Effect of housing modification on indoor thermal comfort and malaria

The evaluation of house modification for vector proofing and heat reduction in a malaria endemic region of western Kenya

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Abstract

Introduction. Doors, eaves and fenestrations facilitate heat transfers between the indoor and outdoor environment through stack and cross ventilation in addition to allowing light into the house. Unfortunately, these also serve as the entry routes for disease carrying vector such as mosquitoes. These fenestrations are usually not oriented or are disproportionate in size to the indoor environment to achieve meaningful cooling. Screening of these openings has the potential of increasing indoor temperatures hence jeopardizing the comfort of the occupants. We assessed the impact of combining passive cooling options with vector proofing for indoor temperature reduction and mosquito control in Siaya County, western Kenya.

Methodology. A randomized control study with ten houses in each arm allocated to either cool roof, cross ventilation or mat ceiling was used to assess the impact of the modification on indoor temperatures in comparison to unmodified controls. Houses with passive cooling options were combined with door, window and eave screening while control houses remained unmodified. Indoor temperatures were monitored daily using data loggers and mosquito numbers were assessed by indoor CDC light traps collected monthly before and after modification. Community knowledge, attitude, and perception on house modification for temperature and mosquito reduction was assessed using structured questionnaires while an infrared camera was used for thermal imaging of the houses.

Results. The number of *An. funestus* were 54% lower in screened compared to unscreened houses and 5 lower than before screening. Houses with cool roof had the lowest mean daily temperature of 26.18°C ±2.80 at the hottest hour of the day compared to control, 28.62°C±3.99 whereas, houses with mat ceiling had the least mean daily temperature variation of between 27.56°C - 25.18°C compared to control 28.62°C-23.38°C.

Conclusion and recommendation. Combination of passive colling options and vector proofing provide practical opportunities for mitigation of the impact the rising temperatures due to global warming and malaria control in rural Africa communities. Further investigation to assess the impact of the modification on health outcomes including sleep quality, heat rate, heat stress and malaria among others is recommended.

Background

Climate change associated with extreme weather events is adversely affecting health of the human population globally [1]. Tropical regions are projected to be most affected due to faster rise in temperatures compared to other areas [2, 3] and low interannual variability [4]. The level of impact of the constantly rising temperatures on an individual's health is dependent on the extent of exposure, indoors or outdoors. While people tend to spend much time indoors, either during occupational engagement or while at home, overheating in the indoor environment due to high temperatures and humidity in the tropics, coupled with poorly designed houses affect health and increases energy demands and carbon emissions [5].

Indoor heat gain in the tropics is largely driven by raised outdoor temperatures, as well as internal heat generated by building occupants, installed equipment and activities such as cooking. To mitigate heat stress resulting from increased environmental heat load, it is important to ensure that the ambient temperature in an indoor living space is maintained within a range, known as thermal comfort zone (TCZ), where the occupants feel comfortable [6]. Passive cooling and overheating protection in tropical buildings design is critical in mitigating against current and future risk of climate change [5]. Inclusion of openings in a building´s exterior surface, e.g. doors, windows and vents [5], is the most common strategy used for indoor-cooling during hot seasons in the tropics. These openings facilitate heat transfer between the indoors and outdoors through ventilation i.e., both cross-ventilation and stack-ventilation. The size of these opening relative to the building and their orientation significantly affects the rate of heat transfer between the indoor and outdoor environment. Tragically, in many households, some of these openings are either missing, poorly oriented or disproportionate to the indoor environment to achieve any meaningful cooling indoor.

Other than providing ventilation into the indoor environment by letting in light and air flow into the buildings, these openings double up as mosquito entry points [7, 8], further risking the health of the occupants. Mosquitoes that transmit malaria are adapted to enter and feed on humans indoors [9, 10]. Recent studies from western Kenya have shown that human-vector interactions that lead to malaria transmission still occur mostly indoors and late at night despite sustained use of long-lasting insecticidal nets (LLINs) [11-15]. The risk of malaria transmission indoors is further exacerbated by climate change crisis that increases overheating indoors as less people tend to use their bed nets during hot nights [16].

House modification, involving blocking of doors, windows and eaves with insect mesh has been demonstrated to reduce malaria transmission [17-20]. Consequently, the World Health Organization has given an interim recommendation for the use of untreated insect screens as a supplementary control measure against malaria [21]. However, blocking of these openings could potentially increase indoor temperatures, further jeopardizing the comfort of the occupants. To achieve TCZ in the indoor environment while effectively keeping away mosquitoes, this study explored the combined effect of housing modification for passive cooling and vector control in Siaya county, western Kenya.

Study sites

The study was conducted in Kedenge Ratuoro village (0.0242° N, 34.1749° E), near Lake Kanyaboli, Siaya county. The residents are of the Luo ethnic group, subsist on farming, fishing and trade, and live in small houses, clustered into family social units of relatives, called compounds [22]. Malaria transmission in the lake endemic region is stable throughout the year, with a prevalence of 18.9% in children between 6 months and 14 years of age [16], with Siaya county having a prevalence of 37%. However, malaria transmission in the is highly heterogeneous and a. *Anophel*es gambiae, *Anopheles funestus* and *Anopheles arabiensis* are the main malaria vector species in the region. The region has a bi-modal rainfall pattern, with long rains between March and May and short rains between October and December. Annual rainfall ranges from 670 to 2200 mm around Lake Victoria. A temperature suitability index (TSI) for malaria transmission shows that western region has ambient temperature and adequate rainfall suitable for endemic malaria transmission [16, 23]. The temperatures are usually between 17°C to 28°C with an average temperature of 24°C in Siaya.

Housing. Houses are typically rectangular, and constructed of stick frames (wattle), compacted soil or cement foundation, and dirt or cement floor. Walls consist of wood ash, mud and cattle dung daubed into the wattle, and either left rough (unfinished) or finished with hand smoothing called “smearing” (Figure 1). Some houses have cement blocks or poured cement walls. Houses are most often roofed with corrugated iron sheets nailed purlins, but traditionally were roofed with grass thatch. A few houses have clay tile roofs. Roofs of corrugated iron are usually a simple open gable design, but some houses have hipped roofs. Doors and windows are unframed or framed with wood to create a jam and sash but are often poorly hung. Some houses do not have windows. Walls rise to a wall plate topped with wooden pole or rough timber headers. Roof rafters, fastened to these headers with nails, extend upward from the wall plate to one or more tie beams which are either poles or rough finished timber and are supported by walls. Typically, the roof rafters and roofing material extend as an eave externally hung past the wall dimensions to allow rainwater to drip and drain away from the foundation. A fascia may or may not be present, but the roof rafters at the wall position lack a soffit, leaving the eaves open to the outside air. This open space, in addition to doors and windows provide ventilation into the houses, allowing entry of light and air. Unfortunately, they are also the main route for unlimited entry of mosquitoes into the houses.

Figure 1: Picture of a typical house with iron roof and smeared mud wall in rural western Kenya.

Study design. A randomized control trial was used to assess the impact of housing modification on indoor mosquito numbers and temperature reduction. Forty houses were randomly allocated to the four different study arms, ten houses per arm. Quantitative and qualitative data collections were conducted before and after house modification.

Identification of study households. Home visits were conducted to enumerate and characterize houses within the study area. A total of 47 compounds with 83 houses where people sleep were enumerated. For every active structure in each compound, structural features including wall type, roof type, presence or absence of ceiling, eave type and number of windows and doors were recorded. From the 47 compounds with a pool of 83 houses, 40 houses with mud walls, open eaves, iron roofs and not more than two rooms were selected for the study. A single house was selected per compound.

Community mobilization. Representatives from all the 47 compounds were invited to a community meeting at a local church venue. All the compounds were represented. In addition, the village elder, area assistant chief and the chief were in attendance. The study was introduced to the community with emphasis on study objectives, rationale, different study arms, participant selection procedure and data collection procedures for assessment of study outcomes.

Training of study personnel. Community Interviewers (CIs) were identified and trained on Informed Consent (IC) procedures. The training covered study procedures, informed consent process, documentation and field work etiquette. Practical demonstrations of informed consent process were conducted to assess comprehension.

Informed Consent Process. Informed consent was sought from the household heads of every selected house, one house per compound. A total of 40 houses were consented to receive either one of the three cooling options plus vector proofing or remain as a control. Two copies of the consent form were signed by each household head, one copy was left with the study participant while the other was filled in the study file. No case of refusal was registered during consenting process.

Randomization into study arms. The study was organized into four arms, cool roof plus vector proofing, cross-ventilation plus vector proofing, mat ceiling plus vector proofing and control (no modification). A random allocation of the houses into the four study arms involved the consented heads of households or their representatives. A representative from each house picked a crumbled raffle ticket marked with one of the study arms. Each house was therefore randomly allocated based on the ticket picked by the house representative.

Structural modification. Structural modification of houses was conducted by a building professional identified based on previous experience with similar modifications. After randomization of houses into the various study arms, the specific house characteristics including floor area, size of doors, windows and eaves were collected to provide guidance for modification. The building expert established a workshop within the study area where all materials including doors, windows and pieces of timber for eaves and ceiling modifications were prepared before installation in the various houses. Modifications were conducted based on the randomization for passive cooling options described above. The passive colling options were installed as follows.

Cross ventilation - Cross ventilation was achieved by installing screened windows on the opposite walls of each room. This involved complete overhaul of the existing windows and creation of new ones if no window existed in a house. The windows were made of timber frame with two wooden panels each hanging on two hinges and closing at the centre (Figure 2). A Fibreglass Insect Mesh (FIM) laid between two sheets of Coffee Tray Mesh (CTM) was attached to the window frame for insect screening. The insect screen was installed outwards while the window panels opened inwards. To install the windows, a section of the wall was cut to create space for the window if none existed before or adjusted if the original window was smaller. After installation of the modified window, the remaining gaps in the wall were filled with mud with the same finish as the original wall.

Figure 2:Image of screened windows, A is a closed window with image taken from outside of the house while B is an open window, image taken inside the house.

Cool roof system and insect proof housing - Iron roofed houses were painted with a reflective white coat to reduce the amount of heat conducted into the house, hence lowering internal temperatures. Two coats of paint were applied on the roofs. We used Crown Roofmaster® (Crown Paint Industries, Nairobi, Kenya), an extremely durable weather-resistant, self-priming acrylic resin-based, waterborne topcoat with matt finish (Figure 3).

Figure 3: Image of a house with the roof painted white, cool roof.

False ceiling and insect proof housing – Locally made papyrus mat Ceilings were installed horizontally covering the roof space just above the eaves. Locally sourced round poles were used as bearings and binders for brandering to hold the mat. Wood biddings were nailed below the mats to hold them to the round poles used for brandering (Figure 4).

Figure 4: Image of mat ceiling

Mosquito proofing. All houses that received passive cooling options were screened for mosquito control. The doors were modified by introducing wooden frames and panels in addition to the originally exiting door. The old doors opened inwards while the newly introduced screened doors opened outwards. The screened doors panel were made of wooden frames and Fibreglass Insect Mesh laid between two sheets of Coffee Tray Mesh (Figure 5). The doors hanged on two self-closing hinges to keep them always closed. The windows were also screened as already described above. The eaves were screened by introducing a piece of timber at the edge of the wall just before the eave space and another piece of timber on the roof directly above the wall. Fiberglass Insect Mesh was then attached to the two pieces of timber, hence covering the eave space (Figure 6).

Figure 5: Image of screened doors, picture A showing closed screened door while B shows and open screen door.

Figure 6: Image of eave screen

Data collection

Temperature and humidity. Daily temperature and humidity were collected in both modified and control houses from March to July 2023 using data loggers. Both Multifunction

Thermometer PCE-WB 20SD - Wet Bulb Global Temperature (WBGT) (figure 7A) and Onset HOBO® UX100-003 data loggers (Figure 7B) were used to monitor temperature and humidity every 15 minutes for the entire period of the study. The data loggers were placed indoor hanging as centrally as possible, but away from potential interference with the household members. Batteries for WBGT were replaced every week while that of HOBO data loggers did not require replacing. Data downlead was conducted twice during the study period.

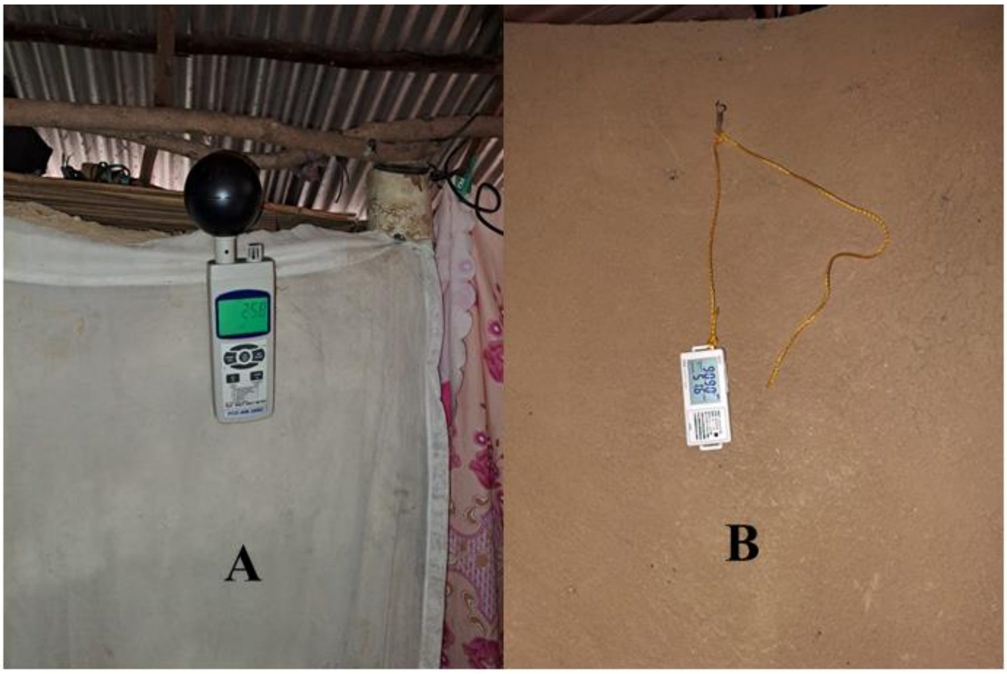

Figure 7: Picture of temperature and humidity data logger, A showing Wet Bulb Global Temperature (WBGT) data logger and B showing HOBO data logger.

Mosquito collection. Mosquito collection was performed indoors by CDC light trap. Collections were conducted twice before (baseline) and three times post modification in each house. The Light traps were set in the sleeping area, next to an occupied bed net, at approximately 1.5m from the floor. The traps were run from 18:00 h to 07:00 h the following morning. During the mosquito collection period, the collector administered a brief questionnaire to collect information on household characteristics, including roof type, wall type, presence of eaves, presence of bed nets and net use, presence of cattle and number of people that slept in the house at every collection. The location of each house was recorded using Global Positioning System (GPS) at each visit. The collected mosquitoes were identified to genus levels as either Anopheles or Culex. The anophelines were further identified morphologically to species level as either *An. gambiae s.l.* or *An. funestus s.l.* Data on household characteristics and mosquito information were collected on a CommCare application run on an Android tablet and transmitted to a project cloud server.

Collection of social science data. A structured questionnaire assessing community perception, knowledge and attitude towards house modification for vector control and temperature reduction was administered to all participating households before and after house modification. Data was collected on community's building practices including; reasons for inclusion or exclusion of certain building elements such as windows, eaves spaces, ceiling, wall and roof types. The questionnaire further assessed community's understanding of the relationship between the various building elements and entry of mosquitoes into houses and indoor heat levels. Additional questions were administered to gauge the community's perception of changes to their houses that may reduce mosquito entry and indoor temperature as well as their willingness to use their own resources to modify their houses. In the post modification survey, we assessed perceived benefits and risks of house modification and community's willingness to continue using the modifications beyond the lifetime of the study. The questionnaire was run on a Commcare® (Dimagi Inc. South Africa) platform run on android tablets and data transmitted to the project server.

Thermal imaging. Indoor and outdoor thermal images of the houses were taken using FLIR T450sc® camera (Teledyne FLIR). The images were takes early in the morning before sun rise, at mid-day and in the evening after sun set to assess source of heating in the houses at different times of the day. Images were taken representative house that were easily accessible for photographs at all times of the day, representing the different structural modifications, cool roof, cross ventilation and mat ceiling as well as control.

Data management and analysis

Field data were collected using CommCare® software run on Android tablets. Every participating house was identified by a unique code and a collection code was generated by the tablet for every mosquito sampling effort. Thes codes were used to track data generated from the different study components for ease of management. Individual mosquitoes from each collection were placed in microcentrifuge tubes labeled with pre-printed barcodes and linked to the field data using a house code and a collection code. Results of species identification by polymerase chain reaction (PCR) were linked to individual mosquitoes by the unique barcode label.

Data analysis was performed using R statistical software version 4.2.1. The risk ratio (RR) was used to assess the statistical significance of differences in mosquito densities between screened and unscreened houses. Data were fitted using Generalized Linear Mixed Effects Statistical Models (GLMMs). Since the data were over-dispersed, we used the package Generalized Linear Mixed Models using Template Model Builder (glmmTMB) to fit negative binomial distribution models for the analysis of mosquito numbers. The numbers of female *Anopheles* and *Culex* species were assessed as a function intervention status (screened or unscreened) as a fixed effect, while sampling period were treated as a random effect. To obtain the risk ratios (RR) and confidence intervals, we exponentiated the model coefficients. Analysis Of Variance (ANOVA) was used to assess differences in the mean daily temperatures between the modified and control houses. A Tukey HSD Post-Hock test was conducted to compare mean daily temperature between all groups.

Results

Mosquito data

A total of 8,297 *Anopheles* and 2,840 *Culex* mosquitoes were collected indoors by CDC light traps. More *Anopheles* mosquitoes, 6,960 (83.9%) were collected before house modification compared to the numbers after modification, 1,337 (16.1%). On the contrary, fewer *Culex* species were collected before modification, 974 (34.3%) compared to the numbers after modification 1866 (65.7%). No *An. gambiae* were collected in the pre-modification period and only 34 in the post-modification period. Therefore, the species was not subjected to further analysis (Table 1).

Table 1: Numbers of mosquito species collected indoor by CDC light trap from different study arms before and after modification.

	Mosquito species	**Control N (%)**	**Cool roof N (%)**	**Cross ventilation N (%)**	**Mat ceiling N (%)**	**Total**
Pre modification	*An. funestus* Female	725 (33.39)	518 (23.86)	453 (20.87)	475 (21.88)	2171
	An. funestus Male	656 (17.70)	972 (20.30)	619 (12.93)	2540 (53.06)	4787
	An. gambiae Female	0	0	2 (100)	0	2
	An. gambiae Male	0	0	0	0	0
	Culex Female	119 (17.63)	218 (32.30)	164 (24.30)	174 (25.78)	675
	Culex Male	78 (26.09)	95 (31.77)	63 (21.07)	63 (21.07)	299
Post modification	*An. funestus* Female	402 (51.34)	132 (16.86)	132 (16.86)	117 (14.94)	783
	An. funestus Male	185 (35.58)	57 (10.96)	79 (15.19)	199 (38.27)	520
	An. gambiae Female	14 (45.6)	11 (35.48)	5 (16.13)	1 (3.23)	31
	An. gambiae Male	1 (33.33)	1 (33.33)	0	1 (33.33)	3
	Culex Female	251 (41.97)	141 (23.58)	136 (22.74)	70 (11.71)	598
	Culex Male	606 (47.79)	288 (22.71)	204 (16.09)	170 (13.46)	1268

Relatively high numbers of female and male *An. funestus* were collected indoors before house modification than after (Figure 8). For female *Culex* mosquitoes, the numbers were relatively higher in control houses after modification compared to before modification while in all the modified houses, the numbers were higher before modification. Male *Culex* species on the other hand where higher in all houses after modification (Figure 9).

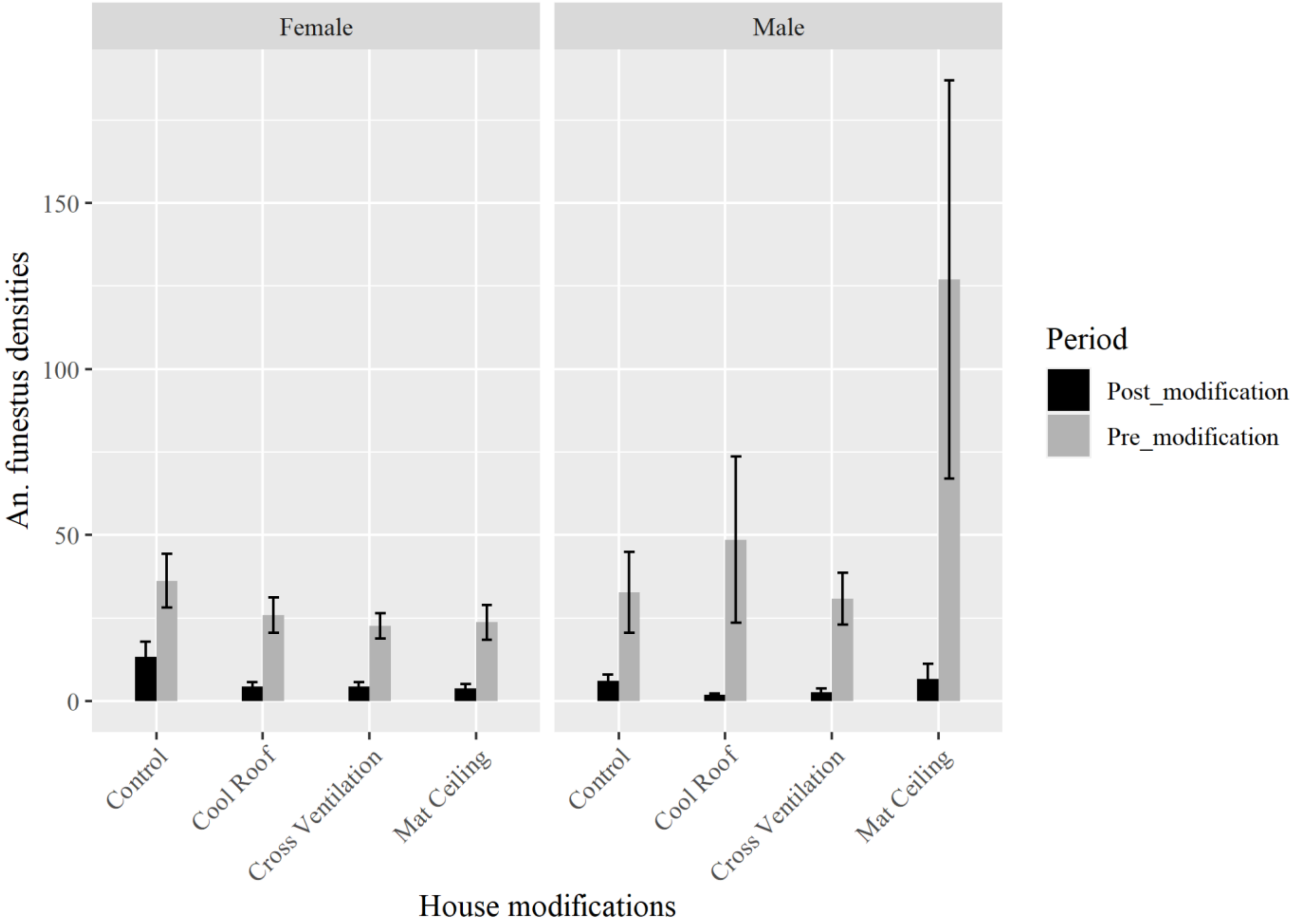

Figure 8: Mean number of male and female *An. funestus* collected indoors in control, cool roof, cross ventilation and mat ceiling houses before and after modification.

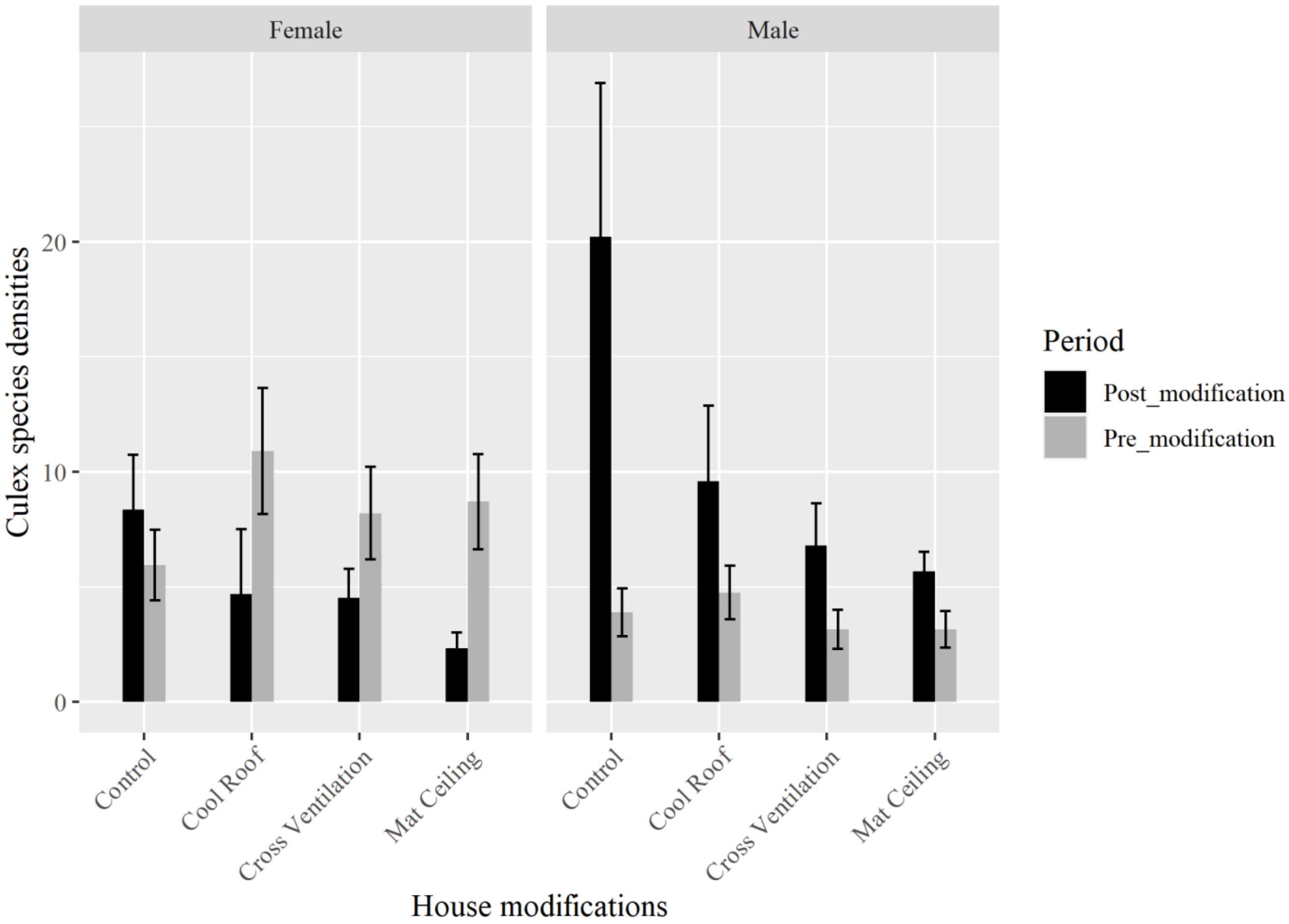

Figure 9: Mean number of male and female *Culex* mosquitoes collected indoors in control, cool roof, cross ventilation, and mat ceiling houses before and after modification.

Screening of doors, windows and eaves significantly reduced the number of female *An. funestus* indoors by 54% compared to unscreened houses (RR=0.46: 95%CI 0.24-085: P=0.014). The number of *An. funestus* were over 5 times higher before screening compared to the period after screening (RR=5.8: 95%CI 3.73-9.00: P<0.001). For *An. funestus* male, no significant differences were observed between screened and unscreened houses. However, they were over 14 times higher indoors before screening compared to after screening (RR=14.17: 95%CI 7.10-28.25: P<0.001). Significantly higher numbers of female *Culex* were observed before compared to after screening (RR=1.83: 95%CI 1.10-3.05: P=0.020), whereas no significant differences of female *Culex* were observed between screened and unscreened houses. The numbers of male *Culex* mosquitoes were significantly lower in screened houses compared to unscreened and were significantly higher after screening (Table 2).

Table 2: Comparison of mean number of male and female *An. funestus* and *Culex* species between different study arms.

Anopheles specie	Parameters	Mean	RR	95%CI	p Values
An. funestus female	Screened	12.18	0.46	0.24-0.85	**0.014**
	Not screened	22.54	1		
	Pre-Screening	27.14	5.8	3.73-9.00	<**0.001**
	Post Screening	6.53	1		
An. funestus male	Screened	29.77	0.71	0.29-1.73	0.451
	Not screened	16.82	1		
	Pre-Screening	59.83	14.17	7.10-28.25	<**0.001**
	Post Screening	4.33	1		
Culex female	Screened	6.02	0.69	0.39-1.23	0.209
	Not screened	7.4	1		
	Pre-Screening	8.44	1.83	1.10-3.05	**0.020**
	Post Screening	4.98	1		
Culex male	Screened	5.89	0.5	0.32-0.78	**0.002**
	Not screened	13.68	1		
	Pre-Screening	3.74	0.42	0.29-0.61	<**0.001**
	Post Screening	10.57	1		

Temperature data

Overall, control houses had a mean daily temperature of 26.00°C, Cool roof 24.73°C, Cross ventilation 26.20°C, while mat ceiling was 26.37°C. The temperatures differed by day (07:00-18:00 hrs) and night (19:00 -06:00 hrs) and between houses in the different study arms (Table 3). In the night, control houses and those with cool roofs had the lowest temperature followed by those with cross ventilation while those with mat ceiling were the warmest. During the day, houses with cool roof had the lowest temperatures followed by Mat ceiling, cross ventilation and control houses were the warmest. Over the data collection period, all the houses were observed to have comparable temperature ranges before modification (late March to early April). However, as modifications were conducted, houses with cool roof were observed to have relatively lower temperatures (Figure 3).

Table 3: Measure of maximum, minimum and mean daily temperatures in control, cool roof, cross ventilation, and mat ceiling house.

Category	Time of the Day	Minimum Temperature (°C)	Maximum Temperature (°C)	Mean (°C)
Control	Day	18.06	46.98	28.62
	Night	18.27	42.55	23.38
Cool Roof	Day	18.80	39.38	26.18
	Night	18.84	30.15	23.29
Cross ventilation	Day	19.60	30.27	28.31
	Night	19.10	30.27	24.09

Mat Ceiling	Day	19.60	37.80	27.56
	Night	19.00	35.99	25.18

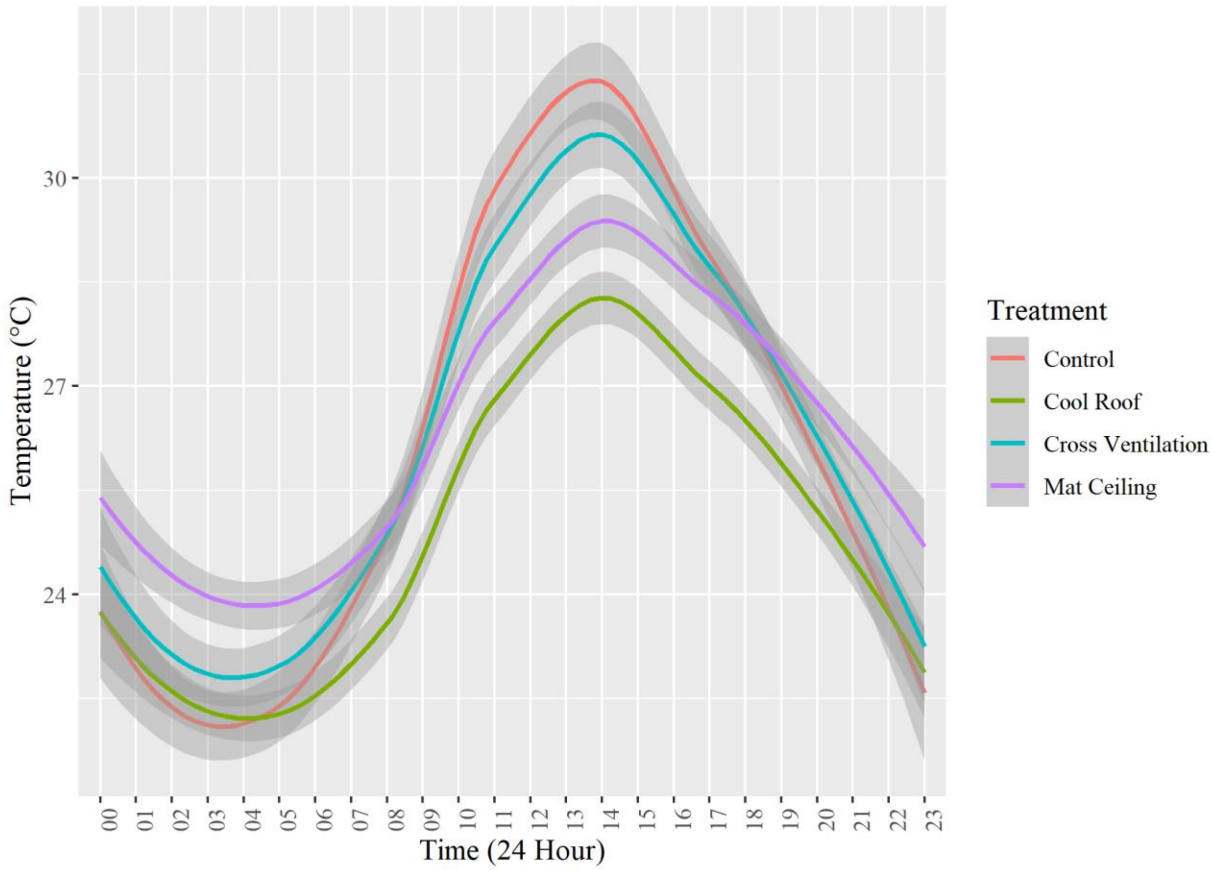

Figure 10: Mean daily temperature in control, cool roof, cross ventilation and mat ceiling houses.

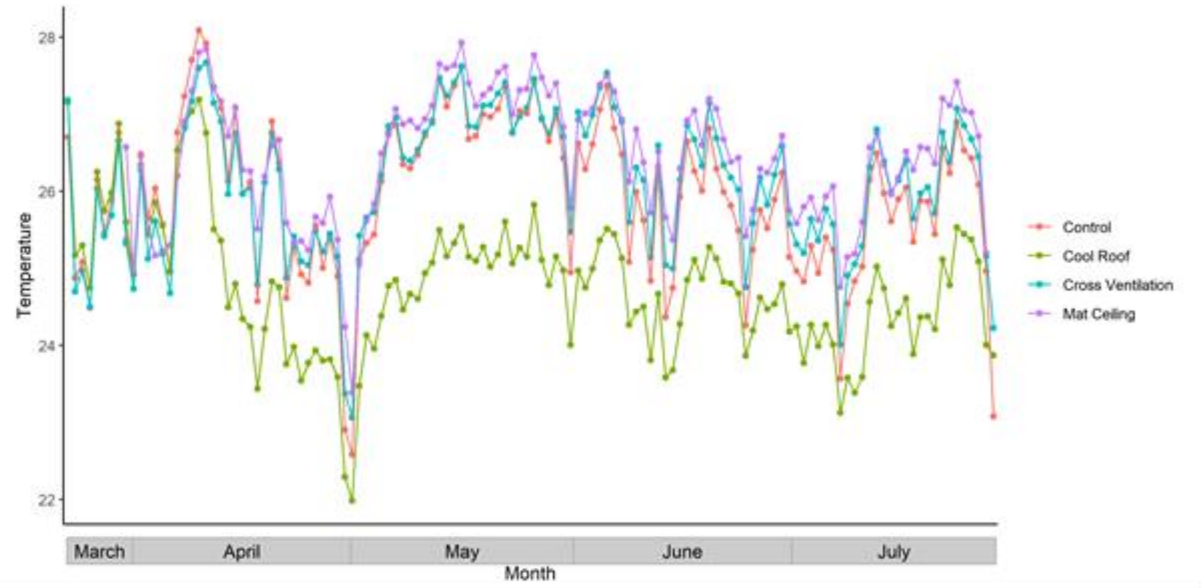

Figure 11: Mean daily temperature in control, cool roof, cross ventilation and mat ceiling houses over the study period.

An analysis of Variance (ANOVA) in the mean daily temperature between control, cool roof, cross ventilation and mat ceiling houses showed statistically significant but small effect (Eta^2=0.06, 95%CI [0.06-1.00], p<0.001). The difference in day and night mean temperature between the different treatment groups was statistically significant and large (Eta^2=0.34, 95%CI [0.36-1.00], P<0.001). A Tukey Honest Significant Difference (HSD) post-hock test comparing all groups of houses to each other showed statistically significant difference in mean daily temperatures between all groups (Table 4).

Table 4: Pairwise comparison of mean daily temperature between houses with different passive colling option and control.

Category	Mean	Estimate	Std. Error	t -value	p-values
Cool roof and Control	24.73 26.00	-2.44	0.01	-163.13	<0.001
Cross Ventilation and Control	26.20 26.00	-0.31	0.01	-21.52	<0.001
Mat Ceiling and Control	26.37 26.00	-1.06	0.01	72.13	<0.001
Cross ventilation Cool roof	26.20 24.73	2.13	0.01	149.25	<0.001
Mat Ceiling Cool roof	26.37 24.73	1.38	0.01	93.66	<0.001
Mat Ceiling Cross Ventilation	26.37 26.20	-0.76	0.01	-53.7	<0.001

Thermal images of a sample of houses from each of the study arms, taken at three different times of the day, morning (6:00 to 7:00am), afternoon (12:00-2:00pm) and evening (7:00 - 8:00 pm) showed variation in distribution of heat by time and house design. In the early morning before sunrise, the highest temperatures were observed on the walls of all the houses compared to the roofs. The lowest temperatures on the walls were from Cool roof and Control houses at 24.0°C, followed by Cross ventilation at 24.5°C and Mat Ceiling at 25.5°C. In the afternoon (12:00 -2:00 pm), the highest temperatures were experienced on the roofs of all houses compared to the walls. House with Cool roofs had the lowest temperatures at 45.6°C compared to Control at 63.1°C, Cross ventilation at 55.8°C and Mat ceiling 49.4°C. In the evening, after sunset, the lowest temperatures were registered on houses with Cool roof at 27.6°C, followed by Mat ceiling at 28.9°C, Cross ventilation at 30.2°C and Control at 33.0°C (Figure 12).

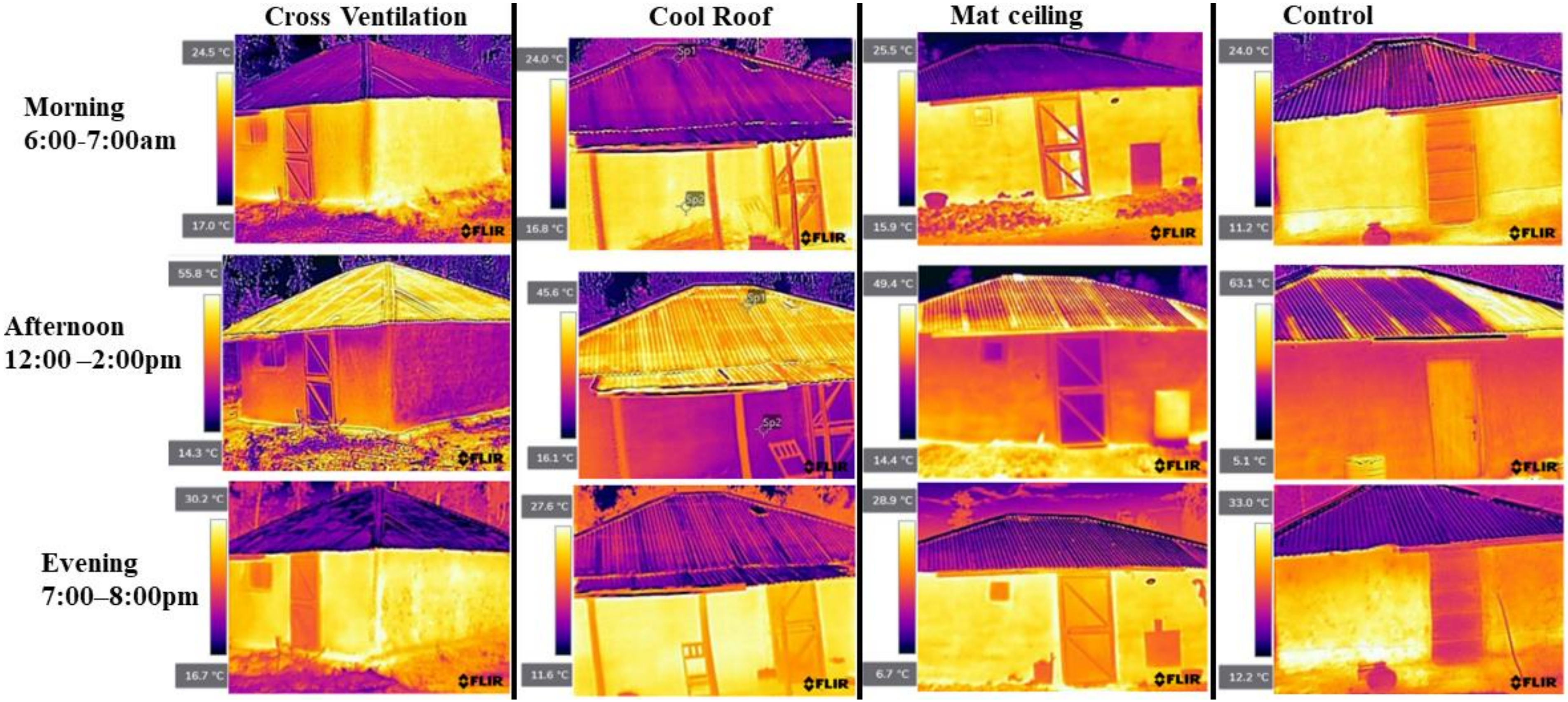

Figure 12: Thermal images of houses with different modifications, taken at different times of the day, morning, afternoon, and evening.

Cost of modification

Table 5 presents the costs incurred in housing modification for vector proofing (screening) and passive cooling. The exchange rate for US Dollar to Kenya Shillings was $1 = KES 133.66 as at April 2023 when the modifications were conducted. The new windows were screened and oriented to provide cross ventilation hence achieving both vector proofing and cooling indoor at a cost of KES 4,994 ($37.36) per window. Additional screening was conducted on existing windows for vector proofing at a cost of KES 1,100 ($8.23) per window. Fabrication and installation of doors for vector proofing attracted a cost of KES 9,392 ($70.27) per door and eave screening at KES 9,290 ($69.50) per house. The cost of door, window, and eaves screening for mosquito control per house was estimated at KES 25, 278.20 ($ 189.12) providing protection to an average of 4 individuals per house. For passive cooling options, cool roof attracted the highest cost per house at KES 19,400 ($145.14) compared to mat ceiling KES 10,560 ($79.01) and cross ventilation at KES 14982 ($112.09) for at least 3 windows per house.

Table 5: Costs of housing modifications

Category	Item	Cost per unit (KES)	Number of units	Total cost (KES)	Total cost ($)
Screening	New windows (Cross ventilation)	4,994	33	164,802	1,232.99
	Doors	9,392	32	300,544	2,248.57
	Screening of existing windows	1,100	13	14,300	106.99
	Eave screening	9,290	30	278,700	2,085.14
	Sub total			758,346	5,673.69
Passive cooling	Cool roof	19,400	10	194,000	1,451.44
	Mat ceiling	10,560	10	105,600	790.06
	Sub total			299,600	2,241.51
Grand total				1,057,946	7,915.20
Cost of screening per house				25,278.20	189.12

Human behaviour data

Knowledge, attitude and perception (KAP) surveys were conducted on 28 and 26 households before and after modification respectively. The participants interviewed were mostly woman, 75% before and 77% after modification. The mean age of the participants 52 years in the pre-modification period and 54 years post-modification, with the median age was 51 and 58 respectively. The highest level of education attained by the study participants was primary education. The main source of income for the study population was peasant farming 15/28

(54%) and small-scale businesses 7/28 (25%). Other sources of income included skilled labour 2/28 (7%), donations 2/28 (7%) and charcoal burning 2/28 (7%).

At the beginning of the survey, 16/28 (57%) of the household reported having no windows. This reduced to 10/26 (38%) in the post-modification period as some houses received windows for Cross ventilation. The main importance of windows identified by participants was to allow in fresh air and light into the house. Other advantages of having windows mentioned by the participants included; 1. access to the house when the door is locked, 2. visibility of the outdoors and 3. an outlet for business purposes if part of the house is used as a shop. The main reason given for not having windows installed was inadequate finances with others being; “the current house is a temporary structure before building the desired house”, “I did not think about it then”, “it is a cottage, so it has no window”, “I just built it without windows”, “I left to fix later” and “fear of house collapsing if the windows are installed after building”. The disadvantages of having windows stated during the pre-intervention survey were; insecurity, mosquito entry, allowing dust into the house, and being used by witches to harm people in the house. Most participants in both surveys noted that there were no disadvantages of having windows. Of houses that had windows, most of respondents 6.67% (8/12) and 92.86 (13/14) reported that they opened their windows daily before and after modification respectively.

All the 26 respondents surveyed in the post intervention reported that house modification reduced indoor temperatures and mosquito numbers. Majority of the respondents, 77% perceived a significant reduction, 15% moderate reduction and 4% reported slight reduction in indoor temperatures.

Most respondents in the pre (64%) and post (65%) intervention survey mentioned the importance of building designs that reflect their cultural values especially when building the first house. Fourteen and 20% of respondents in the pre and post intervention surveys felt the reflection of cultural values in building design is somewhat important while 22% and 15% of respondents in the pre and post intervention surveys respectively did not care for inclusion of cultural values in building. Seventy-one and 96% of the respondents in the pre- and post-intervention periods respectively, expressed willingness to adopt new house designs that are different from their cultural preferences if they help to improve thermal comfort and mosquito control. The proportion of respondents willing to use their family resources increased from 79% in the pre intervention to 85% in the post intervention survey.

Discussion

These results demonstrate significant reduction in mosquito numbers and temperatures indoors in modified houses compared to unmodified ones. The indoor densities of female *An. funestus*, the main malaria vector in the area, were significantly lower in screened houses and in the post screening period compared to unscreened house and pre-screening period respectively. No differences were however observed in the numbers of female *Culex* mosquitoes between screened and unscreened houses. Houses with cool roof, mat ceiling and cross ventilation were generally cooler at the hottest time of the day compared to control houses. Based on thermal images, heating of the houses happened mainly through the roof during the day and walls at night. In interviews with the participating households, most of the community members expressed willingness to adopt new house designs and use of their own resources to improve their houses to control mosquitoes and to achieve thermal comfort.

House modification for vector control has been demonstrated to be effective in keeping away disease transmitting mosquitoes. In most of the western world, mosquito control efforts are mostly targeted outdoors since widespread house screening already excluded mosquitoes from indoor environments [24, 25]. In western Kenya as in many African settings, open eaves are the main routes for mosquito entry into houses at night when doors and windows are closed, and therefore screening of the eaves in addition to doors and windows reduce mosquito entry into the houses as was demonstrated in this study. Recent studies from Busia County, western Kenya demonstrate that the greatest bulk of mosquito biting still occurs indoors, late at night despite widespread use of ITNs for mosquito control (Ichodo et al, In Preparation). While most of the bites experienced indoor are prevented by bed nets, 87% of the remaining bites by *An. funestus* for a bed net user still occur indoors. These findings demonstrate gaps in protection in the context of the present mosquito control tools. House proofing with screened doors, windows and eaves does provide protection for the entire household while indoors and at all times of the day or night. Consistent with previous studies, we observed significantly lower numbers of female *An. funestus* in screened house.

Modification of houses for vectors control, involving blocking of windows, eaves and doors have the potential to raise internal temperatures and make the indoor environment intolerable for the occupants. A phenomenon which is likely to be aggravated with the present global warming crisis. However, our results demonstrate that vector proofing coupled with passive cooling options, provide an indoor environment which is not only devoid of nuisance biting and disease transmitting mosquito, but one that also meets the TCZ for the occupants. This dual benefit of house modification in a rural African village may present far reaching health and economic benefits to the household beyond what was assessed in the current evaluation including but not limited to; improved sleep quality, economic productivity, reduced heat stress level, reduced malaria incidence and heart rate among other health benefits.

Cool roofs was observably the most effective in reducing indoor temperatures at the hottest hour of the day when compared to control houses. Painting roofs with a white reflective coat reflects much of sun’s radiations away hence reducing the amount of heat conducted into the house. Based on thermal images, roofs were the main source of heat in the house during the day and painting them white reduced the amount of heat by approximately 10°C. The reduction in the amount of heat transmitted into the houses during the day by painting the roofs white was also observed to keep the temperatures low at night at a time when the roofs did not provide any additional heating into the houses. Cool roofs most likely reduced the amount of heat gained by the walls during the day, hence reducing the temperatures at night when the walls were the main source of heat in the house. Apart from reducing the indoor temperatures, painting the roofs of houses white has additional benefits of protecting the roof from rusting and improving the beauty of the house.

Mat ceiling was effective in keeping the temperatures below 30°C at the hottest hour of the day. However, houses with mat ceiling were observed to be the hottest during the night compared to control despite the mats hanging above the eaves. The mat ceiling kept the houses cool during the day by gaining much of the heat from the roof thus providing an insulation for the leaving space indoor. However, at night when the roof cools off after sun set, the mat ceiling and walls release the heat gained during the day, hence keeping the house warm. The mats reduced the space available for air circulation indoors and locked up a volume of air above the ceiling with no vents for release of the heated air which, in addition to the walls increased the indoor temperatures at night. It is however interesting to note, that houses with mat ceiling had the least fluctuation in mean daily temperature 23.2°C-29.9°C and humidity of 56.5% – 72.7% compared to other cooling options and control houses. This temperature ranges come closest to the human thermal comfort zone with temperatures between 22°C -27°C and relative humidity of 40%-60%. The indoor thermal conditions of houses with mat ceiling may further be improved by either venting out the heated air from the roof space, aligning the mat ceiling with the roof to increase the space for air circulation within the living area indoors or ensuring cross ventilation within the living space.

Cross ventilation had the least mean daily temperature reduction compared to other cooling options with a range of 22.3°C -31.4°C. To be effective, cross ventilation relies on the house owners keeping their windows and doors open for air flow and cooling. As observed during the study, the doors and windows were closed whenever the household members were not at home. Besides, not all windows were always open whenever the household members were at home. Consequently, cross ventilation was not always achieved as this relied on the willingness of people to keep their windows open.

The cost of housing modification for vector control was estimated at KES 25, 278.20 ($ 189.12) providing protection to approximately 4 individuals per house. Comparatively, 3 long lasting insecticidal nets (LLINs) costed at $6.5 each for procurement and delivery would be required to provide protection to each household within the study area for a period of 3 years. While the cost of house screening is relatively high, LLINs provide only partial protection at a time when people are asleep and when properly used. Studies from western Kenya have demonstrated that the greatest bulk a biting by *Anopheles* mosquitoes happens indoor, in the morning as people leave the protection of their bed nets. These exposures that occurs indoors away from the protection of bed nets are however prevented by house modification as mosquitoes are prevented from entering the houses. Additionally, housing modification for vector control have the potential of lasting the entire lifetime of the house itself hence providing protection to the occupant as long as the house exist. We perceive that vector proofing coupled with passive cooling options have far reaching, sustainable health benefits that remain to be demonstrated.

Weaknesses: The study teams observed that people tended to leave their screen doors open as well given that they culturally leave their doors open in the day. This will require additional community sensitization to enable understanding of the need to keep the screened door always closed. Additionally, many people who has windows for cross ventilation failed to open them consistently and may bias the results presented here.

Conclusion and recommendation. House modification coupling vector proofing and passive cooling options have great potential for controlling the persistent indoor malaria transmission while mitigating the impact of the constantly rising temperatures due to global warming in rural Africa communities. Cool roof, mat ceiling and cross ventilation all offer practical solutions for achieving indoor thermal comfort in the low-income communities of Africa. Further assessment of the impact of these modification on health outcomes including sleep quality, heart rate variability, heat stress and strain and malaria transmission is recommended.

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