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Affordable House Designs to Improve Health in Rural Africa: Field Studies from North-Eastern Tanzania

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Abstract

The population of sub-Saharan Africa is currently estimated to be 1,245 million and is expected to quadruple by the end of the century, necessitating the building of millions of homes. Since up to 80% - 100% of malaria transmission occurs indoors at night exploring ways of keeping out vectors and keeping the house cool is a priority. We assessed the impact of South-East Asian house designs on mosquito density and indoor climate in rural Tanzania. These houses are elevated and made of light-weight permeable materials like bamboo in contrast with traditional rural African homes that are built on the ground from heavy impermeable materials.

Six prototype houses were built in north-eastern Tanzania and compared with modified and unmodified traditional African houses which served as controls. Mosquitoes were trapped indoors and outdoors using tent traps and indoor climate monitored using data loggers. Acceptance of the new house design was evaluated through a qualitative assessment.

The new design houses were 2·3°C (95%CI 2·2°C to 2·4°C) cooler and had 86% (95%CI 76% to 93%) fewer mosquitoes than traditional homes. While both single and two-storey buildings provided a cooler indoor climate than traditional housing, two-story buildings provided the biggest reduction in mosquito densities (96%; 95%CI 89% to 100%). Villagers liked the novel design buildings, particularly the two-storey buildings due to the privacy and security of upstairs bedrooms.

The new design houses had fewer mosquitoes and were cooler than traditional and modified traditional homes. New house designs are an underused intervention and hold promise to reduce malaria transmission in sub-Saharan Africa and keep areas malaria-free after elimination.

Research in context

Evidence before this study

Housing improvements have been traditionally a key component of public health. House screening in Italy at the beginning of the 20th century was one of the first interventions tested to interrupt malaria transmission. Considering that in sub-Saharan Africa up to 80% to 100% of malaria transmission occurs indoors at night the home should be a primary target for malaria prevention. Insecticide treated bednets prevent indoor malaria transmission and conscientious use of bednets results in a significant reduction in malaria burden. Bednets provide little protection during waking hours when people move about their homes or do not use nets in hot, humid climates. Two large reviews have assessed the evidence for housing improvements (other than bednets) to reduce malaria in sub-Saharan Africa. The first was a systematic review and meta-analysis of 90 studies published between 1900 and 2013. Residents of modern houses had 47% lower odds of malaria infection compared to traditional houses and a 45–65 % lower odds of clinical malaria. Traditional homes were considered to have mud walls, thatched roofs, earth floors, open eaves, no ceiling, and no screening. Improved homes had full or ceiling screening, finished walls and floors, corrugate iron roofs, and/or closed eaves. A more recent multi-country analysis of 15 demographic and health surveys and 14 Malaria Indicator Surveys conducted in 21 countries across sub-Saharan Africa confirmed that housing quality is an important risk factor for malaria infection across the spectrum of malaria endemicity. Importantly this analysis found that the protection afforded by improved housing quality against malaria was similar to the protection afforded by impregnated bednets.

Added value of this study

Based on preceding computational flow dynamic models the basic design of rural African homes was revised to elevate the bedrooms off the ground and maximise cross-ventilation through use of permeable walls. Three aspects of the novel design were evaluated in an ensemble of newly constructed houses in Tanzania. Elevated housing with screened windows reduced mosquito densities and improved ventilation resulting in lower indoor temperatures compared to traditional rural homes. Critically, the novel designs were well accepted by the villagers.

Implications of all the available evidence

Observational studies have shown a strong association between house improvements and reduced malaria transmission. Improvements under consideration include metal roofs, closed eaves, eaves tubes, insecticide treated curtains, screened windows and doors. Such incremental improvements do not address the fundamental problems of the traditional rural African house design, namely poorly ventilated structures on ground level. Good airflow is essential for a healthy air quality and a comfortable indoor environment, particularly in hot, humid climates. Elevating buildings insulates the living space from heat radiating from the ground and improves airflow. The set of newly constructed homes in a Tanzanian village illustrates the possibilities to improve health and comfort through changes in house design. Improved ventilation may facilitate the use of bednets and reduce the transmission of respiratory tract infections. Added water harvesting and latrines may reduce the risk of enteric infections. Considering the overall health benefits and improved comfort investments in new house designs in rural Africa could be cost-beneficial.

Introduction

The population of sub-Saharan Africa is growing at an unprecedented rate and is likely to increase from 1.2 billion in 2015 to 4·4 billion by the end of the century[1]. The increase in people will necessitate the building of millions of houses across the region. Because up to 80% -100% of malaria transmission occurs indoors at night[2] there is an unprecedented opportunity to design homes which keep malaria vectors out. A growing body of work demonstrates that improved housing reduces malaria transmission. The findings from a systematic review of the literature and meta-analysis found that improved housing was associated with 47% lower odds of malaria infection and 45-65% less clinical malaria than traditional housing. More recently, a 21-country observational study in sub-Saharan Africa demonstrated that, after adjusting for socioeconomic status, the protective efficacy of good housing may be similar to ITNs[3].

People's main complaint about using ITNs is that they feel uncomfortably hot[4]. When designing houses that reduce mosquito entry it is therefore important to keep the house cool. The climate "comfort zone" is a term used by physiologists and architects to describe the optimum combinations of temperature, humidity and airflow that people find agreeable[5, 6]. Of these variables, airflow is critically important yet often over-looked. In extremely hot and humid conditions even a small attenuation of airflow is sufficient to render a space uncomfortable, if not unbearable. Because airflow is reduced by about 60% in a space enclosed by a bednet[7], it is unsurprising that in tropical Africa ITNs are inconsistently used[4].

The traditional sub-Saharan mud hut is a wattle-daub (adobe) or mud-block construction, built on the ground and poorly ventilated[8]. In contrast, traditional rural homes in South-East Asia tend to be well adapted to the hot humid climate[8]. Spaces are elevated on stilts and permeable materials such as bamboo slats are used for the construction of walls. Elevating the structure and using permeable walls promotes airflow, reduces the indoor temperature and optimises the overall indoor climate. It is also likely that raising the house above ground level may reduce the entry of *Anopheles gambiae* mosquitoes[9], the major African malaria vector, since most fly no more than one metre above the ground[10].

Computational Fluid Dynamics (CFD) modelling developed to predict indoor climate in contemporary urban structures within industrialised countries can be applied to rural housing in low income countries[11]. Such models predict improved indoor climate by elevating living spaces sufficiently to allow airflow under the house. Constructing houses with air-permeable building materials such as shade nets (a plastic fabric used primarily in agriculture to prevent excessive sun and rain exposure), loosely spaced timber planks or bamboo cladding and large, preferably screened, windows will facilitate airflow and cool the interior[8].

Modifying the design of residential buildings has a range of potential health benefits (Figure 1). Improved airflow and a lower indoor temperature make it more comfortable to sleep under a bednet, which could increase bednet use in malaria-endemic countries. Elevating homes can reduce indoor-mosquito densities[12, 13] and thus the risk of mosquito-borne diseases. Laying a floor compared to compacted earth reduces exposure to soil transmitted helminths. Separating wood burning stoves from living and sleeping spaces reduces indoor air pollution and hence the risk of respiratory illness and coronary heart disease [14-16]. Separated kitchens with a fireplace and a chimney also reduce the risk of starting an accidental fire. Including rain collection gutters on the roofs and water storage tanks can provide a safe water supply[17]. Providing well-designed latrines improves sanitation and in combination with a safe water supply reduces the enteric disease burden[18].

There have been a range of interventions to modify individual aspects of rural African homes such as the closing of eaves[19], adding eaves tubes[20, 21], installing insecticide treated curtains[22], screening windows and doors[23] or replacing thatched roofs with corrugate iron[24]. Although such modifications can provide incremental improvements, they cannot overcome the fundamental design flaws of traditional, rural African homes, particularly poor heat insulation and restricted airflow. This study explored how building elements, which have been successfully employed in South-East Asia, could be integrated in a novel low-cost house design in rural east Africa. As a first step to evaluate the benefits of such a new house design, mosquito density, indoor climate, and acceptability were compared across new designs of African houses in rural Tanzania.

Materials and Methods

This is a multidisciplinary study to explore the feasibility and benefits of new housing designs for rural, hot, humid Africa. Three aspects of new housing designs were investigated 1) the impact on indoor mosquito densities, 2) the impact on indoor climate, and 3) the acceptability to the residents.

Study site

The study was conducted in the village of Magoda in Muheza District, Tanga Region, Tanzania. Magoda (5°11'11.6"S 38°51'26.0"E) had a population of 2,934 individuals in 678 households at the time of the 2012 national census[25]. Subsistence farming and informal trade are the major sources of income. The area is endemic for *Plasmodium falciparum* malaria. As in many other parts of sub-Saharan Africa [26], there has been a remarkable decline in the burden of malaria during the last decade. Cross-sectional surveys in Magoda village showed that the prevalence of *P.falciparum* infections in individuals below 20 years of age has decreased from 84% in 1992 to 34% in 2004 and 7% in 2012[27].

House construction

Following meetings with village leaders, the construction and study plans were discussed with the entire village. A free, fair and transparent lottery was conducted in which each interested village household had the same chance to win a new prototype house. The members of the winning households were asked to help in the construction of a new building in direct vicinity of their existing house. Once the construction was completed the household members moved into the new building.

Six prototype houses were constructed which were divided in to three groups based on the material used for cladding (Figure 2). Group 1 houses used unimpregnated bamboo (*Bambusa vulgaris*), Group 2 houses used shade net as cladding material Group 3 used cypress timber (*Cupressus lusitanica*) a traditional cladding material. (Please see supplementary materials for details)

Climate data

Hourly measurements of indoor temperature and humidity were recorded in all study houses using HOBO data loggers (ONSET, Bourne, MA, USA) for one year, from August 2015 through July 2016. The data loggers were installed in the bedroom used by the household head were installed 500mm and 1000mm above the floor.

Psychrometric testing

The software package LadyBug (LadyBug Products, Athol, Idaho, USA) was used to estimate the percentage of time occupants of various house types spent in the comfort zone[28]. The comfort zone is defined by the comfort polygon for temperature and relative humidity and an estimated percentage of people dissatisfied (PPD). The human energy balance model used by the psychrometric chart is the Predicted Mean Vote (PMV) model developed by P.O. Fanger[5]. PMV is a seven-point scale from cold (-3) to hot (+3) that is used in comfort surveys. Each integer value of the scale indicates the following: -3: Cold, -2: Cool, -1: Slightly Cool, 0: Neutral, +1: Slightly Warm, +2: Warm, +3: Hot. The accepted range of comfort is a PMV between -1 and +1 and defines the area of the comfort polygon on the psychrometric chart.

Entomological assessment

Mosquitos were collected using Furvela tent traps [29] during the rainy season from 11th to 25th Feb 2016. (Please see supplementary text for details). Participants agreeing to sleep in the tent traps were males over 18 years old who provided a signed informed consent, abstained from alcohol and smoking and agreed not to leave the tent from 22:00 to 06:00 h, except to use bathroom facilities. Mosquitoes were collected from 22:00h to 06:00h. In the morning, trapped mosquitoes were collected into paper cups covered with netting and killed by placing the cups inside a freezer at -20C for about one hour. Mosquitoes were identified using standard taxonomic keys. Mosquitoes of the *Anopheles gambiae* complex were identified to species using PCR[30].

Acceptability assessment

Attitudes towards the novel designs and modified traditional housing were assessed six to nine months after the residents moved into their new or modified homes through 15 in-depth interviews (IDI) and five focus group discussions (FGD). Household heads of the new houses, modified houses and reference houses were interviewed in Swahili, the local language, using pretested interview guides (supplementary appendix). Neighbours of each group of prototype housing participated in a FGD. Participants were invited to one of the three FGDs according to the neighbouring group of prototype houses (bamboo, shade net and wooden houses). Community members from further afield in the same village or the nearby sub-village also participated in FGDs. The respondents who participated in the FGDs and IDIs were between 35 and 80 years of age, with equal proportions of men and women (see supplementary appendix for participant characteristics). After receiving training in interview techniques, research assistants conducted the IDIs and FGD. To minimise the potential for desirability bias, the research assistants were not part of the study implementation team. All IDIs and FGDs were digitally recorded, transcribed in Swahili then translated into English for analysis.

Data management and analysis

Climate data were downloaded from each data logger at monthly intervals and transferred into a central database. Data collected around 21:30 +/- 30 minutes were used for the analysis. The temperature at bedtime, between 21:00 and 22:00, was considered most relevant for the decision to use a bednet or not. Mean temperatures with 95% confidence intervals were calculated for each building. Bedtime temperatures were modelled using the BoxCox Transformation (BCT) regression model [31, 32]. The predicted bedtime temperatures from the BoxCox Transformation models were smoothed using cubic spline. The cubic splined bedtime values (including a 95% confidence band) were then plotted over time and found to be skewed. The BoxCox Transformation modelling provides a reasonably appropriate transformation to the data and the cubic splining helps to obtain smooth curves [33].

Entomology data were double-entered. The difference in mosquitoes caught indoors and outdoors was calculated for each night and each house. The reduction in total mosquito catches was calculated as (OC-IC)/OC*100, where OC is outdoor catch, and IC indoor catch. Proportions with 95% confidence intervals were calculated.

The IDI and FGD transcripts underwent qualitative content analysis. The analysis process began by developing codes, which are meaningful segments of texts that are used for condensing and organizing qualitative data into smaller units. Initial codes were developed from the main research questions and interview guides. These codes were then used to guide the analysis of the transcripts, whereby meaningful segments of texts were assigned to their respective codes. Additional codes were generated as they appeared within transcripts during the coding process.

An overall heat map that consisted of a matrix of the novel houses' construction cost, indoor bedtime temperature, reduction in indoor mosquito density and acceptability values represented as colours was created to guide the selection of the most appropriate design for the scale up of the project.

STATA 14.1 (StataCorp; 4905 Lakeway Drive; College Station, Texas 77845, USA) was used for statistical analysis of quantitative data.

Approvals/consent

Before study activities started, written informed consent was obtained from the household head and other volunteers sleeping in tent traps. Verbal informed consent was obtained from the IDI and FGD participants of. A Clearance Certificate for Conducting Medical Research in Tanzania was obtained from the National Institute for Medical Research on 14th August 2014 (NIMR/HQ/R.8a/Vol. IX/1797) and extended on 14th January 2016 (NIMR/HQ/R.8c/Vol. II/555).

Role of the funding source:

The funder had no role in study design, data collection, analysis, or writing of the report. The corresponding author had full access to the study data and final responsibility for the decision to submit for publication.

Findings

Over a 12 months' period ending in July 2015 three single-storey and three double-storey houses were constructed, one of each with the following claddings Bamboo (Group 1), shade net (Group2), and timber (Group 3; Figure 2 and Figure S2). A Thai-Karen bamboo house and the teacher's house (Group 4) were subsequently built between July and December 2015. Images of the houses during the day and night illustrate the air and light permeability of the new houses (Figure 4). The building costs were similarly low for the bamboo-, and shade net- buildings and costlier for the timber-clad houses (Table 1). The cheapest of the new buildings was the double-storey shade net building at USD $4,661 and the most expensive building was the timber-clad double-storey building at USD $6,125. The costs for unmodified traditional homes were estimated at USD $4,231. The additional modifications including screened windows and water harvesting cost USD $1,989 (see methods and materials).

Entomology

The most frequently caught mosquitoes indoors were *Anopheles gambiae* s.l. (33%) followed by other anophelines (32%;Table 2). Outdoors, the most frequently caught mosquitoes were *An. gambiae* s.l. (38%), followed by *Mansonia* species (21%) and *Culex quinquefasciatus* (18%). The overall reduction of all mosquitoes caught was highest in the double-storey buildings (96%; 95% CI 92% to 98%) followed closely by the reduction found in single-storey buildings (77%; 95%CI 72% to 82%) and lowest in the modified reference houses (43%; 95CI 36% to 50%), and unmodified reference houses (23%; 95%CI 18% to 29%; Figure 5). The reduction of anophelines alone was also highest in the double-storey buildings (97%; 95% CI 92% to 99%) followed by single-storey buildings (75%; 95%CI 67% to 81%) and lowest in the modified reference houses (33%; 95CI 26% to 43%), and unmodified reference houses (3%; 95%CI 1% to 7%).

Indoor climate

The mean bedtime indoor temperatures, between 21:00 and 22:00, were highest between January and March, coinciding with the malaria season and lowest between June and August (Figure 6). In January 2016, the bedtime indoor temperature in the reference and the modified traditional houses reached up to 30·0°C between 21:00 and 22:00 h. The mean temperature was 28·6°C (95%CI 28·3°C to 28·8°C) in the unmodified reference and 29·8°C (95%CI 29·5°C to 30·1°C) in the modified traditional houses. In contrast, the mean indoor temperatures in the novel design houses were lower at 26·8°C (95%CI 26·6°C to 27·0°C) in the double-storey and 27·2°C (95%CI 27·0°C to 27·4°C) in the single-storey houses. The indoor temperature difference between the new design prototypes and the reference houses between 21:00 and 22:00 h was 2·3°C (95%CI 2·2°C to 2·3°C). The over-all mean indoor temperature at bedtime between August 2015 and July 2016 is shown in Figure 7. The mean indoor bedtime temperature (26·0C; 95%CI 25·8C to 26·2C) was lower in the novel houses than in the matched modified or un-modified reference house (28·1C; 95%CI 27·9C to 28·4C). Between 1st December 2015 and 31st May 2016 during the hours from 19:00 to 22:00 h the mean comfort level measured as PMV, was 27% in the modified traditional houses, in the traditional reference houses 47%, in the double-storey houses 79%, and in the single-storey houses 82%. In comparison, the Karen style bamboo house had the highest comfort level percentage of 85% (Table 3 and Figure 8).

Acceptability

Seven people who moved into the prototype houses and seven of their neighbours (three of whom had their houses modified) participated in in-depth-interviews (IDIs). After living in their new prototype houses for six to nine months, residents expressed satisfaction with the new designs. When asked about their opinions of the different design elements, residents most commonly mentioned the second-storey sleeping area (5 out of 7), describing the room as cooler and safer from insects and crawling animals (including snakes) than in their previous homes. (Please see supplementary text for quotes).

Four of the seven residents preferred the timber houses (Group 3), which they regarded as secure, durable, and protective of privacy. The shade net houses were described as the second preference, particularly in the two-storey configuration, which mitigated concerns about security and durability of this material. The bamboo houses were least favoured, with respondents reporting that an insect-infestation of the bamboo walls produced, in some cases, an annoying dust. Respondents also felt that the bamboo cladding leaves gaps, which prevent complete privacy and can make it difficult to regulate airflow. In contrast, the residents of the Thai – Karen house, which in contrast to the prototypes was built using insecticide-treated bamboo, reported no problems with insect infestation.

A total of 33 adult male and female neighbours of the new houses participated in the FGDs. Overall, there was a preference for double-storey houses. The focus group discussions confirmed a preference for timber and shade net cladding over bamboo cladding.

Other concerns centred on the size of the new houses: although traditional homes tend to be smaller or of similar size to the new buildings, respondents said they preferred big houses to accommodate their extended families. Based on their appearance, neighbours expressed concerns about the construction costs and affordability of the new prototype houses.

An overall heat map that included cost, temperature, mosquito density and acceptability values represented as colours was created (**Table 4**). Double-storey buildings performed best in reducing indoor mosquito densities and temperature. Timber cladding had the highest acceptability but is more expensive than other cladding materials. Double-storey buildings using shade net as cladding appear acceptable, well ventilated, relatively cool and protected from mosquito entry while less costly than timber-clad buildings.

Discussion:

To evaluate the benefits of novel low-cost house design in rural east Africa mosquito density, indoor climate, and acceptability were compared across new designs of rural African houses. Importantly, the study showed that there were 96% fewer mosquitoes in double-storey homes compared with traditional houses. Double-storey buildings performed best in reducing mosquito densities since in sub-Saharan Africa in general mosquito density declines with height[34-36], with one study collecting 80%, or more, from less than one metre above the ground[37]. It may be the double-story buildings were protective against mosquitoes because the space below the second-storey, reduced the ability of mosquitoes to locate a human host. Investments in double-storey buildings are likely to provide protection against several mosquito-borne diseases, and encourage bednet use. This is of relevance when residents spend waking time indoors, while unprotected by a bednet.

This study also showed that year-round night-time temperatures were lower in houses adapted to tropical conditions than in traditional or modified traditional homes. Ground elevation and permeable cladding materials were important design elements that contributed to this improvement. The psychrometric assessment highlighted the superior comfort level in the prototype houses compared to modified and traditional houses. The comfort level assessment was based on temperature and humidity. Improving airflow in the prototype houses should result in a further extension of the comfort zone and even higher comfort levels than reported here. The use of bednets all-night and all-year round for protection against malaria is likely to be enhanced in these cooler, more comfortable rooms.

The long-term success and sustainability of new architectural designs depends on the acceptance by their residents and neighbours. It is reassuring that a formal evaluation of residents' and neighbours' opinions found that the prototype houses were well liked. Their positive assessments of double-storey buildings, which have not traditionally been constructed in rural sub-Saharan Africa, including the study setting, are particularly important. Although residents' positive opinions may have been influenced by a desire not to disappoint the research team, such bias seems unlikely because the acceptability team was independent from the house construction team. The preference of new over old is strongly supported by the fact that none of the residents of new buildings moved back in their previous abode.

Residents and neighbours preferred the two-storey houses over single-storey buildings and the lowest mosquito densities were found in the upstairs rooms. Upstairs bedrooms also address user concerns regarding their privacy and security, provided that other double-storey buildings do not abut and overlook them. Shade nets are a new, low-cost building material, which are currently widely available for a range of purposes other than building materials. In houses that used shade nets both as cladding and to cover eaves, indoor mosquito populations were reduced (100% and 90% in double-storey and single-storey buildings respectively). Importantly, reduction of indoor mosquito density was less pronounced in modified traditional houses with sealed eaves. Further adaptation of shade nets, specifically as building material in double-storey buildings, holds promise for affordable housing in rural sub-Saharan Africa.

Community members' negative attitudes towards bamboo as a construction material are unfortunate. Bamboo is a cheap and ubiquitous construction material throughout Asia hence there is considerable experience how to use this material. Never previously used as a construction material in Magoda, there is no local experience of how to protect bamboo from insect attacks. The bamboo house constructed by Thai craftsmen suffered few attacks from insects probably because of the pre-treatment with insecticides, whereas the bamboo cladding used in prototypes remained susceptible to insect infestation. Prior to further attempts to employ bamboo as a construction material there is now a need to understand which insects attack bamboo in Africa and how bamboo can be protected against such attacks.

Construction costs will play a critical role in the uptake of these new designs. The community showed a preference for timber, a traditional building material in the region which is more expensive than bamboo or shade net. With diminishing forests in subSaharan Africa it is reasonable to expect that timber prices will further increase in the coming years. In contrast, shade net is a novel material that is not yet widely used for facades in housing and may become more affordable through economies of scale. Bamboo, the cheapest of the cladding materials in the study is the most popular building material in rural South-East Asia but is underutilised in sub-Saharan Africa.

This was early assessment of a novel house design to improve health. The study therefore has limitations. Six prototype buildings are not enough to show a clinical impact hence no attempt was made to assess health benefits. Keeping the limited number of units for statistical inference in mind proportions and their 95% confidence intervals are presented. A much larger sample size will be needed to detect a statistically significant impact on mosquitoes, indoor climate and any potential health benefits. There was potential confounding between the two key measurements, indoor climate and mosquito counts, and geographic position. Although unlikely, it is possible that the new houses were constructed at sites with lower mosquito densities and cooler night time temperatures compared to the surrounding control houses. Furthermore, mosquito densities were assessed over four nights only. It is possible that the benefits are less pronounced over longer observation periods. Nonetheless, the magnitude of the reduction in indoor mosquitoes in the novel designs was substantial, suggesting these are real effects. The cost of new buildings reported in the paper includes building materials and cost of labour. Estimating the cost of prototypes is difficult due to the modifications arising during the building process. Labour costs are highly flexible if the future residents and neighbours contribute to the construction as is tradition in rural Africa. It is reasonable to expect that building costs drop when new design houses are built at scale.

Although the investments required for the construction of novel housing are orders of magnitude higher than for example a long-lasting, insecticide-treated bednet that costs around USD $2. The potential health benefits of novel design houses go however far beyond those of ITNs alone: reduced mosquito density combined with a more comfortable environment for bednets to reduce mosquito-borne diseases, permeable wall cladding and separation of cooking facilities to improve air quality and reduce the risks for respiratory tract infections including tuberculosis and the availability of safe water and latrines to prevent enteric diseases. The study shows it is feasible and acceptable to local communities to build houses with a novel design in rural Africa which reduces mosquito house entry and keeps the occupants cooler than traditional houses. With rapid population expansion and economic growth in sub-Saharan Africa there is an opportunity to provide healthier and more comfortable housing in rural Africa. There has never been a better time to modernise the housing stock in sub-Saharan Africa to construct dwellings that reduce the threat from vector-borne diseases and keep the house cool. Based on the overall heat map of the results, it would be reasonable to scale-up the construction of double-storey shade-net buildings and evaluate their impact on multiple aspects of health, including mosquito-borne disease, respiratory illness and enteric infections. Such investments must be based on hard evidence which comes from adequately powered, large randomised trials.

Contributors

LvS an JK conceived the study, JK designed the prototypes, KI adapted and implemented the designs, KI and SM supervised the construction, TEN and WNK conducted the entomological study, SWL advised on the entomological aspects and the overall interpretation of the study findings, SM supervised the acceptance study and CP advised on the analysis and interpretation of the qualitative study aspects. JD advised on the study implementation. LvS, JD, JK, and SWL wrote the first draft of the paper. All authors reviewed and edited the final manuscript.

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