where over one-quarter of primary school students will attend schools experiencing more than 60 hot days a year. In this sense, hot temperatures affect students' learning both directly, by impacting their well-being and performance at school, and indirectly through disruptions to their schooling. Moreover, UNSW [2] report from 14.5 million

students across 61 countries that long-term exposure to elevated temperatures, particularly in school environments, reduces students' ability to learn and retain knowledge, with complex tasks such as mathematics more affected than simpler ones like reading. In Madagascar, the World Bank [3], through the TALIM (Transforming Access and Learning in Madagascar) initiative, identifies poor thermal comfort and inadequate ventilation as major barriers to pupil health and academic performance. These observations underscore the significance of thermal comfort in enhancing the academic performance of pupils. This paper proposes passive cooling strategies for performing indoor thermal comfort in

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school buildings, as Madagascar's electricity access rate reaches painfully 36% [4]. Passive cooling strategies, defined as natural design approaches that maintain thermal comfort without mechanical systems, offer sustainable and cost-effective alternatives for reducing energy demand and greenhouse gas emissions [5,6]. Additionally, Hanan M. Taleb [7] describes it as any technologies or design features adopted to reduce the temperature of buildings without the need for power consumption. Regarding to the literature, research focusing on passive cooling strategies for tropical school climates under natural ventilation remains limited, particularly when it combines the energy and thermal performance of PCM, straw bale insulation, and building orientation. In this context, designers have a significant role in establishing comfortable indoor conditions without depending on mechanical means [8,9]. This paper is focused on traditional and modern passive cooling, including Phase Change Materials, straw bale insulation, and the building orientation effect. In alignment with the findings of [10–13], the building orientation governs the distribution of solar radiation incident on facades and regulates the overheating risk in summer, and exerts a more nuanced and season-dependent influence [14]. Across the winter, the low sun angles provide deep penetration of beneficial radiation, while high summer sun angles need solar protection. Also, combining the effects of glazing, orientation, and wall-to-window ratio (WWR) on cooling demand underscores climatic sensitivity in hot semi-arid climates [15]. Alwetaishi M. [16], in the study conducted in Saudi Arabia's hot-dry, hot-humid, and moderate regions, reveals that south and east facades illustrated the highest heat gains, with the application of 10% of WWR for hot-dry / hot-humid climate and 20% for moderate climate. Consequently, it is crucial to consider sun movement, latitude, and expected shading effect in building direction selection [17]. Additionally, Mirrahimi et al. [18] through the study conducted in the Malaysian tropical climate, indicate that south and north orientations generally provide balanced daylight without excessive glare, while optimal orientations increase daylight penetration and reduce artificial lighting needs. In contrast, east-facing direction exhibits glare and overheating in hot-humid climates. According to Liu et al. [18], bio-based thermal insulation materials is a composite thermal insulation materials composed solely of naturally sourced biological materials, including forest/agricultural residues, recycled materials, and fast-growing economic plants, or formed by mixing these materials with binders and additives in specific proportions. Besides, bio-based insulation materials are emerging as promising alternatives with lower carbon emissions and good thermal performance [19]. In this regard, the study concludes that straw products have the potential to decarbonize opaque elements of the envelope, reducing operational and embodied energy of buildings. Furthermore straw bale embodied carbon varied between 101.2 and 146.5 kg CO₂ eq/m³ [20]. In addition, renewable insulation materials, such as those made from straw, seaweed, grass, reed, and recycled jute fibers, have shown fewer environmental impacts compared to conventional materials, particularly in terms of GHG emissions [21]. Many countries have developed guidelines to further promote the widespread adoption of straw bale construction, such as the USA [22], Germany [23], France [24], and the UK [25]. As a result, Verbeeck G. and Ponet J. [26] have found that straw bale constructions maintain indoor temperatures between 15 °C and 28 °C despite outdoor fluctuations in the Mediterranean, Oceanic, and humid-tropical regions. Sabapathy K.A. and Gedupudi S. [27], and Koh C.H.A. and Kraniotis D. [28], underline the comparative thermal performance of fiber orientation of straw bale and highlight that randomly and perpendicularly fibers to the heat flow displayed similar thermal insulation properties and trends, while the parallel-oriented samples showed distinct differences; Specifically, under high humidity conditions of 80% RH, thermal conductivity values increase respectively by 1.5 to 2.5 times compared to the dry state. Notably, Domenico Palladino et al. [29], through the research conducted in Italy, describe the use of straw bales in walls and exhibit heating and cooling reduction, respectively, of 4–10% and 40–50%.

The integration of PCMs into construction materials improves

thermal regulation, promoting energy efficiency and indoor thermal comfort [30]. In this context, PCM can be embedded in the wall, roof, and floor to enhance the indoor environment. According to the outcome from literature, Riyadh Alturki et al. [31] note that integration of 5Wt% of Microencapsulated Phase Change Material (MPCM) reduced the maximum internal surface temperature from 37.2 °C to 32.1 °C and increased its minimum temperature from 10 °C to 19.8 °C. Furthermore, daily power consumption decreased by 16.24% when 5 wt% MPCM was utilized compared to conventional concrete. Also, performing PCM in inner cavities of hollow brick walls strengthens thermal inertia, cutting the decrement factor from 12 to 17% to 2%, increasing time lag from 1.5 to 2.0 h to 6.2–6.5 h, and lowering peak heat flux from 35 to 39 W/m² to 19–26 W/m² [32]. As stated by Ghafoorian F. et al. [33], three-layer PCM brick cuts peak indoor temperature swings by up to 4 °C in summer, while a single-layer design lets the wall hit peak temperatures about 2 h earlier and up to 5 °C. PCMs are divided into three groups, including organic, inorganic, and eutectics [34]. From this perspective, paraffin as organic PCM demonstrated its performance through the research of Naif Albelwi et al. [35], the integration of pentadecane paraffin 9% into the brick reduces the fluctuation of Temperature inside the surface compared with the no-PCM wall, and attenuates the heat flux respectively by up 11% and DPC by 12–15%. Additionally, paraffin incorporated into the roof and wall reduced average indoor temperature fluctuation by 5–6 °C and the thermal load leveling by 38–59% compared to a room without PCM [36]. This paper aims to develop a measured thermal and energy efficiency gap between conventional elementary school and the performance of passive cooling strategies in a tropical environment, including PCM, straw bale insulation, and building orientation. The study integrates the main conditions of indoor climate quality, such as thermal inertia, solar exposure, and insulation properties. This research is based on the integration of these three passive approaches, while literature perform building orientation, straw bale insulation, and PCM separately. The current study provide practical approach and analysis for policymakers, architects, and engineers in order to support knowledge dissemination of passive cooling principles under rainy and dry seasons for school buildings in hot-humid climates. The bio-based and locally available materials developed in this proposed framework strengthen the circular economy by valorizing agricultural waste as sustainable resources for low-income tropical regions.

2. Materials and methods

This paper is based on two approaches, including a quantitative strategy, which is useful for recording all the environmental parameters such as air temperature, relative humidity. The second one is the numerical method focused on Design Builder software using Energy Plus as the simulation engine. This study is conducted in two public schools dominated by tropical climates, respectively Ambohimitsinjo and Mangarivotra elementary schools. ASHRAE guideline 14 is employed for model calibration, before performing three passive strategies for improving indoor thermal comfort like BioPCM, straw bale insulation and building orientation effect.

2.1. Climatic condition

This research is performed in Antsiranana, Madagascar, which is influenced by a tropical climate. The outdoor temperature range from 18.4 to 33.9 °C while the relative humidity fluctuate from 53 to 90%. Also the wind speed oscillate from 6 to 37 Km/h. According to Köppen-Geiger climatic classification [37], the city is characterized by tropical monsoon (Aw/Am).

2.2. Design configuration

The study designs are based on the official school building plan, created by the National Ministry of Education of Madagascar. The

building wall is constituted by the specific material of the northeast coast of the country which is illustrated by the concrete block with 20 cm of thickness. The roof can be sloped and made of galvanized corrugated steel sheet, such as the case of Ambohimitsinjo School. The building may also consist of terrace roofing like the case of Mangarivotra elementary school. The classroom has 56 m² and can include metal or aluminium joinery. Ambohimitsinjo is equipped by pine wood as ceiling and take advantage of shading effect generating by tree and two building surroundings in west side. The both school are oriented in the west and all descriptions are summarized in the Fig. 1.

2.3. Numerical simulation

The numerical approach is built on the use of thermal software to evaluate the indoor climate of the studied buildings. As part of this study, Design Builder is employed to highlight the indoor thermal comfort of the studied buildings. According to the DesignBuilder 5 Manual user [38], this software is a user-friendly thermal simulation and building energy modeling that enables users to efficiently perform and explore building performance analyses. The main applications include calculation of building energy consumption, thermal simulation of buildings, prediction of daylight distribution using the radiance engine, sizing of heating, air conditioning, and cooling equipment, Computational fluid dynamics, and life-cycle cost assessment. In alignment with the findings of Andreas KARITNIG and Phil. Peter KNOL [39], Table 1 describes the specificity of DesignBuilder. (See Tables 2–4.)

Among the studied schools, the Mangarivotra Primary School has a unique feature. The school's layout consists of two symmetrical classrooms with a washroom in the middle, creating a large open space. Design Builder cannot handle this open space because the interior thermal comfort study is based on enclosed areas. Therefore, the model will be treated as a single zone, focusing solely on one classroom. All cantilevered elements are directly factored into the shading effects. Weather conditions are considered through the "site" in Design Builder and are integrated using annual hourly climate data in epw format obtained from Meteorom. The both studied building are modeled in DesignBuilder, as illustrated in Fig. 2. (See Fig. 3.)

Based on the materials properties used in the both schools, the following tables illustrate the thermal performances, U-value and input parameters.

As heat transfer forms the basis of thermal comfort evaluation, all the main equations used by DesignBuilder are summarized below, in accordance with [40,41].

Conduction through the wall

$$q''_{ki}(t) = -Z_0 T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_0 T_{0,t} + \sum_{j=1}^{nz} Y_j T_{0,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \quad (1)$$

for the inside heat flux.



Table 1
Specificity of DesignBuilder.

Aspect/characteristic	DesignBuilder
Origin/développement	Commercial modeling environment using the EnergyPlus simulation engine
Initial Objective	Provide a user-friendly interface for EnergyPlus
Fundamental concept	Modeling hierarchy: site, building, block, zone, surface, opening
Architecture	Graphical interface based on EnergyPlus; data inheritance across the hierarchy
Flexibility	User-friendly graphical interface; option to export in IDF format for external use
Input files	Original file (.dsb); generates an IDF for EnergyPlus
Graphical interface	Complete graphical interface for geometry, construction, time-based activities, and simulation
Representation of systems	Extrusion of 3D shaped blocks; areas defined by partitions; automated calculation of surfaces and volumes.
Simulation approach	EnergyPlus runs in the background; results are displayed directly in DesignBuilder
Post-processing	Results displayed directly in the interface; inherits EnergyPlus reporting capabilities; connection with Excel

$$q''_{k0}(t) = -Y_0 T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + Y_0 T_{0,t} + \sum_{j=1}^{nz} X_j T_{0,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{k0,t-j\delta} \quad (2)$$

for the outside heat flux ($q'' = q/A$)

X_j = outside CTF coefficient, $j = 0, 1, \dots, nz$; Y_j = cross CTF coefficient, $j = 0, 1, \dots, nz$;

Z_j = inside CTF coefficient, $j = 0, 1, \dots, nz$; Φ_j = flux CTF coefficient, $j = 1, 2, \dots, nq$;

T_i, T_0 : inside and outside face temperature in K

q''_{k0}, q'' : conduction heat flux on outside and inside face in W/m^2

Outdoor convection

$$Q_c = h_{c,ext} A (T_{surf} - T_{air}) \quad (3)$$

Q_c = rate of exterior convective heat transfer in W; T_{surf} = surface temperature in K

$h_{c,ext}$ = exterior convection coefficient $W/(m^2K)$; A = surface area in m^2

T_{air} = outside air temperature in K

EnergyPlus has developed many methods, including simple combined, TARP algorithm, MoWITT algorithm, and DOE-2 model for



Fig. 1. The studied building schools, Mangarivotra (left) and Ambohimitsinjo (right).

Table 2
Thermal properties of materials.

Materials	Thickness [m]	Thermal conductivity [W/(m.K)]	Density [Kg/m3]	Specific heat [J/(kg.K)]	Carbon footprint [KgCO2/kg]
External wall					
Cement coating	0.015	0.88	1800.00	896.00	0.05
Concrete block	0.20	0.51	2000.00	1000.00	0.11
Cement coating	0.015	0.88	1800.00	896.00	0.05
Roof terrace					
Waterproof membrane	0.02	0.23	1100.00	1000.00	0.066
Floor in reinforced concrete	0.10	1.13	2500.00	1000.00	0.198
Cement coating	0.015	0.88	1800.00	896.00	0.228
Ground floor					
Screed	0.02	0.88	1800.00	896.00	0.05
Cast concrete	0.08	1.13	2300.00	1000.00	0.198
Stone basalt	0.15	0.36	2600.00	840.00	0.08
Sloped roof					
Steel sheet		50.00	7800.00	450.00	1.46
Air gap	0.10	0.15	1.20	1008	0.00
Pine wood	0.03	0.14	500	2300	0.36

Table 3
U-value of the material layers assembly.

Material layers assembly	U-Value W/(m ² K)
External wall	1.646
Roof terrace	3.008
Ground floor	1.389
Sloped roof	1.868

Table 4
Input parameters.

Parameters	Mangarivotra school	Ambohimitsinjo school
Activity template	School	School
Density (m ² /people)	1.1	1.1
Activity (Met)	1.00	1.00
Clothing (Clo)	0.50	0.50
Fresh air (l/s-personne)	10.00	10.00
Occupancy schedule	Monday to Friday 7:30–11:30 a.m. 2:30–5:30 p.m	Monday to Friday 7:30–11:30 a.m. 2:30–5:30 p.m
Construction template	Projet construction template	Projet construction template
Air tightness (ac/h)	0.70	0.70
Glazing template	Glazing project	Glazing project
Glazing type	Aluminium	Simple glazing and frame in metal
HVAC	Natural ventilation	Natural ventilation

calculating the exterior convection coefficient.

Convection to zone air

$$q''_{conv} = h_c(T_s - T_a) \quad (4)$$

q''_{conv} = heat transfer rate per unit area in W/m²

T_s, T_a : surface and air temperature in K

h_c : convective heat transfer coefficient in W/(m²K)

Outside surface heat balance

$$q''_{sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \quad (5)$$

q''_{sol} : absorbed direct and diffuse solar radiation heat flux in W/m²

q''_{LWR} : net long wavelength radiation flux exchange with the air and surroundings in W/m²

q''_{conv} : convective flux exchange with outside air in W/m²

q''_{ko} : conduction heat flux into the wall in W/m²

Inside heat balance

$$q''_{sol} + q''_{LWX} + q''_{conv} + q''_{ki} + q''_{sw} + q''_{LWS} + = 0 \quad (6)$$

q''_{LWX} : net longwave radiant exchange flux between surfaces in a zone in W/m²

q''_{sw} : net short wave radiation flux to surface from lights in W/m²

q''_{LWS} : Longwave radiation flux from equipment in a zone in W/m²

q''_{ki} : Conduction flux through the wall in W/m²

q''_{sol} : Transmitted solar radiation flux absorbed at the surface in W/m²

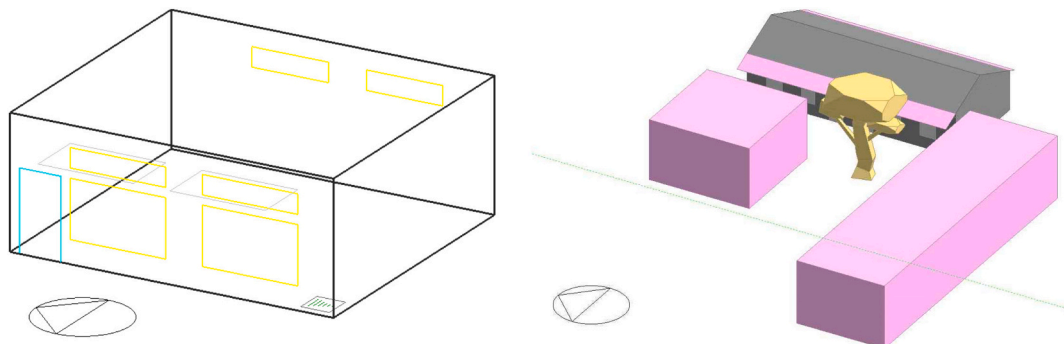


Fig. 2. Buildings modeling on DesignBuilder, Mangarivotra (left) and Ambohimitsinjo (right).



Fig. 3. In-situ measurements taken via Arduino recorder, Ambohimitsinjo (left) and Mangarivotra (right).

q''_{conv} : Convective heat flux to zone air in W/m^2

According to Gilbert Larochelle Martin and Danielle Monfet [42], EnergyPlus has developed many algorithms for outside and inside convective heat transfer coefficients, as presented in Table 5. (See Table 7.)

2.4. Quantitative approach

Arduino is an open-source electronic prototyping platform that allows the creation of interactive objects using programmable electronic boards. It is used to assess the indoor and outdoor environment of study buildings and allows the measurement of thermal parameters such as air temperature and relative humidity. The Arduino recorder is configured to provide air temperature and relative humidity readings every 2 s. The DHT22 sensor is connected to the Arduino and provides continuous measurements of air temperature in °C and relative humidity in %. A 32GB SD card is used to store the data every 30 min. An LCD screen is also exploited to view the recorded data. Measurements are taken during school hours, from 7:30 to 11:30 a.m. and from 2:30 to 5:30 p.m. The experiment lasted one month for all schools and will run from September to October 2025 for the Ambohimitsinjo and Mangarivotra Primary Schools. The instrument is placed in an area with a high concentration of students and positioned 1.00 m above the finished floor, as shown in the following figures.

2.5. Model calibration

The model calibration is based on the comparison between measurement from Arduino recorder and simulation through DesignBuilder software, during the school hours ranging from 7:30 to 11:30 in the morning, while the afternoon spanned from 2:30 to 5:30. Mean value per hour during one month ranging from September and October 2025 is

Table 5
Convective heat transfer algorithm [42].

Algorithm	Variables	Details
Simple TARP	Constant $f(\Delta T, \theta)$	Developed for natural convection cases Only surface tilt angle and temperature are considered
Ceiling diffuser	$f(ACH)$	Developed for an isothermal room with a cold ceiling jet
Adaptive convection	$f(\Delta T, \theta, ACH, D_h, H, T_{si}, T_{SA}, R_a, k, V, L)$	Algorithm available for finer control over the model used for particular surface (outside and inside face) classified with 4 different categories and depending on the current wind orientation and heat flow directions [40].
ASTMC1340	$f(Gr, Pr, Ra, Re, \theta, k, L)$	Developed for attic space

Table 6
Describing scenarios.

Scenarios	Description
0	Original configuration
1	Wall/roof embedded by BioPCM
2	Wall/roof embedded with straw bale insulation
3	Variation of building orientation

Table 8
Specification and thermal Properties of studied PCM [30].

Parameters	PCM type	BioPCM	InfiniteR PCM	Winco Enerciel PCM
Origin		Organics	Inorganics	Eutectic mixture
Melting temperature [°C]		21, 23, 25, 27, 29	18, 21, 23, 25, 27, 29	21, 23, 29
Latent heat of [J/g]		250	200	175
Specific heat [J/Kg.K]	Liquid	1970	2000	2200
	Solid	4500	3140	2500
Thermal conductivity [W/m.K]	Liquid	0.15	0.54	0.148
	Solid	2.5	1.09	1.8
Relative density [Kg/m³]	Liquid	850	929	832
	Solid	1400	1540	1170
Thickness [cm]		1, 2.1, 3.7	2, 4	0.3
Containment		Macro-encapsuled	Macro-encapsuled	Micro-encapsuled (Interior coating)

Table 9
PCM melting point recommendation [43].

Climate type	Main objective	Recommended PCM melting temperature	Typical PCM placement	Recommended thickness
Hot-dry	Reduce overheating and delay heat flow	28–35 °C	Roof, external walls	20–50 mm
Hot-humid	Limit indoor temperature peaks	26–32 °C	Internal walls, ceilings	15–40 mm

employed for measured and simulated analysis. According to ASHRAE guideline 14 [54], errors metrics such as Mean Bias Error (MBE) and Root Mean Square Error are applied to calibrate the models, as described in the following equations:

Table 10
PCM sub-scenarios.

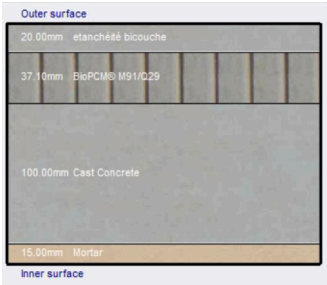
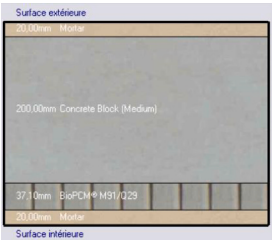
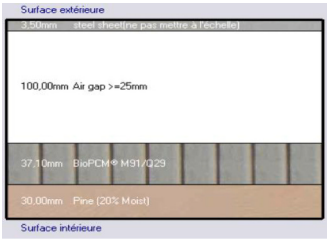
Parameters	Walls	Roofing
Sub-scenario1: wall+PCM Sub-scenario2: roof+PCM	BioPCM M91/Q29 embedded with wall	BioPCM M91/Q29 embedded with sloped roof for Ambohimitsinjo and roof terrace for Mangarivotra
Photo illustration (Mangarivotra)		
Photo illustration (Ambohimitsinjo)		

Table 11
Thermal properties of straw bale insulation.

λ [w/m.k]	ρ [kg/m ³]	Specific heat [J/kg.K]	Carbon footprint [kgco2/kg]	Fiber orientation	References
0.044	90–110	1400–2000	1700	Perpendicular	[44,45]
0.067	90–110	1400–2000	1700	Parallel	[44,45]
0.06	133	753.5		Parallel	[46]
0.041	80			Perpendicular	[47]
0.044	81–111			Perpendicular	[48]
0.067	105			Parallel	[49]
0.063	65.7			Parallel	[50]

$$MBE (\%) = 100 \frac{\sum_{i=1}^n (m_i - s_i)}{\sum_{i=1}^n m_i} \quad (7)$$

where i : is the measured value at instant i ; s_i is the simulated value at instant i ; n : the total number of data points.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (m_i - s_i)^2}{n}} \quad (8)$$

$$CV(RMSE) (\%) = 100 \frac{RMSE}{M} \quad (3)$$

where M is the average of the measured value and determined by this equation

$$M = \frac{\sum_{i=1}^n m_i}{n} \quad (9)$$

On the other hand, hourly indoor temperature and relative humidity parameters are adopted for calibration, as presented in Fig. 4.

The collected data indicate that indoor environmental parameter depend not only on the climate of the case study but also on the school configuration. A clear trend was observed whereby indoor air temperature increase gradually in the morning and reach peak around 11:00 a.

m. to 2:00 p.m. and decrease until the school dismissal time around 5:30 p.m. These findings describe a concave curve, where the minimum observed in the entry time can no longer be reached when the exit time take place. This difference is due to the thermal time lag of the materials in releasing heat, acquired through heat transfer. Additionally, calculating the error parameters, the MBE range from -0.315% and -0.06% , respectively for Ambohimitsinjo hourly indoor air temperature and relative humidity while Mangarivotra ranged from -0.811% and -0.46% . As a complement for both physical variables, CV (RMSE) fluctuate from 0.988% and 1.907% in Ambohimitsinjo, and from 1.343% and 1.435% in Mangarivotra. As all the hourly data: $MBE < \pm 10\%$, CV (RMSE) $< \pm 30\%$ specified by ASHRAE are verified, the findings highlight the greatest calibration of the models.

In-situ measurements were conducted over a one-month period during school hours, particularly from 7:30 to 11:30 a.m. and 2:30 to 5:30 p.m., to calibrate the numerical models of the studied schools. Following model validation in accordance with ASHRAE Guideline 14 recommendations, annual simulations were performed using EPW-format weather files generated by Meteororm software; these files were subsequently utilized in DesignBuilder to run the thermal and energy simulations. This hourly data represents a typical climate year. Consequently, the validated and calibrated models made it possible to extrapolate the thermal, energy, and economic performance of various passive strategies over a full year.

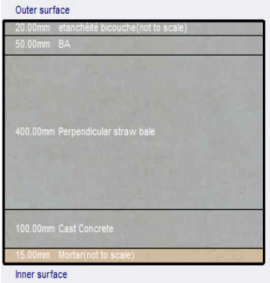
3. Results

3.1. Original configurations

As the both models are perfectly calibrated, the followings figures reported the comfort result for the studied buildings during one year. The finding is based on the occupancy period ranging from 7 a.m. to 6 p.m. for one year. As the heat transfer operate during holiday time, dry and rainy seasons are presented to have accurate analysis. Many parameters such as Indoor air temperature and relative humidity are analyzed for comfort evaluation.

Fig. 5. is focused on the evolution of simple environmental parameters such as indoor air temperature and relative humidity within the

Table 12
Sub-scenarios description.

Parameters	Roofing
Sub-scenario1: roff+perpendicular straw bale	Straw bale embedded with roof in the external position and where fibers are perpendicular to the heat flow
Sub-scenario2: roof+parallel straw bale	Straw bale embedded with roof in the external position and where fibers are parallel to the heat flow
Photo illustration (Mangarivotra)	Outer surface  Outer surface 
Photo illustration (Ambohimitsinjo)	Surface extérieure  Surface extérieure 

studied school. It is very important to highlight the indoor thermal comfort of school buildings. On the other hand, The Givoni [55] describes the comfort zone boundaries of a naturally ventilated building, subject to air velocities between 0 and 0.5 m/s, to better assess the results. In this sense, P. O. Fanger [56], stated that human beings are not only sensitive to the dry air-bulb temperature but also the air relative humidity, the mean radiant temperature, the air velocity, the personal clothing, and the activity level. For this reason, ASHRAE 55 recommends using operative temperature, which combines air temperature and radiant temperature, for a more accurate understanding for naturally ventilated environment.

In this study, both schools feature concrete block as envelope; Mangarivotra has a reinforced concrete roof terrace, while Ambohimitsinjo exhibit a pitched roof made of corrugated galvanized steel. Ambohimitsinjo's roof appears more thermally vulnerable, though heat transfer is mitigated by a pine-wood ceiling and a 10 cm air gap. Additionally, the surrounding environment provides shading effects from neighboring buildings and a massive tree located at the western entrance. The situation at Mangarivotra appears more complex due to the unbalanced ratio of openings between the front and rear facades, and the choice of sliding aluminium windows, which reduces the effective opening area by 50%.

It was observed that the indoor environment varied between the different schools. Indoor air temperature and hourly relative humidity ranged from 26.60 °C to 32.85 °C and 54.36% to 83.02% for Ambohimitsinjo, while Mangarivotra span from 27.11 °C to 35.25 °C and 50.50% to 74.21%. Given the effects of solar radiation on the building envelope and roofs during the day, the radiant temperature was higher than the indoor air temperature. The data collected indicated an inverse correlation between indoor air temperature and relative humidity. As the temperature increased, the relative humidity decreased, and vice versa. Both schools face west due to the topography of their sites and a tight budget. Lacking any sun protection measures, they allow glare from sunlight inside the buildings, resulting in a feeling of discomfort experienced by the occupants. The city of Antsiranana has a tropical climate dominated by two seasons: dry and rainy seasons. This situation is quite difficult for users, as the sun's path is rather low during the rainy season, generating a significant impact, especially in the afternoon.

Consequently, many schools, such as the Mangarivotra Primary School, eliminate afternoon pre-class assembly queues and even remove students' undergarments, requiring only smocks. Geographically, Antsiranana is subject to high humidity due to its tropical climate. The choice of sliding doors for the Mangarivotra Primary School is also less effective, reducing the opening area by 50%, which is one of the causes of overheating inside the rooms. There is as well a disproportionate distribution of opening rates, with 37.34% on the main facade and 7.86% on the rear facade. The psychrometric analysis of these schools highlights climatic dynamics specific to a hot climate, which directly affect the indoor environment of the occupants. The average enthalpy values ranged from 73.16 kJ/kg to 77.24 kJ/kg for Ambohimitsinjo, and 69.97 kJ/kg to 82.15 kJ/kg for Mangarivotra. These values are both outside the ranges of human comfort, which vary from 31.02 kJ/kg to 68.12 kJ/kg and are below 50 kJ/kg for hot periods, as specified respectively by Firmo Sousa Campos et al. [57] and Toftum J. et al. [58]. All of this reflects an increase in latent and sensible heat loads. Wet-bulb temperatures for the schools range from 20.87 °C to 25.70 °C (Mangarivotra Primary School) and from 21.01 °C to 24.23 °C (Ambohimitsinjo Primary School). However, these ranges do not exceed the maximum permissible wet-bulb temperature and the limits tolerable by humans, which are 35 °C [59]. According to [60–62], wet-bulb temperature characterizes the evaporative capacity of human skin, which is linked to the combination of temperature and humidity. Indeed, when the indoor climate is warmer and more humid, the body's ability to cool itself decreases.

3.2. Improvement scenarios

As indoor comfort is not achieved during the teaching period for both studied schools, three scenarios are developed, as reported in Table 6.

3.2.1. Scenario 1

In tropical regions, passive thermal comfort strategies play a crucial role, particularly in educational settings where thermal discomfort can negatively impact the quality of teaching. Phase-change materials offer ingenious solutions by absorbing heat when their melting point is reached. Several studies have demonstrated their remarkable potential in various heat transfer and energy storage applications, notably

Table 7
PCM heat transfer equation.

Parameters	Equations	Description	References
Energy balance equation for PCM	$\frac{\partial}{\partial t}(\rho H) = \nabla \cdot (k \nabla T) + q_{int}$	ρ is the density (kg/m³) T is the temperature (K) k is the thermal conductivity (W/m.K) H is the enthalpy of PCM q_{int}, the internal heat generation rate (W/m³)	[40,51]
Enthalpy	$H(T) = H_{ref} + \int_{T_{ref}}^T C_p(T') dT'$	$H(T)$ is the enthalpy at the temperature T (J/Kg) H_{ref} is the reference enthalpy C_p is the specific heat capacity (J/Kg.K) T_{ref} is the reference temperature	[40,52]
Total load	$Q_{total} = Q_{conv} + Q_{cond} + Q_{rad} + Q_{int} + \frac{d}{dt}(mH)$	Q_{total}, total load (W) Q_{conv} is the convective heat flux (W) Q_{cond} is the conductive heat flux (W) Q_{rad} is the radiative heat flux (W) Q_{int} is the internal heat flux (W) m is the mass of PCM (Kg) H is the enthalpy PCM (J/Kg)	[40,53]
Heat capacity of PCM	$C_p = C_{p,solid}$ $C_p = C_{p,liquid}$	$C_{p,solid}$, for solid phase $C_{p,liquid}$, for liquid phase	[40,53]
Effective heat capacity of PCM	$C_p^{eff} = C_{p,solid} + \left(\frac{L}{\Delta T}\right)$	$C_{p,solid}$, heat capacity in the solid state L is the latent heat (J/Kg) ΔT is the temperature range over which the phase change occurs	[40,53]
Electricity consumption for cooling	$E_{cool} = COP_{cool} \times \frac{Q_{cool}}{\eta_{electric}}$	E_{cool} is the Electricity consumption for cooling (Kwh) COP_{cool} is the coefficient of performance for a cooling system Q_{cool} is the energy required for cooling (watts or kilowatts) $\eta_{electric}$ is the efficiency of electrical conversion by HVAC systems	[40,53]

examining their use as thermal storage media in refrigeration and air conditioning systems. The objective of this study is to highlight the thermal performance of BioPCM. The material will be integrated with the various building components (envelope, and roof) to evaluate its energy efficiency in the school building using numerical simulation based on DesignBuilder.

PCM heat transfer equation

PCM Heat transfer equation models in EnergyPlus are studied and summarized in the following table.

The PCM simulation in EnergyPlus is performed using a finite-difference (CondFD) conduction solution algorithm with varying thermal properties, calculated at internal nodes, as reported in [40,63,64]. This CondFD is based on two numerical schemes, namely the Crank-Nicolson and fully implicit schemes, which are described in eqs. (7)

and (8), respectively.

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2} \left(k_w \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} + k_w \frac{T_{i+1}^j - T_i^j}{\Delta x} + k_E \frac{T_{i-1}^j - T_i^j}{\Delta x} \right) \quad (10)$$

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(k_w \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right) \quad (11)$$

T is the node temperature; Δt , the calculation time step; Δx , finite difference layer thickness.

C_p , the specific heat of material; k_w , the thermal conductivity for interface between node i and node $i + 1$; k_E , the thermal conductivity for interface between node i and node $i - 1$; ρ is the density of material; i is the node being modeled; $i + 1$ is the adjacent node to interior of construction; $i - 1$ is the adjacent node to exterior of construction; $j + 1$ is the new time step; j is the previous time step.

These described nodes are illustrated in Fig. 6, following the findings of [40,65,66].

According to DesignBuilder specification [67] and Zeyad Amin Al-Absi et al. [63], the space discretization constant is « 3 », the time step « 2 min », relaxation factor « 1 » and the inside face surface temperature convergence criteria of « 0.01 ».

Choice of PCM

There are many kinds of materials employed for PCM to improve the indoor thermal comfort of school buildings. As reported by M. Jaradat et al. [30], Table 8 described the properties of PCM.

In alignment with DesignBuilder library, the following figures illustrate the correlation between enthalpy and temperature for different PCM type.

According to specifications in the literature, several commercially available phase-change materials exist: BioPCM, InfiniteR PCM, and WincoEnerCiel PCM. BioPCM is an environmentally friendly alternative to traditional PCMs, derived from renewable biomass sources and characterized by its non-toxicity and biodegradability [30]. In addition, among the various possible thickness configurations of BioPCM (11.2 mm, 20.8 mm, 37.1 mm), it has been observed that increasing the thickness of phase-change materials significantly contributes to reducing electrical energy consumption [30]. As the choice of PCM depend on the outdoor climatic condition and indoor temperature fluctuation within the school buildings, Fig. 8. Illustrates its climatic dataset.

It was observed for Ambohimitsinjo that indoor climate range from 23.97 to 28.48 °C during nighttime and 25.77 to 32.95 °C for daytime. Thus conducting to BioPCM M91/Q29, as PCM choice in the inner side of wall and roof. The melting point is so high, reflecting the tropical climate and a high temperature comfort under natural ventilation. All these factors enable PCM to melt during the daytime and freeze while the nighttime. During the hot season corresponding to the rainy period (November to April), Mangarivotra records high temperature fluctuating from 29.24 to 32.09 °C for the night period and 29.70 to 35.25 °C during the day period. Under these conditions, PCM cannot be effectively embedded on the inner side. Instead, it should be placed on the outer side where a strong diurnal temperature gradient exists, using BioPCM M91/Q29. The observed finding is consistent with the previous work of Mustafa Özdemir and Ayça Gülsen [68], who specify that PCMs with a melting temperature of 21 °C and 23 °C used in buildings did not affect the cooling load since they were in liquid form, due to the higher average air temperature in Elazığ, generally greater than 23 °C. Thus, conducting to the PCM at a melting temperature of 29 °C, which offers better energy performance than the melting points of 21 °C and 23 °C. The melting temperature of 29 °C was chosen to allow for the charging and discharging cycle of PCMs, ensuring the longevity and cost-

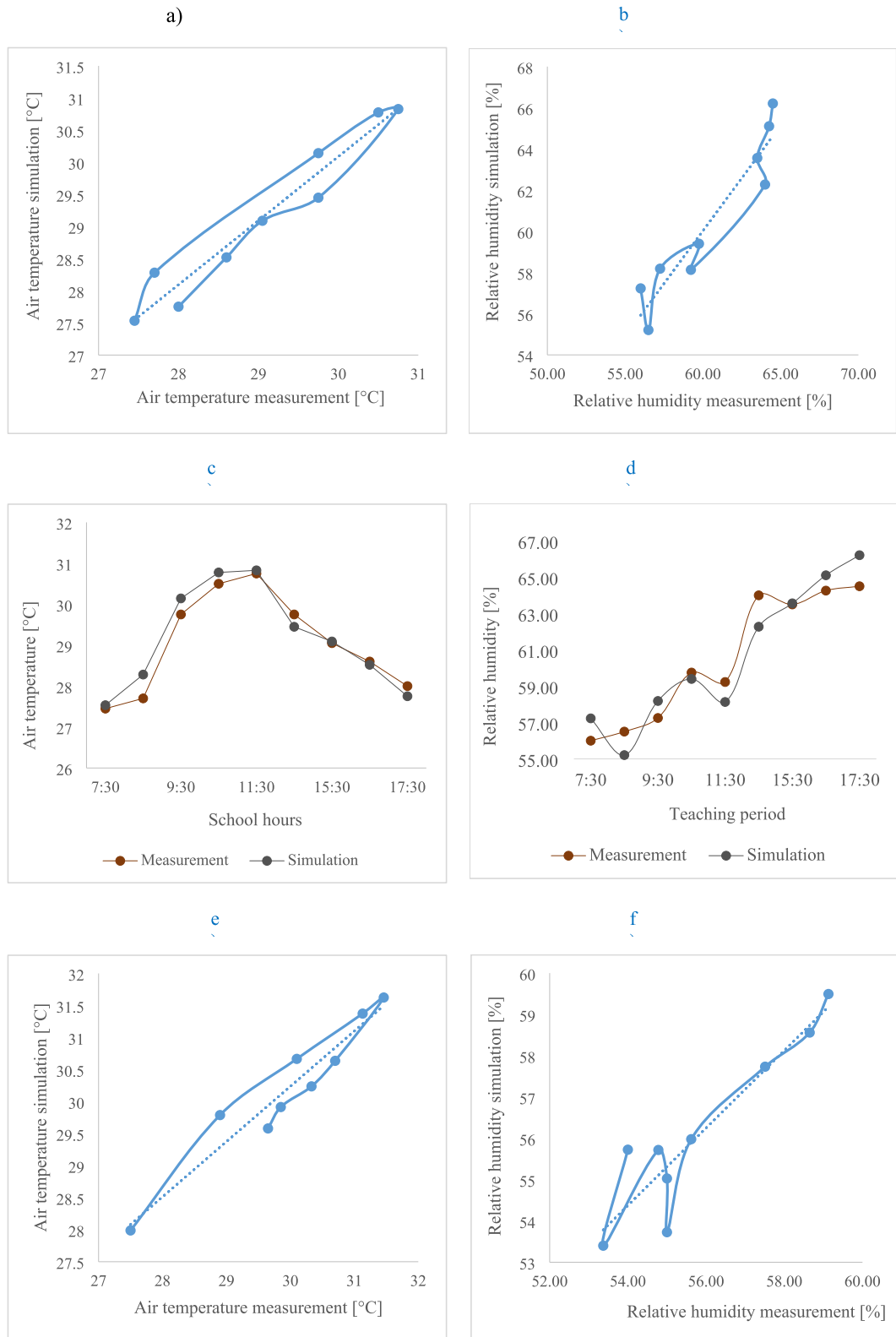


Fig. 4. Comparison between Arduino recorder and DesignBuilder software result. Ambohimitsinjo elementary school: a-b) correlation between measurement and simulation indoor air temperature and relative humidity; c-d) Temporal variation of indoor air temperature and relative humidity across the teaching period; Mangarivotra school: e-f) correlation between measurement and simulation indoor air temperature and relative humidity; g-h) Temporal variation of indoor air temperature and relative humidity across the school hours.

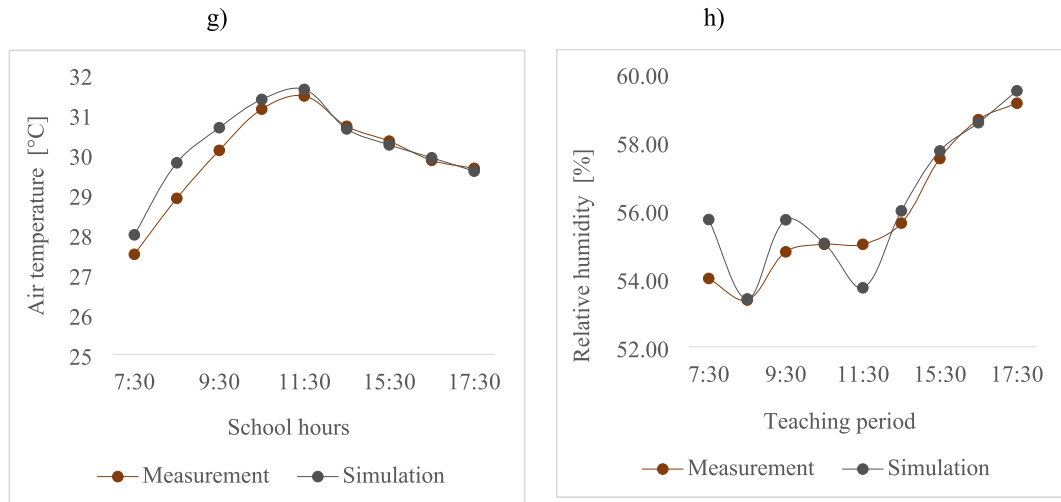


Fig. 4. (continued).

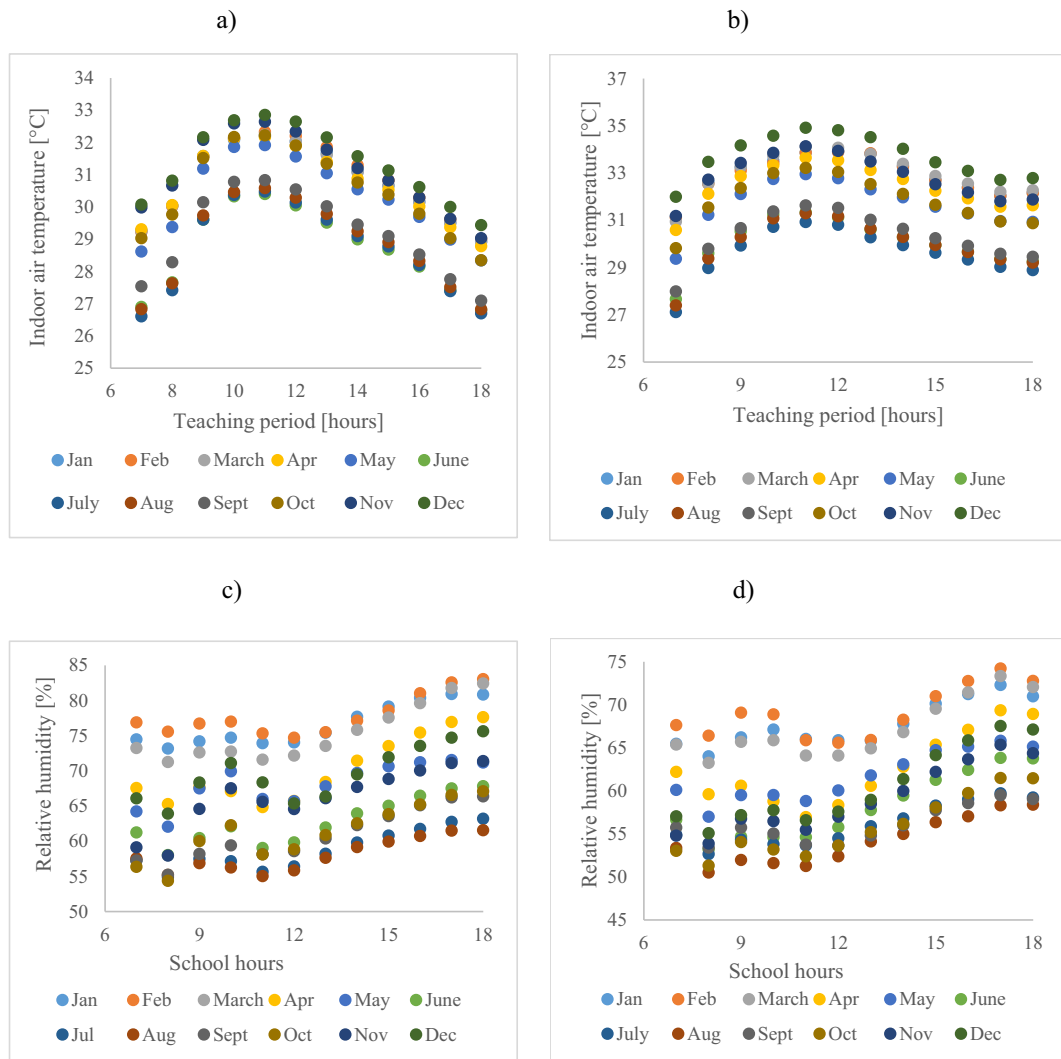


Fig. 5. Comfort result of the studied buildings, a-b) hourly indoor air temperature for Ambohimitsinjo and Mangarivotra; c-d) hourly relative humidity for Ambohimitsinjo and Mangarivotra.

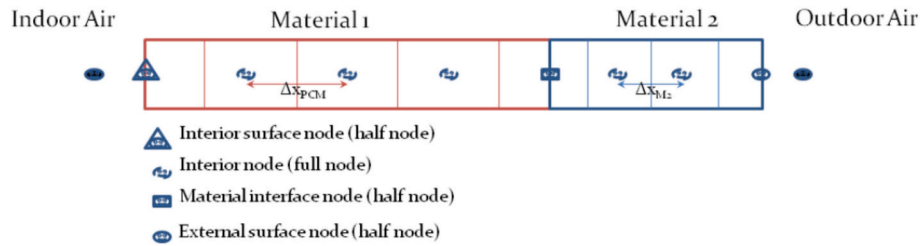


Fig. 6. Node depiction for CondFD model [40,65,66].

effectiveness of the materials. The melting temperature greatly depends on the indoor/outdoor diurnal temperature fluctuation. As the temperature is generally high during the day and lower at night, corresponding respectively to the liquid state when the indoor climate exceeds the melting condition and solidification when the temperature falls below this threshold. As confirmed by [69], the PCM absorbs latent heat during melting and releases it across freezing. This process phase-change enhances the performance of this modern passive system. A trend is observed whereby the melting temperature is elevated for a warm climate. In this context, Lei et al. [70] have found in the study conducted in a tropical climate, a melting point temperature of 28 °C, which can decrease the annual heat gains by 21% to 32%. As a complement, Jiang Liu et al. [71] determined the optimum PCM melting point temperature for 10 selected cities in western China during hot seasons, coupled with

night ventilation spanning from 23 °C to 29 °C, with the most favorable results observed in transition seasons where diurnal temperature differences exceed about 6.8 °C.

The BioPCM M91/Q29 was performed following these properties: 3.71 mm of thickness, 0.20 W/(m.K) of thermal conductivity, 1970 J/(kg.K) as specific heat, and with density of 235 Kg/m³. The materials adhere to the enthalpy-temperature relationship, which provided by DesignBuilder library through Fig. 7-a. As the PCM is incorporated with wall and roof, Finite difference algorithm was implemented for conduction transfer according to the recommendation of EnergyPlus [40]. (See Figs. 9–13.) (See Figs. 15–18.) (See Fig. 21.)

As stated by [72], solid PCMs melt when heated, and liquid PCMs solidify when cooled. Additionally, Sana Dardouri et al. [73], confirm that PCM with a high melting temperature of 29 °C favored cooling

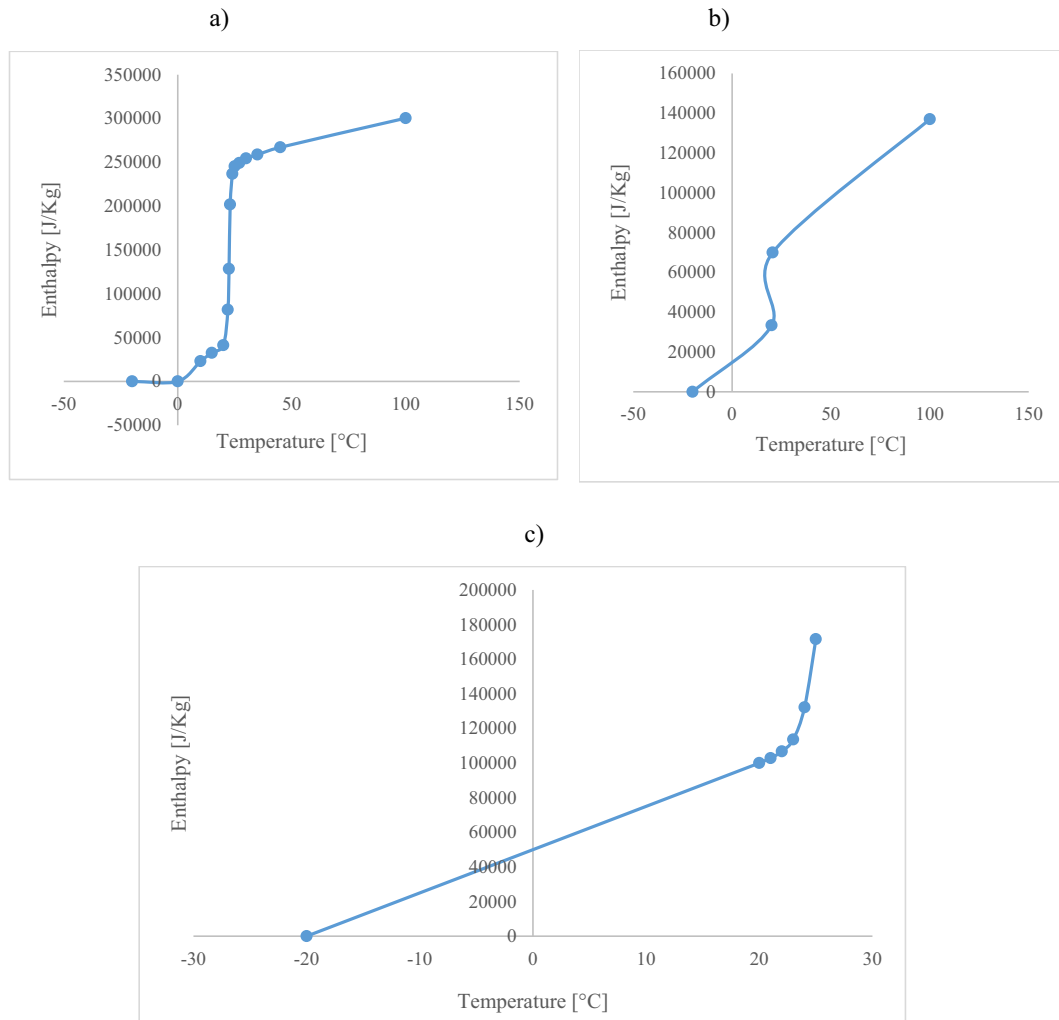


Fig. 7. Correlation between temperature and enthalpy, (a) BioPCM; (b) InfiniteRPCM; (c) Winco Enerciel PCM.

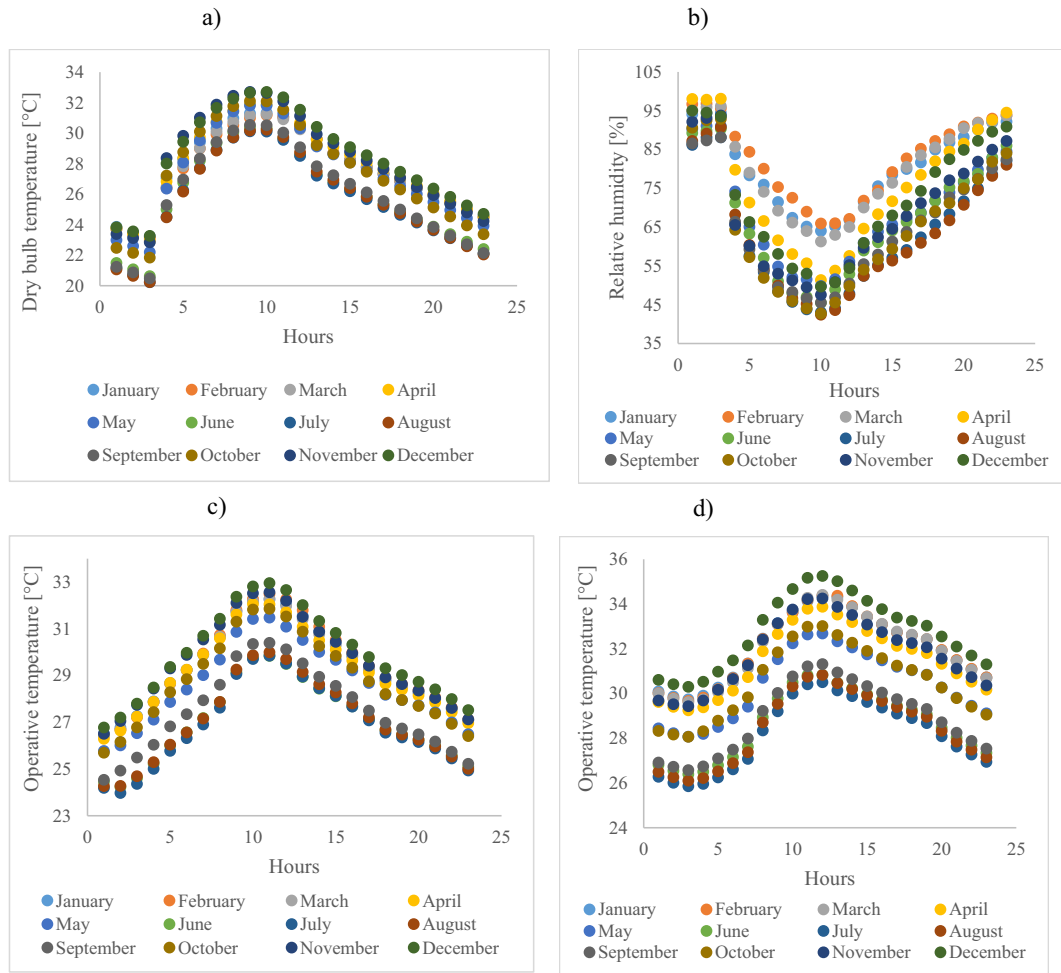


Fig. 8. Outdoor and indoor climatic environment, a) dry bulb temperature; b) outdoor relative humidity; c) Ambohimitsinjo operative temperature; d) Mangarivotra operative temperature.

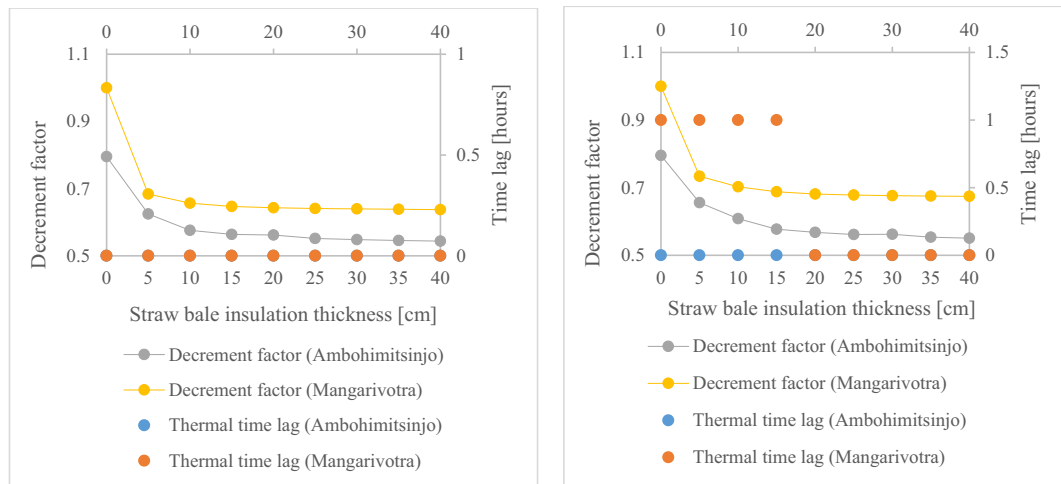


Fig. 14. Decrement factor and thermal time lag of different sub-scenarios of straw bale insulation for perpendicular (left) and parallel (right) case.

energy savings while PCM with a low melting temperature of 21 °C enhances heating energy savings. Moreover, Abdelkader Laafer et al. [43], describe in Table 9, the PCM melting temperature choice based on the climatic condition.

The collected data indicate that warm tropical climate such as Antsirana, exhibit relatively high melting temperature, where PCM can

be placed, closer to the inner side for Ambohimitsinjo case study and in the exterior layer for Mangarivotra school.

The optimization of the thermal performance of these studied schools is based on several sub-scenarios performing the quality of teaching, as illustrated in Table 10.

Scenario1 perform sub-scenario 1 including BioPCM of 37.1 mm

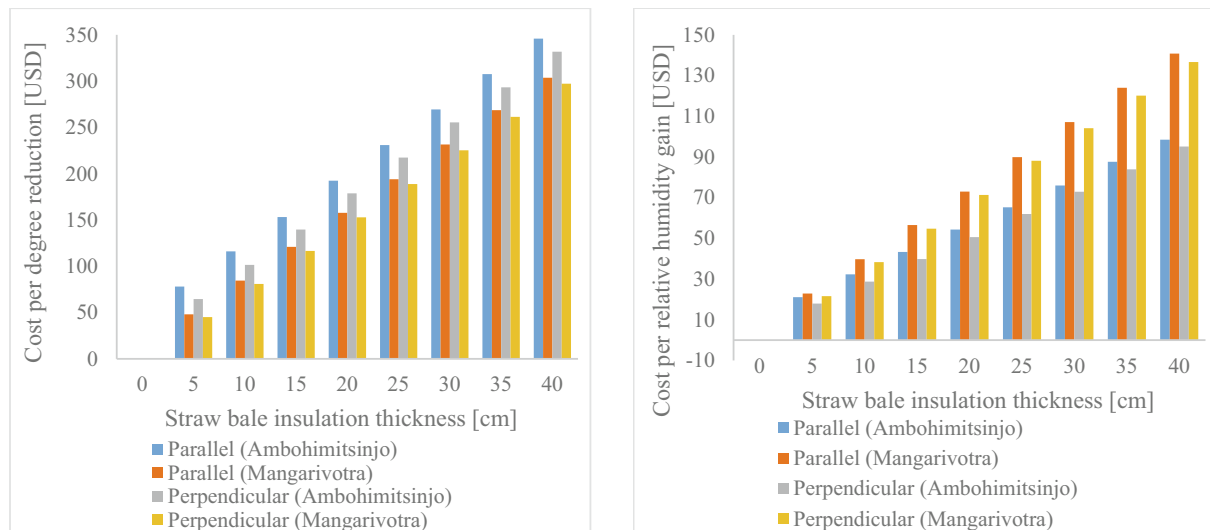


Fig. 19. Cost per degree temperature reduction (left) and cost per relative humidity gain (right).

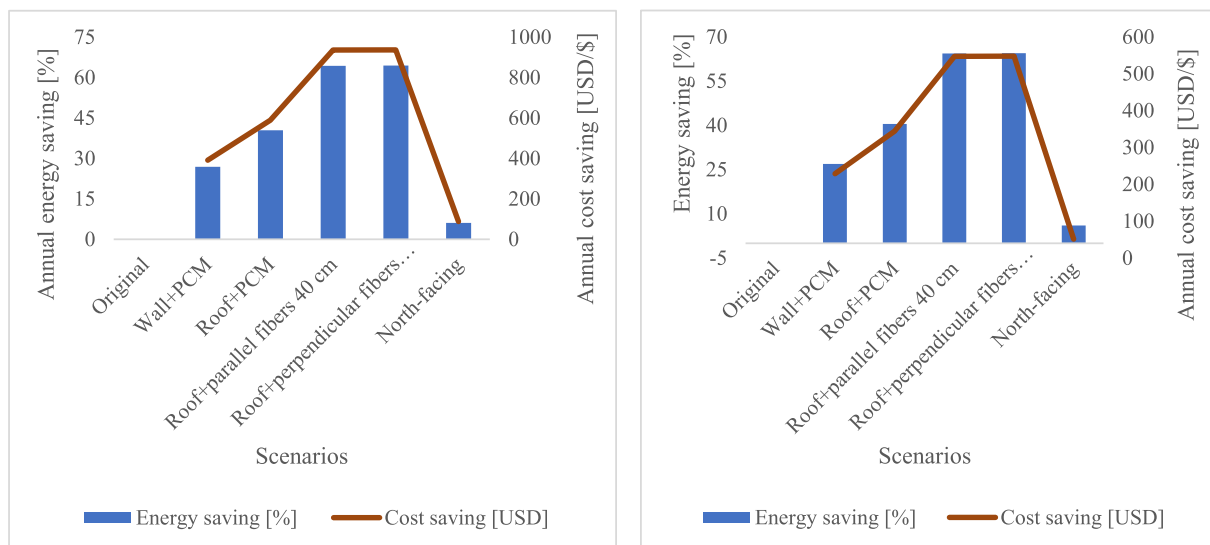


Fig. 20. Annual energy and cost saving for Ambohimitsinjo school under business electricity (left) and residential tariff (right).

with wall in the inner position followed by 200 mm of concrete block and 20 mm of cement coating for Ambohimitsinjo elementary school while Mangarivotra operate from outer to interior location with respectively 15 mm of render finish, BioPCM of 37.1 mm, 200 mm of concrete and 15 mm of finishing layer. Sub-scenario 2 develop materials incorporated the PCM with roof terrace in the outer location following this configuration waterproofing layer of 20 mm, BioPCM 37.1 mm, 100 mm of floor and 15 mm of mortar as coating. In the Other side, Ambohimitsinjo implement BioPCM closer the inner layer and succeeded by 100 mm of air gap and galvanized corrugated sheet metal.

Based on the simulation of the studied schools through the various scenarios developed, the following figures highlight the different results, including the comparisons with the original configuration.

Simulations show that phase change materials (PCMs) produce considerable effects and contribute to improving the indoor environment of schools. Two PCM sub-scenarios were analyzed: walls + PCM and roofs + PCM. During the hottest month, the first scenario shows a clear improvement in the indoor environment of both schools. Ambohimitsinjo recorded an operative temperature ranging from 28.29 to 30.67 °C, while the relative humidity fluctuated from 68.67 to 82.79%.

In contrast, at Mangarivotra, the operative temperature ranged from 31.17 to 34.11 °C, while the relative humidity ranged from 58.10 to 69.32%.

All of this corresponds to an increase in relative humidity from 3.34% to 11.69% in Ambohimitsinjo, compared to 1.80% to 3.12% in Mangarivotra. However, throughout the cooler season, Ambohimitsinjo exhibits an operative temperature between 25.96 and 28.57 °C and a relative humidity between 56.24% and 70.95%. Mangarivotra, on the other hand, shows a temperature between 26.72 and 30.01 °C and a relative humidity between 53.87% and 60.41%. All these parameters indicate a very comfortable indoor environment for both schools during the cooler period. A similar trend was observed in the work of Adetoye M. Aderinsola et al. [74], who noted that occupants exposed to tropical climates often reported a fairly high indoor comfort temperature, reaching up to 30 °C. Furthermore, Tajudeen Dele Mustapha [75], in a study on thermal comfort in a school exposed to a tropical climate, indicated a comfort temperature peaking at 31 °C. Other researchers have found similar results; for example, Hussein et al. [76] and Mishra and Ramgopal [77] highlighted comfort ranges varying from 26 to 30.7 °C and from 22.1 to 31.5 °C, respectively. Overall, Ambohimitsinjo

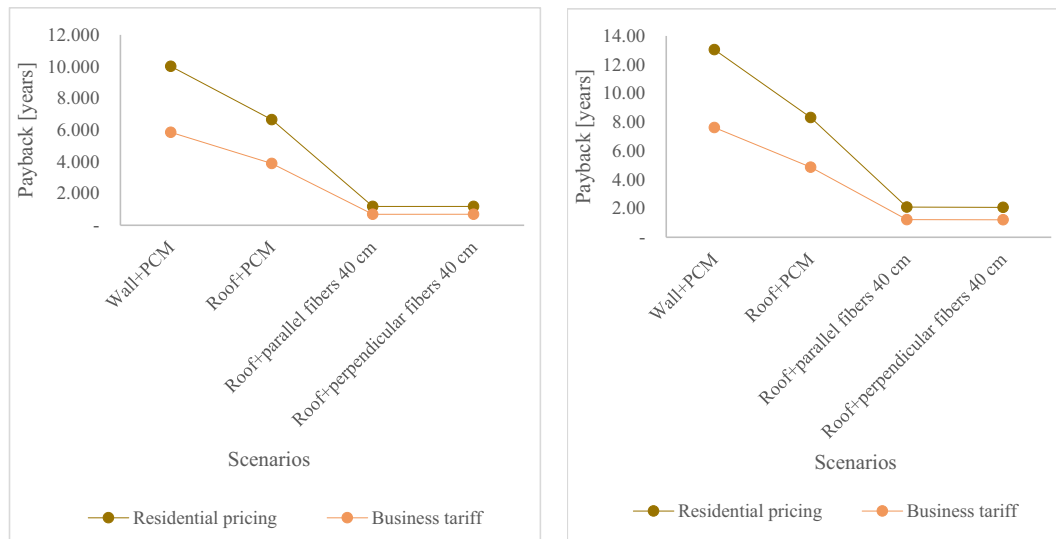


Fig. 22. Payback for Ambohimitsinjo elementary school (left) and Mangarivotra school (right).

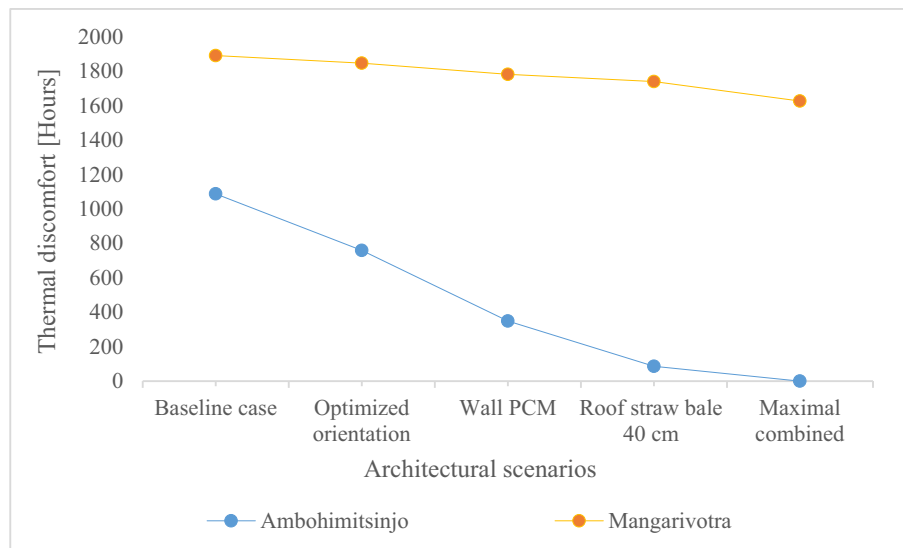


Fig. 23. Thermal discomfort hours.

remains comfortable through all seasons over the teaching period.

Furthermore, simulations show that the thermal resistance of the integrated PCM building envelope for both schools was improved by 31% compared to the original configuration. This optimization resulted in a decrease in maximum operative temperature 2.36 °C for Ambohimitsinjo and 1.19 °C for Mangarivotra. As Ambohimitsinjo records a comfortable indoor climate for sub-scenario 1, the roof+PCM improve the indoor thermal environment, respectively with gradient operative temperature from 0.69 to 2.60 °C. Consequently, the gradient of relative humidity fluctuates from 2.65 to 12.53%. Sub-scenarios 2 provide a significant reduction in operative temperature during both the dry and rainy seasons. Throughout the dry season (June, July, August, and September), occupants remain within the thermal comfort range, with operative temperatures varying from 26.61 to 30.35 °C and relative humidity ranging between 52.23 and 64.36%. On the other side, Mangarivotra perform an operative temperature between 30.77 and 33.31 °C and relative humidity ranging from 59.39 to 69.85%, during the hottest month. Therefore, sub-scenario 2, record a maximum indoor temperature reduction of 2 °C, while the relative humidity gain reach 4%.

A trend is observed whereby PCM has a significant effect on the indoor thermal comfort of school buildings. The PCM-incorporated building model decrease the heat loss, heat gain and the net heat balance. As clearly observed trending from simulation, the PCM with Mangarivotra elementary school exhibit the lowest annual energy saving than Ambohimitsinjo, with respectively 14.53% and 13% % for sub-scenario 2 and 1. This findings are consistent Muruganantham K. et al. [78], as they respectively found 12 to 26% for energy savings.

3.2.2. Scenario 2

According to the French Bio-based Construction Industries Association, between 2015 and 2023, bio-based materials (straw, hemp, and wood) saw a 93% increase in production volume in France. Bio-based insulation materials accounted for 11% of the market in 2023, up from 6% seven years earlier. This surge in demand stems from the imperative to decarbonize the building sector, driven by the new environmental regulations for new construction, known as RE2020 [79], which came into effect on January 1, 2022. Consequently, straw bales were chosen for this scenario because they are a 100% ecological material. Based on passive design strategies, the approach focuses

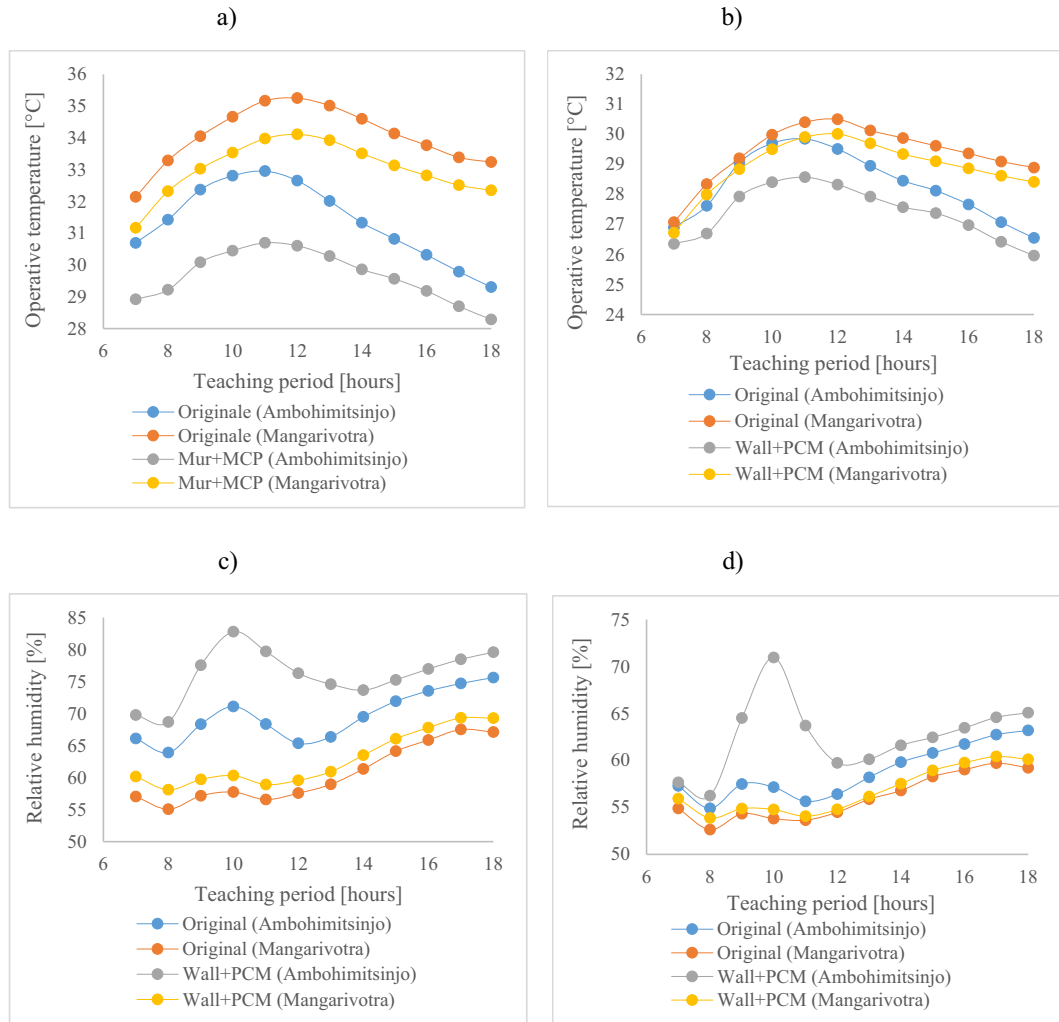


Fig. 9. Sub-scenario wall+PCM result, a) operative temperature during hottest period; b) operative temperature across coolest period; c) indoor relative humidity through december; d) indoor relative humidity over july.

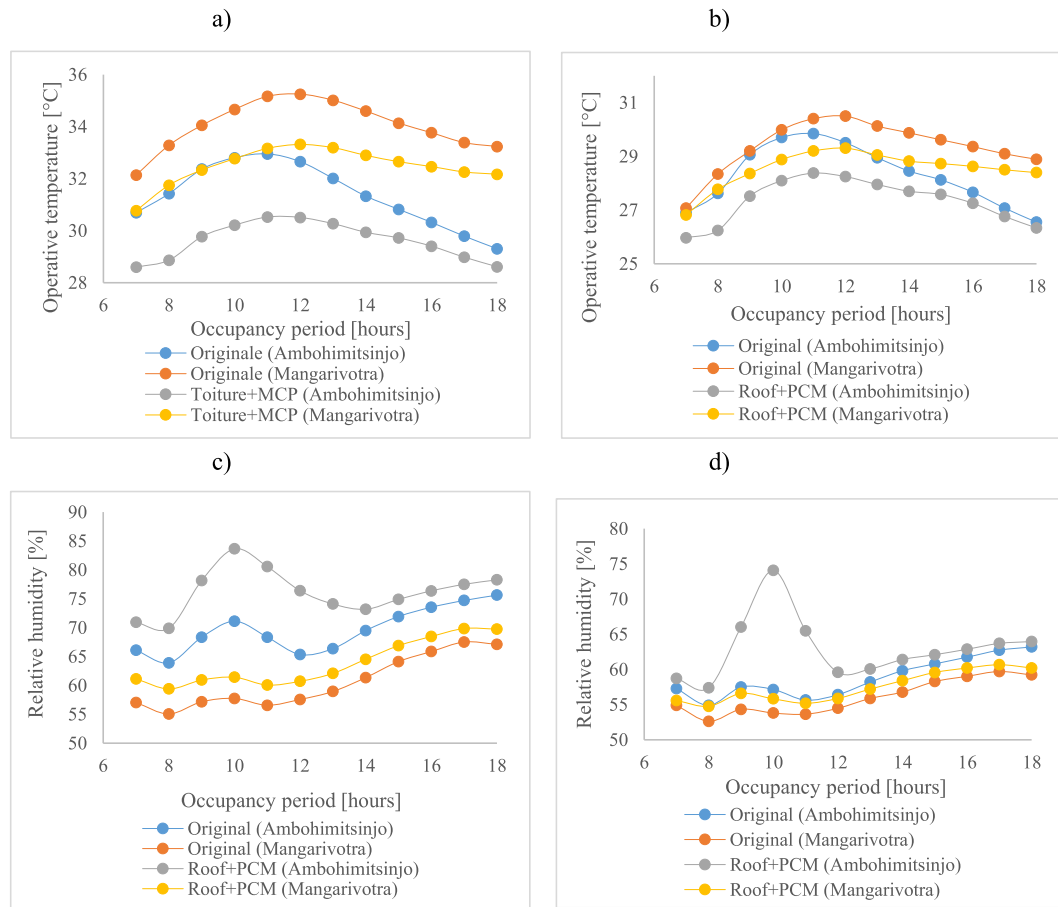


Fig. 10. Sub-scenario roof+PCM result, a) operative temperature during hottest period; b) operative temperature across coolest period; c) indoor relative humidity through december; d) indoor relative humidity over july.

exclusively on insulating the walls and roof using straw bales. It involves preserving all the original building components while adding straw bale insulation to the aforementioned structural elements. In accordance with the literature, the thermal characteristics of the straw bales are presented in Table 11.

These various thermal properties show that the thermal conductivity of straw bale insulation varies from 0.041 to 0.044 W/(m·K) for an orientation perpendicular to the heat flow and from 0.06 to 0.067 W/(m·K) for a parallel orientation. From a thermal performance standpoint, the perpendicular orientation offers greater comfort. The analysis also reveals that straw bales with the lowest density exhibit relatively high thermal efficiency. For the upcoming simulation, the highest conductivity values will be used to consider the most unfavorable scenario for thermal comfort.

Two sub-scenarios are analyzed for the studied schools to highlight the performance of straw bale insulation installed close to the external layer, as described in Table 12.

Scenario 2 operate only with the roof and consist of three main layers for Ambohimitsinjo (steel sheet roofing, straw bale insulation where the thickness fluctuate from 5 cm to 40 cm, and 3 cm of pine wood as ceiling), and five layers for Mangarivotra (20 mm of water proofing, 50 mm of reinforced concrete, straw bale insulation with thickness ranging from 5 cm to 40 cm, 100 mm of cast concrete, and 15 mm of cement coating). This improvement scenario is divided into two groups, including straw bale insulation with fibers perpendicular to the heat flow as sub-scenario 1 whereas sub-scenario 2 employes parallel configuration.

As part of the application of straw bale techniques in hot and humid climates, moisture and thermal intrusion did not appear to be

detrimental to the health of the building regardless of the climate [80], and these passive materials confer better moisture buffer capacity compared to the reference wall using glass fiber insulation [81]. Furthermore, these materials are likely to offer acceptable fire safety, especially when used solely as roof insulation, as in this study. Research conducted by Katharine Wall [82] involved a 135-min fire resistance test of straw bale panels covered with lime plaster, in accordance with the requirements of standard BS EN 1364-1:1999, described by [13]. The results showed black carbonization of the straw and one side still covered with plaster which, after its removal, still revealed intact yellow straw. This entire process has demonstrated performance exceeding four times the minimum required duration. Because the roofs of both schools are continuous and gap-free, insects cannot develop and damage the straw bale materials. In short, the use of this bio-based material ensures durability and offers significant performance in terms of thermal comfort.

As result, the following figures highlight the thermal performance of straw bale including parallel and perpendicular configuration.

The analysis reveals that straw bale insulation offers excellent thermal performance for the indoor thermal comfort of school buildings. The evaluation takes place during the scholastic period, when eight sub-scenarios based on straw bale insulation embedded in the external layer of the studied school's roof are considered. The insulation thickness was progressively increased up to 40 cm in order to highlight the efficiency of straw bale. The dry season exhibits a comfortable thermal range across the scholastic period for both studied schools, from 5 cm thickness, the performance improved progressively as the straw bale insulation thickness increased until 40 cm. For the worst-case scenario, the operative temperature and relative humidity range respectively from

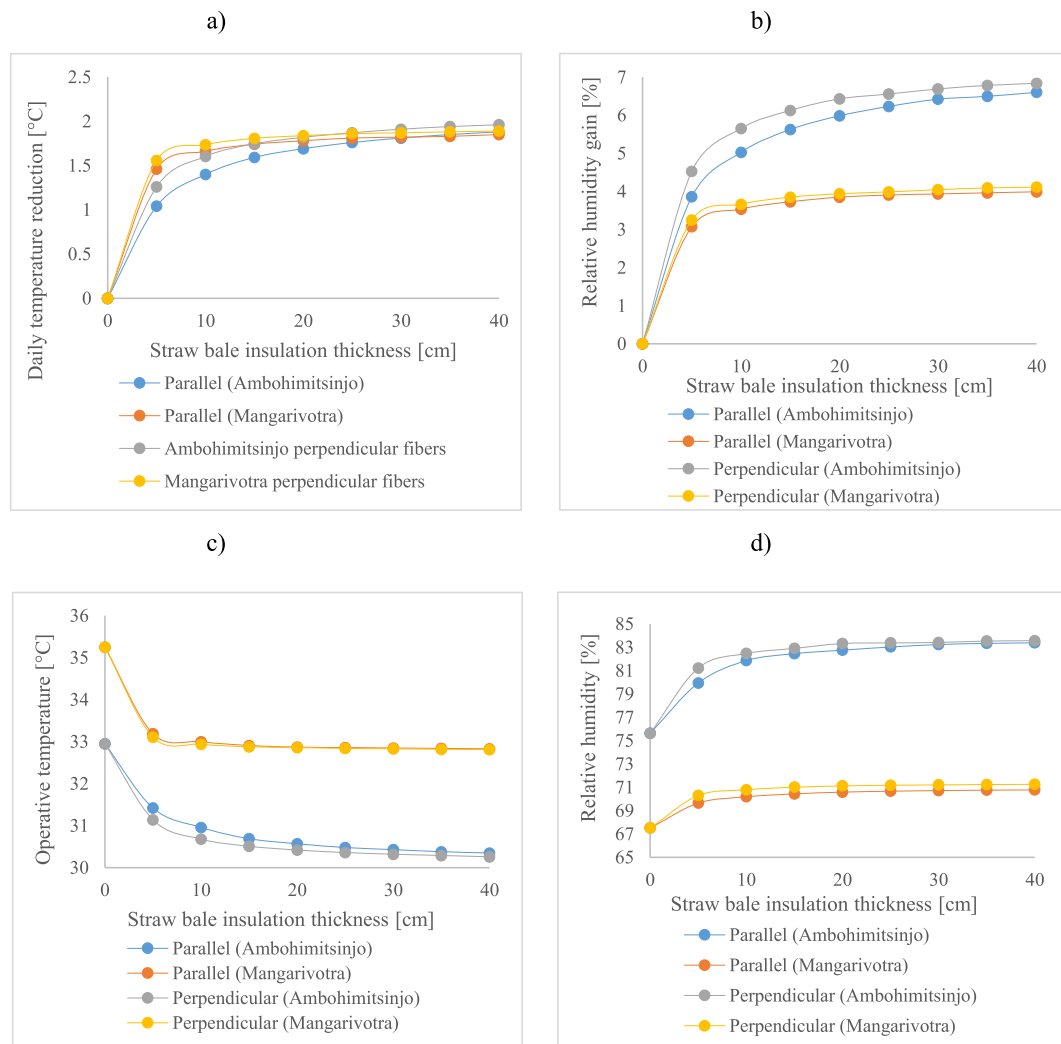


Fig. 11. Average daily temperature reduction and relative humidity gain during hottest month (a,b); peak shifting temperature and relative humidity (c, d).

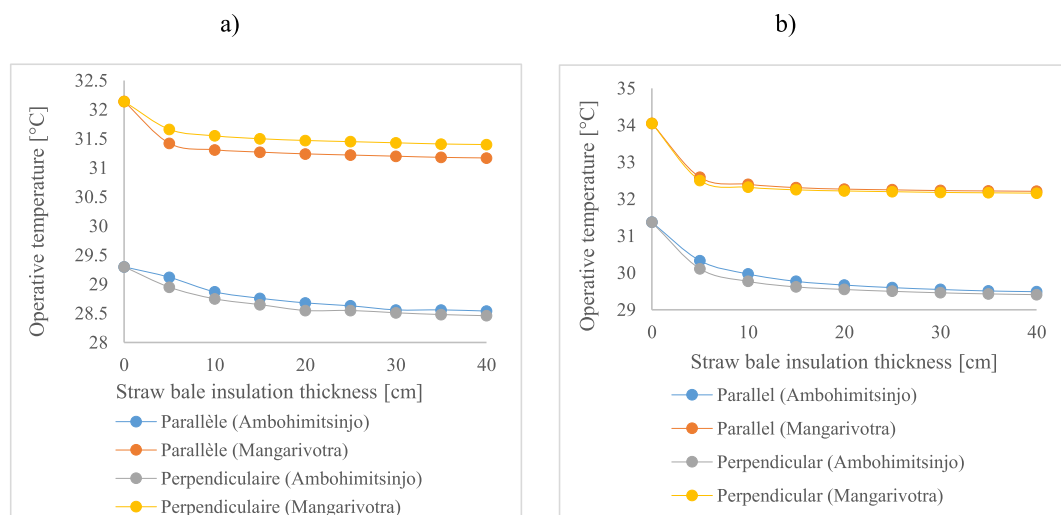


Fig. 12. Temperature reduction, a-b) minimum and average values.

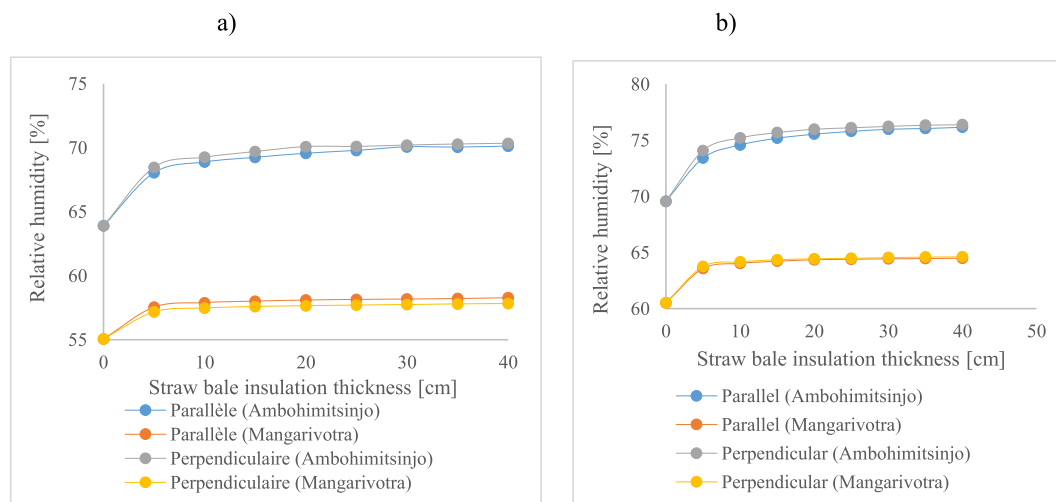


Fig. 13. Relative humidity gain, a-b) minimum, and average values.

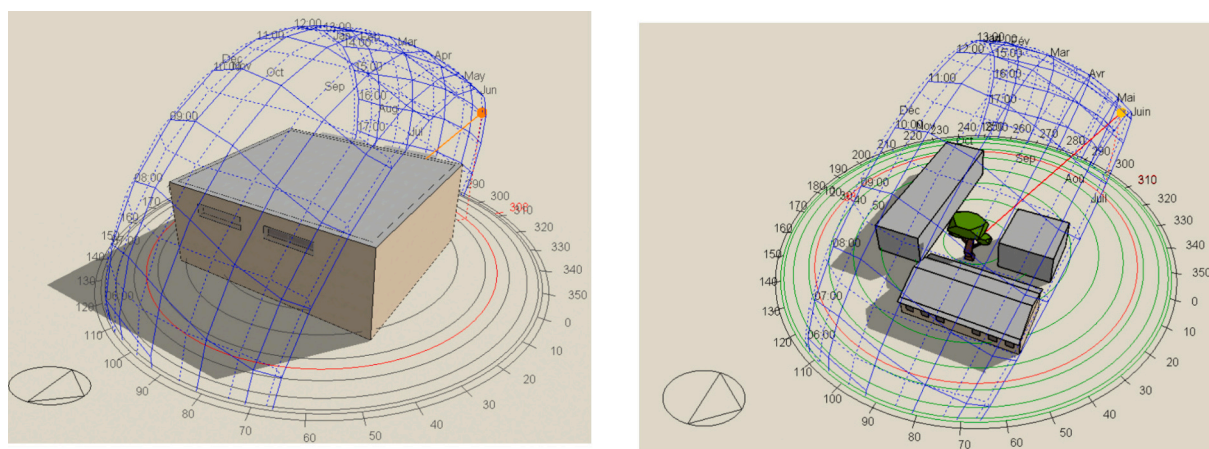


Fig. 15. Sunpath diagram illustration, Mangarivotra (left) and Ambohimitsinjo (right).

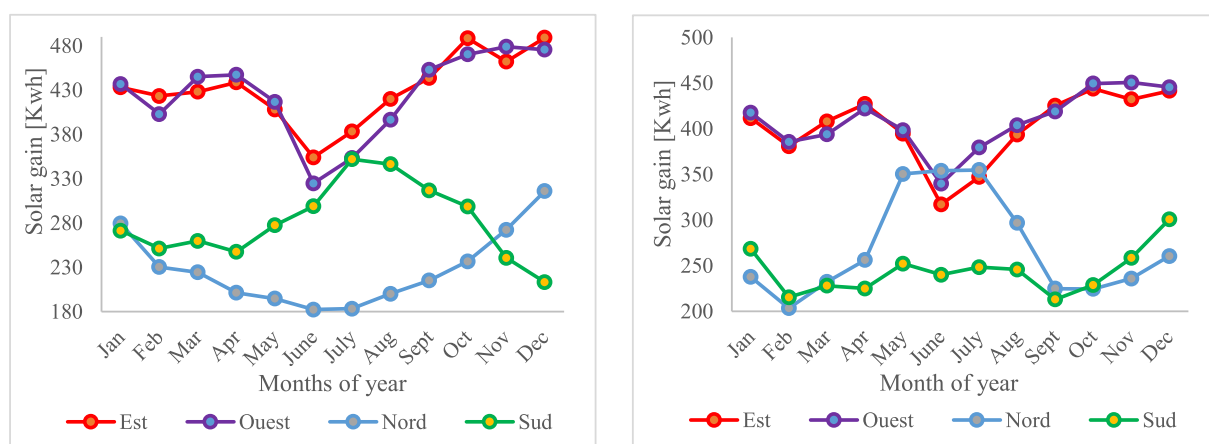


Fig. 16. Solar energy transmitted by classroom via windows by exterior rooms depending on the different orientations, Ambohimitsinjo (left) and Mangarivotra (right);

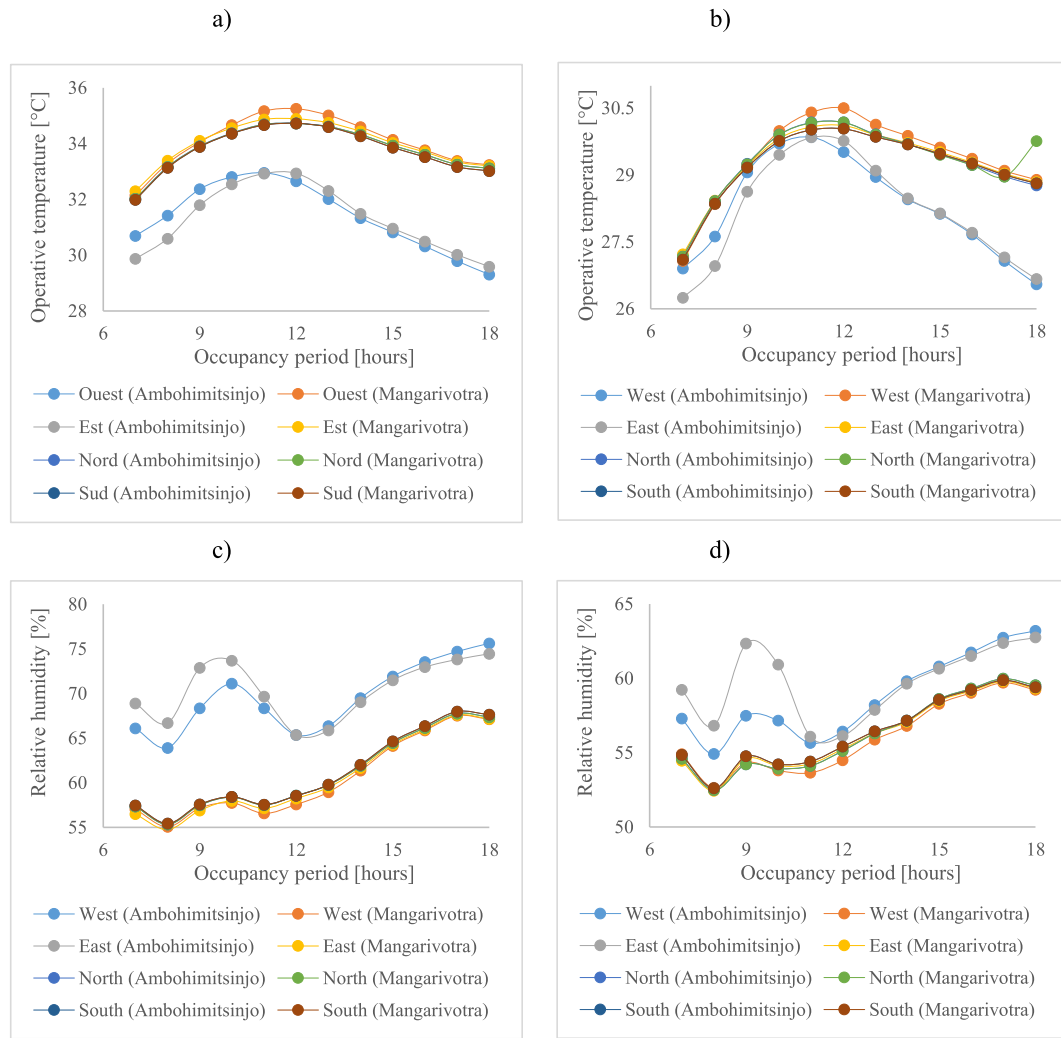


Fig. 17. Comfort result for different sub-scenarios, a-b) operative temperature across the hottest and coolest months; c-d) relative humidity over December and July.

27.28 to 29.53 °C and 52.36 to 60.35% for Mangarivotra and 26.14 to 28.86 °C and 56.73 to 66.69% for Ambohimitsinjo. Additionally, Ambohimitsinjo reaches the indoor thermal comfort under all seasons and the scholastic period. Therefore, this school failed acceptable indoor environment, from 10 a.m. to 2 p.m. for the sub-scenario 5 cm and 10 cm insulation thickness, across December. By increasing the thickness from 15 cm to 40 cm, the indoor climate is significantly refined, thereby enhancing the quality of teaching. As the thermal conductivity of straw bale with fibers perpendicular to the heat flux is lower than the parallel case, the former reveals better thermal performance. Mangarivotra expresses comfortable indoor conditions over the course of the dry season. Across the rainy season, Mangarivotra highlights, for an insulation thickness of 5 cm, the temperature reduction ranged from 0.72 to 2.06 °C and from 0.48 to 2.20 °C for the parallel and perpendicular fiber orientations, respectively. Increasing the insulation thickness to 40 cm further enhanced the thermal performance, resulting in temperature reductions ranging from 0.96 to 2.44 °C and from 0.74 to 2.55 °C for the parallel and perpendicular orientations, respectively. These improvements were associated by corresponding increases in relative humidity, ranging from 1.84 to 4.07% and from 1.05 to 4.46% for the 5 cm thickness, and from 2.58 to 5.15% and from 1.86 to 5.29% for the 40 cm thickness. Based on the minimum and maximum temperature values obtained for insulation thicknesses of 0, 5, 10, 15, 20, 25, 30, 35, and 40 cm, the temperature reduction ranged from 0.61% to 2.59% and from 4.64% to 7.80% in Ambohimitsinjo, and from 2.24% to 3.01% and from 5.84% to 6.38% in Mangarivotra for the parallel fiber orientation. In

contrast, the perpendicular fiber orientation yielded temperature reductions ranging from 1.19% to 2.86% and from 5.49% to 8.16% in Ambohimitsinjo, and from 1.49% to 2.30% and from 6.07% to 6.92% in Mangarivotra for the minimum and maximum temperature values, respectively. Similarly, based on the minimum and maximum relative humidity values obtained for the same insulation thicknesses, the relative humidity gain ranged from 6.49% to 9.74% and from 5.71% to 10.27% in Ambohimitsinjo, and from 4.52% to 5.84% and from 3.16% to 4.84% in Mangarivotra for the parallel fiber orientation. In contrast, the perpendicular fiber orientation resulted in relative humidity gains ranging from 7.16% to 10.09% and from 7.40% to 10.51% in Ambohimitsinjo, and from 3.85% to 5.03% and from 4.13% to 5.55% in Mangarivotra for the minimum and maximum relative humidity values, respectively.

As the thermal performance of straw bale insulation is relatively dependent on the material thickness, Figs. 19 and 20 summarize the operative temperature reduction and relative humidity gain under all improvement sub-scenarios. The figures present average, minimum, and maximum values for the two environmental comfort parameters including operative temperature and relative humidity. The insulation thickness varies from 0, corresponding to the original configuration without straw bales, and 5 cm to 40 cm with insulation. It was found that for both schools, the reduction in operative temperature occurs in two phases characterized by different linear regressions: a steep slope between the 0 cm and 5 cm configurations, and a shallow slope from 5 cm to 40 cm. In the first phase, the maximum temperature gradient between

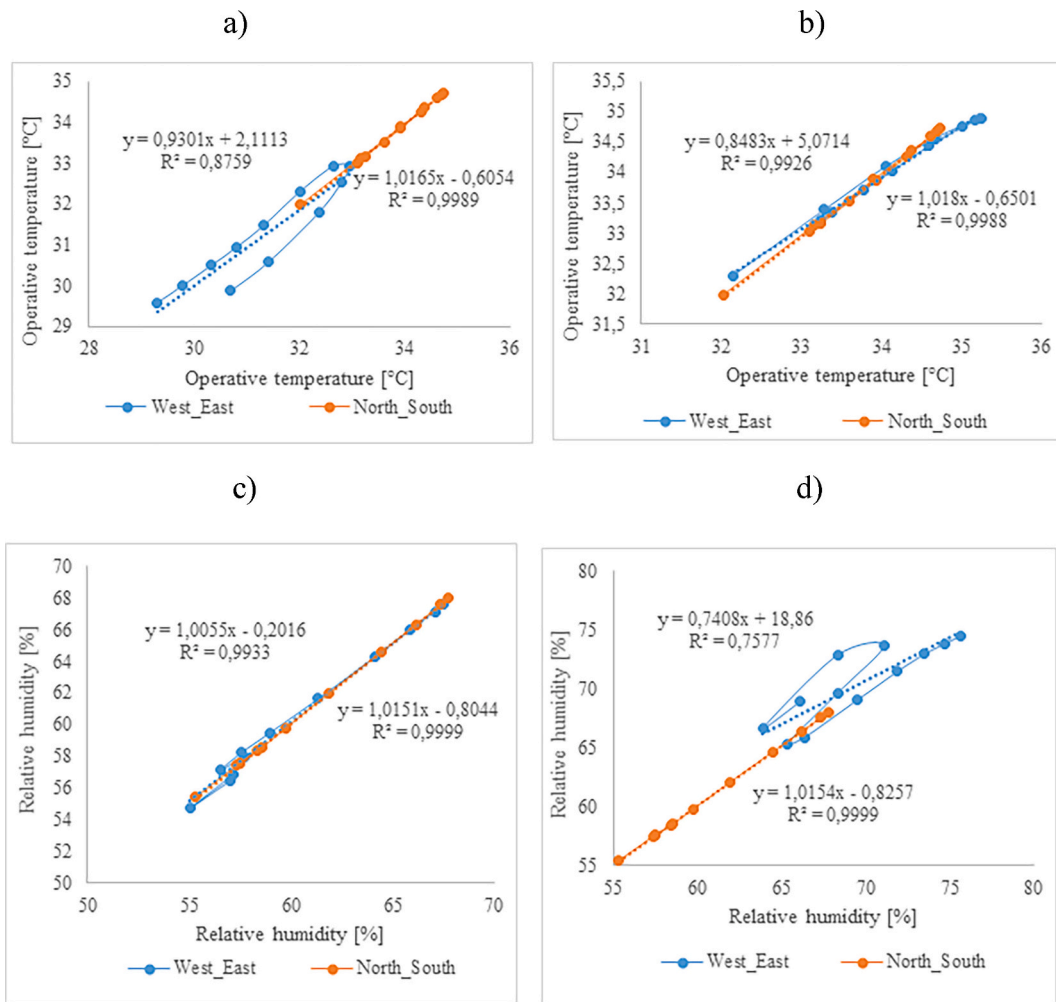


Fig. 18. Correlation between orientation comfort result, a-b) operative temperature of Ambohimitsinjo and Mangarivotra; c-d) relative humidity of Ambohimitsinjo and Mangarivotra.

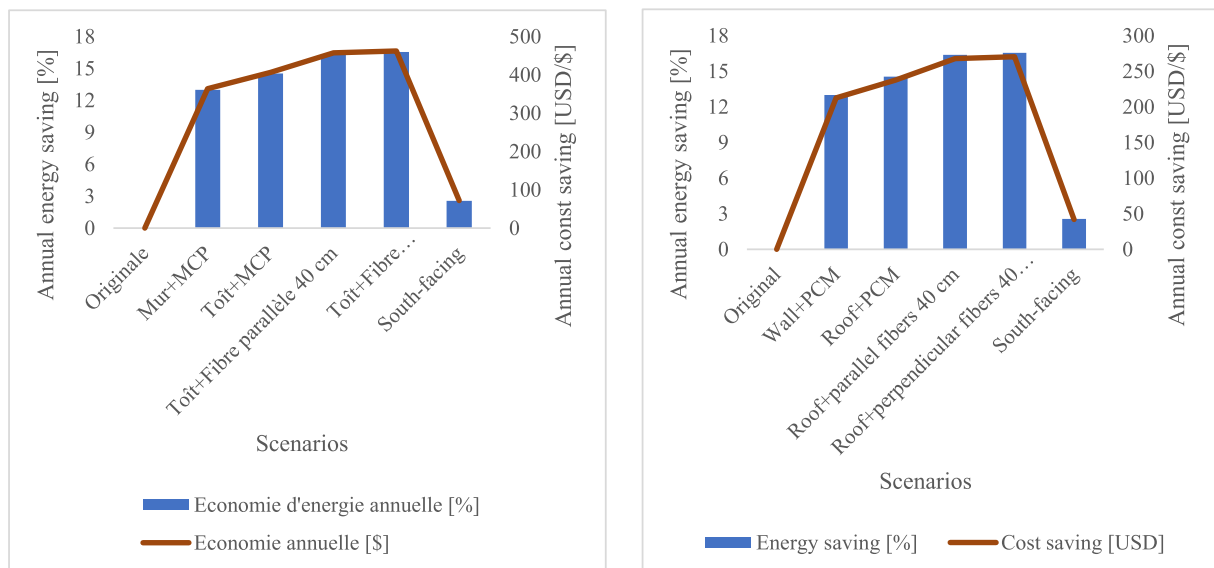


Fig. 21. Annual energy and cost saving for Mangarivotra elementary school under business electricity (left) and residential tariff (right).

configurations with fibers parallel and perpendicular to the heat flow varies, showing minimum, maximum, and average values of 0.35 °C, 1.81 °C, and 1.26 °C for Ambohimitsinjo, and 0.78 °C, 2.14 °C, and 1.55 °C for Mangarivotra. In the second phase, the temperature reduction becomes more pronounced, peaking at an insulation thickness of 40 cm; the reductions are 0.84 °C, 2.69 °C, and 1.96 °C for the Ambohimitsinjo elementary school, and 0.97 °C, 2.44 °C, and 1.89 °C for Mangarivotra. A contrast is also observed regarding indoor comfort indices: as temperature decreases, relative humidity increases, exhibiting two phases with maximum gains at 40 cm thickness reaching 6.45%, 7.95%, and 6.83% (for minimum, maximum, and average values, respectively) at Ambohimitsinjo, and 3.22%, 3.75%, and 4.11% at Mangarivotra. As straw bale insulation thickness increase, the operative temperature decrease while relative humidity growth. Thus corresponding respectively to negative and positive linear regression.

Referencing the research conducted by Pape Moussa Toure et al. [83], the thermal time lag φ and the decrement factor was calculated following these equations:

$$\varphi = t_{T_{i,max}} - t_{T_{e,max}} \text{ and } f = \frac{T_{i,max} - T_{i,min}}{T_{e,max} - T_{e,min}} \quad (12)$$

where.

$t_{T_{i,max}}$: The time when the ambient-air temperature inside building is maximum.

$t_{T_{e,max}}$: The time when the outdoor average equivalent temperature is maximum.

$T_{i,max}, T_{i,min}$: The maximum and minimum ambient-air temperature inside buildings.

$T_{e,max}, T_{e,min}$: The maximum and minimum outdoor average equivalent temperature.

Fig. 14 provide a visual representation of decrement factor and time lag for improvement scenarios including straw bale insulation thickness ranging from 0 to 40 cm and the fibers orientations.

A clear trend was observed indicating that time tag exhibit minimal variation for both school, as the peak hour outside is almost similarly the same inside the buildings. Thus conducting to thermal time lag spanning from 0 to 1. Applying the improvement scenarios, the indoor climate was enhanced with relative humidity gain and temperature reduction, while the peak hour does not change. On the other side, decrement factor decrease with increasing the straw bale insulation thickness. The reduction is very significant when the thickness range from 0 to 15 cm and follow a smaller variation between 20 and 40 cm. As the decrement factor of Ambohimitsinjo is lower, its thermal efficiency is so high comparing to Mangarivotra public school.

3.2.3. Scenario 3

As both studied school are oriented in the west-side, this scenario aims to determine the optimal orientation for thermal comfort, taking into account the different shapes of school buildings. The orientation of the study buildings will be varied in 15° increments, from 0° (initial position) to 360° (initial position). Different north, south, east, and west orientation scenarios will be applied to each model. The study aims to identify the orientation that will result in the lowest indoor air temperature and the highest relative humidity, thus providing guidance for energy-saving efforts in each case study.

The following table and figures describe respectively the orientation of doors and windows for the studied school and the sunpath diagram.

Description	Orientation	
Doors	EPP Ambohimitsinjo West	EPP Mangarivotra West
windows	East, West	East, West
Walls	North, South, East, West	Nord, Sud, Est, Ouest

standard designs, with each classroom providing 56 m² of space. The ratio of openings to floor area is consistent across both—approximately 20%. Therefore, the effective opening area at Mangarivotra is reduced by 50% due to the choice of sliding aluminium fenestration. Both schools feature cantilevered elements that create shading effects, thereby limiting the impact of solar radiation. Ambohimitsinjo benefits from additional shading provided by trees and two neighboring buildings, whereas Mangarivotra is fully exposed to local weather conditions, as it is the first building constructed on a previously open site.

The simulation results under the different orientation sub-scenarios are illustrated in the figures below. The analysis of comfort parameters is based on indoor air temperature, relative humidity, radiant temperature, operative temperature and solar gains.

The findings highlight the variation in energy transmitted per classroom via exterior windows, according to east, west, north, and south orientations. The results show a trend for the classrooms at the Ambohimitsinjo and Mangarivotra Primary Schools. East and west orientations exhibit relatively high solar energy throughout the year, with a peak during the rainy season (January to April and September to December) and a decrease during the dry season (May to August).

The highest energy output was observed in the Ambohimitsinjo Primary School classroom, with a value of 489.12 kWh. Conversely, north and south-facing building schools exhibit variations opposite to those of east and west-facing schools: solar energy levels are lower during the rainy and dry season. It is clear that the orientation of the school buildings has a significant impact on the indoor environment experienced by the occupants (students, teachers, and administrative and technical staff). Observations from Mangarivotra Elementary School indicate that, after the east- and west-facing orientations, the north-facing orientation receives higher solar gains than the south-facing orientation. This finding is consistent with the solar geometry of the Southern Hemisphere, where north-facing façades generally receive greater annual solar exposure than south-facing façades. Consequently, the north-facing orientation experiences higher solar gains than its south-facing counterpart. Thus, given that the openings are located on the opposite side to the building's orientation, solar radiation from the east in the morning and from the west in the afternoon, combined with insufficient cross-ventilation, generates overheating inside the school. As highlighted in the study by Asrun Safiuddin and Abdin Abdin [80], the building's orientation and the distribution of window openings impact the indoor temperature of classrooms in a school setting. For Ambohimitsinjo, the East and west orientation provides better indoor thermal comfort with the operative temperature fluctuating between 29.30 and 32.95 °C and relative humidity from 63.90 to 75.62%. Normally, East and West facing present the worst comfort, as reported by Brandt Andersson et al. [81]. In this sense, Mangarivotra records display a high indoor temperature from 32.14 to 35.25 °C and relative humidity from 55.06 to 67.51%, in the west side. However, the presence of tree and surrounding school may have caused the shading effect, thus improving the indoor climate. Comparing the orientations of west and north-facing for Ambohimitsinjo, the collected data indicate a temperature reduction of 1.32 to 3.80 °C, yielding an average of 2.43 °C, while the relative humidity gain fluctuates from 6.61 to 12.70%. This findings report an existence of correlation between building orientation and indoor thermal performance as described by Rifar Manani et al. [82]. In the south-facing and during the hottest month, Mangarivotra exhibit the highest thermal performance with operative temperature (31.98 to 34.73 °C) and relative humidity (55.43 to 67.98%). The results obtained are consistent with those reported by Zaynab EL KRIMI et al. [13]. The data collected indicate a clear trend in radiant temperature that is strongly influenced by variations in building orientation. Average variations range from 34.05 °C to 34.41 °C for the Mangarivotra Primary School and from 30.46 °C to 31.40 °C for the Ambohimitsinjo Primary School. The optimal orientation for thermal comfort is North/South. A significant similarity is observed in the work of Asrun Safiuddin and Abdin Abdin [80], who emphasize that an east-west orientation with

Both schools adhere to the Malagasy Ministry of National Education's

north-south openings best mitigates heat accumulation through natural ventilation. This results in a marked improvement in indoor comfort, consistent with the findings of Bueno et al. [84], who demonstrate that an optimized thermal environment can increase productivity by up to 5%. Conversely, east-west orientations offer the worst thermal performance and therefore necessitate the use of sunshades or other passive strategies to reduce glare from sunlight. Fig. 23 illustrates the existence of a correlation between the orientation west-east and north-south, corresponding to the high and moderate solar radiation. The greatest coefficient correlation ($R^2 = 0.9999$) is performed in the north-south relationship, for the relative humidity parameters for both studied schools. It is observed that Mangarivotra exhibit the larger correlation with all parameters including operative temperature, relative humidity and the orientation. Therefore, in the west-east relationship, Ambohimitsinjo record slightly lower correlation statistique may due to the existence of shading effect generated by tree and surrounding building where located in the west side.

4. Discussions

Applying the findings reported by Mukhaya Ismankhodjaeva et al. [85], describing the overall cost of a retrofit for straw bale insulation with 26 USD/m³, Fig. 20. Summarize the performance cost balance of scenario 2. The insulation thickness spanning from 5 cm to 40 cm coupling with the straw bale based on fibers oriented parallel and perpendicular to the heat flow are presented to highlight the performance-cost balance of this agricultural waste configuration.

Fig. 19. illustrate the variation of straw bale insulation cost while the material thickness fluctuate from 5 cm to 40 cm. Ambohimitsinjo elementary school record the worst cost with 78.17 to 345.93 USD when Mangarivotra oscillate from 64.58 to 331.81 USD. For both studied school, fibers oriented perpendicular to the heat flow register the lower expense than parallel case. On the other side, Mangarivotra perform relative humidity price between 22.86 and 140.79 USD for parallel case while Ambohimitsinjo range from 21.07 to 98.52 USD. Based on the both environmental parameters, 5 cm constitute the optimal design thickness and the reach the lower spending with 45.11 USD and 17.96 USD, respectively with Mangarivotra School and Ambohimitsinjo (perpendicular fibers).

According to Aia A. Qindil et al. [86], the annual cost saving can be calculated through this formula: Annual cost saving = total annual energy savings x electricity price (13).

Moreover, GlobalPetrolPrices [87] illustrate the electricity price of Madagascar as, 0.138 USD per KWh for residential electricity price and 0.236 USD per KWh for business cost. The electricity pricing model in Madagascar varies according to the specific needs and connection requirements; there is no administrative tariff reserved for government ministries or basic social services such as schools, hospitals, and primary health centers. Consequently, two pricing methods may be applied, depending on the needs of each facility.

The following figures illustrate the comparison between cost performance of scenario 1, 2 and 3.

Comparing all the developed scenarios, it was found that straw bale insulation with fibers perpendicular to the heat flow offers the highest thermal performance with 40 cm thickness applying in the roof, followed by bales oriented parallel to the flow, the PCM + roof system, the wall+roof system, and finally, a north or south-facing building. The annual energy and cost saving was calculated relying on the comfort gap which be complete by the use of mechanical ventilation. The baseline case for both studied school was taking as the based of comparison for all improvement scenarios. The forced-air ventilation is employed when the indoor air temperature exceed 30 °C, which constitute the upper limit

range stated by Nicol J. F. et al. [88], J. Fergus Nicol & Susan Roaf [89] and Modeste Kameni Nematchoua et al. [90]. In this sense, the air conditioning system is operated from 8:00 a.m. to 6:00 p.m. for the baseline case of both studied school and for all improvement scenarios of Mangarivotra public school. For Ambohimitsinjo school, the use of mechanical cooling spanned from 10:00 to 14:00 for PCM scenarios including wall+PCM and roof+PCM, while straw bale insulation scenarios such as parallel and perpendicular cases range from 10:00 to 13:00. The cooling system is based on public electricity from grid as fuel and depend on the following specifications: Cooling system seasonal COP 1.80, minimum supply air temperature 12 °C, minimum supply air humidity ratio 0.0077 g/g. The perpendicular to the heat flow configuration offers an annual energy reduction of 64.42% for Ambohimitsinjo and 16.54% for Mangarivotra, expressing cost savings of 270.35 USD to 462.33 USD for Mangarivotra and 547.74 USD to 936.72 USD for Ambohimitsinjo. Given the slightly lower performance of fibers parallel to the flow, this configuration leads to slightly lower results compared to the perpendicular configuration. However, the difference in air conditioning energy costs does not exceed 0.9 USD for Ambohimitsinjo and 4 USD for Mangarivotra. This findings are consistent with [50], as perpendicular fibers provide better thermal efficiency than parallel orientation. As the meteorological conditions fluctuate more significantly outdoors than within the school building, the annual energy savings reach 14.53% and 13% respectively for roof+PCM and wall+PCM in Mangarivotra, compared to 40.48% and 26.91% for Ambohimitsinjo. Therefore, operating PCM with Ambohimitsinjo elementary school achieves the comfort range thanks to the shading effect generated by the tree and surrounding buildings. On the other side, Ekrem Tunçbilek et al. [91] in the numerical study incorporating PCM into the wall closer to the inner position provide an energy savings of 12.8%. It can be due to its lower PCM thickness of 23 cm, thus conducting to limited energy saving. These findings are consistent with previous studies of Jaradat M. et al. [30] which state that increasing the thickness of the incorporated PCM panel contributes to greater reductions in electrical energy consumption. The analysis highlights that Ambohimitsinjo offered greatest energy saving than Mangarivotra, extending the findings reported by Köse E. and Manioglou G. [92], describing that PCM closer to interior show the highest energy saving rate.

As specified by Xindan Kang et al. [50], trees regulate microclimatic conditions, reduce heat exposure, enhance outdoor thermal comfort, and mitigate heat-related health risks.

Applying the BioPCM price of 3.7 cm pannel, including the installation cost of 36.65 \$/m² for PCM [30] and coupling with straw bale insulation expense stated by Mukhaya Ismankhodjaeva et al. [85], Fig. 22. Provide visual representation of payback for both studied schools.

The obtained values allow the conclusion that Ambohimitsinjo record the lowest payback period than Mangarivotra, may be thanks to the tree and surrounding buildings, thus generating shading effect to the studied building. For both schools, roof+perpendicular fibers 40 cm register the efficient payback under 2 years for all the pricing scheme followed by roof+parallel fibers 40 cm, roof+PCM and wall+PCM. Economic analysis illustrated payback period of wall+PCM reveal the poorest optimization with 13 years for Mangarivotra and 10 years for Ambohimitsinjo.

The actual hours of school occupancy by students and teachers form the basis for calculating discomfort hours, as illustrated in Fig. 23.

Both schools are occupied from 7:00 a.m. to 11:30 a.m. and from 2:30 p.m. to 6:00 p.m., accross Monday through Friday. Since the occupants already presents before and after the effective teaching period, the schedule has been extended to start at 7:00 a.m. and end at 6:00 p.m.

Weekends, including Saturdays and Sundays, and the holiday periods corresponding to July and August are excluded. Thus conducting in a total of 2170 h based on the year 2025 as the study period for this project. Indoor conditions are considered uncomfortable when the operative temperature exceeds 30 °C, in accordance with adaptive comfort standards under naturally ventilated environments and hot-humid climates [93]. The results highlight the fact that implementation of improvement scenarios yielded highly significant results for Ambohimitsinjo, reducing the hours of discomfort from the 1087 h associated with the baseline case to zero, thanks to a combined scenario integrating 40 cm straw bale insulation operated in the roof where the fibers are perpendicular to the heat flow and optimal north-facing orientation. Mangarivotra shows a reduction in discomfort hours from 1890 to 1626 h through the use of improvement scenarios, such as optimized orientation (south-facing), PCM walls, and 40 cm straw-bale roofing with fibers perpendicular to the heat flow, and a maximum combined scenario (BioPCM walls paired with optimized orientation and straw-bale roofing). However, the improvement is more limited in Mangarivotra, where indoor temperatures exceed the thermal comfort threshold by as much as 5 °C. Although the combined adaptation scenario reduces indoor temperatures by up to 3 °C, it is insufficient to fully offset the initial thermal excess.

5. Conclusion

This study evaluated the effectiveness of three passive cooling strategies—BioPCM integration, straw bale insulation, and building orientation—for improving indoor thermal comfort and reducing cooling energy demand in naturally ventilated tropical primary schools located in Antsiranana, Madagascar. The research combined field measurements using Arduino-based monitoring with dynamic building energy simulations in DesignBuilder/EnergyPlus. The numerical models were successfully calibrated according to ASHRAE Guideline 14 using hourly indoor air temperature and relative humidity, providing a reliable basis for annual thermal and energy performance assessment. The baseline analysis revealed that both school buildings experienced severe overheating throughout the teaching period, recording 1087 and 1890 annual discomfort hours for Ambohimitsinjo and Mangarivotra, respectively. These findings confirm that conventional school buildings constructed without climate-responsive design strategies are unable to provide acceptable thermal conditions under tropical climates. Among the passive cooling strategies investigated, **straw** bale roof insulation with fibers oriented perpendicular to the heat flow consistently exhibited the highest thermal and economic performance, outperforming parallel fiber orientation, roof-integrated BioPCM, wall-integrated BioPCM, and building orientation optimization. Increasing straw bale thickness progressively improved thermal insulation, while the perpendicular fiber configuration benefited from lower thermal conductivity, resulting in greater reductions in operative temperature and higher indoor relative humidity. The analysis further demonstrated that roof-integrated BioPCM provided greater thermal benefits than wall applications, particularly when appropriate melting temperatures were selected according to local climatic conditions. Building orientation also played an important role, with north- and south-facing configurations reducing solar heat gains compared with east- and west-facing orientations. The combined implementation of passive strategies produced substantial improvements in indoor environmental quality. At Ambohimitsinjo Primary School, integrating 40 cm straw bale roof insulation, BioPCM, and optimized building orientation completely eliminated thermal discomfort during occupied hours, reducing annual discomfort hours from 1087 to zero. In contrast, Mangarivotra Primary School achieved a more modest reduction, from 1890 to 1626 discomfort hours,

because baseline indoor temperatures exceeded the adaptive comfort threshold by as much as 5 °C, whereas the combined passive strategy reduced peak temperatures by approximately 3 °C. These results demonstrate that passive strategies alone may be insufficient for buildings exposed to more severe thermal loads, highlighting the importance of climate-responsive architectural design from the earliest stages of building conception.

The economic assessment further demonstrated the practical feasibility of the proposed solutions. Straw bale insulation achieved the greatest annual energy savings and the shortest payback period, with the 40 cm perpendicular configuration recovering its investment in **less than two years** under both residential and commercial electricity tariffs. Given its low environmental impact, local availability, and agricultural origin, straw bale insulation represents a particularly attractive solution for low-income tropical regions where access to electricity remains limited.

Beyond the individual technologies evaluated, the principal contribution of this research lies in the integrated assessment of multiple passive cooling strategies within a single modeling framework. Unlike most previous studies that investigate BioPCM, natural insulation materials, or building orientation independently, this work demonstrates their combined thermal, energy, and economic performance under real tropical school conditions. The findings provide practical design recommendations for architects, engineers, and policymakers seeking to improve learning environments while reducing cooling energy demand and greenhouse gas emissions. Several limitations should nevertheless be acknowledged. The study focused on two representative school buildings located in a single tropical city and considered naturally ventilated conditions without evaluating future climate scenarios or occupant adaptive behaviour. Future research should therefore investigate the combined effects of passive cooling strategies under projected climate change, integrate additional nature-based solutions such as green roofs, green façades, and courtyard vegetation, and explore advanced passive systems including wind catchers, hybrid ventilation, and solar-assisted cooling. Coupling these approaches with optimization algorithms and life-cycle carbon assessment would further support the development of climate-resilient and carbon-neutral educational buildings in tropical regions. Overall, this study demonstrates that appropriately designed passive cooling strategies can substantially improve indoor thermal comfort, reduce cooling energy requirements, and enhance the resilience of tropical school buildings. The proposed framework offers a practical pathway toward healthier, more energy-efficient, and more sustainable educational infrastructure, particularly in developing countries where affordable, low-carbon building solutions are urgently needed.

CRedit authorship contribution statement

Sinta Rivel: Writing – review & editing, Validation, Software. **Modeste Kameni Nematchoua:** Writing – original draft, Visualization, Supervision, Software. **Florin Emilian Turcanu:** Visualization, Methodology. **Roshan Unmar:** Writing – original draft, Methodology. **Rostand Moutou Pitti:** Validation, Methodology. **Norbert Tovondrainy:** Writing – original draft, Resources. **Rafefimanana Sambilason Richard:** Writing – review & editing, Investigation. **Raminosoa Chrysostôme:** Writing – original draft, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Straw bale insulation scenario full results

The full findings applying scenario including straw bale insulation with parallel and perpendicular fiber to the heat flow for different thickness spanning from 5 cm to 40 cm are summarized in the following figures.

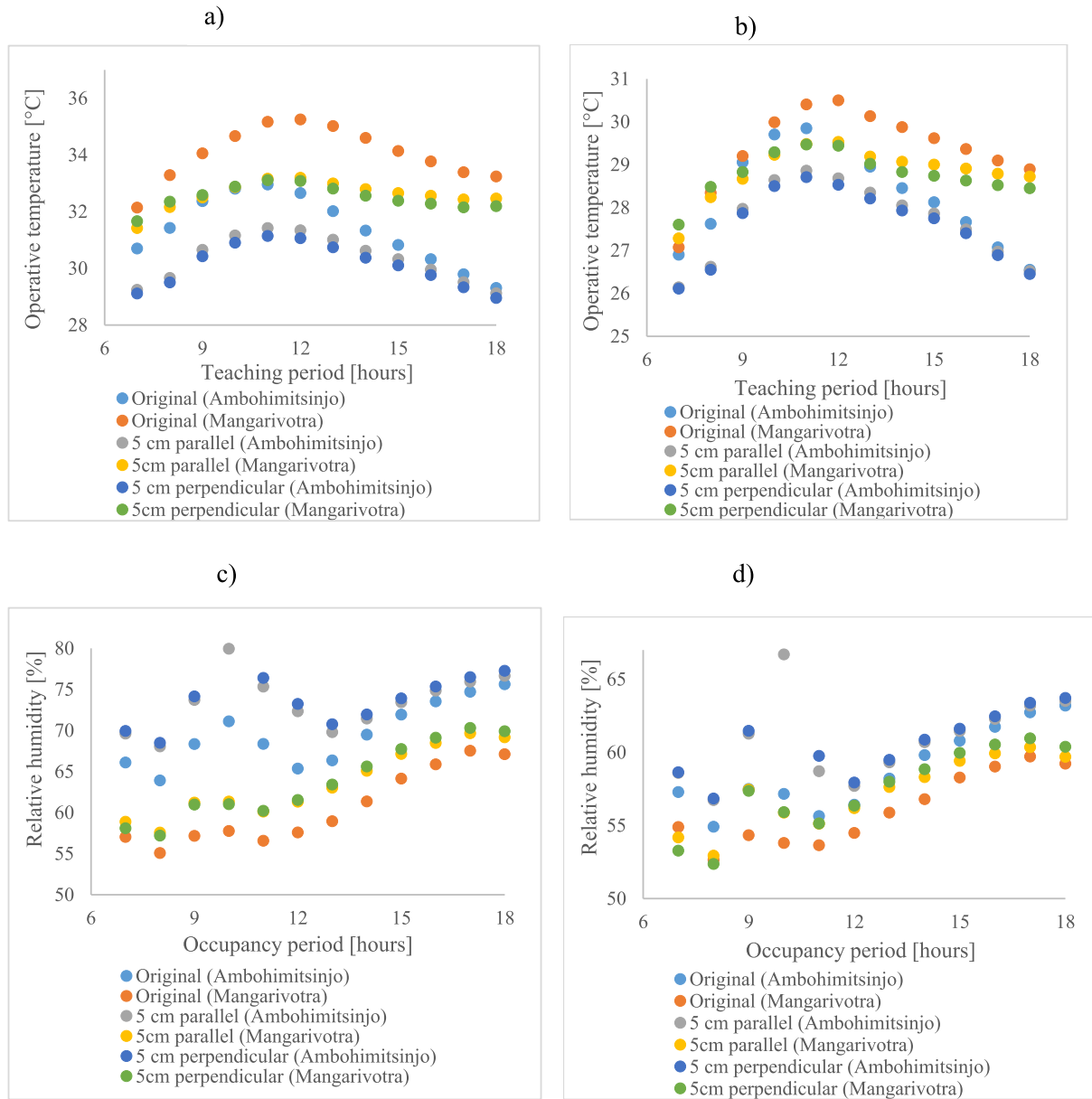


Fig. A1. Sub-scenario roof+5 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

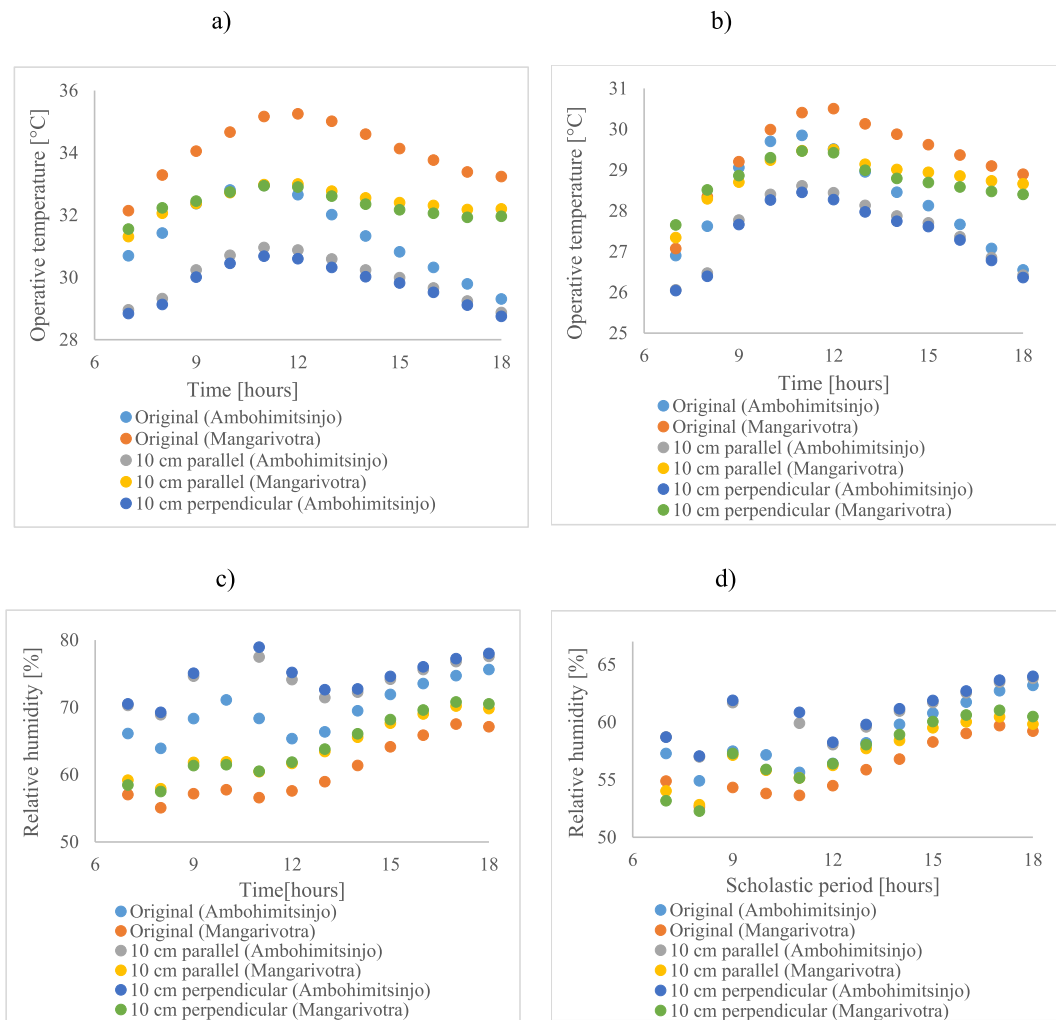


Fig. A2. Sub-scenario roof+10 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

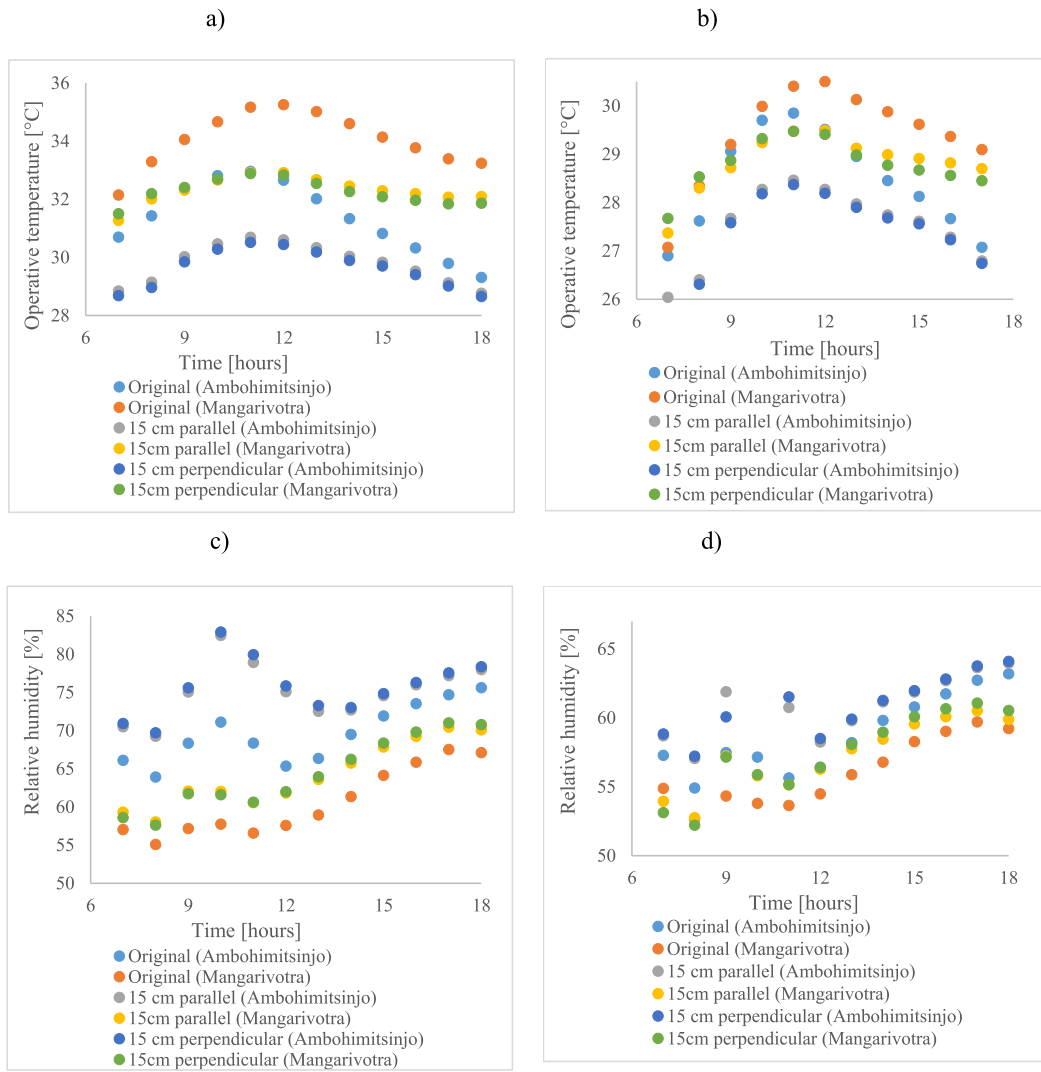


Fig. A3. Sub-scenario roof+15 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

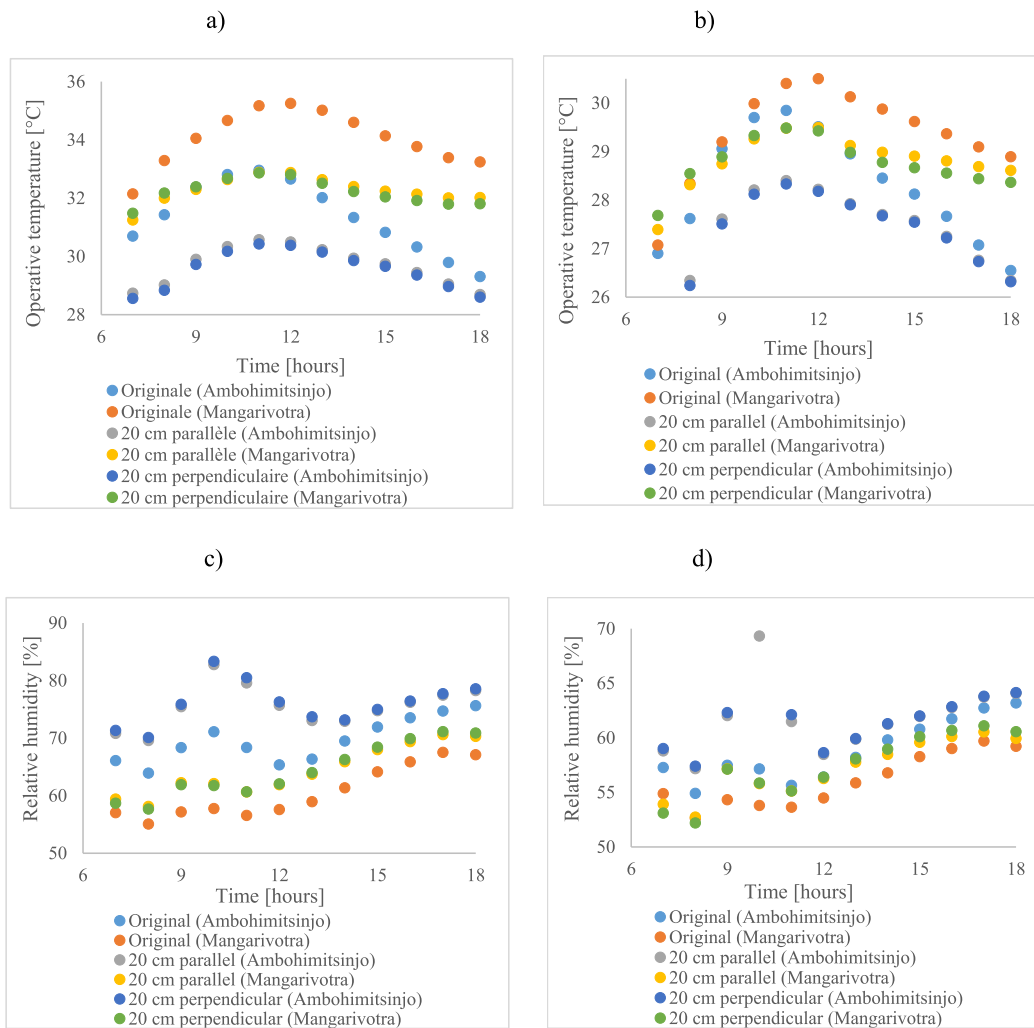


Fig. A4. Sub-scenario roof+20 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and julya).

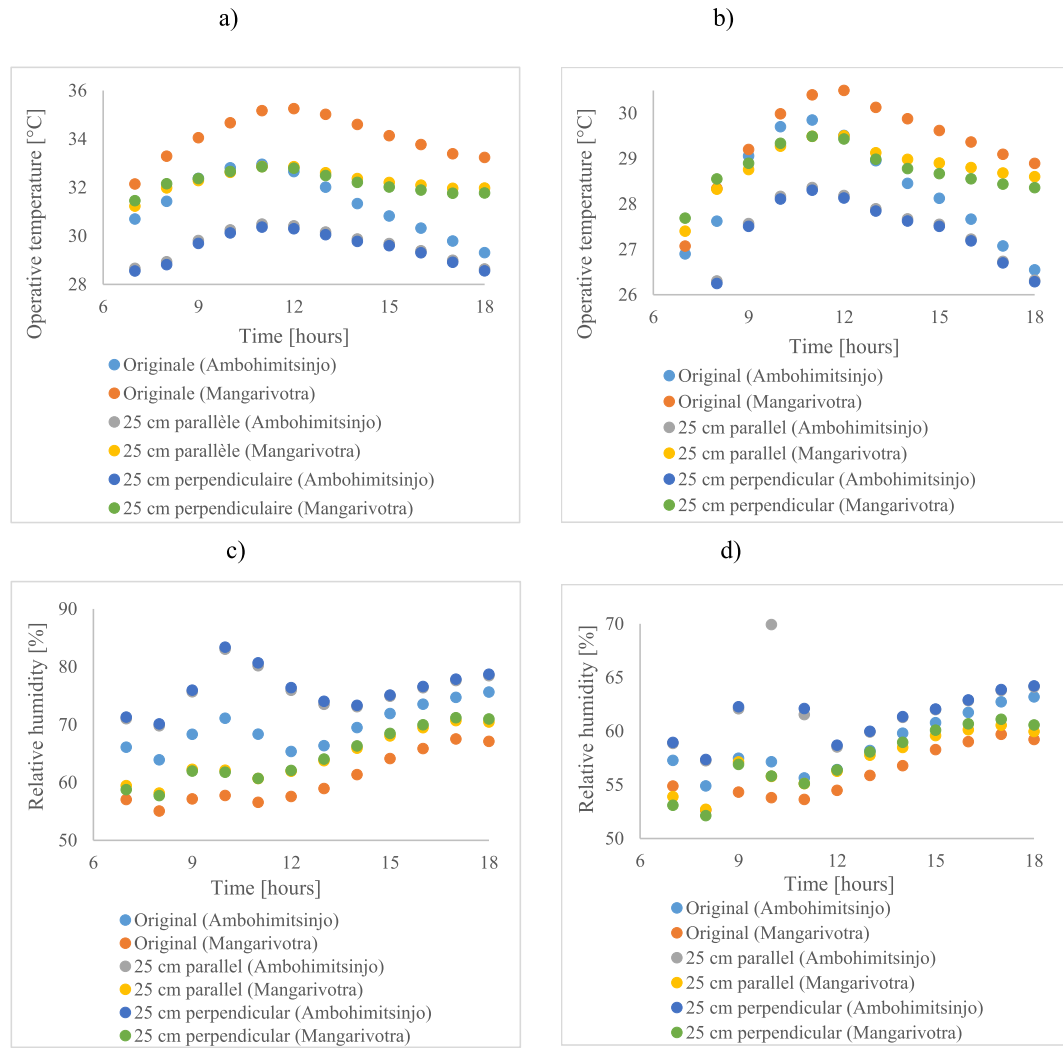


Fig. A5. Sub-scenario roof+25 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

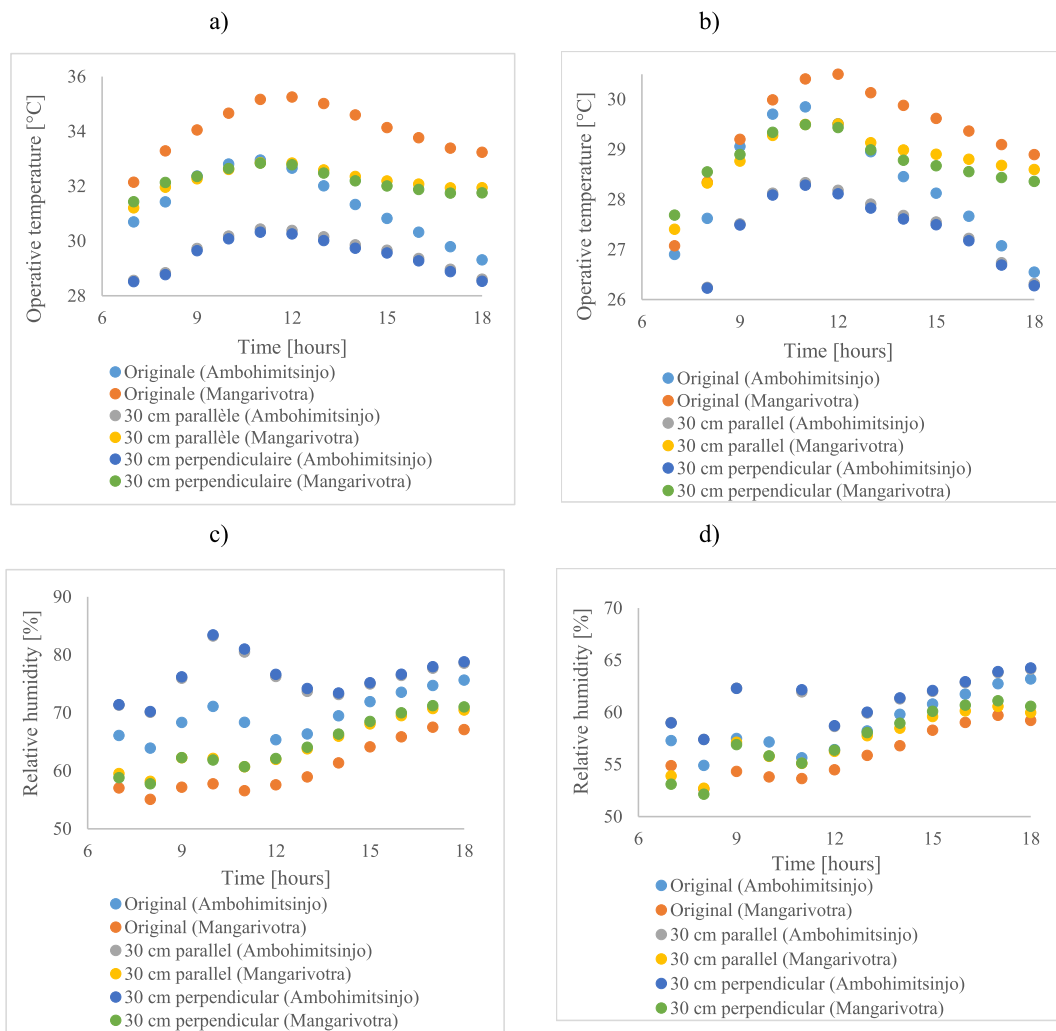


Fig. A6. Sub-scenario roof+30 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

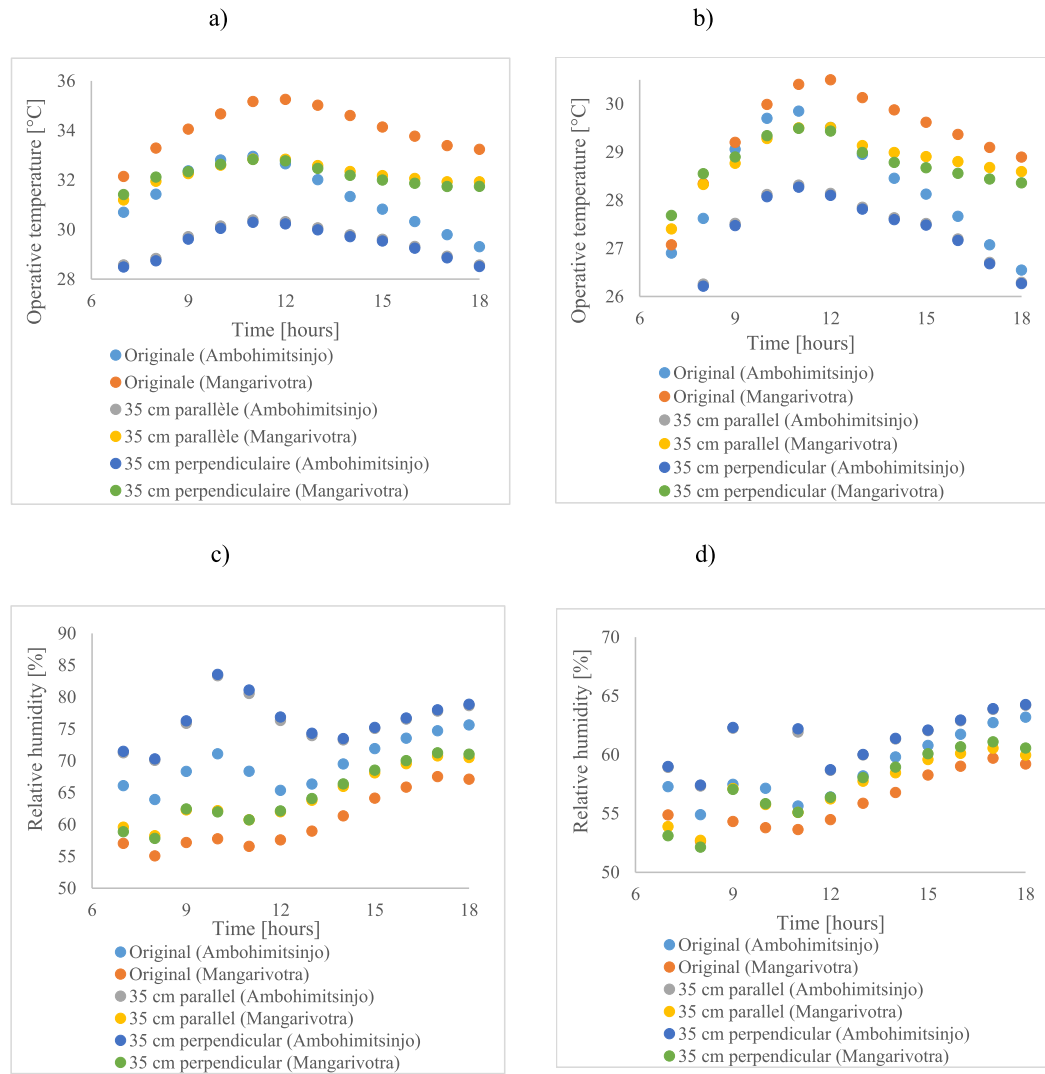


Fig. A7. Sub-scenario roof+35 cm straw bale insulation result, a-b) operative temperature during hottest and cooler period; c-d) relative humidity across december and july.

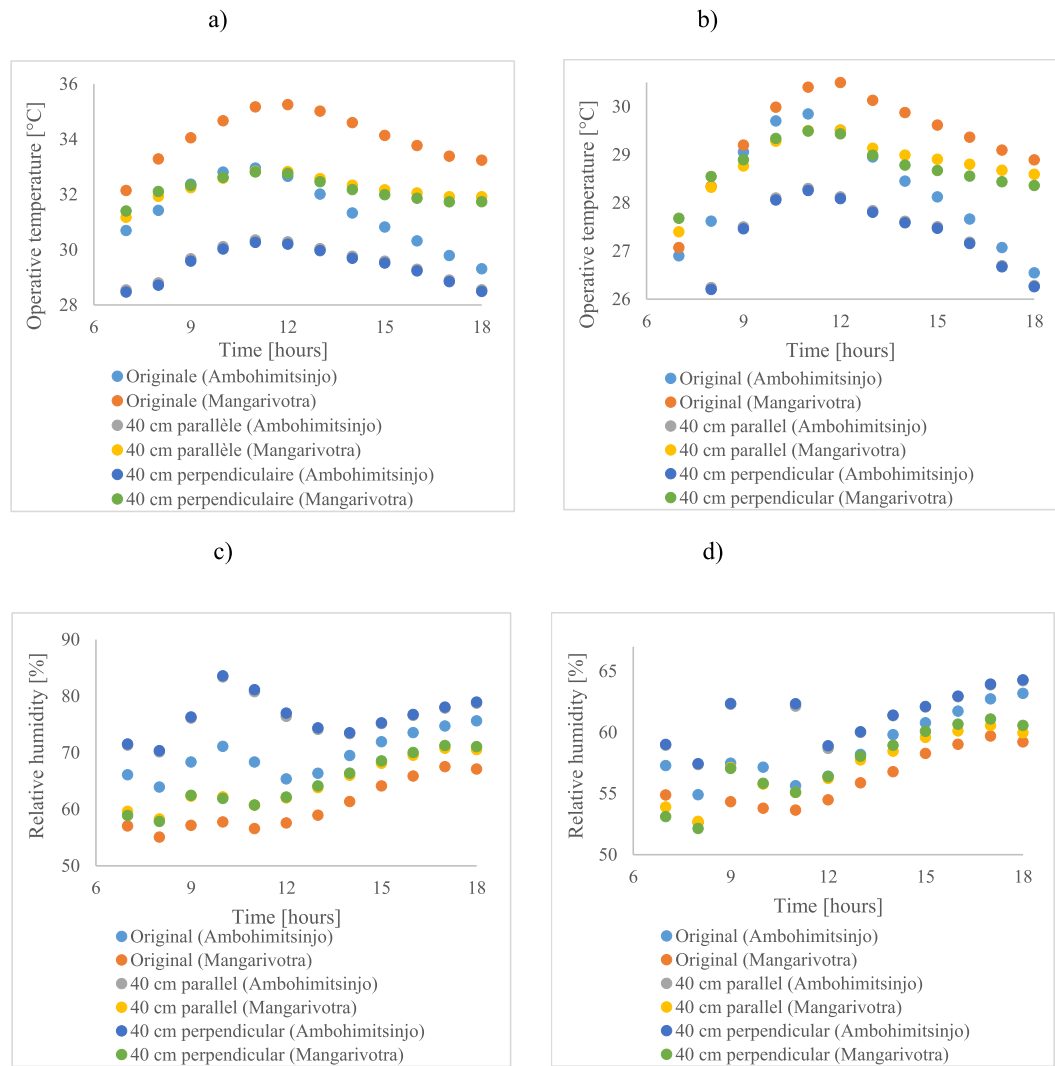


Fig. A8. Sub-scenario roof+40 cm straw bale insulation result, a-b) operative temperature during the hottest and cooler period; c-d) relative humidity across December and July.

Data availability

Data will be made available on request.

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