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ARTICLE

Window Design for Mosquito Control: An Architectural Solution for Reducing Malaria Burden in Tropical African Homes

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ABSTRACT

Housing design in tropical regions of Africa necessitates that windows are created for natural ventilation and aeration of indoor spaces. However, the menace of malaria carrying mosquitos makes natural ventilation more risky that comforting. Naturally in most buildings in this region, windows are designed to integrate both the functions of passive (natural) ventilation and mosquito repelling, which is achieved by the adoption of mosquito netted-screens. However, review of existing mosquito screening designs identified in the study region, indicates the existence of interlude periods between operating the netted screens and opening of windows panels. These minute interlude periods when the windows are exposed to the open environment, is responsible for the admittance of mosquitos and other harmful insects. This study presents a design option for mosquito screening which provides homes with constant aeration periods and zero contact with vectors via the windows. While a typical/conventional window design in this region consists of Mosquito screening systems (MSS) comprising of two or more layers of openings which harbor tendencies of exposure to the outdoor malaria vectors, the optimized design presented in this study nullifies this tendency of exposure. During the course of operating the netted and main window panels of a typical two layered MSS, the interlude period provides sufficient time frame (mostly within the range of 10 seconds) for the influx of vectors, this timeframe is totally eliminated by the optimized MSS, which provided zero obstruction timeframe while operating the system. Comparative review of the screening systems showed significant mosquito repelling capability by the optimized MSS compared to conventional ones. This is a significant result as most homes in tropical environments depend largely on open windows for natural cooling and ventilation and thus, the option of operating windows without interruption from the MSS is indispensable in achieving mosquito-free indoor spaces.

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ARTICLE INFO

Received: 10 March 2024 | Revised: 2 April 2024 | Accepted: 25 April 2024 | Published Online: 3 May 2024
DOI: https://doi.org/10.30564/jaeser.v7i2.7634

CITATION

Anselm, A.J., 2024. Window Design for Mosquito Control: An Architectural Solution for Reducing Malaria Burden in Tropical African Homes. Journal of Architectural Environment & Structural Engineering Research. 7(2): 10–19. DOI: https://doi.org/10.30564/jaeser.v7i2.7634

Keywords: Malaria Control; Window Design; Mosquito Control; Mosquito Screening System; Mosquito Free Design; Window Screening

1. Introduction

Housing is a concept that has been in existence since the onset of human civilization. With its definition mostly centered on the provision of homes and shelter, housing plays a critical role in determining the quality of life for its occupants, families and the community at large. Though intensive efforts and ideas are regularly devised by governments and individuals towards the improvement of housing objectives, however, experience shows that most people (especially those in poorer enclaves of society) do not live in shelters that meet even the most basic requirements. It is also notable that for an increasing numbers of dwellers, available accommodations not only fails to protect against but rather exposes them to health risks that may be easily preventable. In this regard, developing an effective home must cut across the basic needs of its human inhabitants as well as provide improvements to people's health, safety, livelihoods, wealth, assets, and overall sense of well-being[1]. With one of its fundamental functions being the provision of healthy environment for living, a healthy home must be designed to secure its inhabitants from unhealthy elements. One of the most severe menaces to healthy living in Africa and other tropical regions is the 'Mosquito'. Mosquitos are the primary vectors of viruses, parasitic protozoa (plasmodia) and filarial worms[2]. Amongst the diseases transmitted by mosquitoes, the deadliest in the Sub-Saharan region of Africa is 'Malaria'.

Study shows that the practice of effecting improvements in housing has resulted in significant reductions of the malaria burden[3]. Likewise, reviews of housing stocks identified that the potential for further reducing transmission through housing improvements such as the application of screening doors and windows has added significantly in the fight against endemic malaria[4]. The impact of these studies resulted in the World Health Organization recommendation of the use of untreated mosquito screening of homes[5]. With the significant achievements attained through housing improvements over the years, this paper seeks to introduce an added context to housing improvements by the introduction of an architectural feature in the design of windows for homes in Sub-Saharan Africa and beyond.

1.1. Background of the Study

Malaria is the leading public health burden in Sub-Saharan, making it a public health challenge that is endemic in most of these tropical countries. Latest reports from the WHO identified Africa as the continent with the most recorded cases of malaria globally[6]. According to the roll back malaria reports from WHO, malaria is notable for about 31% of global deaths. It reported that in 2021 alone, about 80% of these deaths resulting from the disease were in children under the age of 5 years, with about 40% of these fatalities in the WHO African Region[7]. Equally, reports on the study area (Nigeria) identified the disease as the major public health concern. Nigeria alone recorded an estimated 68 million cases with about 194,000 of these cases resulting in fatalities in the year 2021, with majority of the cases concentrating in the northern part of the country as shown in **Figure 1**. Current data identified Nigeria as the nation with the highest malaria burden globally, as the verified cases reported in 2022 accounted for nearly 27% of the global malaria burden and 28% in the WHO African Region[8]. These mortality cases are resultant from bites from several breeds of the Anopheles mosquito[9]. The activities of mosquitos relative to human susceptibility can be classified into indoor and outdoor exposure. While the class of mosquitoes that transmit malaria, particularly with those often found in Africa fall into the category that feed indoors, such as the *An. gambiae (sensu stricto), An. funestus sensu stricto* and the Asian vector *An. stephensi sensu stricto,* the other class such as the *An. arabiensis*, feed both indoors and outdoors[10]. With this insight, it is paramount to note that the significance of minimizing the risk of exposure to human vs. mosquito vector contact is equal to minimizing the burden of malaria in known endemic areas[11]. Over the years, the most commonly used malaria prevention techniques comprise of the vector control tools such as the Indoor Residual Sprays (IRS) and the Insecticide Treated Netting (ITNs)[12]. Since 2010, it has been noticed that the percentage of communities

protected by the use of IRS in malaria-endemic countries declined by at least 3.2% to 2.6%. This significant change was observed by the World Health Organization in 2021 as representing a change in prevention strategy [13]. Apart from the issue of the effectiveness of the use of IRS for suppressing indoor carrying vectors as a measure for prevention, also comes the case of resistance. The common disadvantages of these insecticide based malaria control measures include the advent of vector resistance to known insecticides as well as drug-resistant parasites [14]. According to studies, when there is prevalent use of potent IRS and ITNS elements over prolonged time, the result is resistance [15]. These studies indicate a growing concern which suggests that insecticide resistance against mosquitoes could lead to increase in cases of malaria and subsequent rise in fatalities in endemic communities such as sub-Saharan Africa. Owing to these, there is increase in research to identify effective and more environmentally friendly measures that may not be dependent on IRS. Study identified the major challenge with dependence on IRS as a prevention strategy is based on the fact that it only target malaria vectors once they have entered the home. However the challenge still lies in identifying measures to keep mosquitos away from homes owing to the massive need for passive ventilation in most poor homes in sub-Saharan Africa. This is the case as windows are the most common means of introducing wind driven ventilation into these homes for the purposes of cooling and aeration. Foremost on the list of new methods and techniques identified for mosquito resistance, includes:

1. Screening of homes; a traditional concept which have long been practiced in many countries and usually designed to keep insects and pests away by adopting door and window screens and shut roof spaces. Study identified this method as effective in protecting people against malaria when implemented in malaria endemic areas [16].
2. Screening and trapping; study showed that combining house screening and mosquito trapping methods for the control of the populations of mosquitoes, indicated significant reduction in populations of indoors vector carrying mosquitoes as well as the killing of the trapped mosquitoes [17].

Further studies on the relevance of House modifications for preventing malaria equally presented the potential for adopting house screening in reducing the incidence of clinical malaria for communities and people living in modified houses [18]. Owing to the significant achievement in the reductions of the malaria burden recorded by the adoption of House modifications for preventing malaria in many areas, the WHO eventually recommended the usage of untreated door and window screening of homes especially in tropical regions like sub-Saharan Africa [19].

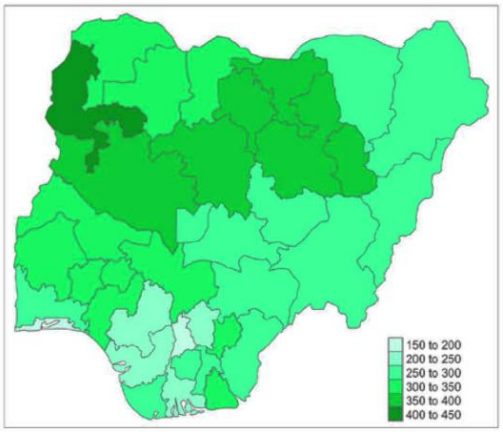


Figure 1. Estimated malaria incidence in Nigeria (per 1000 population) as reported in 2021 [8].

Typical residential house style produced in most areas in Africa are made up of walls constructed of heavy materials like concrete bricks, adobe, mud or clay bricks, with little fenestration openings across the walls owing majorly to the need to keep off external elements. This is further compounded by the regular closure of doors and windows in the evening hours, resulting in uncomfortable indoor thermal and humidity conditions. These uncomfortable conditions are caused by lack of active airflow and ventilation in and out of the houses, most often prompted by the action of shutting the windows and doors in order to keep the external disease causing vectors (like mosquitoes) out of the homes. Even with the use of mosquito netting as window screens, the conventional designs of window netted screens requires that the screens are opened briefly to access the windows. These brief seconds (referred to as 'Interludes' for the purpose of this study) required to open the screens in order to gain access to the window controls is enough time for influx of the amount of disease carrying mosquitoes/vectors into the homes. Since the challenge of healthy housing in sub-Saharan Africa doubles between the menace of malaria carrying mosquitoes and quality of indoor airflow for ven-

tilation and cooling purposes, the importance of significant window-opening hours cannot be overemphasized.

1.2. Significance of the Study Area

This study is focused on the tropical Nigerian environment. This is significant owing to the degree of the malaria burden already established in this region of Africa. Likewise, the choice of the Nigerian environment is important due to the high mosquito presence as well as the significant climatic properties that validate the need for mosquito screening in houses. Research attributes the tropical zones of the world as climatically overheated regions. This is owing to the distinctive high temperatures and humidity conditions that are unique to this zone[20]. Nigerian which is located along 10° N and 8° E, it is however classified as a hot-humid climate. This hot-humid climate, which is similar to most of the sub-Saharan West African countries is influenced by two main factors which are the daily heating and cooling of the Sahara Desert and the heating and cooling of the vast body of water within the Atlantic Ocean. These two phenomena creates the two major seasons typical to these regions, classified under the dry and wet seasons. While the dry season lasts through November to March (5 months), the rainy or wet season lasts through April to October (7 months)[21]. Significant research in the study of malaria incidents identified the peak malaria season in Nigeria as occurring during the wet or rainy season when the environment is humid and wet thereby enabling mosquito breeding. The major relationship between mosquito breeding and the climate of Nigeria is presented in **Figure 2**. According to Okorie et al. (as seen in **Figure 2**), the quantity of mosquitoes decreased with increase in rainfall, while it increased as temperature and relative humidity increased[22].

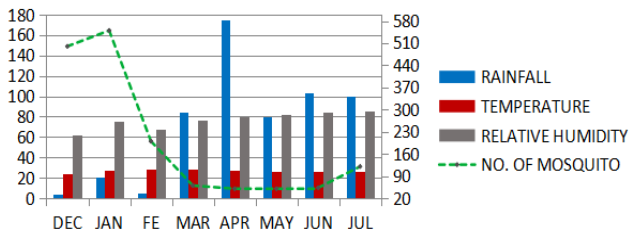


Figure 2. The Relationship between rainfall, relative humidity, temperature and mosquito swarm[22].

1.3. Understanding the Behaviors of Mosquitos for Effective Vector-Control in the Study Area

Research identified that Mosquitos in the study region are known to be mostly active towards the evening and night times than during the afternoon hours[23]. Mosquito bites are known to occur indoors, most often at evening and night times as observed in countries of Sub-Saharan Africa. This situation highlights the significance of ensuring mosquito proof house design as means of protection against malaria[24, 25].

Research reveals that adult mosquitoes are mostly active from their aquatic habitats at evening times. It normally takes an adult 24 hour period for full development, during this time the cuticle of the mosquitos hardens as the adults mature and they disperse erratically upwind searching for feeding grounds and opportunity to mate. Mating activities also frequently occur in swarms during the evening periods, with the well fed females mating before blood feeding, while the poorly fed ones end up lacking energy for mating. The female mosquitos are particular monogamous in nature, while the male ones swarm at night times and can mate up to 4 different partners at a time. A particular trait also indicates that in close proximity with their host, mosquitos adopt visual signals aided by air temperature factors and relative humidity. These nocturnal activities surrounding blood feeding occurs mostly indoors, as mosquitos gain access into houses through gaps in window openings, walls and roofs. With respect to reproduction, female mosquitos are often classified as gonotrophically concordant. Their egg development process takes about 2 to 3 days depending on temperature conditions. Also, apart from their first feeds, a single blood meal facilitates production of a complete egg-batch. These females loaded with their eggs leave the swarm sites at dusk times in search of volatile chemicals and water sources which offer appropriate aquatic habitat for laying their eggs[26]. Through the study of mosquito behaviors and their inherent activities around the human environments, it is easily inferred that humans unintentionally create conducive habitats (aquatic environments) for the development stages of mosquitos within the human living environments, hence it could be inferred that human activities enable the processes of mosquito development which are nocturnal, thus creating risks of access into houses to feed on human at the most

vulnerable periods (night times). Research also identified that although the malaria parasite itself has adapted its transmission mode in mosquitoes, the insects themselves on the other hand, have equally altered their ecology and activities in the mission to exploit humans [27], thus making the task of mosquito and malaria control more challenging.

Following the study of mosquito behaviors in the study area which also recognized common combative practices for controlling access into houses in this region, identified that windows are mostly shut during the evening hours, as reaction to mosquito activities after dusk. This practice of shutting windows observed as preventive measures in this region also prove to be unfavorable to indoor air quality and thermal comfort conditions, as most windows in residential homes are denied natural ventilation from the hours of 6:00pm to 6:00am.

1.4. Significance of Study

It is noteworthy that malaria and other vector related diseases are responsible for majority of infant deaths as well majority of adult ailments across Africa. Study identified that about 80 to 100% of malaria transmission within sub-Saharan Africa occurs indoors. This situation has redirected major focus on the issues of malaria control towards House modification [28]. Consequently, owing to the significant achievements in malaria reduction recorded through the adoption of house modifications, the concept of mosquito screening becomes more attractive than the use of chemical aerosols which are mostly unhealthy. With the intent to develop a more effective Housing model for Mosquito repellence, an adaptive window design was developed as a model for modification of the conventional window screening system. The adaptive window design presented in this study intends to eliminate the interlude periods, thereby providing the homes with constant aeration periods and zero contact with vectors via the windows. This study presents and analyses the architectural design alongside conventional mosquito screening systems as well as discusses its potential for mosquito blockage with the tendency to enable unobstructed natural ventilation in homes all through the day.

2. Study Methodology

The main objective of this paper is to evaluate window designs and their impacts in restraining mosquito activities in the study area. This involves the review of existing Mosquito Screening Systems (MSS), with the intent of identifying operational systems and their performance towards mosquito blockage from indoor spaces. The significance of this is to justify the effectiveness of screening system that will improve if not achieve a total mosquito free indoor environment.

To do this, this study employs descriptive analysis method by way of physical observation and analysis of existing MSS. After careful observation and comparative analysis to identify the effectiveness of each system, the study goes on to recommend an architectural design which annuls all the inadequacies identified in the conventional MSS designs.

In order to accurately identify the standard MSS, major window manufacturing/installation factories in the study area were visited. The paper goes ahead to classify the identified MSS according to their functions for mosquito blockage. The observation process of screening techniques identified operable models from different window types, which were presented graphically for the purpose of visualizing effectiveness. These conventional operable screening systems were finally compared with the fixed MSS system and the results presented as justification of the architectural solution for reducing mosquito accessibility in houses in this region.

3. Review and Analysis of MSS in Study Area

3.1. Description of Window Screening Designs in Study Area

Window screening which involves the conventional use of mosquito netting mesh (as physical barriers) to check mosquito entry is known to contribute enormously towards the reduction of mosquito presence in houses [29]. The use of MSS in windows and doors is most suitable because it is seen as effective and affordable, as the materials and equipment are easy to develop, environmentally friendly and acceptable to the general philosophies, and customs of people [30]. The custom of window design in Nigeria is such that every window system carries an added netting-mesh in it. Studies of major window types used in Nigeria identified four significant types. These include the Casement type, Sliding windows, Louvre windows and Projected windows. In his research, Anunobi et al. identifies the sliding window type

as the most adopted type, followed by casement windows, projected type and lastly the louvre type[31]. **Figures 3–6** illustrates the different window types and their MSS operational modes. The four commonly adopted opening modes for the MSS includes; the Swing mode, Sliding mode, Slit mode and the Lifting mode. Each of these opening modes offers different degrees of effectiveness in their mosquito restraining ability.

A typical conventional MSS consists of 2 layers (the netted screen and the main window panels). The architectural design of the 2 layers placed the netted screen before the main window panels. By so doing, the netted panels must be opened before accessing the window panels. Practical operation of the opening styles of these four conventional MSS mentioned above was done and the time lag between opening the netted screen panels and the main window panels was observed. This exercise revealed the time spent in operating each MSS panels, the size of exposure attained and the time spent in operating the systems. The information gotten in this exercise was recorded and utilized in analyzing the effectiveness of each technique and the probabilities for mosquito influx due to the exposure aperture sizes observed. While the Swing type MSS provides a 100% aperture which allows for ease of operating the window panels (sliding, casement, projected or louvre types), it however exposes the indoor space for a couple of seconds (termed interlude period), which is time enough for mosquitos to gain access inwards. On the other hand, the Sliding MSS allows only 50% opening for operating the window panels, which also presents a potential risk for admitting mosquitos in that operational interlude period. The Lift type MSS offers a much reduced aperture of about 25% of the entire window opening while operating the window panels. However the operational interlude here offers enough time for mosquito influx as well. In the case of the Slit type MSS, the size of the slits are often dependent on the window type, though it was observed that only the casement window type commonly adopt the slit system. It was also observed that the slits are made smaller in order to reduce the exposure aperture to about 10% of the window opening while operating the window panels. However, this too carries a potential for mosquito admittance while operating the window panels. Conclusively, in the course of operating the netted panels and main window glazed panels of these conventional screening systems, the perceived interlude periods offers sufficient time (often within a range of about 8 to 12 seconds), which is enough for the admittance of mosquitos and other harmful insects. This typical interval witnessed in the operation of these conventional MSS is identified in this paper as a flaw in the use of netted MSS as solution for mosquito control. Hence, there is need to develop a much effective architectural design targeted at minimizing or eliminating this interlude period in order to achieve a mosquito free indoor environment. This optimized option is presented in this paper as an architectural solution as described in **Figure 7**.

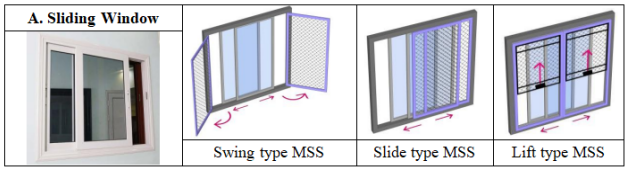


Figure 3. Image of Sliding window and sketch of the different adoptable options of MSS with their opening modes.

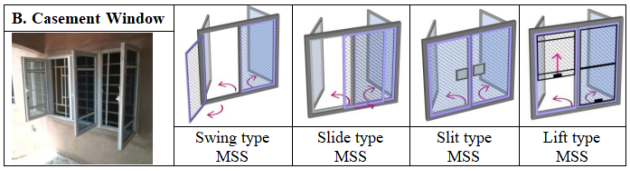


Figure 4. Image of Casement window and sketch of the different adoptable options of MSS with their opening modes.

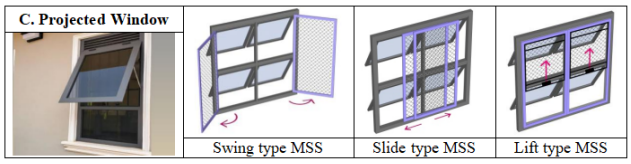


Figure 5. Image of Projected window and sketch of the different adoptable options of MSS with their opening modes.

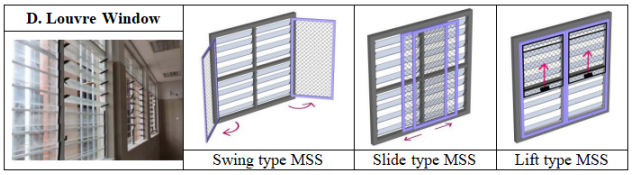


Figure 6. Image of Louvre window and sketch of the different adoptable options of MSS with their opening modes.

3.2. Architectural Design of an Optimized MSS

Having observed the general flaws identified while opening windows and MSS components in the conventional window types, the author ventured into creating a design

intended to repress mosquito admittance into homes through open windows. Having recognized that the natural window-state in tropical environments (due to the reliance on natural ventilation) necessitates more frequency of an *Open-state* rather than a *Closed-state,* the design aimed at achieving the constant natural ventilation of internal environment in homes without upsetting the MSS. Research into performance of window systems' operation identified that windows ought to be opened for a period of 5 to 10 minutes within every 3 hours in a day for effective control of indoor air quality and thermal comfort [32]. Further study suggests that any given window-state is established on indoor and outdoor climatic conditions, it also infers that the most significant indicators of the window opening are the outdoor temperatures. Probabilities of home occupants switching their window-state from a closed-state to an open-state were noted to increase with increasing outdoor temperature. Equally, altering the state from that of an open to a closed state was noticed to increase with decrease in outdoor temperatures [33, 34].

Following this realization, the major considerations in the design of the optimized MSS, was to attain the possibility of an open-state which may last 24 hours if necessary without accessing through the main window panels (thereby eliminating possibility of influx of vectors) nor affecting security of the internal spaces. By so doing, the system can be made adaptable to any of the conventional window types.

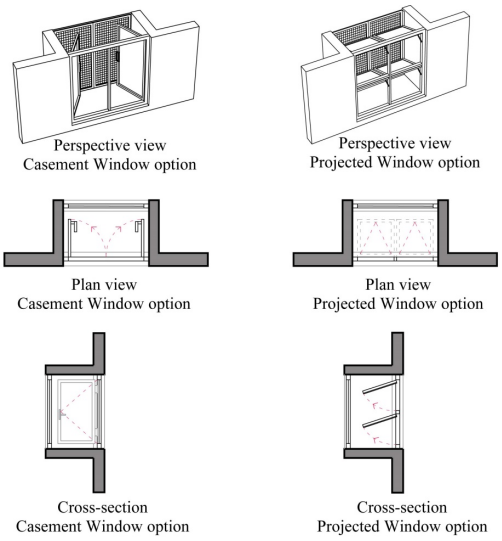


Figure 7. Architectural design of the Optimized MSS, applicable in all window types including the Casement and Projected window options, (source: authors design sketches).

As shown in **Figure 7** and similar to the conventional MSS, the design of optimized MSS consists of a 2 layered system (the main window panel and the screening). However, unlike the conventional systems which are joined with each other, the optimized design separates the panel with an air space to accommodate the 90o outwards swing of any conventional window type (in the case of casement or projected type panels as seen in **Figure 7**). More so, unlike the conventional MSS architecture which placed the netted screen before the main window panels, the optimized (fixed) MSS architecture places the window panels before the netted screen. By so doing this design would not need to operate the netted screen in order to access the operating devices of the main window panels. For purpose of affordability of the design in typical residential homes in the region, the construction of the optimized design employed the use of lightweight composite materials comprising of sandwiched polystyrene boards in sandcrete mortar as seen in **Figure 8**.

Figure 8. Pictures of different stages of construction to finished MSS in a typical residential house (Source: author's project).

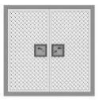
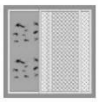
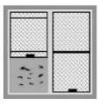
4. Results and Discussion

4.1. Comparative Analysis of the Effectiveness of Conventional and the Optimized MSS in Restriction of Access to Mosquitos

The different architectural design and specifications for window and MSS operations significantly affect the effectiveness of mosquito control in homes. Through the review of the mosquito screening systems presented in this paper, the significant potential of the optimized (fixed-type) MSS can be identified. A comparison of all types of MSS analyzed in this study is presented in **Table 1**, which indicates the significant characteristics of each screening method. From the practical operation of the opening styles of all the five

MSS discussed in this paper and the records of the interludes observed between opening the netted screen panels and the main window panels, the results of the time spent in operating each MSS panels and the sizes of exposure were attained. This result is used to evaluate the effectiveness of the architectural designs of each MSS in mosquito blockage as presented in **Table 1**. In the case of the Swing style and Sliding style architecture, 50% of the entire netted screen size was observed to be exposed while accessing the operating devices of the main window panels. A time lag of 11 and 12 seconds respectively was recorded between opening the main window panels and shutting the netted screen panels. With the exposure of about 50% of the entire window space to the outdoor environment, the probability rate of mosquito influx during this interlude period is considered as high probable. For that of the Slit and Lifting styles, a time lag of 8 seconds was recorded between opening the main window panels and shutting the netted screen panels. With the exposure of about 10% and 25% of the entire window space to the outdoor environment, the probability rate of mosquito influx in this case is considered as low and medium, hence occasionally probable. However in the case of the Fixed style architecture, there is no exposure as the windows are operable without interfering with the netted screen. Therefore the probability rate of mosquito influx in this case is considered as zero or improbable.

Table 1. Comparative analysis of effectiveness of MSS in the study region.

	Architectural Description	Applicable Window Type	Operational Effectiveness	Exposure Interlude	Size of Exposure Aperture	Mosquito Influx Probability	Mosquito Screening Potential
1	Swing system	All window types	Moderate	11 seconds	50% of window opening 	High (probable)	Moderate
2	Slit system	- Louvre window - Casement window	Good	8 seconds	<10% of window opening 	Low (occasional)	Fairly effective
3	Sliding system	All window types	Moderate	12 seconds	<50% of window opening 	High (probable)	Moderate
4	Lift system	All window types	Good	8 seconds	<25% of window opening 	Medium (occasional)	Moderate
5	Fixed system	All window types	Best	0 seconds	0% of window opening 	None (improbable)	Effective

5. Conclusions

The improvement of architectural features in housing design that interfaces with the external environment like doors and windows is recognized as key in the fight against malaria. This paper studied the various window designs and mosquito screening systems adopted in the tropical Nigerian environment where the presence of mosquito swarms are very high leading to prevalent malaria burden in this region. As the culture of housing in most tropical African regions necessitates the constant opening of windows for natural

ventilation purposes, the task of maintaining well aerated interiors as well as keeping away harmful mosquitos and other insects remains a challenge. Consequently, windows in this region are fashioned to integrate the dual functions of passive ventilation and mosquito resistance. This is often achieved by the adoption of mosquito screens, referred to as MSS in this study. This paper presented the study of both the conventional MSS available in Nigeria as well the architectural design of an optimized option in order to identify the most effective in mosquito resistance. The study identified the existence of interludes between the time of opening netted screens and the operation of window panels. It also identified that the combination of the interlude periods and the exposure apertures (when the interior spaces are exposed to the outdoor environment), increases the probability of mosquito influx into homes. The architectural design of the optimized (fixed) MSS and its preliminary evaluation identified potentials for improving mosquito blockage by eliminating the exposure of the indoor spaces to mosquito influx through windows; this is seen as significant in the strategies for malaria reduction. The design is thus recommended for adoption in residential house design in tropical regions where mosquito prevalence is prominent. It is believed that the use of affordable materials in the construction of the fixed type MSS could eventually make its adoption an effective option for malaria control in regions where malaria burden has become a public health threat.

Author Contributions

In this study, the main and single author A.J.A., composed the structure of the work as well as formulated the research methods and analysis. This included producing the architectural design and building construction of the model home used for the study. The idea for this was driven by the author's interest in developing a home that is free from mosquito incursions at the same time as achieving 24 hours of window openings for natural ventilation in mosquito infested tropical environments. The main author likewise produced all the sketches, observations and descriptions used in the analysis for the study.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Please contact the corresponding author for all detailed data.

Acknowledgments

In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflict of Interest

There are no conflicts of interest.

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