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Physical and insecticidal durability of PermaNet[®] 3.0 and Olyset[®] plus piperonyl butoxide-synergist insecticide-treated nets in Sierra Leone: results of durability monitoring from 2020 to 2023

Raymond Kiproop Sudoï^{1*}, Keith Esch², Frederick Yamba³, Laurent Iyikirenga⁴, Charlene Youssef⁵, Prince Nallo⁵, Isabel Swamidoss⁶, Carla Mapp⁶, Dennis Marke³, Samuel Juana Smith³, Ronald Carshon-Marsh³, Musa Sillah-Kanu³, Dave Schnabel⁷, Jacky Raharinjatovo⁸, Jenny Carlson⁹, Rebecca Levine⁶, Evelyne Alyko⁴, Ramlat Jose⁷, Tony Hughes⁶, Djenam Jacob¹⁰, Yemane Yihdego¹¹, Kevin Opondo^{4,12} and Stephen Poyer²

Abstract

Background The performance of two piperonyl butoxide (PBO-synergist) insecticide-treated net (ITN) brands, PermaNet[®] 3.0 and Olyset[®] Plus, were evaluated under field conditions in two neighboring districts in Sierra Leone over 36 months to estimate median ITN survival, understand insecticidal efficacy, and identify factors influencing ITN durability. This assessment can help guide future PBO-synergist ITN procurement and replacement strategies.

Methods This prospective study tracked 370 households and 652 campaign-distributed ITNs from 2020, followed annually for 36 months. Districts were purposefully selected based on shared characteristics. Household surveys were conducted, and 30 ITNs per round were tested for bioefficacy and chemical residue. Key indicators included ITN survival, 24-h mosquito mortality, and chemical content reduction compared to manufacturer targets doses. Cox proportional hazard models identified factors influencing ITN survival.

Results Median useful life was 3.0 (95% CI 2.7–3.5) years for PermaNet[®] 3.0 ITNs in Bo and 2.2 (95% CI 2.0–2.4) years for Olyset[®] Plus ITNs in Moyamba. PermaNet[®] 3.0 ITNs displayed 13% 24-h mortality against pyrethroid-resistant mosquitoes on roof panels, with a 46% reduction in PBO content 34 months post-distribution. Olyset[®] Plus ITNs had 3% 24-hour mortality against pyrethroid-resistant mosquitoes, with a 77% reduction in PBO content. Several factors were associated with improved ITN survival, including cohort ITNs from Bo (adjusted hazard ratio [aHR]=0.33, $p < 0.001$), households without children under five (CU5) (aHR=0.64, $p=0.003$), highest socio-economic status tertile (aHR=0.63, $p=0.016$), exposure to social and behaviour change (SBC) messages combined with positive net attitudes (aHR=0.63, $p=0.008$), lack of food storage in sleeping spaces (aHR=0.56, $p=0.006$), exclusive adult use of ITNs (aHR=0.72, $p=0.048$), net folding when not in use (aHR=0.67, $p=0.015$), and drying nets outside (aHR=0.44, $p=0.008$).

*Correspondence:

Raymond Kiproop Sudoï

Raymond.sudoï@gmail.com

Full list of author information is available at the end of the article



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Conclusion ITNs in Bo outperformed those in Moyamba in both physical and insecticidal performance. However, ITN survival is highly context specific, and further investigation into field performance of new ITN types is necessary across diverse epidemiological settings.

Keywords Insecticide treated net, Physical durability, Piperonyl butoxide-synergist, Insecticidal effectiveness, Sierra Leone

Background

The global effort to combat malaria has seen a significant increase in the distribution of insecticide-treated nets (ITNs) since 2004, raising population access from 3% in 2004 to 54% in 2021 and contributing to declines in malaria-related mortality in sub-Saharan Africa during that period [1]. The World Health Organization (WHO) issued guidelines in 2011 for routine durability monitoring after mass ITN campaigns, aiding National Malaria Programmes (NMPs) in estimating average ITN useful life in their context to support decision-making around ITN procurement and deployment [2]. Durability monitoring is now a common practice among NMPs in sub-Saharan Africa and results are available for pyrethroid-only ITNs from several countries [3–10].

The emergence and escalation of pyrethroid resistance in critical mosquito populations across sub-Saharan Africa has prompted the introduction of innovative ITNs, which incorporate a second active ingredient (AI) or a piperonyl butoxide (PBO)-synergist to complement pyrethroids, targeting resistant mosquito populations through various mechanisms. In 2017, the WHO expanded their guidelines to include the use of PBO-synergist ITNs [11]. In 2023, the WHO provided guidance for NMPs on prioritizing ITN procurement under conditions of limited resources [12]. About 259 million ITNs were shipped by manufacturers to sub-Saharan Africa in 2022; of those, about 153 million (59%) were dual AI or PBO-synergist ITNs [13]. Durability monitoring literature on the field performance of new dual AI or PBO-synergist is emerging, but is relatively limited [14–19]. While these studies demonstrated the benefit of PBO ITNs against pyrethroid-resistant mosquitoes, none looked at bioassay and insecticide chemical results together, conducted a risk factor analysis for physical durability, or focused on Sierra Leone.

Malaria continues to pose a substantial public health challenge in Sierra Leone, a country in which the entire population of 8.4 million people are at risk, with 2.8 million documented cases and 8,300 reported malaria-attributable deaths in 2021 [1]. While transmission occurs all year, incidence increases during the rainy season (May to October), when conditions are ideal for the mosquito vectors' breeding [20].

As part of its 2021–2025 National Malaria Strategic Plan, the Sierra Leone National Malaria Control Programme (NMCP) has set a target of 80% ITN use for both children under five (CU5) and pregnant women. To achieve this target, the NMCP supports mass distribution campaigns every 3 years, as well as regular distribution of ITNs to pregnant women through antenatal care and to infants through routine childhood immunization visits, all of which occur at no cost to the end user. The Demographic and Health Survey was last conducted in Sierra Leone in 2019, 1 year before their most recent mass ITN campaign [21]. The survey demonstrated that 68% of households owned at least one ITN (74% in urban areas and 60% in rural areas). Population-level ITN access, the proportion of the population that could sleep under an ITN if each ITN in the household was used by two people, was 47% (40% in urban areas and 51% in rural areas). The night before the survey, 51% of Sierra Leoneans slept under an ITN (41% in urban areas and 57% in rural areas). The use:access ratio, calculated by dividing potential ITN users by total household members, reflects the behavioural gap in net utilization independent of net availability [21]. The global target for use:access is ≥ 0.80 [22]. In Sierra Leone this target was exceeded with a use:access ratio of 1.08 (1.02 in urban areas and 1.12 in rural areas).

In collaboration with the U.S. President's Malaria Initiative (PMI) and the Global Fund, the Sierra Leone NMCP elected to deploy PermaNet® 3.0 and Olyset® Plus ITNs during the 2020 mass distribution campaign. These ITNs both feature a combination of a pyrethroid AI and the insecticide synergist PBO. The campaign delivered over 4.6 million ITNs to Sierra Leone's population, and in doing so, became the world's first country to achieve universal coverage with a PBO ITN. Of Sierra Leone's 14 (at the time) districts, the distribution specifically targeted eight districts with PermaNet® 3.0 ITNs (Kono, Bo, Koinadugu, Port Loko, Bonthe, Bombali, Pujehun, Tonkolili) and six districts received Olyset® Plus ITNs (Western Area Rural, Kenema, Western Area Urban, Kailahun, Moyamba and Kambia). While district selection for ITN distribution was based primarily on logistical convenience, available insecticide resistance data was reviewed prior to the distribution to ensure ITNs were being deployed appropriately.

This evaluation explored the field performance of these two PBO-synergist ITN brands in similar geographic localities under natural conditions for 3 years following the 2020 mass campaign in Sierra Leone. It focused on ITN physical durability to estimate median survival and to identify key factors affecting ITN performance, and chemical durability to evaluate the lasting effects of both bioefficacy and insecticide content. This was the first evaluation of ITN durability monitoring in Sierra Leone, for any brand of ITN.

Methods

Study sites and ITN brands

Data collection took place in Bo and Moyamba districts, which share a border in the Southern Region of Sierra Leone. In coordination with the NMCP and PMI, study clusters were randomly selected from a study frame that was restricted to clusters that lie along the shared border (Fig. 1). These districts were chosen to minimize differences in epidemiological, economic, climatic and population characteristics. Sites in Bo received PermaNet® 3.0 ITNs during the May 2020 mass campaign. PermaNet® 3.0 ITNs, manufactured by Vestergaard (www.vestergaard.com), are rectangular, with 75-denier polyester sides and a 100-denier polyethylene roof. Side panels

contain 2.8 g per kilogram (g/kg) of deltamethrin. The roof panel contains 4 g/kg of deltamethrin and 25 g/kg of PBO. Sites in Moyamba received Olyset® Plus ITNs, manufactured by Sumitomo Chemical (www.sumivector.com). Olyset® Plus ITNs are rectangular and incorporate 20 g/kg of permethrin and 10 g/kg of PBO on all 150-denier polyethylene panels. Both ITN brands are on the WHO prequalified ITN product list [23].

Study design

The 2020–2023 ITN durability monitoring evaluation in Sierra Leone employed a prospective cohort design, outlined in depth in the standard evaluation materials on www.durabilitymonitoring.org and elsewhere in published literature [24].

In both evaluation districts, a baseline data collection round was conducted in November through December 2020, 6.3 months after the mass campaign. ITNs enrolled in the evaluation cohort at baseline were followed up in surveys conducted 11.9, 22.9 and 34.1 months after the 2020 campaign. These rounds will be referred to as 12-, 24- and 36-month/endline survey rounds, henceforth. Slight fluctuations in regular 12-month data collection intervals were due to logistical challenges and personnel availability. During each survey round, data was collected

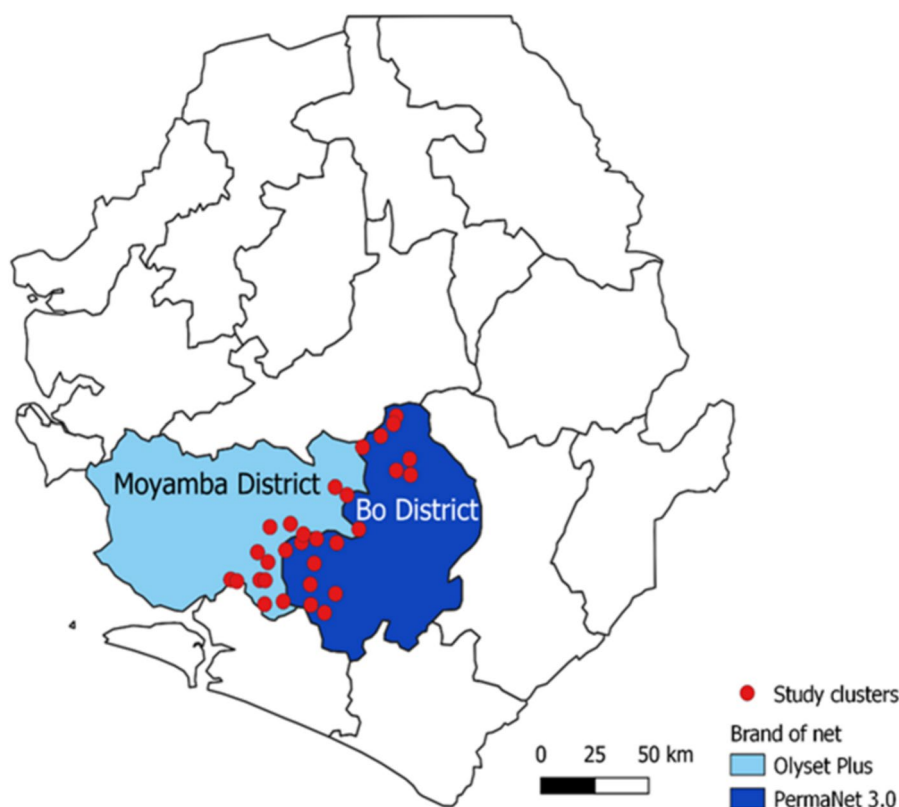


Fig. 1 Location of study clusters within Bo and Moyamba districts in Sierra Leone

via household survey on cohort ITN status (e.g., ITN was present, discarded, lost/unknown, given away, elsewhere, household moved or refused), ITN durability risk factors, respondent knowledge, and attitudes to ITNs and ITN care and repair, and ITN handling practices. The evaluation used Likert scale questions to assess attitudes towards nets and net care/repair. Respondents indicated their level of agreement with a set of standard statements, which were then recoded to a scale of -2 for 'strongly disagree', -1 for 'disagree', +1 for 'agree', and +2 for 'strongly agree'. The values for each response were summed and divided by the number of statements to calculate an overall attitude score. A score greater than 0 indicates a favorable attitude towards the topic. The physical integrity of remaining cohort ITNs was assessed by data collectors using the standard hole assessment tool to count and categorize holes by size. Data was also collected on ITNs that had left the household's possession since the previous survey round. Each round, 30 ITNs per district were withdrawn to undergo later bioefficacy and chemical content analysis. Households from which a cohort net was withdrawn immediately received a like-for-like replacement.

Sample size and sampling

Standard PMI guidance [25] for durability monitoring sample size calculations was employed, which assumed a design effect of 2.0 due to the clustered study design. A buffer of 5% was added to address loss-to-follow-up over the 3-year data collection period. In total, 770 ITNs (385 per site) were required to be enumerated during the baseline survey to detect a 10% difference between study sites from the expected 50% survival after 3 years. Prior to the evaluation, it was determined that 15 clusters of 10 households in each district would be sufficient to achieve the target number of ITNs (150 households total per district). At baseline, a lower-than-expected number of 2020 campaign ITNs were enumerated, despite the number of target households in seven clusters being increased by 35 to make up the gap in enrolled ITNs (bringing the total households in the evaluation to 185 per district). At the 12-month survey round, 41 additional campaign ITNs (23 in Bo and 18 in Moyamba) that were present in cohort households, but had not been enumerated at baseline, were identified by the data collection team and added to the evaluation, bringing the total sample to 98% of the original target. During analysis, these ITNs were considered active since evaluation onset. ITN- and household-level field sampling methods, as well as methods for withdrawing ITNs for laboratory analysis, followed those described elsewhere in the literature [24]. An additional file detailing the follow-up status of

households enrolled at baseline provides more comprehensive information (see Additional file 1).

Training and fieldwork procedures

Data collection was overseen by the NMCP and implemented by a local research agency, Nest Builders International (NBI). Prior to each survey round, a training of trainers and 4–5 day data collector training was held in Freetown. The final training day was a practical exercise held in communities near the training facility. Data collection was carried out by staff with knowledge of the local language, who had previous experience collecting survey data. Prior to commencing data collection, approval was sought from chieftom heads, and community members were enlisted to locate cohort households, when necessary. The training and fieldwork procedures employed in this evaluation were consistent with those outlined in the existing literature [10, 24].

Laboratory procedures

After each survey round, WHO cone bioassays were conducted by PMI VectorLink Sierra Leone to assess insecticidal effectiveness [26]. For both PermaNet® 3.0 and Olyset® Plus ITNs, bioassays used a pyrethroid-susceptible Kisumu strain of *Anopheles gambiae* sensu stricto (s.s.), maintained in the insectary and a wildtype pyrethroid-resistant *An. gambiae* sensu lato (s.l.), collected from Western Rural Area as larvae and reared to adults in the insectary. Both strains were characterized at 12-, 24-, and 36-months to confirm their status as sufficiently pyrethroid-susceptible or resistant.

Adult mosquitoes maintained on 10% sugar solution were aspirated and transferred to holding tubes 20 min prior to bioassay exposures. Each ITN was exposed to two sets of mosquitoes, susceptible and wild-caught resistant, aged 3–5 days old in groups of five per cone. For Olyset® Plus ITNs, four locations (standard positions 2, 3, 4, and roof) were tested on each ITN with two replicates per location for a total of eight cone tests per ITN. For PermaNet® 3.0 ITNs, six locations (standard position 2, 3, 4 and 3 roof locations) were tested on each ITN with two replicates per location for a total of 12 cone tests per ITN for each susceptible and wild-caught resistant strains [26]. Each set of bioassays on field sampled ITNs was accompanied by tests on netting from a positive control (samples from the sides and roof of new PermaNet® 3.0 and Olyset® Plus ITNs) and untreated netting as a negative control. Outcome measures were 60-min knock-down and 24-h mortality.

Chemical content testing was conducted by the Centers for Disease Control and Prevention (CDC) in Atlanta, Georgia (USA) using procedures described elsewhere in the literature [10]. Briefly, ITN swatches were taken

from areas adjacent to those cut for bioassays. AI were extracted using the Collaborative International Pesticide Analytical Council method 454/LN/M/3.2 [27]. Outcomes were pooled mean and median AI across ITN samples in g/kg, compared to manufacturer target dose.

Data management

Household- and ITN-level questionnaires were adapted from existing durability monitoring tools to the Sierra Leonean context and digitized using the Open Data Kit-based software, SurveyCTO (www.surveycto.com). Data was captured electronically and uploaded either daily, or when the data collection team had access to an internet source, which was typically within 24 h of data collection. Data was accessed via the server by PMI VectorLink research personnel for routine remote monitoring. When each round of data collection was complete, one household- and one ITN-level dataset were generated and exported into Stata v15.1 (Stata, Texas, USA) for preparation, cleaning, and analysis. Longitudinal household- and ITN-level datasets were created by combining data from each survey round to facilitate survival analyses.

Definition of outcomes and explanatory variables

Durability monitoring outcomes and explanatory variables are aligned and elaborated upon elsewhere in the literature [4, 8–10, 24, 28]. Physical ITN survival is the main outcome, defined as the proportion of cohort ITNs present and in serviceable condition each round. Physical ITN survival incorporates two measures, ITN attrition and ITN physical integrity. Cohort ITNs undergo attrition when their outcome is known, but they are no longer present in the evaluation household. ITN attrition due to wear and tear, sometimes termed as ‘discarded,’ refers to cohort ITNs that were thrown away, destroyed, or used for other purposes. The proportionate hole index (pHI), a WHO-recommended metric, measures mosquito net damage by analyzing the number and size of holes to classify ITNs as either “torn” or “serviceable,” thereby assessing their physical integrity and serviceability [24]. ITNs that are categorized as serviceable are further classified as “good” or “damaged.” Following WHO recommendations [24], the proportion of cohort ITNs surviving in serviceable condition was plotted against a set of hypothetical survival curves with defined median survival values, and the median survival was taken as the relative position of the data point on a horizontal line between the two adjacent median survival curves. After the final survey, median survival was calculated as the linear extrapolation of the survival values from the last two rounds to the $y = 50\%$ line, provided both points were below 85% (when the hypothetical survival curves are themselves approximately linear). Kaplan–Meier survival curves were

generated from longitudinal data to depict ITN failures (ITNs that are no longer physically serviceable or have failed due to wear and tear) and censoring.

Three groups of durability monitoring explanatory variables were collected at the household- and ITN-levels to measure risk factors to cohort ITN physical durability. These include ITN handling factors; ITN sleeping space environment factors; and factors related to exposure to ITN messages and related attitudes to ITN care and repair. Attitudes towards ITNs and, separately, ITN care and repair were measured using a set of Likert scores ranging from -2 to 2 [10, 24]. Data on basic household assets were recorded at baseline to calculate a wealth index, which was divided into tertiles for analysis. Based on the high correlation between exposure to social behavioural change (SBC) messages, attitudes toward ITNs and attitudes towards ITN care and repair, a composite variable was created and used during multivariate analysis that combined the exposure to SBC messages and positive ITN attitude. The variable was categorized as (i) having a positive ITN attitude and/or exposure to SBC messages never (implying a negative ITN attitude or no SBC exposure) or once (ii) having any combination of positive ITN attitude and/or exposure to SBC messages two or three times and (iii) Always having positive ITN attitudes and exposure to SBC messages.

Statistical analyses

Univariate and bivariate analyses were conducted using methods appropriate to the measurement type (proportions or continuous variables) with significance testing for differences between groups. Analysis accounted for the clustered survey design when calculating standard errors and 95% confidence intervals (CI).

An ITN was considered a failure if it was classified as either “torn” or missing due to attrition (discarded from the household because of wear and tear). Failure time for attrition was directly calculated based on respondent recall of the length of time an ITN was in the household’s possession. When no valid recall was known, and for ITNs failing due to physical integrity, the failure time was taken as the mid-point between the last two survey rounds. Determinants of survival were explored using Cox proportional hazard models with standard errors to account for clustering of ITNs within households. Two Cox proportional hazard models were fitted following the two survival analysis approaches. The first was a household-level model that fit failure with risk starting at the distribution date, which considered household-level determinants that were invariant for ITNs within a given household (e.g., evaluation district, household size, household head characteristics, household wealth tertile). The second was an

ITN-level model that fit ITN failure with risk starting at the date of the first observation that an ITN was hanging and examined both the household-level determinants mentioned above as well as ITN-level determinants such as user type (e.g., adults, children or both), food storage practices, ITN folding, washing, and drying. Bivariate analysis identified factors significantly associated with survival and all variables with p -values below 0.3 were included in a first multivariate model. Models were then refined stepwise by dropping variables exceeding the $p = 0.1$ level, comparing model specifications using the likelihood-ratio test. The choice of $p = 0.1$ for stepwise selection was conservative relative to automated approaches and all alphas reported in the paper are significant at the typical 5% significance level. Schoenfeld residual plots and analysis of time-varying covariates were used to check the proportionate hazard assumption.

Results

Household and cohort ITN sample description

A total of 370 households were enrolled at baseline, with 652 campaign ITNs designated for follow-up. The follow-up status is summarized in Table 1, and round-specific details are provided in supplementary materials (see Additional Files: A and B). After 3 years, 69% of households in Bo and 71% in Moyamba still possessed one or more cohort ITNs. The most common reason for households leaving the evaluation and being lost-to-follow-up was relocation (Bo: 18%; Moyamba: 15%). A known outcome was determined for 58% of cohort ITNs in Bo and 51% in Moyamba. In both sites, unknown outcomes were most frequent due to ITNs

being given away to others or taken to be used elsewhere (Bo: 21%; Moyamba: 30%).

Household characteristics

Demographic characteristics and household assets for all enrolled households at baseline were examined (Table 2). Key demographic and household characteristics and assets variables were similar between sites. However, Moyamba had a higher proportion of female-headed households (36% vs. 19% in Bo, $p < 0.001$). The educational profile of heads of households did not differ significantly between the two sites for both male and female heads. Though not statistically significant, households in Bo had trend of better access to water and basic hygiene than those in Moyamba (Bo: 39%; Moyamba: 18%, $p = 0.152$). Other household characteristics and assets showed no significant differences between the two sites, except for ownership of radios, which was more common in Bo than in Moyamba (Bo: 49%; Moyamba: 33%, $p = 0.039$).

Risk factors for durability (household environment and ITNs environment)

Household-level ITN durability risk factors differed between evaluation districts (Table 3). Rodents serve as an ITN durability risk factor because they can damage nets and particularly if nets are also in locations where food is cooked, eaten, and/or stored [5]. While respondents in Bo reported always seeing rodents around the house in the last 6 months significantly more than respondents in Moyamba (89% vs. 61%, $p < 0.001$), the practice of always storing food in sleeping quarters was significantly lower in Bo than in Moyamba (2%; vs. 48%, $p < 0.001$).

Table 1 Follow-up status of households and cohort ITNs at 36-months

Variable	Bo (PermaNet® 3.0) % (95% CI)		Moyamba (Olyset® Plus) % (95% CI)	
Households	N = 185		N = 185	
Still has any cohort ITN	69.3	(60.0–77.3)	71.1	(65.0–76.5)
Lost all their cohort ITNs	5.5	(2.7–11.3)	11.1	(7.4–16.4)
Moved away	17.8	(11.3–26.8)	15.1	(10.3–21.6)
Refused	1.6	(0.5–4.7)	0.0	(–)
Nobody home at survey or not reached	5.8	(3.2–10.2)	2.7	(1.0–6.7)
Labelled cohort ITNs	N = 358		N = 294	
Known outcome	57.9	(50.3–65.1)	51.0	(44.6–57.3)
Unknown outcome	42.1	(34.9–49.7)	49.0	(42.7–55.4)
Household moved away or refused	16.0	(9.8–25.1)	12.1	(7.2–19.7)
Net given away or used elsewhere	20.8	(17.6–24.5)	30.3	(25.5–35.5)
Fate of net unknown	5.3	(3.0–9.1)	6.3	(3.3–11.7)

In general, net care attitudes and practices were better in Bo compared to Moyamba. In Bo, a significantly higher proportion (82%) (Table 4) of cohort ITNs were always tied or folded when hanging, whereas in Moyamba, this practice was observed in 45% of cases ($p < 0.001$). Recall of ITN use or care messages in the 6 months preceding each survey was significantly higher in Bo, where 63% of households recalled messages at two or more rounds, compared to 5% in Moyamba ($p < 0.001$). Respondents in Bo exhibited significantly more positive attitudes toward ITN use (86% vs. 35%, $p < 0.001$) and ITN care (56% vs. 36%, $p < 0.001$) compared to their Moyamba counterparts. Cohort net use varied significantly across categories between Bo and Moyamba, with greater net use by children overall in Bo compared to Moyamba (children only 5% vs. 1%, children with adults 64% vs. 58%, and adults only 31% vs. 40%; $p = 0.015$ across categories).

Attrition

At evaluation endline, total campaign ITN attrition was significantly higher in Moyamba district than in Bo (Bo 53% vs Moyamba 60%, $p = 0.001$) (Fig. 2) (see Additional File C). The most common reason for attrition was ITNs being given away to others (Bo 31%; Moyamba 43%, $p = 0.05$). Though not statistically significant, attrition due to wear and tear was higher in Bo (21%) compared to Moyamba (13%) district, $p = 0.066$. A notable observation is that, at the evaluation endline, a lower proportion of cohort nets were reported stolen in Bo compared to Moyamba (4% versus 12%, $p = 0.01$) (see Additional File C).

Physical integrity

At evaluation endline, Bo had a higher proportion of serviceable ITNs than Moyamba (86% vs 40%; $p < 0.001$). ITNs in Bo were more commonly categorized to be in “good” physical condition compared to Moyamba (68% vs 19%; $p < 0.001$) (Table 2). A lower proportion of ITNs had any holes in Bo than Moyamba (66% vs. 93%; $p < 0.001$) and median pHI was lower in Bo than Moyamba (63 and 1,540, respectively). The repair rates for ITNs with any hole were consistently lower in Bo across all survey rounds and significantly lower at endline (Bo: 14% vs Moyamba: 24%; $p = 0.008$).

Survival

Cohort ITN survival was significantly higher in Bo than Moyamba at evaluation endline (56% vs. 28%, respectively; $p < 0.001$) (Table 3). Olyset® Plus ITNs from Moyamba consistently exhibited significantly lower survival rates across all survey rounds. Extrapolating from the physical survival data in Fig. 3, along with non-overlapping CIs, the estimated median lifespan of PermaNet® 3.0 was higher in Bo at 3.0 years (95% CI 2.7–3.5) compared to 2.2 years (95% CI 2.0–2.4) for Olyset® Plus ITNs in Moyamba.

PermaNet® 3.0 ITNs in Bo exhibited higher ITN survival than Olyset® Plus ITNs in Moyamba, whether considering time since distribution or time since first hanging (Fig. 4).

Determinants of survival

Household- and ITN-level Cox proportional hazard models were constructed to identify determinants of

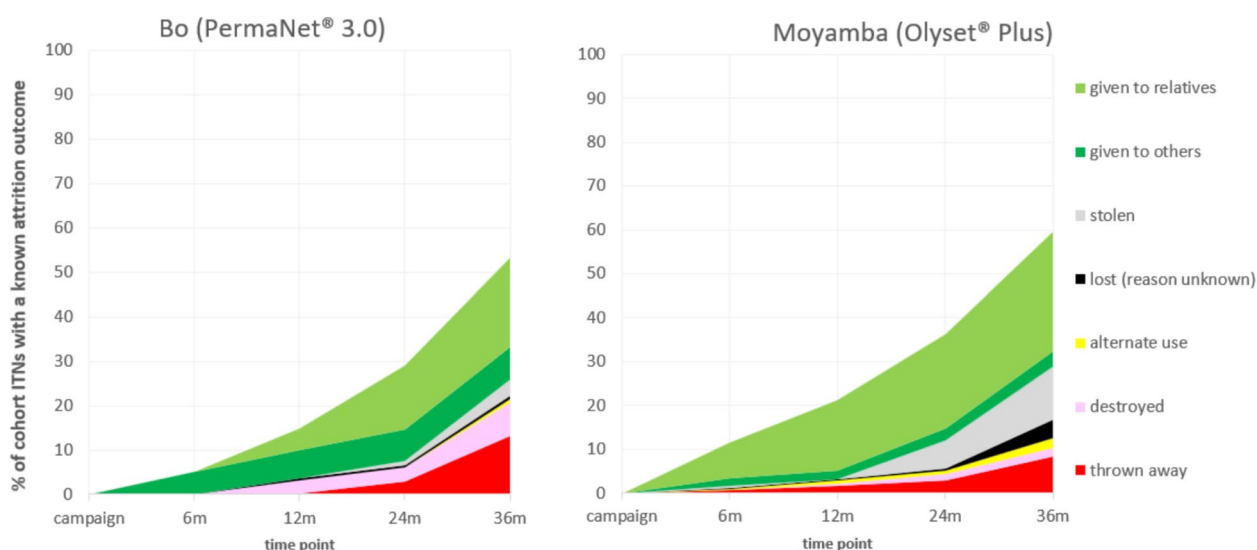


Fig. 2 Reported causes of ITN attrition

Table 2 Physical integrity of observed cohort ITNs

	First round 6 months % (95% CI)		Second round 12 months % (95% CI)		Third round 24 months % (95% CI)		Fourth round 36 months % (95% CI)	
Bo (PermaNet® 3.0)	N = 276		N = 244		N = 190		N = 131	
Mean months since campaign	6.3		11.9		23		34.1	
Net has any hole (%)	11	(6.4–18.8)	17	(9.9–26.8)	44	(35.4–52.9)	66	(58.6–73.0)
Physical condition (pHI)								
Good (0–64)	96	(93.4–97.1)	93	(88.7–96.2)	77	(69.1–83.2)	68.0	(58.8–76.0)
Damaged (65–642)	4	(2.1–6.1)	5	(2.7–9.6)	16	(10.7–23.1)	18	(11.4–26.5)
Torn (643 +)	1	(0.2–3.5)	2	(0.6–3.6)	7	(4.0–12.3)	14	(9.3–21.3)
Serviceable (0–642)	99	(96.5–99.8)	99	(96.4–99.4)	93	(87.7–96.0)	86	(78.7–90.7)
Median pHI if any hole [IQR]	49	[3–169]	48	[23.5–76]	69	[24–422]	63	[7–613]
Has any repairs if any hole (%)	13	(4.7–32.0)	12	(4.7–28.4)	12	(5.1–24.8)	14	(6.9–26.0)
Moyamba (Olyset® Plus)	N = 276		N = 214		N = 147		N = 107	
Mean months since campaign	6.3		11.9		22.9		34.1	
Net has any hole (%)	40	(36.4–43.6)	54	(46.5–61.1)	79	(73.6–83.7)	93	(85.7–96.4)
Physical condition (pHI)								
Good (0–64)	78	(72.9–83.1)	71	(64.9–76.9)	41	(35.4–47.7)	19	(13.6–25.7)
Damaged (65–642)	13	(8.9–18.3)	16	(10.5–22.5)	26	(20.3–32.6)	21	(14.5–29.0)
Torn (643 +)	9	(5.9–12.7)	13	(9.3–18.2)	33	(26.3–39.5)	60	(51.7–68.1)
Serviceable (0–642)	91	(87.3–94.1)	87	(81.8–90.7)	67	(60.5–73.7)	40	(31.9–48.3)
Median pHI if any hole [IQR]	72	[4–578]	75	[25–615]	324	[53.5–1753.5]	1539.5	[227–5780]
Has any repairs if any hole (%)	6	(2.1–14.1)	5	(1.9–14.3)	10	(5.7–17.4)	33	(27.4–39.0)

IQR Interquartile Range

Table 3 Cohort ITNs surviving in serviceable condition and estimated median survival in years

	Second round 12 months % (95% CI) P-value	Third round 24 months % (95% CI) P-value	Fourth round 36 months % (95% CI) P-value
Percentage surviving in serviceable condition			
Bo (PermaNet® 3.0)	94.3 (91.2–96.3)	83.9 (75.0–90.0)	55.6 (44.0–66.6)
Moyamba (Olyset® Plus)	81.6 (77.5–85.1)	60.9 (53.8–67.7)	28.2 (21.3–36.4)
	< 0.001***	< 0.001***	< 0.001***
Median survival in years			
Bo (PermaNet® 3.0)			
Graphical interpretation from Fig. 3	N/A	3.9	3.0
Calculated from last two data points	N/A	N/A	3.1 (2.7–3.5)
Moyamba (Olyset® Plus)			
Graphical interpretation from Fig. 3	N/A	2.2	2.2
Calculated from last two data points	N/A	N/A	2.2 (2.0–2.4)

physical ITN durability (Table 7). Variables included in the final household-level regression model were study site, presence of CU5 in the household, socio-economic status tertiles (based on household wealth index), observation of rodents, the combination of positive net attitudes and exposure to SBC messages.

PermaNet® 3.0 ITNs in Bo households had a significantly lower failure risk, about two-thirds the risk of Olyset® Plus ITNs in Moyamba households (adjusted hazard ratio [aHR] = 0.33, 95% CI 0.23–0.48, $p < 0.001$). Nets in households with no CU5 had a 36% lower risk of failure than nets in households with at least one CU5 (aHR = 0.64, 95% CI 0.47–0.86, $p = 0.003$). Nets in

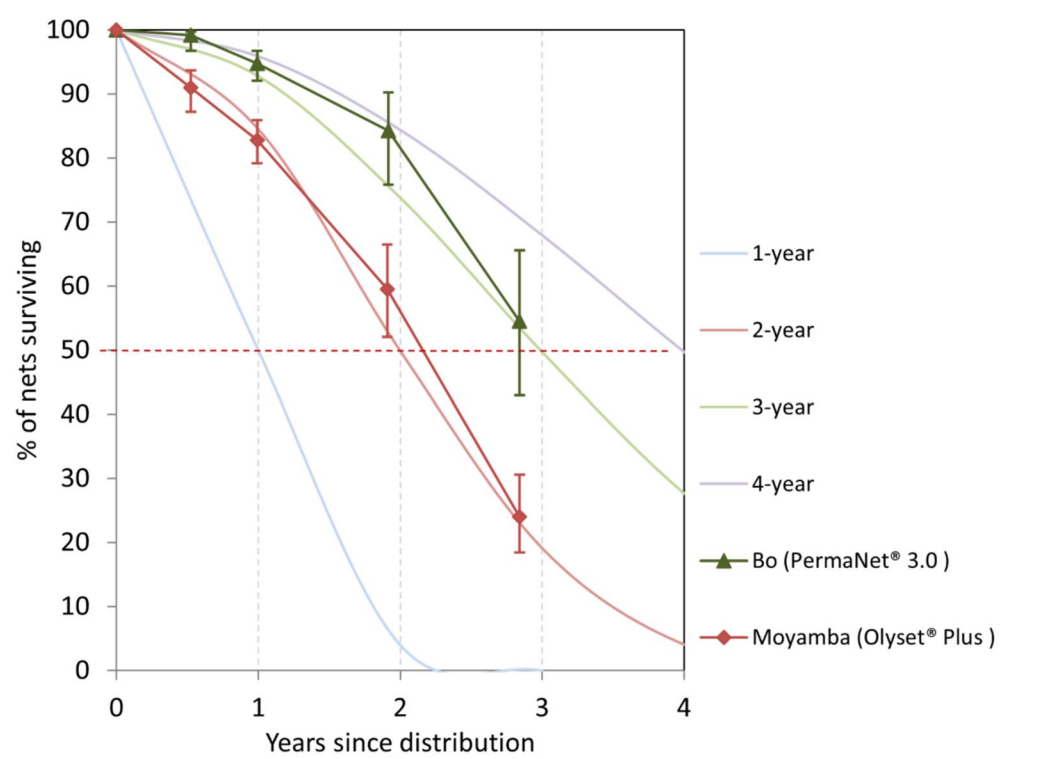


Fig. 3 Physical survival

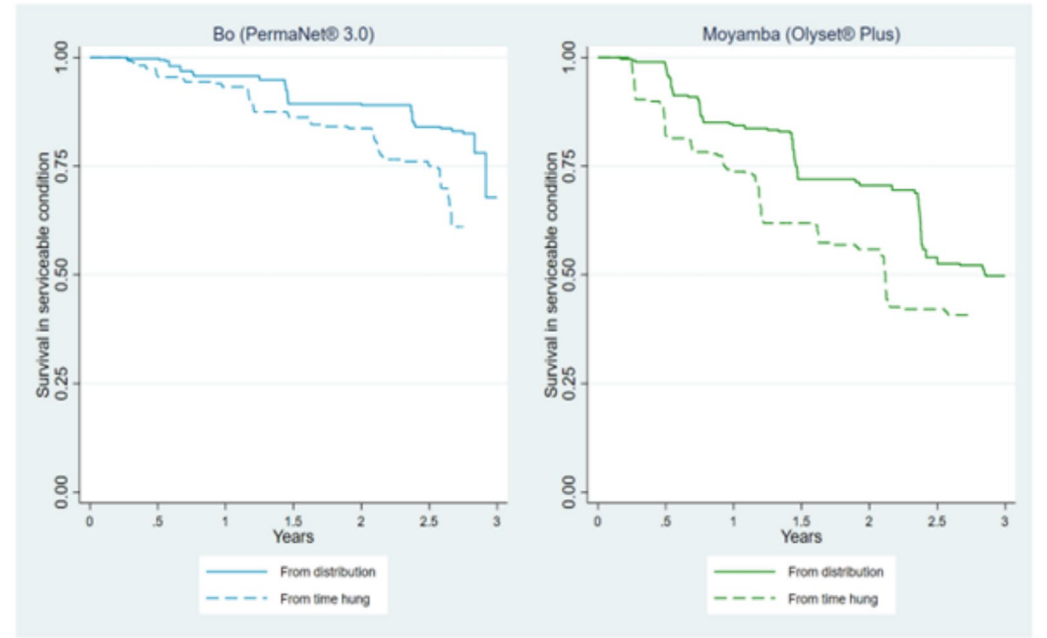


Fig. 4 Kaplan–Meier curves for ITNs surviving in serviceable condition

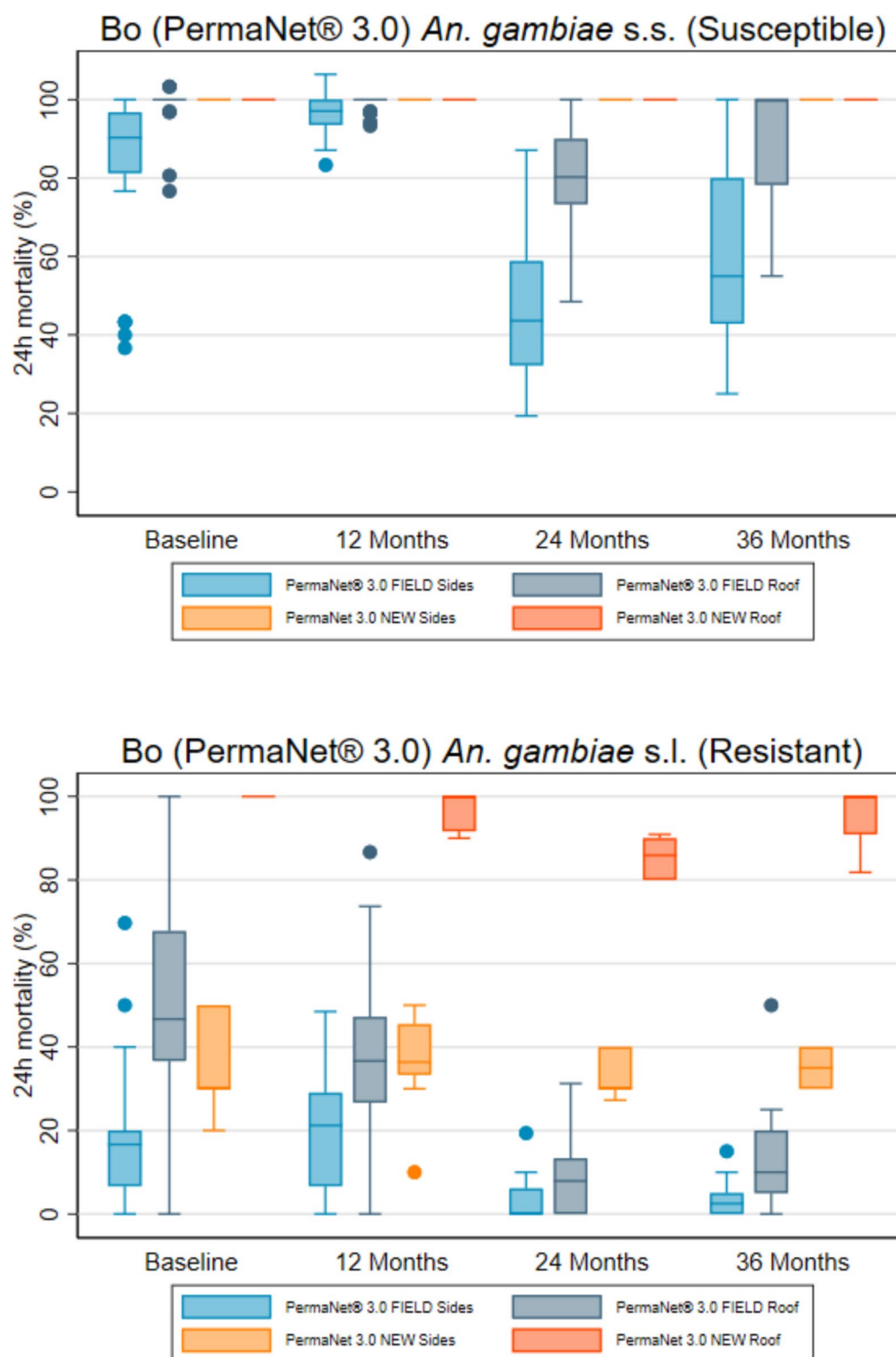


Fig. 5 Box plot of PermaNet® 3.0 cone bioassay results for residual efficacy of Pyrethroid

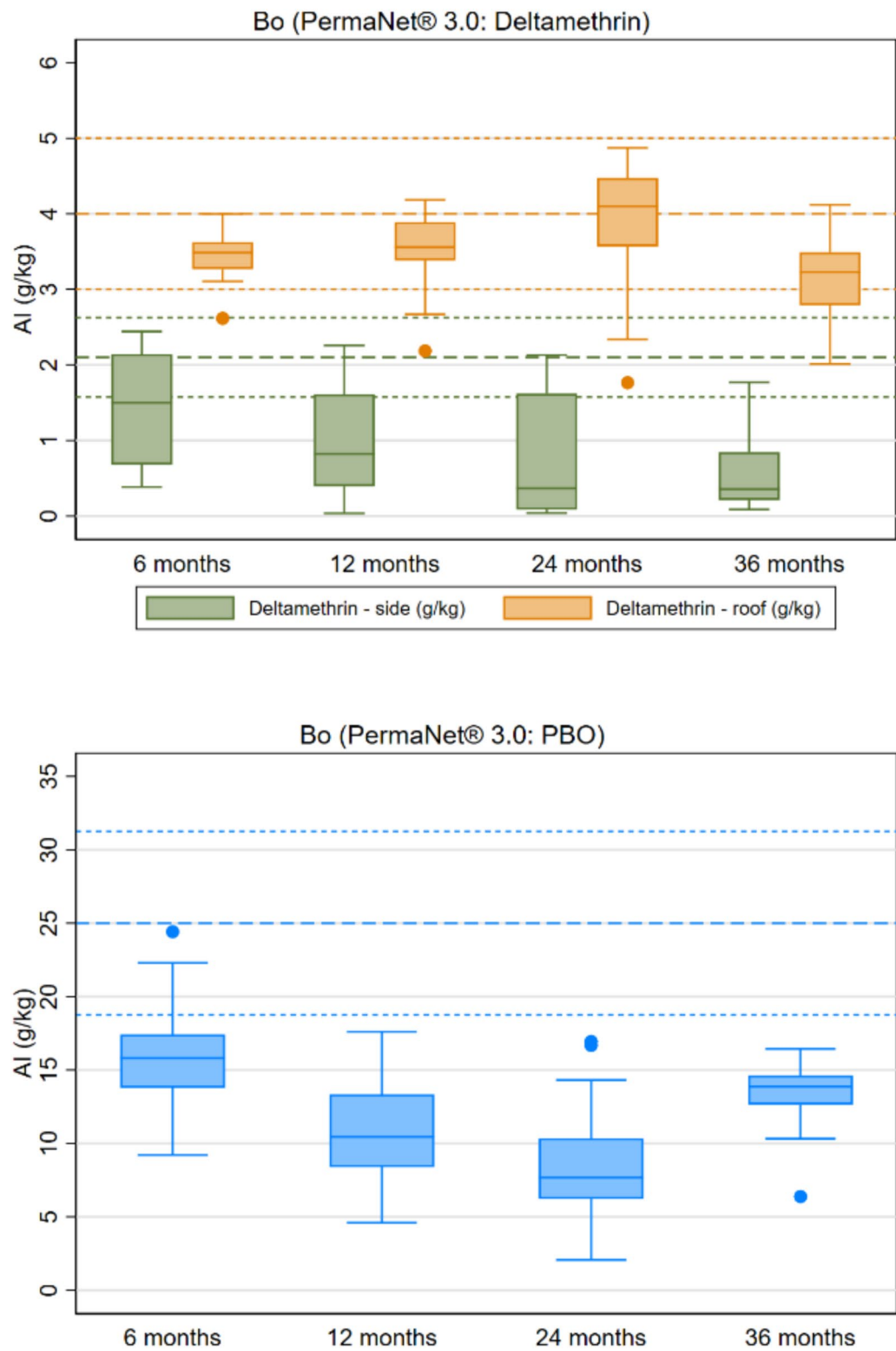


Fig. 6 Box plot of PermaNet® 3.0 chemical content results of Pyrethroid and PBO

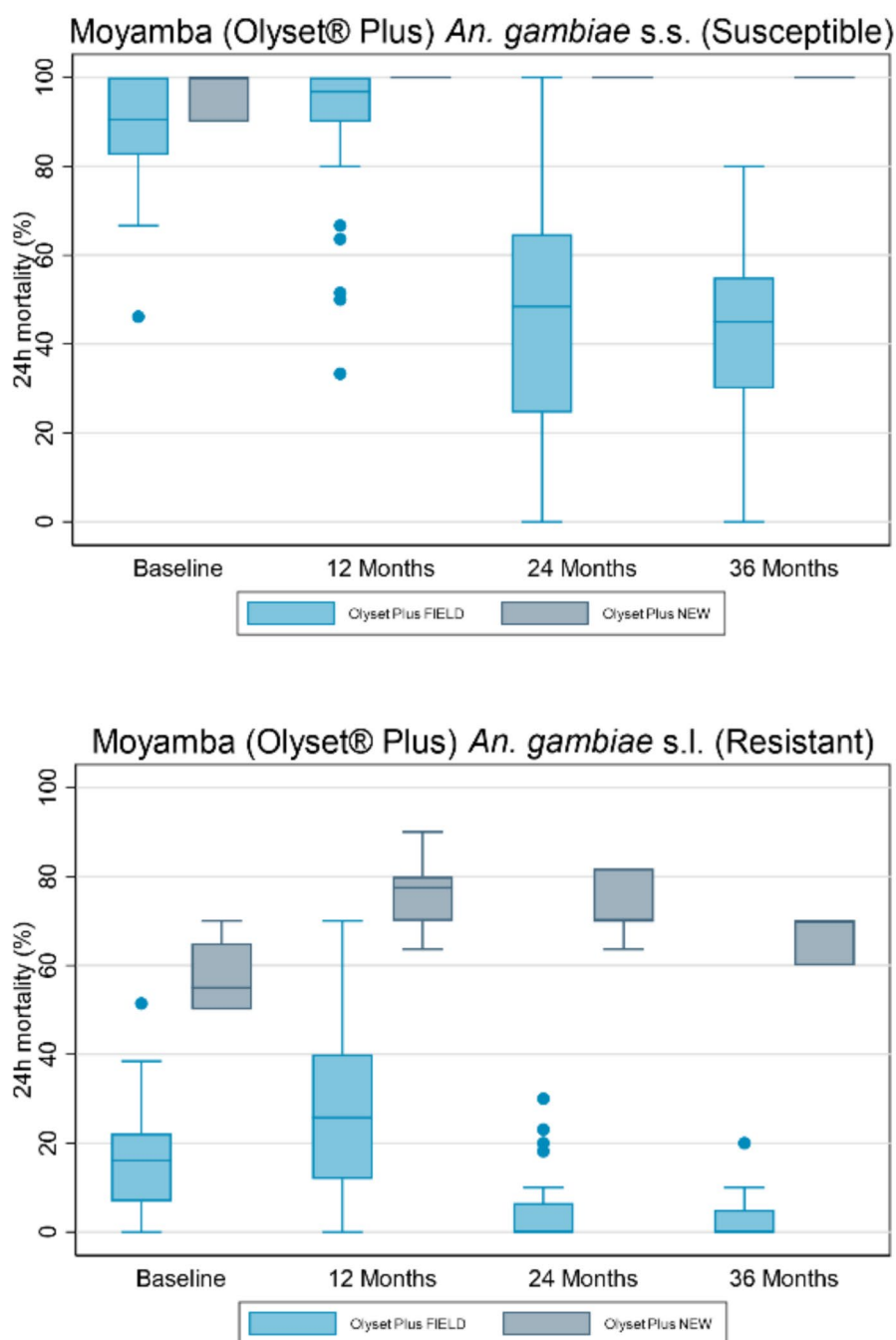


Fig. 7 Box plot of Olyset® Plus cone bioassay results for residual efficacy of Pyrethroid

households from the highest socio-economic status tertile had a 37% lower risk of failure than those in households in the lowest tertile (aHR = 0.63, 95% CI 0.44–0.92, $p = 0.016$). Exposure to SBC combined with positive net attitudes was protective. Those households having any combination of positive net attitude and exposure to SBC

messages two or three times (aHR = 0.63 95% CI 0.45–0.89, $p = 0.008$) or always (across all rounds) (aHR = 0.56 95% CI 0.33–0.94, $p = 0.028$) had a 37% and 44% lower risk of failure, respectively, compared to households that had positive net attitudes that were never exposed to SBC or were exposed once.

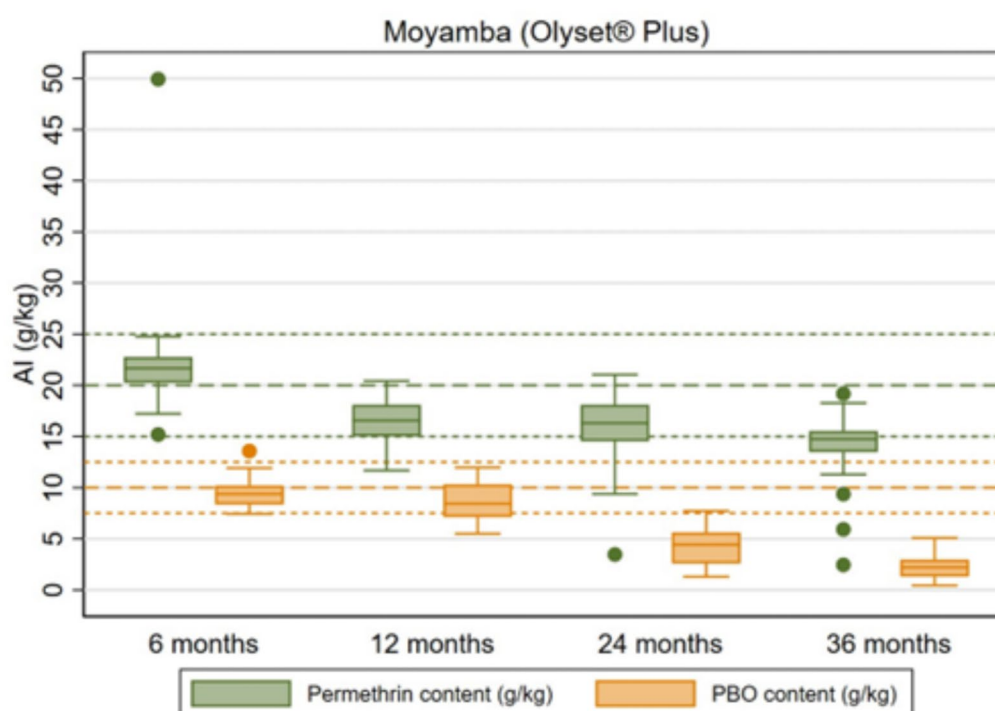


Fig. 8 Box plot of Olyset® Plus chemical content results of Pyrethroid and PBO. Results from chemical content testing: the box plot shows the median (horizontal line), IQR (box), adjacent values (whiskers) and outliers (circles). Long dashed lines represent the manufacturers target dose and short dashed lines represent the $\pm 25\%$ dose range, with colours corresponding to the chemicals in the legend

At the net-level, variables included in the final model were socio-economic status tertiles, presence of CU5 in the household, observations of rodents, head of household's history of attending school, the combination of positive net attitudes and exposure to SBC messages, food storage in a sleeping area, net user (children only, adult only, or both children and adults), folding of nets while not in use and ITN drying practices after washing.

As with the household-level model, at the net-level, having any combination of positive net attitude and exposure to SBC messages two or three times ($aHR = 0.59$ 95% CI 0.41–0.86, $p = 0.006$) or always ($aHR = 0.47$ 95% CI 0.29–0.76, $p = 0.002$) was protective compared to no or one exposure. Nets in households that reported never or only storing food in a room used for sleeping once had a 44% lower risk of failure than nets in households that always stored food in sleeping rooms ($aHR = 0.56$, 95% CI 0.37–0.85, $p = 0.006$). Nets that were slept under exclusively by adults had a 28% lower risk of failure than nets used exclusively by children or by both children and adults ($aHR = 0.72$, 95% CI 0.52–1.0 $p = 0.048$). Nets that were always folded when not in use had a 33% lower risk of failure than nets that were never folded or folded only once when not in use ($aHR = 0.67$ 95% CI 0.49–0.92, $p = 0.015$). Nets always dried outside after washing had a 56% lower risk of failure than nets that were never dried

outside after washing ($aHR = 0.44$ 95% CI 0.24–0.80, $p = 0.008$).

Insecticidal efficacy

In Bo, 24-h mortality for PermaNet® 3.0 field side samples containing pyrethroid-only declined from 84% at baseline (95% CI 74.5–92.5) to 59% at 36 months (95% CI 53.0–64.4) against susceptible mosquitoes (Table 8). Field roof samples incorporating PBO maintained consistently high 24-h mortality rates, ranging from 99% at baseline (95% CI 96.6–100.6) to 89% at endline (95% CI 83.2–94.7). Against resistant mosquitoes, 24-h mortality of field side samples decreased from 17% at baseline (95% CI 11.7–23.2) to 3% at 36 months, while the 24-h mortality of PermaNet® 3.0 roof samples decreased from 48% at baseline (95% CI 37.8–58.5) to 13% at endline. Positive control results from tests on roof samples were consistently high in each round at 100% against susceptible mosquitoes and ranging from 86 to 100% against resistant mosquitoes. Negative control results were < 10% for tests with both mosquito species at all time points. Mean deltamethrin concentration in side panels decreased from 1.5 g/kg (95% CI 1.2–1.8) at baseline to 0.6 g/kg (95% CI 0.4–0.8) at 36 months. Mean deltamethrin content in roof panels remained relatively stable, ranging from 3.5 g/kg (95% CI 3.3–3.6) at baseline to 3.2 g/kg

(95% CI 3.0–3.4) at 36 months. Mean roof PBO content decreased from 15.9 g/kg (95% CI 14.6–17.2) at baseline to 13.4 g/kg (95% CI 12.5–14.3) at 36 months.

The rate of 24-h mortality for Moyamba Olyset® Plus field samples against pyrethroid-susceptible (*An. gambiae* Kisumu) mosquitoes decreased from 89% at baseline (95% CI 86.3–92.5) to 41% at 36 months (95% CI 35.7–46.8) (Table 9). Against pyrethroid-resistant (*An. gambiae* s.l.) mosquitoes, 24-h mortality for Olyset® Plus field samples decreased from 16% at baseline (95% CI 12.2–19.6) to 3% at 36 months (95% CI 1.8–4.1). Positive control results were consistently high in each round, exceeding 97% against susceptible mosquitoes and ranging from 58 to 76% against resistant mosquitoes. Negative control results were <5% for tests with both mosquito species at all time points. Mean permethrin content decreased from 22.3 g/kg (95% CI 20.3–24.4) at baseline to 14.1 g/kg (95% CI 12.9–15.3) at 36 months. Mean PBO concentration declined from 9.5 g/kg (95% CI 8.8–10.1) at baseline to 2.3 g/kg (95% CI 1.8–2.7) at end-line (Figs. 5, 6, 7, 8).

Discussion

This evaluation investigated the field performance of two PBO-synergist ITN brands, PermaNet® 3.0 ITNs in Bo district and Olyset® Plus ITNs in Moyamba district, for 3 years after Sierra Leone's national mass ITN distribution campaign in 2020. Specific attention was applied to ITN physical durability, including risk factors affecting durability, as well as insecticidal efficacy.

ITN physical durability

Three years post-distribution, PermaNet® 3.0 ITNs in Bo exhibited a significantly higher survival rate (57%) than Olyset® Plus ITNs in Moyamba (30%, $p < 0.001$), corresponding to a significantly longer estimated median lifespan of 3.0 years (95% CI 2.7–3.5), compared with 2.2 years (95% CI 2.0–2.4) in the two districts, respectively. Estimated median survival of PermaNet® 3.0 ITNs in Bo was similar to the 3.2-year median survival estimate recorded in a PMI-supported durability monitoring evaluation in Orodara district, Burkina Faso [29], but lower than the 4.0-year median survival estimate for PermaNet 3.0 ITNs in Kikukiro district, Rwanda [30].

The household-level proportional hazards model showed that higher socio-economic status, education level, and absence of a CU5 in the household were all associated with decreased ITN failure risk. These factors were found to interact significantly within the net-level model, implying a combined effect on ITN survival. Findings align with previous research, where higher socio-economic status and increased education were identified

as protective factors contributing to better net survival rates [4, 7], underscoring the importance of addressing socio-economic disparities to combat malaria.

Although it was found that attrition due to wear and tear was not significantly different between the two evaluation districts, significantly more of remaining ITNs in Bo were in serviceable physical condition than in Moyamba. Moreover, Bo had a significantly lower proportion of ITNs with any holes and a substantially lower median PHI. Findings on physical integrity and attrition due to wear and tear collectively contribute to the higher survival rate and estimated median useful life of ITNs in Bo. These results were supported by the household level Cox regression model, where ITNs from Bo showed a significantly lower risk of failure (approximately two-thirds that of Moyamba).

Generally, the two districts were similar for key socio-demographic indicators, household characteristics (including household assets), as well as a set of environmental and climatic factors. Similarly, data from the 2021 MIS showed comparable levels of population access to ITNs (56.7% in Bo vs. 59.3% in Moyamba), population use of ITNs in the previous night (87.9% in Bo vs. 86.4% in Moyamba) and ITN use:access ratio (1.55 in Bo vs. 1.46 in Moyamba) [31].

As done in other durability monitoring studies [7, 28], exposure to SBC messaging and positive attitudes were combined due to their interaction as individual covariates during multivariate analysis. The combination of positive attitudes and exposure to SBC messaging had a significant protective effect on ITN survival, with evidence of a dose–response relationship between those exposed to SBC having positive attitudes and ITN survival, findings that are consistent with existing literature [4, 7, 8, 24]. This finding also underscores the effectiveness of targeted messaging campaigns in bolstering ITN longevity and the importance of SBC interventions in malaria control efforts. Notably, recall of ITN use or care messages was significantly higher in Bo than Moyamba, potentially explaining some of the differences seen in net survival between the two districts. While both districts received similar SBC support, District Health Management Team (DHMT) staff in Bo proactively monitored community members routinely to ensure care of ITNs. This proactive approach should be expanded during future SBC efforts.

Neither rodent sightings nor frequent food storage in sleeping rooms were significant determinants of ITN survival at the household level. However, frequent food storage in sleeping rooms emerged as a significant determinant of ITN survival in the ITN-level model. Rodents were more frequently observed around households in Bo, however households in Moyamba exhibited a higher inclination to store food in sleeping quarters than in Bo.

Although rodents are known contributors to net damage, owing to their attraction to food stored near nets [3, 5], and food storage practices were found to be significant predictors of net survival in bivariate analysis, the multivariate analysis suggests that the habitual storage of food in sleeping areas and not necessarily the visual sighting of rodents emerged as significant determinants of net survival when controlling for other factors.

Consistent net tying or folding practices significantly influenced net durability and survival in bivariate analysis. Net folding was also significant in the ITN-level model. Existing literature reinforces that these practices are crucial determinants associated with a reduced risk of net failure [4, 7, 24]. In Bo, a significantly higher proportion (82%) of ITNs were consistently tied or folded when hanging than in Moyamba, where this practice was observed in only 45% of ITNs ($p < 0.001$), suggesting that adoption of consistent net tying or folding practices may be contributing to extended ITN survival in Bo.

ITN insecticidal effectiveness

Insecticidal efficacy and chemical residue analysis findings provide crucial insights into multi-year field performance of Olyset® Plus and PermaNet® 3.0 ITNs. For both ITN brands, reductions in bioefficacy over the evaluation period were driven primarily by decreases in mean PBO content. However, no consistent correlation was found between declines in bioefficacy and PBO content across brands.

In Moyamba, a decline in bioefficacy of Olyset® Plus ITNs was observed against both pyrethroid-susceptible and resistant mosquito strains, where 24-h mortality decreased from 89 to 41% and from 16 to 3%, respectively. These declines were driven by a 77% reduction in mean PBO content compared to the manufacturer's target dose. Mean permethrin content decreased by 30% (just outside of the manufacturer's $\pm 25\%$ acceptability threshold).

In Bo, there was a decline in 24-h mortality against resistant mosquitoes on side panels (from 17% at baseline to 3% at endline) and roof panels (from 48% at baseline to 13% at endline). Superior mortality in pyrethroid plus PBO panels compared to pyrethroid-only panels throughout the evaluation suggests that the PBO restored some protection against pyrethroid-resistant mosquitoes, despite mean PBO content declining by 46% compared to the manufacturer target dose by evaluation endline. This further supports the WHO recommendations emphasizing the prioritization of PBO ITNs over pyrethroid-only ITNs in areas with pyrethroid-resistant mosquitoes [32].

At evaluation endline mean PermaNet® 3.0 deltamethrin content on side panels reduced by 71% compared to the manufacturer target dose corresponding to a substantial decline in 24-h mortality against the resistant

strain. Notable reductions in mean side panel deltamethrin content and corresponding low resistant strain mortality in PermaNet® 3.0 ITNs has been recorded via the PMI VectorLink-supported durability monitoring evaluation in Orodara district, Burkina Faso (72% deltamethrin reduction, with an 11% 24-h mortality against the resistant strain by endline) [24]. In Kicukiro district, Rwanda a PMI VectorLink durability monitoring evaluation showed that deltamethrin reduced by 81% compared to the manufacturer's target dose. However, mortality against the resistant strain was not measured [30].

Limitations

In adherence to COVID-19 prevention measures, data collectors avoided entering homes, and instead, relied solely on respondents' recollection of ITN handling practices. This adaptation may have introduced recall bias. The Hawthorne effect may have been introduced, as interventions from data collectors could have influenced the behaviour of those living in households under evaluation, although there is no reason to expect any differential effect between the two districts.

Location has been noted to be a stronger determinant of ITN durability than brand [33]. ITN brands were distributed by the NMCP to different districts. The evaluation could therefore not be designed to examine two net brands in a single district, which potentially introduced confounding due to inter-district variability. To minimize potential disparities resulting from epidemiological and climatic factors, clusters were randomly selected from a restricted study frame comprising clusters situated along the border between Bo and Moyamba districts.

As in other durability monitoring studies, ITNs selected for analysis, except at the endline, were from neighboring, not cohort, households. This sampling methodology may introduce uncertainty about their usage duration, potentially affecting insecticidal efficacy results.

Due to a shortage of nets during the distribution campaign, fewer cohort ITNs were enrolled than expected. The sample was boosted during the 12-month survey round, and an additional 41 ITNs were added that had not been enumerated at baseline. To ensure that this did not introduce bias, a sensitivity analysis of estimated ITN survival and campaign cohort ITN attrition for the original only, and boosted samples was conducted. Estimated ITN survival differed by just one-tenth of a percent between samples, while campaign cohort attrition differed by just one percent.

Conclusion

Results from this evaluation contribute to the growing body of literature on field performance of PBO-synergist ITNs over 3 years of use. Significant variation was

noted in the physical durability and insecticidal efficacy of PermaNet® 3.0 ITNs in Bo district and Olyset® Plus ITNs in Moyamba district, Sierra Leone. The PermaNet® 3.0 ITNs in Bo demonstrated higher survival rates, prolonged median lifespan, and better physical integrity compared to the Olyset® Plus ITNs in Moyamba.

This evaluation demonstrated that PermaNet® 3.0 ITNs in Bo survived longer than their 3-year survival expectation, while Olyset® Plus ITNs in Moyamba did not. Stakeholders should consider DM survival estimates when quantifying ITN needs. Despite covering only two districts, this evaluation generated empirical survival estimates which surpassed those derived from stock and flow model estimates of less than 2 years used to inform procurement decisions. Across evaluation rounds, reductions in bioefficacy against resistant mosquitoes were driven by decreases in mean PBO content. However, both ITN brands, particularly PermaNet® 3.0, provided at least some protection against pyrethroid-resistant mosquitoes. These findings underscore WHO recommendations related to the use of PBO-synergist ITNs in areas with confirmed pyrethroid resistance. However, the low estimated median survival and bioefficacy results for Olyset® Plus ITNs in Moyamba should be considered by ITN stakeholders in Sierra Leone. Additional data from varied evaluation sites is necessary to identify trends in physical and chemical performance trends.

Key determinants of ITN longevity were identified, which include district, lack of CU5 present in a household, higher socioeconomic status, positive net attitudes combined with exposure to SBC messaging related to ITNs, education of the household head, net user, net folding practices and net drying outside. These findings highlight the importance of considering local contexts and the need for tailored interventions and SBC messages to ensure sustained effectiveness.

Abbreviations

aHR	Adjusted hazard ratio
AI	Active ingredient
An	<i>Anopheles</i>
CDC	Centers for Disease Control and Prevention
CI	Confidence interval
CU5	Children under five
IQR	Interquartile range
ITN	Insecticide-treated net
NBI	Nest Builders International
NMP	National Malaria Programme
NMCP	National Malaria Control Programme
PBO	Piperonyl butoxide
pHI	Proportionate hole index
PMI	President's Malaria Initiative
PSI	Population Services International
SBC	Social and behaviour change
USAID	United States Agency for International Development
WHO	World Health Organization

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12936-025-05421-7>.

Supplementary material 1.

Author contributions

Design of study and tools: SP, YY, SS, EA, DS, RL, JC, RJ, SS; implementation and supervision: RS, SP, FY, SS, EA, KO, LI, CY, PN, DS, RL, JC, RJ, TH, SS, KE; bio-assay: RS, SP, EA, IS, KO, LI, YY, DS, RL, TH, KE PVSLG; analysis of data for publication: SP; interpretation: RS, SP, KE; manuscript: all. All authors read and approved the final manuscript. This paper is dedicated to the memory of our dear colleague and friend, NMCP Director Dr. Samuel Juana Smith, who passed away unexpectedly while this evaluation was in progress. His contributions to fighting malaria in Sierra Leone, and thus to the successful implementation of the work contained herein, were immeasurable. We would also like to acknowledge the PMI VectorLink Sierra Leone Group for their invaluable support in conducting the bioassay lab work for this study. Special thanks to the following individuals from the Group: Conteh Samuel, Jalloh Alpha, Kamara Abdulai, Kamara Sulaiman, Khanu Chernor, Lamin Franklin, Lolleh Umaru, Nicol Regina, Samura Fasineh, Rosetta Kpange.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The evaluation, initiated in 2020, was a collaborative effort between researchers from Population Services International (PSI), PMI, NBI, and the Sierra Leone NMCP. Ethical approval was secured from the Sierra Leone Ethics and Scientific Review Committee (Version 2020), subsequently renewed for subsequent rounds. Additionally, clearance was obtained from the Research Ethics Board of PSI, Washington, DC, USA. Prior to each evaluation round, all participants gave informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

¹PMI VectorLink Project, Population Services International, Nairobi, Kenya. ²PMI VectorLink Project, Population Services International, Washington, D.C., USA. ³National Malaria Control Programme, Freetown, Sierra Leone. ⁴PMI VectorLink Project, Abt Associates, Freetown, Sierra Leone. ⁵Nest Builders International, Freetown, Sierra Leone. ⁶Entomology Branch, Division of Parasitic Diseases and Malaria, U.S. Centers for Disease Control and Prevention, Atlanta, GA, USA. ⁷U.S. President's Malaria Initiative, Malaria Branch, U.S. Centers for Disease Control and Prevention, Freetown, Sierra Leone. ⁸PMI VectorLink Project, Population Services International, Antananarivo, Madagascar. ⁹U.S. President's Malaria Initiative, USAID, Washington, DC, USA. ¹⁰PMI VectorLink Project, Abt Associates, Washington, DC, USA. ¹¹PMI VectorLink Project, Abt Associates, Accra, Ghana. ¹²School of Community Health Sciences, Njala University, Bo, Sierra Leone.

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