# Malaria Prevention Design Challenge

Final assessment report and recommendations 2022

Habitat for Humanity®

Terwilliger Center for Innovation in Shelter

Kenya Medical Research Institute

KEMRI

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The Kenya Medical Research Institute (KEMRI) is a State Corporation established in Kenya in 1979 through the Science and Technology (Repealed) Act, Cap 250 of the Laws of Kenya operated under the Science Technology and Innovation Act, 2013 as the national body responsible for carrying out research in human health in Kenya. Currently, KEMRI operates under Legal Notice No. 35 of March 2021. KEMRI has grown from its humble beginning over 40 years ago to become a regional leader in human health research. The Institute currently ranks as one of the leading Centres of excellence in health research both in Africa as well as globally.

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The Terwilliger Center for Innovation in Shelter, a unit of Habitat for Humanity International, works with housing market actors to expand innovative and client-responsive services, products and financing so that households can improve their shelter more effectively and efficiently. The goal of the Terwilliger Center is to make housing markets work more effectively for people in need of decent, affordable shelter, thereby improving the quality of life for low-income households. To learn more, visit habitat.org/tcis.

## Acknowledgements

The authors wish to acknowledge the many contributors that made this research possible. Our gratitude to **SeaFreight Labs**, particularly Harry Sangree for the financial support that made the crowd-sourced design innovation challenge possible. Thanks as well go to the team at **Wazoku** – including Jon Fredrickson, Elaine Chin and Olivia Dudley – for their support in facilitating and promoting the challenge. The challenge and research were strengthened by the expert interdisciplinary panel that completed the secondary and final evaluations, including representatives from **Habitat for Humanity Kenya**, the **Architectural Association of Kenya** (AAK), **Women in Real Estate** (WIRE) and **The President's Malaria Initiative**, implemented by the CDC in Kenya.

## Abbreviations

| | |
|---|---|
| **AAK** | Architectural Association of Kenya |
| **ATSB** | Attractive Targeted Sugar Baits |
| **CI** | Confidence Interval |
| **GLM** | Generalized Linear Model |
| **IRR** | Incident Rate Ratios |
| **KEMRI** | Kenya Medial Research Institute |
| **RR** | Risk Ratios |
| **SERU** | Scientific and Ethics Review Unit |
| **WIRE** | Women in Real Estate |

# Introduction

Housing is cited as an important social determinant of health. This recognises the range of ways in which a lack of housing, or poor-quality housing, can adversely affect health and wellbeing of people. A healthy house/home has a sound structure, is free from hazardous elements, provides adequate facilities for sleeping, personal hygiene, preparing and storing food, provides a comfortable environment for relaxation, privacy and quiet, and a conducive environment for social exchange with friends, family and others.

A healthy house should also shield its inhabitants from elements of weather and disease-causing vectors. This protection is critical as over 80% of the world's population is threatened by at least one disease transmitted by insects, ticks, rodents or other vectors, with 50% threatened by two or more. These diseases represent 17% of the global burden of infectious diseases that kill over 700,000 people each year.[1] Much of the burden occurs among the poorest of the poor in sub-Saharan Africa. However, most of these disease-causing vectors like mosquitoes and fleas can be controlled through proper house designs and improvements.

As COVID-19 spread around the world, many cities and countries imposed lockdowns that required people to shelter in place. Under the new normal, home has become the first line of defence against public health emergencies. As more and more businesses transition to remote and hybrid structures, our we are spending an increasing amount of our days at home.

As simple as sheltering in place is as public health measure, it is increasingly difficult for majority of low-income households living in overcrowded and unhealthy homes to achieve in practice. The pandemic has redefined how people go about their business, laid bare and heightened humanity's need for decent and healthy homes. Children, their caregivers, the disabled, and the elderly spend more the majority of their time indoors hence are the most impacted by the negative effects of poor housing.

Habitat for Humanity's Terwilliger Center for Innovation in Shelter partners with key stakeholders to promote the development and adoption of healthy housing practices, starting with those aimed at keeping vectors out of houses. In this case, the focus is on demonstrating how the built environment can play a role in vector control and by extension, vector-borne diseases. Housing design elements, including roofs, eaves, ceilings, floors, doors and windows, as well as other maintenance practices in and around the house, closely correlate with vector entry into the house. Overall, Habitat for Humanity aims to identify and facilitate housing practices that keep out vectors and ultimately contribute to the reduction of vector-borne diseases like malaria and jiggers by improving the design and construction of a typical low-income home.

In March 2021, Habitat for Humanity – in partnership with SeaFreight Labs and open innovation firm InnoCentive, launched a challenge to find solutions for retrofitting existing houses across Africa in ways that would reduce the spread of malaria. Focusing particularly on Kenya, where around 70% of the population is thought to be at risk of malaria,[2] the challenge – Malaria Prevention through Innovations in Home Design or Home Life – aimed at finding affordable and sustainable home design solutions to significantly reduce the number of mosquitoes inside the home and/or reduce the number of mosquito bites from mosquitoes that get into a home, lowering transmission of malaria and other diseases. In the regions most affected by mosquitoes, most houses are built with open features, including windows, eaves, and ceilings that do not keep mosquitoes out.

[1] WHO. (2017). Global vector control response 2017–2030. Geneva, Switzerland: WHO. Retrieved July 21, 2022, from https://apps.who.int/iris/handle/10665/259205

[2] Sultana, M., Sheikh, N., Mahumud, R. A., Jahir, T., Islam, Z., & Sarker, A. R. (2017). Prevalence and associated determinants of malaria parasites among Kenyan children. Tropical Medicine and Health, 45(1). https://doi.org/10.1186/s41182-017-0066-5

## Screening and Evaluation Process

A total of 78 solutions were received by the close of the application period. These were subjected to a multistage screening by an interdisciplinary panel of judges between June and November 2021. The evaluation stages included:

**Screening.** The InnoCentive team screened submitted solutions for completeness, appropriateness to the challenge and duplicate submissions. They passed on 55 shortlisted solutions to Habitat for Humanity for evaluation.

**Preliminary evaluation.** The preliminary evaluation involved narrowing down the shortlist of solutions from the initial screening to an appropriate number of high-quality solutions, as deemed reasonable by a panel of representatives from **Habitat for Humanity International** and **SeaFreight Labs**. A total of 19 solutions were selected to advance from this stage.

**Secondary Evaluation.** A larger panel of representatives from Habitat for Humanity International and **Habitat for Humanity Kenya** assessed the remaining solutions using a more detailed criterion developed to evaluate and scale down shortlisted solutions for prototyping. A total of 9 solutions were selected and from this stage for final evaluation.

**Final Evaluation.** An interdisciplinary expert panel was assembled at this stage, including representatives from Habitat for Humanity International, **Kenya Medical Research Institute (KEMRI)**, **Architectural Association of Kenya (AAK)**, **Women In Real Estate (WIRE)** and **The President's Malaria Initiative**, implemented by the CDC in Kenya. The criteria focused more on the practicality of the solutions to be implemented and adopted. Four out of the nine solutions were shortlisted for field testing.

## Field Testing

To support final selection, the four shortlisted solutions had be evaluated to undergo field testing. Habitat for Humanity partnered with KEMRI's Research World to carry out the field testing. KEMRI's comments on the feasibility and value of field testing are outlined for each solution below:

| Solution # | Summary | Comments for or against field testing |
|---|---|---|
| 116755 | Dispersing Carbon Dioxide from Homes, Barns, Coops and Screening Windows | In consultation with KEMRI, during a reconnaissance visit of the testing sites, concerns were raised that given the porous nature of housing construction in the region, testing – and scaling – this technology would be a challenge. The Solver proposed a number of solutions including:<br>**Ventilation control using:**<br>• Vent pipe made from plastic shopping bags or PVC pipes: Single use plastic bags are banned in Kenya; this was not a feasible solution.<br>• Solar powered fans: The initial cost for this installation will be too high, more than the threshold of $200 set for this challenge. |

| | | |
|---|---|---|
| | | • Heat sinks: The details provided by the solver are not clear enough to implement. In addition, this will only apply to an occupied home, which precluded the use of experimental huts available for field testing.<br>• Vent fans: This is a pre-existing way of ventilating spaces. In addition, it would not fit into the experimental huts<br>**Handmade screening nets from plastic bags:**<br>• Single use plastic bags are banned in Kenya; this was not a feasible solution.<br>**Existing window modification to allow efficient screening:**<br>• This was the most promising solution by the solver. However, it needed a lot of technical work to implement. It is more suitable on permanent and semi-permanent houses and not the experimental huts, which are made of mud and wattle to typify rural Kenyan homes. However, if the modification and screening was done successfully, the solution had potential to be effective. |
| 116754 | Jaza Screen | Solver was requested to put together a prototype product to help in field testing. The solver then opted to pull out of the challenge hence solution did not undergo field testing |
| 116781 | Malaria Prevention through innovations in home design | Solver declined request to undergo field testing and pulled out of the challenge |
| 116767 | Mosquito free homes – Air Cavities and Screens | KEMRI confirmed that it was possible modify the semi-field huts in their centre to the solver's proposition, with some modifications as noted:<br>**Introduction of air cavities in homes that have no or small windows.**<br>• This was done tested as proposed by the solver. The only variation was the sizes were altered slightly to avoid affecting the structural integrity of the house<br>**Using redesigned mosquito net with different colour schemes, material and fitting technique**<br>• Velcro mosquito nets were used as proposed by the solver, but only for the door. Windows were not screened with Velcro nets because they had already incorporated with screened air cavities. It is not possible to test this within the same experimental design.<br>**Using lighter colours to paint outside/inside of homes**<br>• This was not feasible as the walls of the experimental huts are made of mud. This would have applied better for homes made of cement or with sand plastered walls. |

As a result, only one solution, 116767: Air Cavities and Screens was subjected to screen testing. The scope of the field testing included:

i. Designing an entomological experiment to test the shortlisted solution.
ii. Replicating the shortlisted solution through modification of existing semi-field experimental huts in preparation for testing.
iii. Evaluating the modified semi-field experimental huts to ascertain the efficacy of the solution to preventing mosquitoes from getting into the house.
iv. Data analysis and preparing the final report.

## Solution 116767: Air Cavities and Screens

This solution introduces air cavities in homes that have no or very small windows. It provides for a screened frame that opens outwards as the door opens inwards and ceiling screens to control entry of mosquitoes into the house. The Kenya Medical Research Institute – Centre for Global Health Research (KEMRI-CGHR) campus in Kisumu has four semi-field stations that are double netted, double door structures measuring 20m length and 8m wide and rise to 4.5m at the apex. There is additional netting at the 3m height to ensure ease of mosquito recapture (Figures 1 and 2).

**Figure 1: Semi-field structure at KEMRI-CGHR campus**

Each semi-field station contains one hut, 3m by 3m and 2m tall. The huts have an open ceiling, one wooden door and one window (Figure 2). All the huts are identical before modification and are similar to a typical, simple traditional house structure in the western Kenya region. Each hut has two rooms (bedroom and living area) one tiny wooden window, one external timber batten door, mud walls (dung and mud smeared finish internally and externally), earthen floor and grass thatched roof with open eaves. All the ceilings are closed with netting for experimental purposes to make it possible for recapturing indoor mosquitoes. Floors for all huts are covered with a white canvas carpet to aid mosquito recapture.

For this study two of the huts in semi-field stations 2 and 3 were modified identically according to the proposed solution (figures 7 and 8), whereas the remaining two other huts in semi-field stations 1 and 4 were left unmodified to act as controls (figure 2). All four huts were evaluated for mosquito entry.

**Figure 2: Typical unmodified hut in a semi-field structure**

# Methods

## Structure Modification

An external building contractor was hired to complete modifications to two structures – hut 2 and hut 3 – according to the proposed solutions. The changes made to the structures includes:

i. Use of a tough netting material to block of the eaves all around the house.
ii. Replacement of windows with screened air cavities.
iii. The placement of a screen frame opening outwards on the door of the structure.

## Mosquito Collection

*Anopheles arabiensis* larvae were collected from rice fields in Ahero, Kisumu County and reared to adulthood at the KEMRI-CGHR insectaries in Kisumu, as shown in figures 4 and 5 below. These were raised to three-day old adults for the release experiments.

Adult *Anopheles funestus* were collected from Uranga in Siaya County and given laying pads to collect eggs. Once eggs hatched, the larvae were reared in the insectary conditions (27±2˚C, 80±10% Humidity) to three-day old adults for the release experiments. *Anopheles funestus* were included because they are currently the major vector of malaria in western Kenya and prefer to rest indoors (endophilic) and feed on humans (anthropophilic) in comparison to the more exophilic and opportunistic *Anopheles arabiensis.*

**Figure 4: Mosquito larvae capture**

**Figure 5: Mature mosquitos in the lab**

## Semi-Field Experiments

Five releases of *Anopheles arabiensis* from Ahero, two releases of *An arabiensis* Dongola strain and four releases of *Anopheles funestus* F1 generation from Siaya were completed in each of the semi-field structures over a total of 11 nights in March 2022. Each release comprised 800 female mosquitoes (200 per semi-field structure).

Adult male volunteers[3] slept under an untreated net in each of the huts during each experiment. The

3 The trial was guided by the ATSB (Attractive Targeted Sugar Baits) protocols approved by KEMRI's Scientific and Ethics Review Unit (SERU) that safeguards study participants in the semi-field structures

volunteers were required to stay inside the huts from 2000HRS until 0600HRS the following morning except for bathroom breaks.

Mosquitoes were released between 1800-1900Hrs each evening and collections completed in two sets; the first collections between 0600-0700hrs and a second and final collection between 0900-1000Hrs the next day. Mosquito collection was done using mouth aspiration as well as mechanical aspiration using Prockopack aspirators. Mosquitoes collected indoors and those collected outdoors were kept in separate cups and labelled by the semi field structure as well as the location of capture.

**Figure 6: Outdoor mosquito recapture**

**Figure 7: Indoor mosquito recapture**

### Data Analysis

Mosquito recapture rates were calculated as the proportion of the released mosquitoes that were recaptured the next morning. The caught mosquitoes were aggregated by location of capture. Incident rate ratios (IRR) – also known as risk rations (RR) – were calculated using generalized linear model (GLM) for Poisson regression. This modelled the number of mosquitoes as a function of the hut (treatment). The estimates from the model output were exponentiated to obtain incident rate ratios (IRR) and 95% confidence interval (CI), and this was then used to estimate the incident of mosquitoes in the huts based on treatment.

## Results

### Modification of Structures

Huts 2 and 3 were modified as described by proposed solution;

**Screening.** Eaves were screened with untreated mosquito netting all round shown in figure 7 below. A self-closing, wood framed Velcro screened door was added to the existing batten door to enhance ventilation when then main door is open without allowing mosquitoes into the house, as described by the solver.

**Figure 7: Modified hut with screen door and screened eaves**

**Introduction of screened air cavities in the place of windows to provide permanent ventilation in the house.** Two air cavity windows were introduced, one in each of the two rooms (1m$^2$ for each cavity window) as described by the solver and shown in figure 8.

**Figure 8: Screened air cavities**

## Results of Semi-Field Experiment

Overall, 1000 *Anopheles arabiensis* Ahero were released inside each semi-field structure (but outside each hut) over a five-day period with recapture rates between 18.6% and 20.8%. 400 *Anopheles arabiensis* Dongola (lab colony) were released in each hut over a two-night period with recapture rates between 43% and 67%, while 800 *Anopheles funestus* were released in each hut over a four-night period with average recapture rates of 26.25 and 29.63 (Table1).

**Table 1: Sum of *An. arabiensis* and *An. funestus* recaptured indoor and outdoor of the experimental huts within a semi-field enclosure.**

| Species strain | Treatment | Indoor recaptured | Outdoor recaptured | #Released | #Total Recaptured | % Recaptured |
|---|---|---|---|---|---|---|
| Ahero Anopheles arabiensis | Hut 1 - Unscreened | 109 | 85 | 1000 | 194 | 19.40 |
| | Hut 2 - Screened | 17 | 191 | 1000 | 208 | 20.80 |
| | Hut 3 - Screened | 1 | 185 | 1000 | 186 | 18.60 |
| | Hut 4 - Unscreened | 35 | 156 | 1000 | 191 | 19.10 |
| Dongola Anopheles arabiensis | Hut 1 - Unscreened | 120 | 53 | 400 | 173 | 43.25 |
| | Hut 2 - Screened | 15 | 213 | 400 | 228 | 57.00 |
| | Hut 3 - Screened | 6 | 231 | 400 | 237 | 59.25 |
| | Hut 4 - Unscreened | 80 | 188 | 400 | 268 | 67.00 |
| Siaya *Anopheles funestus* | Hut 1 - Unscreened | 117 | 93 | 800 | 210 | 26.25 |
| | Hut 2 - Screened | 18 | 209 | 800 | 227 | 28.38 |
| | Hut 3 - Screened | 8 | 229 | 800 | 237 | 29.63 |
| | Hut 4 - Unscreened | 135 | 85 | 800 | 220 | 27.50 |
| **Total** | | **661** | **1918** | **8800** | **2579** | **29.31** |

Generally, there were more mosquitoes captured indoors in the unmodified huts compared to the modified huts across all species. There were significantly lower numbers of Anopheles arabiensis – Ahero indoors in huts 2 and 3 (screened), compared to hut 1 (unscreened), with much lower incident rate ratios in huts 2 and 3 compared (screened) to huts 1 and 4 (unscreened). Similarly for Anopheles arabiensis Dongola, there were much lower incident rate ratio (IRR) in screened huts 2 and 3 compared unscreened hut 1. The same trend was observed with Anopheles funestus where screened huts 2 and 3 had significantly lower numbers of mosquitoes compared to hut 1, while no significant difference was observed between huts 1 and 4. For both Anopheles arabiensis, Ahero and Dongola strains, significantly lower numbers were observed in the unmodified hut 4 compared to unmodified hut 1, which is likely an artefact of the opportunistic behaviour of Anopheles arabiensis.

Looking at the trends outdoors, the modifications seemed to increase mosquito numbers outside huts 2 and 3 compared to huts 1 and 4 in all species. This trend was much clearer in *Anopheles funestus* where there was a 1.87- and 2.68-fold increase in mosquitos following the modifications (Table 2, Figure 9).

**Table 2: Comparison of means of *An. arabiensis* and *An. funestus* recaptured indoor and outdoor between screened and unscreened experimental huts within a semi-field enclosure**

| Species | Recapture location | Treatment | Mean | IRR (95% CI) | P value |
|---|---|---|---|---|---|
| *Ahero Anopheles. arabiensis* | Indoor | Hut 2 - Screened | 3.40 | -1.86(0.09-0.25) | <0.0001 |
| | | Hut 3-Screened | 0.20 | -4.69(0.00-0.04) | <0.0001 |
| | | Hut 4-Unscreened | 7.00 | -1.14(0.22-0.46) | <0.0001 |
| | | Hut 1-Unscreened | 21.80 | Ref | |
| | Outdoor | Hut_2 - Screened | 38.2 | 0.81(1.74-2.91) | <0.0001 |
| | | Hut 3-Screened | 37.00 | 0.78(1.69-2.83) | <0.0001 |
| | | Hut_4-Unscreened | 31.20 | 0.61(1.41-2.40) | <0.0001 |
| | | Hut_1-Unscreened | 17.00 | Ref | |
| *Dongola Anopheles. arabiensis* | Indoor | Hut_2 - Screened | 7.50 | -2.08(0.07-0.21) | <0.0001 |
| | | Hut_3-Screened | 3.00 | -3.00(0.02-0.10) | <0.0001 |
| | | Hut_4-Unscreened | 40.00 | -0.41(0.50-0.88) | 0.005 |
| | | Hut_1-Unscreened | 60.00 | Ref | |
| | Outdoor | Hut_2 - Screened | 106.5 | 1.39(3.00-5.48) | <0.0001 |
| | | Hut 3-Screened | 115.5 | 1.47(3.26-5.93) | <0.0001 |
| | | Hut 4-Unscreened | 94.00 | 1.27(2.64-4.86) | <0.0001 |
| | | Hut 1-Unscreened | 26.5 | Ref | |
| *Siaya Anopheles. funestus* | Indoor | Hut 2 - Screened | 4.50 | -1.87(0.09-0.25) | <0.0001 |
| | | Hut 3-Screened | 2.00 | -2.68(0.03-0.13) | <0.0001 |
| | | Hut 4-Unscreened | 33.75 | 0.14(0.90-1.47) | 0.257 |
| | | Hut 1-Unscreened | 29.25 | Ref | |
| | Outdoor | Hut 2 - Screened | 52.25 | -1.87(0.09-0.25) | <0.0001 |
| | | Hut 3-Screened | 57.25 | -2.68(0.03-0.13) | <0.0001 |
| | | Hut 4-Unscreened | 21.25 | 0.14(0.90-1.48) | 0.549 |
| | | Hut 1-Unscreened | 23.25 | Ref | |

## Understanding Incident Rate Ratios (IRR)

IRR is a relative risk measure used to compare incident rates of events occurring at the same point in time, in this case, house entry by mosquitoes. A negative IRR means a reduction when compared to the reference while a positive IRR means an increase when compared to the reference.

Consider the following example with Ahero *Anopheles arabiensis*; when we compare hut 2, which is screened, and hut 3 which is also screened to hut 1 which is not modified, there is a 1.86-fold (186%)

and 4.69-fold (469%) reduction in mosquitoes in huts 2 and 3 respectively, compared to hut 1. However, this is a noisy trend pointing to the opportunistic behaviour of *Anopheles arabiensis* because we also see a 1.14 (114%) fold reduction in mosquitoes in hut 4 which is unscreened. All these differences are significant.

The clearest comparison in incident rates is in *Anopheles funestus* where we see 1.87 (187%) and 2.68 (268%) fold reductions in huts 2 and 3 as compared to hut 1. These differences are statistically different, while the difference between hut 4 and 1 is not, meaning the 0.14 (14%) fold increase between these two unmodified huts is purely due to chance. This is logical as hut 4 and hut 1 are physically the same and were tested under the same conditions.

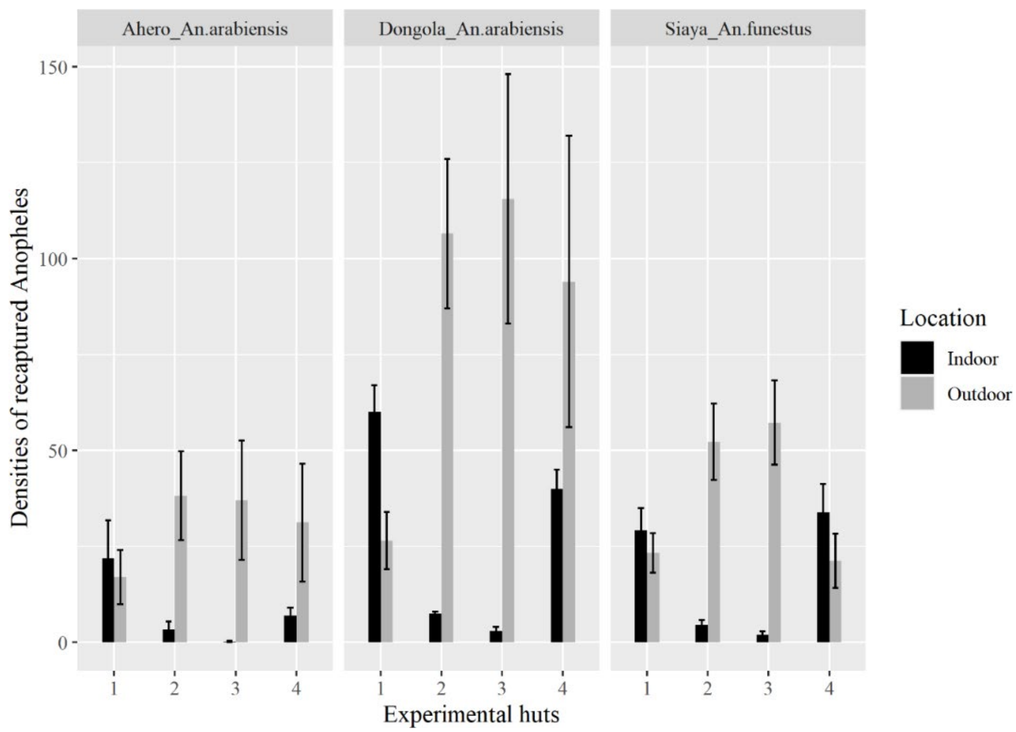


**Figure 9: Comparison of means of *Anopheles arabiensis* and *Anopheles funestus* recaptured indoor and outdoor of experimental huts (1-unscreened, 2-screened, 3-screened and 4-unscreend) within a semi-field enclosure**

## Key Findings

The primary routes of mosquito entry into houses are through the windows, doors and gaps in the eaves. Modifying these entry points is likely to reduce mosquito entry into the house as was demonstrated in this study. The following inferences can be made from this study:

i. The recapture rates varied between mosquito colonies released in the experimental huts with the best recapture rates in *Anopheles arabiensis* Dongola, followed *by Anopheles funestus* and lastly *Anopheles arabiensis* Ahero. However, since there was not much variation around the recapture rates across the four experimental huts, this variation likely to be species specific and would not bias the experiment in any way.

ii. The house modification significantly reduced the recapture rates of mosquitoes indoors in all the species tested indicating that the modification works effectively to keep out mosquitoes and could complement current vector control efforts, such as bed nets and insecticides.

iii. On average, there was an 89.09% reduction in mosquito numbers entering the modified huts compared to unmodified huts. The best reduction rates were with *Anopheles funestus* Siaya - 89.68%, *Anopheles arabiensis* Dongola – 89.5% and finally *Anopheles Arabiensis* Ahero – 87.5%. In general, the house modification had a significant reduction in mosquito entry across different mosquito strains, which implies that the solution can be used to keep out all types of mosquitoes across different geographies in Kenya

iv. The house modification increased the number of mosquitoes recaptured outdoors probably indicating the potential to shift of malaria transmission from indoors to outdoors. It may be worth considering insecticide treatment in these modifications so that these mosquitoes are killed as they attempt to come into the house.

v. Each modified hut costed Ksh 16,540 (US$142.94) for both labour and materials for a two-room house. A three-room house would cost Ksh 24,810 (US$214.41), which is still within the threshold set by the challenge (materials only) as this figure also includes labour costs.

vi. Based on the results of this test, the modification has been seen to significantly reduce mosquito numbers inside the house.

## Recommendations

The primary routes of mosquito entry into houses are through the windows, doors and gaps in the eaves. Modifying these entry points is likely to reduce mosquito entry into the house as was demonstrated in this study. The following inferences can be made from this study:

i. We recommend that insecticide treated material be used for the modification in the next experiment, after which the experiment should be moved to the field for further evaluation.

ii. There was perceived improvement in ventilation in the modified huts 2 and 3, which partly contributed to the low indoor mosquito numbers, as mosquitoes struggled to locate the huts.[4] However, it was not possible to measure this parameter given that the trial was conducted in a semi-field structure set up. We recommend that field trials in the next phase to explore the extent to which this solution improves ventilation and indoor temperatures of modified huts.

[4] Mosquitos are attracted to the release of carbon dioxide from humans breathing; increased airflow dissipated the carbon dioxide from sleeping volunteers more effectively, making it more challenging for mosquitos to track their location within the huts.

# everyone

## needs a place to call home