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Effect of straw bale insulation on indoor thermal comfort in school building under tropical climates

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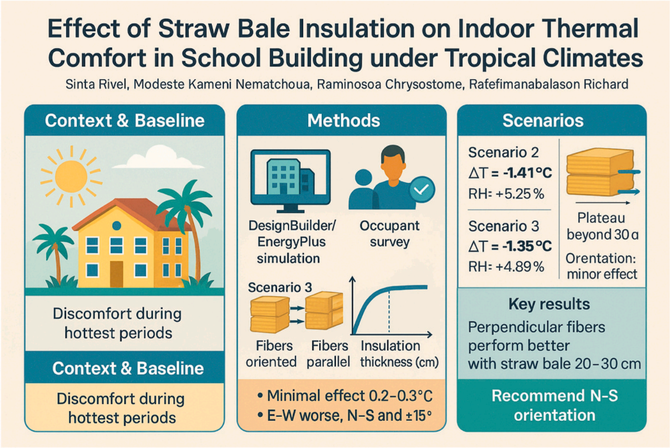
GRAPHICAL ABSTRACT



Effect of Straw Bale Insulation on Indoor Thermal Comfort in School Building under Tropical Climates

Sinta Rivel, Modeste Kameni Nematchoua, Raminosoa Chrysostome, Rafefimanabalason Richard

Context & Baseline

Discomfort during hottest periods

Context & Baseline

Discomfort during hottest periods

Methods

DesignBuilder/ EnergyPlus simulation

Occupant survey

Scenario 3

Fibers oriented

Fibers parallel

Insulation thickness (cm)

- Minimal effect 0.2–0.3°C
- E-W worse, N-S and ±15°

Scenarios

Scenario 2
ΔT = **-1.41°C**
RH: +5.25 %

Scenario 3
ΔT = **-1.35°C**
RH: +4.89 %

Plateau beyond 30 a

Orentation: minor effect

Key results

Perpendicular fibers perform better with straw bale 20–30 cm

Recommend N-S orientation

ARTICLE INFO

Keywords:
Tropical climate
Design builder
Straw bale

ABSTRACT

This study assesses the impact of straw bale insulation on indoor thermal comfort in school buildings, aiming to develop customized solutions for tropical climates. The approach involves simulations conducted with Design Builder software, powered by the Energy Plus engine, and

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Classrooms
Orientation
Fiber

validated through occupant feedback via survey (students and teachers) and field measurements using meteorological sensors. Initial findings revealed that school configurations failed to meet thermal comfort requirements during the hottest periods. Three scenarios were explored to mitigate this issue. The first focuses on adjusting the building orientation in 5° increments from 0° to 360°, while the second highlights walls and roof external insulation reinforced with straw bales, where the fibers are oriented perpendicular to the heat flow. The last scenario emphasizes the same insulation system with fibers facing parallel to the heat flow. Results indicate that orientation has a minor effect on temperature, with variations of approximately 0.2–0.3 °C depending on the angle. Orientations around 90° and 270° (East-West) tend to exacerbate thermal discomfort due to increased solar radiation in the morning and afternoon. In contrast, North-South orientations (0° and 180°) and slight deviations of ±15° provide better thermal comfort. The temperature reduction trend relative to insulation thickness shows a steady decrease in indoor temperatures as the insulation layer thickness increases. A more pronounced temperature drop is observed between 5 cm and 20 cm of insulation, while beyond 30 cm, the reduction stabilizes, suggesting a thermal saturation effect where additional insulation offers minimal improvement. Scenario 2 reaches a temperature gradient of 1.41 °C during November and December. In comparison with the original scenario, it observed a mean value of relative humidity deviation of +5.25 %, attesting to an enhancement in indoor freshness and a reduction in internal heat stress. Scenario 3 shows the same trend, a relative humidity deviation of +4.89 % and a temperature gradient of 1.35 °C. Scenario 2 demonstrates a slightly greater reduction than Scenario 3, due to straw fibers oriented perpendicularly to the heat flow, providing better thermal resistance compared to parallel fibers.

1. Introduction

Thermal comfort in educational environments is a critical issue worldwide, directly influencing students' health, well-being, and academic performance. According to the World Health Organization (WHO), approximately 15 % of schools globally experience inadequate thermal conditions, affecting over 150 million students each year. Research has shown that poor indoor temperatures can lead to a 20 % decrease in cognitive performance, whereas maintaining optimal thermal comfort can improve student productivity by 15 %. Despite its importance, thermal comfort in classrooms remains a significant challenge, particularly in developing regions where school infrastructure is often inadequate. Poor thermal regulation results in extreme indoor temperatures, disrupting the learning environment and compromising students' ability to concentrate.

Several studies have investigated the factors affecting thermal comfort in classrooms. A study on adaptive thermal comfort in Madagascar compared traditional buildings to schools, revealing that traditional structures provided superior comfort conditions. The comfort temperature ranged between 24.6 °C and 28.4 °C, with more than 80 % of occupants reporting satisfaction within a range of 24.5 °C–27.5 °C [1]. These findings highlight the potential for improving school design by integrating traditional architectural principles. Additionally, research indicates that pupils have lower comfort temperatures compared to adults and reach higher thermal sensations in the afternoon, tending to prefer a cooler environment [2]. The thermal behaviour of residential building envelopes is significantly influenced by thermal bridges with exterior insulation and finish systems (EIFS). Authors describe that EIFS decreases the heat transmission with the outdoor environment by 13.9 % for classical walls and 51.2 % for autoclaved aerated concrete bearing [3]. Arash Shahee et al. [4] describe the use of external horizontal awnings coupled with a thermal insulation sheet on the external wall of the building, reducing 200 kWh of energy consumption compared to the normal state, corresponding to the standard energy consumption of the building. Studies also show that adaptive comfort models like optimal building, adaptive facades, and cross-ventilation reduce cooling loads by up to 35.9 %, improve daylighting by 69 % and lower indoor temperatures by an average of 2.2 °C [5]. Additionally, the use of energy in many buildings has been reduced by adopting passive strategies [6]. The building envelope plays a fundamental role in regulating the indoor environment, and a 391 review study analyzed by Saleh Abu Dabous et al. [7] indicates a large interest in external structure, with 70 % of published papers during the last five years. Additionally, wall system retrofits are the most commonly used (47 %), pursued by glazing (37 %) and shading effect (16 %). Also, another study introduces the indoor driving temperature to assess the building envelope performance and underline the capacity of envelope insulation to reduce thermal energy use between 19 and 56 % and give a potential for energy saving up to 10 % driven by users' behaviour [8].

Moreover, 90 selected papers by Modupe Cecilia Mewono et al. [9] assess the controlling system of indoor climate and demonstrate the need to consider the indoor environment, the indoor air quality, indoor thermal comfort, visual comfort, and acoustic satisfaction. Studies also emphasize the evolution of insulation materials in construction creates a habitable space in buildings and protects the environment [10]. Also, An Li et al. [11] reported the capability of straw bales in reducing material waste, greenhouse gas emissions, and the ecological impact. Furthermore, research conducted in Sicily, Italy, mentions the advantages of using wall-sample solutions with durum wheat straw bales and may reduce heating and cooling, respectively, by 4–10 % and 40–50 % [12].

This study proposes a practical and effective approach to improving thermal comfort in schools located in hot tropical climates. It integrates local materials, passive design techniques, and modern technologies, while considering economic and environmental constraints. The research addresses the often-overlooked issue of inadequate thermal comfort in school infrastructure, which negatively affects students' health and academic performance. By implementing targeted solutions, this study aims to enhance occupant well-being while optimizing building energy efficiency. The article is structured as follows: first, it defines key thermal comfort parameters, including climatic conditions, school layouts, construction materials, and occupant activities. Then, thermal comfort studies using Design-Builder simulations are conducted and compared with in-situ measurements. Subsequently, various improvement scenarios are proposed and analyzed. Finally, an in-depth discussion highlights the implications of the results and their relevance to the global educational context. The study concludes with key findings and recommendations for future research and practical applications.

2. Material & methods

A numerical approach using Design Builder software, incorporating EnergyPlus as the simulation engine, was used to model the thermal conditions of the school building. Once the simulation was completed, the results were verified by surveying the occupants (students and teaching staff) and using meteorological sensors to gather their subjective perceptions of thermal comfort. These surveys are based on the standardized questionnaire method commonly used in thermal comfort studies, as recommended by Fanger [13]. Additionally, in-situ measurements were carried out using a weather sensor to continuously record temperature, relative humidity, and airspeed in the classrooms during the hottest month of the year, to ensure data representativeness, in accordance with the methods described in our last research [14].

2.1. Presentation of case study

This study was conducted in the elementary schools of Antsiranana, Diego-Suarez, Madagascar, where the climate is hot tropical year-round, with a relatively cool and dry period from June to August and a hot and rainy period from November to March. Antsiranana’s consistently hot tropical climate makes it a representative example of the thermal challenges faced in other similar regions. This city highlights the importance of addressing thermal comfort, which is often overlooked in local school infrastructures. By focusing on Antsiranana, the study aims to propose solutions that can be replicated in similar contexts, both locally and internationally. According to the database from the meteorological service of Antsiranana, climatic parameters such as Relative humidity (RH), outdoor air temperature max (Tair max), outdoor air temperature min (Tair min), rainfall, sunstroke, and wind speed (W) are provided in Table 1.

2.2. Configuration of standard study design

The study plan for simulation is based on the new official design from the Malagasy Ministry of National Education (MEN) called “Manarapenitra School” which is composed by two classrooms with a bathroom in the middle, as shown in Fig. 1.

Table 2 presents the main characteristics of the standard study plan, describing direction, dimensions, space distribution, and materials used for construction.

2.3. Simulation on Design Builder

Based on the numerical approach, Design Builder is used as simulation software, including EnergyPlus as the simulation Engine. As the case of study presented, a void in the middle (bathroom), the geometry of primary school building is limited to a single zone modelling, as illustrated in Fig. 2.

Since the study plan consists of a school building with two perfectly symmetrical classrooms, only one classroom will be modelled. All cantilevered elements have already been taken into account through the openings due to shading effects. The simulation in Design Builder enables the modeling and prediction of thermal conditions in classrooms under various configurations and scenarios. This approach complements the previous studies by providing a theoretical and predictive perspective. Referring to data from CIBSE Guide A [15] and the ArchiCAD 23 software library [16], the material properties of the two study schools are described in Tables 3 and 4.

The following table presents the input data used for the simulation of building characteristics, occupancy, HVAC systems, and energy consumption parameters.

2.4. Validation of the models

Several approaches are employed to finalize this research work (see Table 5). Through 223 questionnaires, occupants (pupils and teaching staff) describe their dissatisfaction due to thermal discomfort and heat stress, causing degradation of teaching effectiveness.

Table 1
Climatic data of Antsiranana.

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
RH [%]	81	84	82	76	71	69	67	67	66	67	69	75
Tair max [°C]	31.0	30.6	31.1	31.4	31.0	29.7	29.0	29.2	30.1	31.0	31.9	34.0
Tair min [°C]	23.0	23.0	23.0	22.7	21.7	20.3	19.5	19.6	20.2	21.2	22.4	23.1
Rainfall [mm]	295.3	288.8	164.7	60.8	17.3	16.5	14.9	17.1	7.8	23.3	39.3	159.7
Sunstroke [h]	188.7	169.5	213.8	255.9	283.5	257.0	271.9	289.7	292.4	306.4	282.7	226.4
W [km/h]	15	13	14	17	20	23	27	29	30	28	22	17

Fig. 1. Case study design, a) view plan; a1) perspective view.

Table 2
Characteristics of standards study design.

Plan	Modern plan
Directions	North/South
Distribution	02 classrooms with a bathroom
Built surface	121.20 m2
Dimension	19.50 x 7.48 × 3.30 m3
Ceiling height	3.30 m
Opening surface	16.12 m2
opening type	Aluminum joinery;
Colors	Interior: white; exterior: white, purple, fuchsia,
Student population	108
Roofing	Roof terrace
Wall	Hollow Concrete block 23 cm

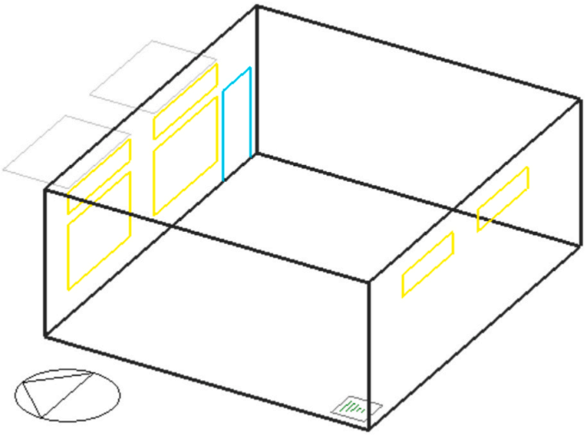

Fig. 2. Design modelling.

On the other hand, numerical simulation and field measurement constitute the base of the model's validation. Both approaches take place during the hottest period in the year and range over the period of study (07:30–11:30 a.m. and 02:30–05:30 p.m.). Calibration is important to enhance model reliability between simulated and measured values. In accordance with ASHRAE guideline 14 [17], the assessment of the following parameters is critical: Mean Bias Error (MBE), which measures the systematic bias between the measured and simulated values. It is expressed as a percentage and calculated as follows:

$$MBE\ (\%) = 100\frac{\sum_{i=1}^{n}(mi - si)}{\sum\limits_{i=1}^{n} m_i} \tag{1}$$

Where: is the measured value at instant i; *si* is the simulated value at instant i; *n*: the total number of data points; Root Mean Square Error (RMSE), which evaluates the dispersion of errors between the measured and simulated values. It is calculated in absolute units of the measured variable.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(mi - si)^2}{n}}; \tag{2}$$

Table 3
Thermal properties of materials.

Component	Thinkness [m]	Thermal conductivity [W/mK]	Density [Kg/m3]	Specific Heat Capacity [J/kgK]	Embolied Carbon [KgCO2/kg]	U-Value [W/(m^2K)]
External wall						
Cement mortar coating	0.015	0.88	1800.00	896.00	0.228	2.318
Hollow concrete block	0.20	1.63	2300.00	1000.00	0.08	
Cement mortar coating	0.015	0.88	1800.00	896.00	0.228	
Partition wall						
Cement mortar coating	0.015	0.88	1800.00	896.00	0.228	2.318
Concrete block	0.20	1.63	2300.00	1000.00	0.08	
Cement mortar coating	0.015	0.88	1800.00	896.00	0.228	
Roof terrace						
Waterproofing	0.02	0.23	1100.00	1000.00	0.066	3.008
Solid slab	0.10	1.13	2300.00	1000.00	0.198	
Cement mortar coating	0.015	0.88	1800.00	896.00	0.228	
Flooring						
Linoleum	0.02	0.17	1200.00	1400.00	0.38	2.265
Cast concrete	0.08	2.30	2300.00	1000.00	0.198	
Stone basalt 40/70	0.15	2.30	2880.00	840.00	0.08	

Table 4
Input data for simulation.

Parameters	Modern plan
Height (m)	3.40
Area (m^2)	121.20
Activity template	Classroom
Density (people/m^2)	0.892
Activity (Met)	0.90
Clothing (Clo)	0.5–1.0
Fresh air (l/s-person)	10.00
Occupancy schedule	Monday - Friday 7:30 a.m. to 11:30 a.m. 2:30 p.m. to 5:30 p.m.
Construction template	Project construction template
Air tightness (ac/h)	0.70
Glazing template	Project glazing template
Glazing type	Aluminum joinery
Shanding	Local shading
HVAC template	Fan coil unit (4-pipe) Air Cooler chiller
HVAC Schedule	Monday – Friday
Heating: Fuel	No
Cooling: Fuel	No
Other ventilation	Natural ventilation

Table 5
Summary of the validation of the new simulation model.

Validation criteria	Hourly relative humidity	Hourly air temperature
MBE [%]	−7.49	0.54
RMSE	7.97	2.03
CV(RMSE) [%]	14.11	6.04

coefficient of variation of RMSE (CV(RMSE)), which is calculated by the average of the measured value, expressed in percentage, and indicated as follows:

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

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

$$M = \frac{\sum_{i=1}^{n} m_i}{n}; \tag{4}$$

ASHRAE defines acceptability thresholds for these indicators to evaluate the accuracy of energy simulation models. Monthly data: MBE < ±5 %, CV(RMSE) < ±15 %; hourly data: MBE < ±10 %, CV(RMSE) < ±30 %. The following table illustrates the summary of error metrics.

Fig. 3 shows the variation of indoor air temperature and relative humidity using field measurement as measured values and numerical approach as simulated result during the hours of study ranging from 07:30–11:30 a.m. and 02:30–05:30 p.m.

The results of the indoor air temperature are very satisfactory. The MBE of 0.54 % indicates a negligible bias, meaning that the simulation model does not present any significant systematic deviation from the measurements. The RMSE of 2.03 °C is acceptable (although ideally, an RMSE below 1 °C would be preferred), especially in real-world conditions where errors of a few degrees can be tolerated. The CV(RMSE) of 6.04 % is also very low, indicating that the errors are fairly consistent and that the simulation is relatively stable in its results.

The results for relative humidity also show that the simulation is acceptable: The MBE of −7.49 % is below the ±10 % limit, which is in accordance with the standard. The RMSE of 7.97 % is within the acceptable range according to ASHRAE Guideline 14, although it could be improved for optimal accuracy. The CV(RMSE) of 14.11 % is well below the 30 % limit, indicating that the variability of the errors remains reasonable.

Based on ASHRAE Guideline 14, the results of the simulations for air temperature and relative humidity are generally within the standards. The bias errors (MBE) and the variability of the errors (CV(RMSE)) are well within the acceptable limits for hourly evaluations, suggesting that the simulation model is reliable for predicting environmental conditions. The RMSE for both parameters is also acceptable, although further adjustments could be considered to optimize the accuracy of the simulations, particularly for relative humidity.

3. Result and discussion

The simulation results of this school building configuration is presented in Fig. 4. The comfort results generated by the Design Builder software is analyzed taking account radiant temperature (RT), relative humidity (RH), indoor air temperature (Tair), PPD, PMV, and operative temperature (OT) (see Fig. 5).

According to Kameni et al. [1] and Brahim Belgaid [16], internal thermal comfort for tropical countries is ensured when the air temperature is between 24.6 °C and 28.4 °C, relative humidity is between 30 % and 70 %, and air velocity is less than 0.1 m/s. During the hottest months of the year, thermal comfort is not achieved. However, air temperature decreases to become comfortable during the cooler months of the year (July and August). Overall, the annual discomfort rate is 71 %. The analysis of thermal parameters reveals significant thermal discomfort in the studied classrooms. Air temperature fluctuates between 28 °C and 32.18 °C throughout the year, with particularly high values at the beginning and end of the year. Radiant temperature follows a similar trend, suggesting heat accumulation within the building, thereby amplifying thermal discomfort. Operative temperature, which accounts for both air and radiant temperatures, confirms this pattern, frequently exceeding 30 °C. The PMV consistently remains above 1.5, reaching up to 2.61, indicating an excessive sensation of heat for most occupants. Consequently, the PPD frequently exceeds 80 %, meaning that a large proportion of students experience significant thermal discomfort. Although relative humidity varies between 57 % and 70 %, it tends to exacerbate the perception of heat, particularly when temperatures are highest, thereby reducing the effectiveness of evaporative cooling through perspiration.

Three scenarios ranging from 1 to 3 are presented to improve the indoor environment of classrooms and are developed in Table 6.

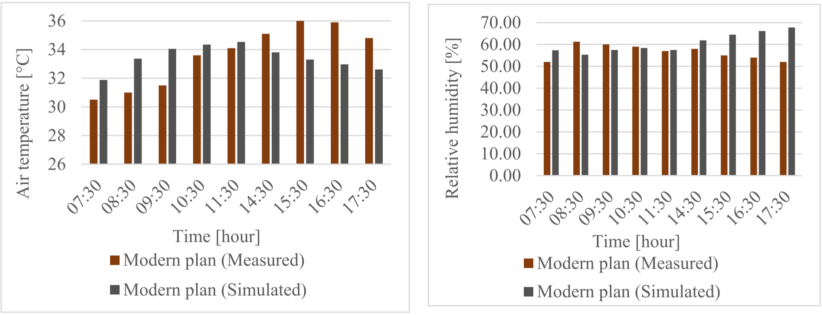
b) b1)

Fig. 3. Comparison between simulated and measured values, b) indoor air temperature; b1) relative humidity.

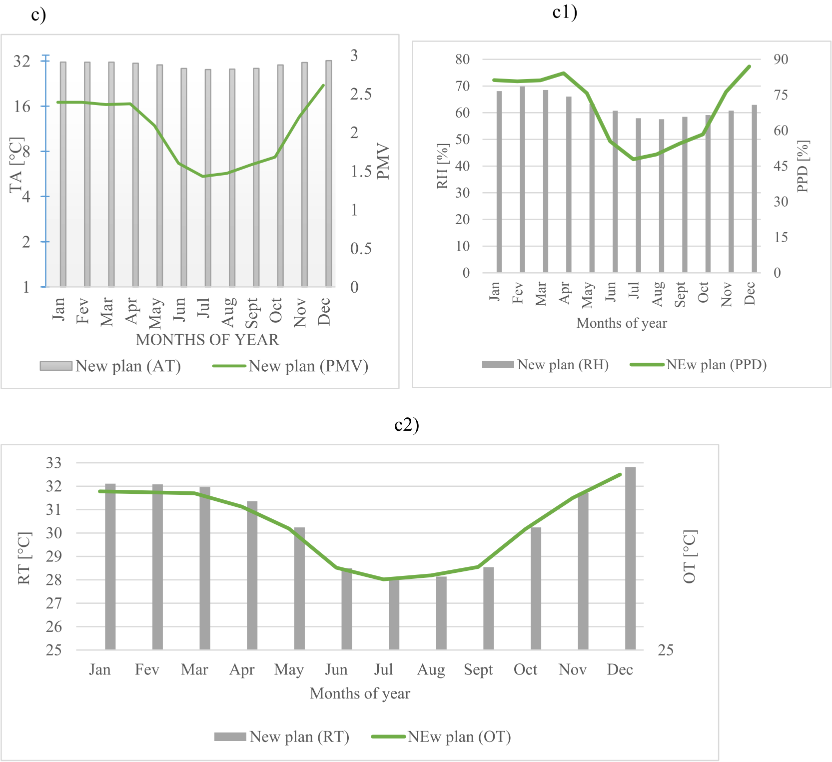

Fig. 4. Comfort result, c) indoor air temperature and PMV; c1) relative humidity and PPD; c2) radiant temperature and operative temperature.

3.1. Scenario 1

After performing simulations with 5° incremental variations per operation and trending from 0° to 360°, the following figures present the comfort results.

The results indicate notable variations based on months and orientations. Air temperature ranges between 28.05 °C and 32.33 °C, depending on the month and orientation. From May to August, the lowest temperatures, PMV (Predicted Mean Vote), and PPD (Predicted Percentage of Dissatisfied) values are recorded, corresponding to the relatively cooler season. Orientations have a slight influence on temperature, with variations of about 0.2–0.3 °C depending on the angle. However, the primary influence remains seasonal. The lowest PMV values are observed between June and August, aligning with the decrease in temperatures during this period. Orientations near 90° and 270° (East-West) exhibit the highest PMV and PPD values, indicating increased thermal discomfort due to greater sun exposure in the morning and afternoon. On the other hand, the North-South orientation (0° and 180°) and ±15° show more balanced PMV values and moderate PPD levels, providing an advantage for optimal thermal comfort. Compared to this, the average discomfort rate of occupants (PPD) related to the East-West orientation peaks at 2.26 %. In alignment with Mostafa Habibi et al. [18], the south-facing orientation records option during the hottest period, acquiring only 23 % of the radiation collected by a horizontal surface.

3.2. Scenarios 2 & 3

According to the Association of Bio-based Construction Industries [19], between 2015 and 2023, bio-based materials (straw, hemp, and wood) experienced a 93 % growth in production volume in France. Bio-based insulation materials accounted for 11 % of the market in 2023, compared to 6 % seven years earlier. This surge in demand stems from the imperative to decarbonize buildings, driven by the new environmental regulation for new constructions, known as RE2020 [11], which came into effect on January 1, 2022. Consequently, straw bales were prioritized for scenarios 2 and 3 as they are a 100 % ecological material. Based on the research by Stéphane FUCHS et al. [20], the thermal characteristics detailed in Table 7 will be used for the simulation.

These two scenarios are based on passive design principles and focus exclusively on insulating the walls and roof using straw bales. They involve preserving all the original building components while adding straw bale insulation to both external and partition walls, as well as to the roofs. Table 8 presents the characteristics of the composite materials for Scenarios 2 and 3.

By running the simulation again in DesignBuilder and considering all the improvements made to the building envelopes and roofs, the summarized results are illustrated in Fig. 6.

The result demonstrate a significant reduction in air and operative temperatures in Scenarios 2 and 3 compared to the initial

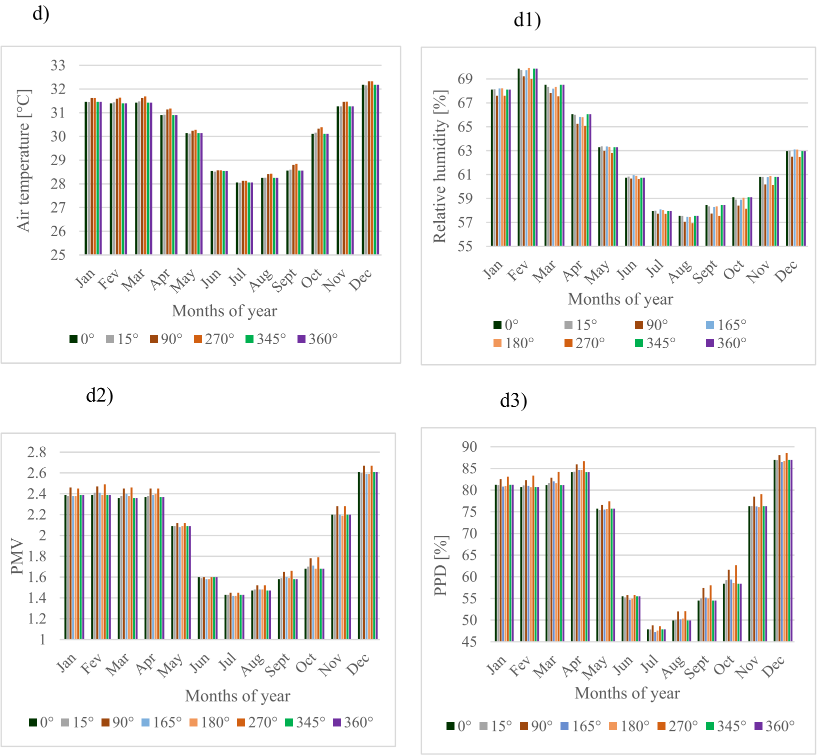

Fig. 5. Variation of comfort result, d) indoor air temperature; d1) relative humidity; d2) Predicted Mean Vote; d3) Predicted Percentage of Disatisfied

Table 6
Describing scenarios.

Scenarios	Description
1	Variation of building orientations in 5° increments, ranging from 0° to 360°, to determine the optimal indoor comfort.
2	External insulation (walls and roof) reinforced with straw bales, where fibers are oriented perpendicular to the heat flow.
3	External insulation (walls and roof) reinforced with straw bales where fibers are oriented parallel to the heat flow.

Table 7
Thermal properties of straw insulation.

λ [w/m.k]	ρ[kg/m3]	Specific heat [J/kg.K]	Embodied carbon [kgco2/kg]	Observation
0.044	90–110	1400–2000	1700	Scenario 2
0.067	90–110	1400–2000	1700	Scenario 3

scenario. For the hottest months, such as January and December: initial scenario: AT ≈ 31.5 °C–32.2 °C; OT ≈ 31.7 °C–32.5 °C; Scenario 2: AT ≈ 30.0 °C–30.7 °C; OT ≈ 29.9 °C–30.7 °C; Scenario 3: AT ≈ 30.1 °C–30.8 °C; OT ≈ 30.0 °C–30.8 °C. This temperature reduction is a direct result of more effective insulation, which has minimized solar heat gains and reduced thermal accumulation in the indoor space. Relative humidity (RH) slightly decreases in the improved scenarios. For June and July: initial scenario: RH ≈ 60.7 %–57.9 %; Scenario 2: RH ≈ 64.1 %–57.8 %; Scenario 3: RH ≈ 68.6 %–57.7 %. This variation can be attributed to better thermal regulation, which reduces temperature differences between the interior and exterior, thereby limiting condensation phenomena and humidity fluctuations. The PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices indicate a clear improvement in thermal comfort with Scenarios 2 and 3: Initial scenario PMV: 2.2 to 2.61; Scenario 2 PMV: 1.76 to 2.01; Scenario 3 PMV: 1.8 to 2.03; Initial scenario PPD: above 75 % on average, reaching 87 % in December; Scenario 2 PPD: around 47 %–65 %; Scenario 3 PPD: around 48 %–67 %. The PMV approaches a more acceptable value (close to 1), indicating less thermal discomfort. This is also reflected in a reduction in PPD, with 14 % fewer dissatisfied individuals, and the rate approaches less than 1.60 % between scenarios 2 and 3. The temperature reduction graph based on insulation thickness shows a progressive decrease in indoor temperature as insulation thickness increases. Greater insulation thickness achieves a more significant reduction in indoor temperature, with a notable gain between 5 cm and 20 cm. Beyond 30 cm, temperature reduction tends to stabilize, suggesting a thermal saturation effect,

Table 8
Thermal properties of the composite materials.

Composite materials	R value [m2K/W]	U value [m2K/w]	R value [m2K/W]	U value [m2K/w]
	Scenario 2		Scenario 03	
Flat roof	9.458	0.106	6.337	0.158
Walls	9.722	0.103	6.601	0.151
Ground floor	0.441	2.265	0.441	2.265

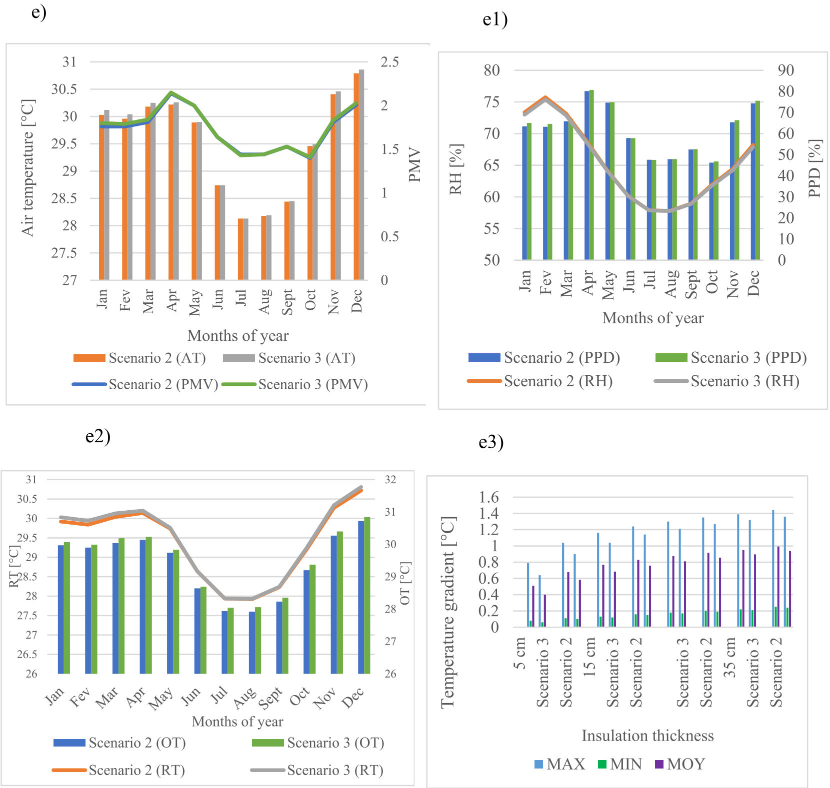

Fig. 6. Result of scenario 2&3, e) indoor air temperature and PMV; e1) relative humidity and PPD; e2) radiant temperature and operative temperature; e3) temperature gradient.

where further insulation no longer yields significant improvements. Scenario 2 demonstrates a slightly greater reduction than Scenario 3, possibly due to straw fibers oriented perpendicularly to the heat flow, providing better thermal resistance compared to parallel fibers. This could result from the improved thermal resistance of perpendicular straw fibers, which more effectively slows heat conduction. Thermal insulation has a significant positive impact on indoor temperature and thermal comfort in classrooms, achieving temperature reductions of more than 1.44 °C for the maximum tested insulation thicknesses.

4. Conclusion

This study addresses the critical issue of thermal comfort in schools situated in tropical climates. A thorough analysis has demonstrated that thermal comfort directly influences students' health, well-being, and academic performance.

The adopted approach, based on simulations conducted using DesignBuilder software, was rigorously validated through occupant surveys and on-site measurements. The coefficient of variation of the root mean square error (CV (RMSE)) and the mean bias error (MBE) values indicated an acceptable level of accuracy in the modeling process. These results confirm the robustness of the approach and the reliability of the simulations performed.

The study revealed that, in their initial configurations, the two analyzed variants did not meet thermal comfort criteria, particularly during the hottest periods of the year. To address this issue, three scenarios were proposed: the first involved adjusting the study plan orientation in 5° increments, ranging from 0° to 360°, while the other two focused on adding external straw bale insulation to the building envelope and the flat roof.

The analysis highlighted the importance of using locally sourced bio-based materials, passive design techniques, and modern technologies to enhance thermal comfort while considering economic and environmental constraints. It was demonstrated that these approaches not only reduce energy consumption but also significantly improve the living conditions of occupants by reducing the indoor air temperature by 1.41 °C during the hottest period of the year, such as in [21,22].

This study has shown that adaptive comfort models can be implemented to enhance thermal comfort in classrooms, even in resource-limited contexts. However, it is important to note that certain variables, such as shading effects, Phase Change Materials, the Provençal well, and wind catchers, were not fully explored in this study. These aspects could be the subject of future research, opening new perspectives for improving thermal comfort in schools in tropical regions.

CRediT authorship contribution statement

Sinta Rivel: Visualization, Validation, Supervision. **Modeste Kameni Nematchoua:** Visualization, Validation, Supervision, Methodology, Investigation, Data curation. **Raminosoa Chrysostôme:** Validation, Software, Methodology. **Rafefimanana Sambilason Richard:** Validation, Supervision, Methodology.

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.

Data availability

Data will be made available on request.

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