Final Assessment Report and Recommendations for solution 116767: Air Cavities and Screens

Table of Contents

1 Summary

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. Ideally, 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.

Apart from providing a place to sleep, a healthy house should also shield its inhabitants from elements of weather and disease-causing vectors. For instance, 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. Much of the burden occurs among the poorest of the poor in sub-Saharan Africa. Yet most of these disease-causing vectors like mosquitoes and fleas can be controlled through proper house designs and improvements.

As COVID-19 spreads around the world, the imposed lockdown has forced many people to shelter in place. Under the new normal, home has become the first line of defence, a workplace for many, a place for children to learn and play and a place of sanctuary among other roles. As simple as this public health preventative measure is, it is increasingly difficult for majority of low-income households living in overcrowded and unhealthy homes to achieve. 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 than 70% of their time indoors hence are the most impacted by the negative effects of poor housing.

Habitat for Humanity's Terwilliger Center for Innovation 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 like roofs, eaves, ceilings, floors, doors and windows and other maintenance practices in and around the house closely correlate with vector entry into the house. Overall, Habitat aims to identify and facilitate housing practices that build out vectors and ultimately contribute to the reduction of vector-borne diseases like Malaria, jiggers, etc. by improving the design and construction of a typical low-income home.

In March 2021, Habitat for Humanity, in partnership with open innovation firm InnoCentive, launched a challenge to find a solution for retrofitting houses across Africa to reduce the spread of malaria. Focusing particularly on Kenya, where around 70% of the population is thought to be at risk of malaria, 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[1] 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.

2 Screening and Evaluation Process

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

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[1] Malaria is an important health and economic problem in Africa. Habitat for Humanity, through its Healthy Housing project, works with private sector and innovators for solutions to incorporate in rural houses in Kenya to reduce the burden of malaria.

i. ***Screening*** – submitted solutions we screened for completeness, appropriateness to the challenge and to remove any repeated submissions. This was done by the Innocentive team who then passed on fifty-five (55) shortlisted solutions to Habitat for Humanity for evaluation,
ii. ***Preliminary evaluation*** – this involved narrowing down the shortlist of solutions from the initial screening to an appropriate number as deemed appropriate by the panellists and depending on the quality of solutions submitted. Evaluation panellists were representatives from HFHI and Sea Freight Labs. A total of nineteen (19) solutions were selected from this stage,
iii. ***Secondary Evaluation*** –panellists from within Habitat were added to this stage and a more detailed criterion developed to evaluate and scale down shortlisted solutions with promising solutions being shortlisted for prototyping. The evaluation panel had representation from HFHI and Habitat for Humanity Kenya. A total of nine (9) solutions were selected and from this stage for final evaluation.
iv. ***Final Evaluation*** –Panellists at this stage included experts from Habitat for Humanity International (HFHI), Kenya Medical Research Institute (KEMRI), Architectural Association of Kenya (AAK), Women In Real Estate (WIRE) and President Malaria Initiative CDC in Kenya. The criteria focused more on the practicality of the solutions to be implemented and adopted. Four (4) out of the nine (9) solutions were shortlisted for field testing.

To support final selection the four (4) shortlisted solutions had to undergo field testing. Habitat for Humanity partnered with KEMRI's Research World to carry out the field testing as below;

Solution No	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 this technology will be challenging. The Solver proposes a number of solutions including: a) Ventilation control using: • *Vent pipe made from plastic shopping bags or PVC pipes*: Single use plastic bags are banned in Kenya, this was not going to work • *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. In addition, this will only apply to a real-life house, which was difficult given the sensitive nature of this undertaking • *Vent fans:* This is an already existing way of ventilating spaces. In addition, it would not fit into the experimental huts b) *Handmade screening nets from plastic bags:* • Single use plastic bags are banned in Kenya; this was not going to work. c) *Existing window modification to allow efficient screening*: This was the most promising solution by the solver. However, it needed a lot of technical work to make it work. 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 is done successfully, the solution has potential to work.

116754	Jaza Screen	Solver was requested to put together a prototype product to help in field testing. The solver opted to pull out of the challenge hence solution did not undergo filed testing
116781	Malaria Prevention through innovations in home design	Solver declined request to field testing and pulled out of the challenge
116767	Mosquito free homes – Air Cavities and Screens	KEMRI confirmed that could modify the semi-field huts in their centre to the solver's proposition except for a few modifications as described below: • **Introduction of air cavities in homes that no or small windows**. This was done as proposed by the solver. The only variation was the sizes were slightly altered to avoid affecting the structural integrity of the house • **Using redesigned mosquito net with different colour scheme, material and fitting technique** – 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 screened air cavities. It is not possible to test this within the same experimental design • **Using lighter colours to paint outside/inside of homes** – This was not possible since the walls are made of mud, making it difficult to paint. This would have applied better for cement; sand plastered walls.

Only one solution, 116767: Air Cavities and Screens was subjected to screen testing. The scope of the field testing included;

i. Design 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

3 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 a netting at the 3m height to ensure ease of mosquito recapture (Figure 1 & 2).

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

Figure 2: Typical Unmodified hut in a semi-field structure

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 & 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 9-15) whereas two other huts in semi-field stations #1 and #4 were not modified to act as controls (figure 2). All the four huts were evaluated for mosquito entry.

4 Methods

4.1 *Structure modification*

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

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

4.2 *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 3, 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 3: Mosquito larva capture

Figure 4: Mosquito larva in the lab

Figure 5: Mature mosquito in the lab

4.3 *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 done in 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[2] slept under an untreated net in each of the huts during each experiment. The 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 done 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: Indoor mosquito recapture

Figure 7: Outdoor mosquito recapture

Figure 8: Recaptured mosquitoes in cup

4.4 *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.

5 **Results**

5.1 *Modification of Structures:*

Huts #2 and #3 were modified as described by the solver;

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[2] 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

a. Screening: Eaves were screened with untreated mosquito netting all round shown in figure 9 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.
b. 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 figures 3, 4, 5 & 6

Figure 9: External view 1

Figure 10: External view2

Figure 11: Internal view - Sitting room

Figure 12: Internal View - Bedroom

Figure13: Self-closing wood framed Velcro screened door

Figure 14 & 15: Unscreened eaves vs Screened Eaves

Results of the Semi-Field Assessments

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	Hut_1-Unscreened	117	93	800	210	26.25

Anopheles funestus	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, whereas no significant difference we 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 16).

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.

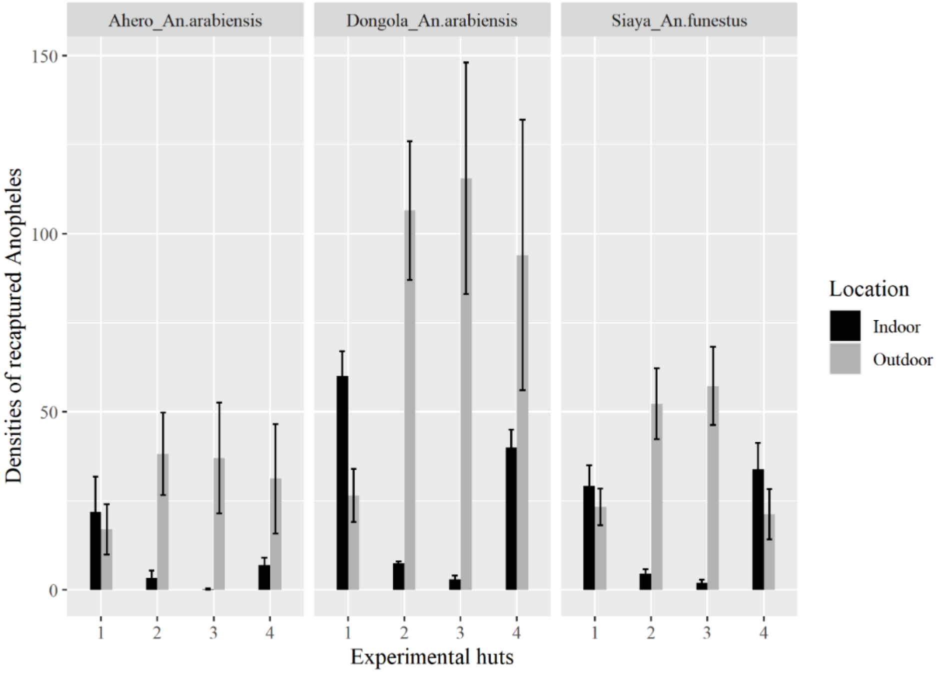

Figure 16: Comparison of means of Anopheles. arabiensis and Anopheles. funestus recaptured indoor and outdoor of experimental huts (1 -unscreened, 2-screened, 3-screened and 4-unscreend) within a semi-field enclosure

6 Key findings

The primary routes of mosquito entry into houses is through the windows, doors and gaps in the eaves. Blocking 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. Exponentially, a 3 roomed house would cost Ksh 24,810 (US$214.41), which is slightly higher than the US$200 threshold for materials. However, this is still within the threshold since the amount also includes labour costs.

7 Recommendations

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

ii. 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.

iii. 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. 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.

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