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Streamlined durability monitoring of DuraNet® Plus and Interceptor® G2 insecticide-treated nets in Northern Region, Cameroon: assessment results in two sites from 2022 to 2025

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Abstract

Background

Insecticide-treated nets (ITNs) are a critical vector control and malaria prevention tool. Routine monitoring of ITN physical and chemical durability is key to assessing their performance under real-world conditions. A streamlined ITN durability monitoring methodology, focusing on bioeffectiveness, was deployed in Northern Region, Cameroon from 2022 to 2025. Assessment objectives were to measure the insecticidal efficacy of pyrethroid (pyr) + piperonyl butoxide (PBO) DuraNet Plus (DNP) and pry + chlorfenapyr (CFP) Interceptor G2 (IG2) ITNs, monitor physical integrity and estimate attrition.

Methods

This was a prospective assessment using repeat cross-sectional cluster surveys of ITNs randomly sampled from a primary sampling frame after annual assessment timepoints. Two study districts, Lagdo and Pitoa, were selected for their proximity and similarities in climate, demographics and malaria burden. Questionnaires captured information on ITN use in households from which ITNs were sampled. Sampled ITNs underwent physical hole inspection, as well as bioassay and chemical residue analyses. Primary outcomes of interest were pyr-resistant mosquito mortality (measured as 24-hour mortality for DNP ITNs and 72-hour mortality for IG2 ITNs) and mean chemical content. ITN attrition was also assessed, as were potential associations between ITN use factors and chemical content retention.

Results

Pry-resistant strain mortality was just 5% at endline for DNP ITNs, corresponding with an 82% decrease in PBO content compared to the manufacturer's target dose. Endline IG2 pyr-resistant strain 72-hour mortality was 55%, corresponding with a 79% decrease in CFP content compared to the manufacturer's target dose. Ever washing an ITN ($p = 0.046$), use of bleach ($p = 0.009$) and net physical integrity ($p = 0.004$) were significantly associated with reductions in mean chemical content in IG2 ITNs. All cause attrition was estimated at 51% for DNP ITNs and 32% for IG2 ITNs at endline.

Conclusion

These are the first published SDM results. IG2 ITNs in Lagdo outperformed DNP ITNs in Pitoa on measures of pyr-resistant strain mortality and chemical residue loss. Durability monitoring or post-market ITN surveillance data from other sites is necessary to identify trends in DNP performance under real-world conditions.

Background

In 2024, there were an estimated 282 million global malaria cases, resulting in 610,000 deaths (1). The extent of this morbidity and mortality is staggering given that malaria is a preventable disease. Insecticide-treated nets (ITNs) are the most effective malaria prevention tool, responsible for averting an estimated 451 million malaria cases between 2000 and 2015 (2). Over 3.2 billion ITNs were shipped to malaria-endemic countries between 2004 and 2024 (3). Since 2000, population ITN access and population ITN use have increased from 2%-3% to 47%-54%, respectively (1). Globally, the median ITN use to access ratio (the ratio of those who use an ITN to those given access to one) was most recently estimated at 0.85 (4). Given their crucial role in malaria prevention, routine ITN chemical and physical durability monitoring is critical for ensuring performance under field conditions meets expectations of three-year useful life expectations (and early detection of problems when it does not).

The proliferation of pyrethroid (pry) resistance (5) across sub-Saharan Africa due to use of pyr-only ITNs has led to the development of ITNs containing pyr and either piperonyl butoxide (PBO) or chlorfenapyr (CFP). Several such ITN brands have been prequalified by the World Health Organization (WHO) (6). In 2023, citing emerging evidence (7–9), the WHO began recommending pyr + CFP ITNs and conditionally recommending pyr + PBO ITNs over pyr-only ITNs (10) in areas with established pyr resistance.

Several ITN durability monitoring assessments – also referred to as post-market ITN surveillance assessments – have been conducted on these new net types (11–16).

The landscape of ITN types has shifted dramatically in the last five years. In 2022, when our assessment commenced, 47% of shipped ITNs were pyr + PBO (3). By 2025, the share of pyr + PBO ITNs had decreased to 15% (3). Conversely, the percentage of pyr + CFP ITNs shipped increased from 8% of total ITNs in 2022 to 71% in 2025 (3). The durability and field performance of DuraNet® Plus (DNP), a pyr + PBO ITN that received WHO prequalification in 2020, has not been widely studied (11). Interceptor® G2 (IG2), a type of pyr + CFP ITN prequalified in 2018, has been studied in various use settings (11, 12, 15, 16).

In 2024, 2.7% (7,586,000) of global malaria cases and 1.9% (11,590) of global deaths occurred in Cameroon (1). The country's National Strategic Plan for the Control of Malaria 2024–2028 set the objective of protecting 80% of the population by at least one malaria prevention intervention (18).

The U.S. President's Malaria Initiative (PMI) supported standardized durability monitoring of ITNs from 2014 until its transition to the U.S. Department of State in 2025 (19). Because of the resource intensity of the standard methodology, a revised methodology called streamlined durability monitoring (SDM) was initiated in 2022 to focus on bioeffectiveness testing at a lower implementation cost in six countries, including Cameroon (20, 21).

The Cameroon SDM study was conducted in the Northern Region and had three main objectives. First, to assess the insecticidal efficacy of pyr + CFP IG2 and pyr + PBO DNP ITNs in two sites using cone bioassays, tunnel tests, and chemical testing over a three-year period of field use and compare the insecticide effectiveness across these brands and identify major determinants of field performance. Second, to monitor the physical integrity of the nets as measured by a net hole assessment and short questionnaire. Finally, to estimate the level of attrition of the nets at each timepoint. Results from this assessment aimed to provide the Cameroon National Malaria Control Program (NMCP), donors, and other stakeholders with valuable information regarding the distribution of 1,204,600 py + CFP and 673,250 py + PBO ITNs during the 2022 mass campaign.

Methods

Study sites and ITN brands

This study was conducted in the Northern Region of Cameroon, where ITN use and access are higher than the national average (22). National ITN use is 54% compared to 70% in the Northern Region, while national ITN access is 64% compared to 86% in the Northern Region. The national use to access ratio is 0.84, comparable to 0.81 measured in Northern. Malaria transmission intensity in Norther Region is seasonally-dependent, intensifying during rainier months of June through October (23).

Monitoring sites were selected in Lagdo and Pitoa Districts (Fig. 1) for their geographic proximity and for their similarities in climate, demographics and malaria burden profiles. Assessment organizers also factored in accessibility, security and proximity to existing entomological surveillance sites.

The mass campaign from which this assessment drew its ITNs took place June 5–12 in Pitoa and August 28-Sept 4 in Lagdo. DNP ITNs were distributed in Pitoa. DNP ITNs, manufactured by Shobikaa Impex Private Limited (24) are 150 denier, rectangular, and polyethylene with 270 mg/m^2 of alpha-cypermethrin and 99 mg/m^2 of PBO. IG2s ITNs were distributed in Lagdo. IG2 ITNs, manufactured by BASF (25), are 100 denier, rectangular, and polyester with 100 mg/m^2 of alpha-cypermethrin and 200 mg/m^2 of CFP.

Study design and sampling procedures

SDM in Cameroon was a prospective study using repeat cross-sectional cluster surveys of ITNs randomly sampled from a (updated) primary sampling frame at each timepoint (Fig. 2).

Between six and eight months after their arrival in Cameroon, and prior to the launch of the mass distribution campaign, 40 ITNs per brand were sampled from the central store to undergo bioassay testing, 10 of which were then randomly selected for chemical

testing. Results from these tests formed the pre-distribution time point against which study results were compared.

Prior to field data collection, ITN campaign registers were used to develop a sampling frame of study clusters, which for this assessment were Cameroonian villages. For both study sites, 15 clusters were selected using probability proportional to size, with the number of ITNs distributed per cluster used for cluster size measurement. Sample size determinations followed standard WHO guidance for field testing of ITNs (26).

The first data collection activities occurred between 12.6 and 15.8 months post ITN campaign distribution. For simplicity, this round is referred to as the 12-month round throughout the paper. During this timepoint, 12 households in each cluster were randomly sampled, and a primary sampling frame of campaign ITNs was created by visiting each household and tagging present ITNs from the campaign distribution with a unique identifier. For campaign ITNs that were no longer present, information on their status and reason for loss was collected. A minimum of 258 ITNs per study site was necessary to satisfy the sample size requirements. The sampling frame exceeded this minimum, with 347 campaign ITNs in Pitoa and 356 ITNs in Lagdo identified and listed.

From the primary sampling frame of ITNs present at 12 months, 30 campaign ITNs per study site were identified by randomly sampling two ITNs per cluster from the list. Sampled ITNs were located and withdrawn for a physical integrity assessment, bioassays, and chemical residue testing. At each subsequent survey timepoint (24-month round conducted between 22.5 and 25.3 months post-distribution and 36-month/endline round conducted 32.5 to 35.4 months post-distribution), 30 campaign ITNs per site were randomly sampled from updated versions of the primary sampling frame, modified to account for ITNs withdrawn and ITNs known to be no longer present (based on household interviews in previous rounds). For these rounds, more than 30 ITNs were sampled into an ordered list, as some ITNs had undergone attrition and were no longer available. Interviewers worked down the ordered list until two ITNs per cluster had been sampled for a total of 30 ITNs per site. When sampled ITNs were not present or available in the household, attrition information was captured for the target ITN before interviewers moved onto the next ITN in the sample.

Concise household questionnaires captured information on ITN use that may be associated with bioeffectiveness (e.g. frequency of use, number of net users, how nets were washed and dried) along with basic household information on household construction and size. Reasons for attrition were recorded for solicited nets no longer present in the household. Question wording and response options were the same as those used in standard durability monitoring questionnaires (11, 27). Household questionnaires were digitized using SurveyCTO software (version 2.81). All withdrawn ITNs were replaced on a like-for-like basis with new ITNs by data collectors.

Prior to undergoing destructive bioassay and chemical residue testing, the physical integrity of sampled ITNs was determined at each timepoint using the standard hole assessment approach (28).

Training and fieldwork procedures

Training and data collection methods in Cameroon were largely similar to those employed for standard durability monitoring supported by PMI VectorLink and PMI Evolve (11, 27). Data collection was implemented by the Centre for Research in Infectious Diseases (CRID), with support from the Cameroon NMCP as well as regional and district malaria offices. An in-person training-of-trainers (TOT) was held for senior CRID and NMCP staff over two days before the 12-month round, and remotely over one day before the 24- and 36-month rounds. All TOTs were followed by a three-day data collector training led by CRID and NMCP staff, which included a one-day practical exercise in a community neighboring the training location.

For the 12-month round, a Population Services International (PSI) regional researcher travelled to Cameroon to provide in-person training and data collection supervision support. For the 24- and 36-month rounds, PSI provided virtual refresher training and remote data collection support.

Data collectors were recruited locally to the region and had knowledge of local languages. Most data collectors participated in all survey rounds. Community leaders were approached prior to each round of data collection for permission to enter the area and conduct the assessment.

Laboratory procedures

Susceptible and resistant mosquito strain bioassay testing was carried out at the CRID insectary using Innovation to Impact standard operating procedures (29, 30). Bioassay analysis used the pyr-susceptible Kisumu strain of *Anopheles (An) gambiae* s.s. maintained by CRID's insectary. Larvae of pyr-resistant *An gambiae* s.l. wildtype were collected annually during the rainy season from a PMI sentinel site in Monatélé, in Centre Region, and reared to adulthood in the CRID insectary.

Both strains were characterized prior to bioassays each round using standard procedures (26): WHO tube tests were conducted with 0.05% alpha-cypermethrin and alpha-cypermethrin 0.05% after pre-exposure to 4% PBO, and Centers for Disease Control and Prevention (CDC) bottle bioassays using 100ug/bottle CFP were performed. Genotyping of pyr DNA-based markers' knockdown resistance (kdr) *(L995F and L995S*) was also conducted (31).

Bioassays for DNP ITNs

Cone bioassays were used for PBO-containing DNP ITNs. Both susceptible and resistant strains were used with five mosquitoes per replicate and two replicates per ITN piece (two pieces from side panels and two pieces from the roof panel). A total of eight cone tests were used with 40 susceptible and 40 resistant mosquitoes per ITN sample. Positive and negative control ITNs were tested along with ITN samples withdrawn from study sites. Three new control ITNs were tested per day: an untreated ITN, a new pyr + PBO ITN, and a new pyr-only ITN. Pyr-only and untreated nets were tested against both strains as negative controls. Abbott's formula was used to adjust mortality based on the negative control results from untreated netting. New DNP ITNs were tested against the resistant strain as a positive control. For each of the positive control ITNs, one piece was tested per day, with two replicates conducted per piece and five mosquitoes used in each replicate (six cone tests with 30 mosquitoes per net per day).

Bioassays for IG2 ITNs

Tunnel tests were used for IG2 ITNs against both strains. For each sampled ITN, one piece was taken from the side panel and one from the roof panel. One untreated negative control ITN was used during testing. Tunnel tests were completed over three days (26) and each negative control net was similarly cut into two pieces (side and roof) and used for negative control testing, with results pooled among all IG2 ITN samples tested over the same period. For each ITN sample, approximately 100 female mosquitoes from each of the pyr-susceptible and pyr-resistant strains, aged five to eight days and sugar starved for six hours were introduced into the end opposite the bait at 18:00 hours. The lights in the room were turned off and only turned on when the tunnel test finished the following morning at 07:00 hours, giving exposure of 13 hours. At 07:00 hours, mosquitoes were collected from the tunnel and enumerated based on the compartment in which the mosquitoes were collected (initial compartment versus animal compartment), blood feeding status (fed versus unfed), and mortality status (alive versus dead). Surviving mosquitoes were put into cups and covered with untreated netting. Cotton wool soaked with 10% sugar was placed on top of the cups so that mosquitoes could feed. Mortality was recorded 24 hours, 48 hours and 72 hours after the tunnel test commenced.

Chemical testing

At pre-distribution, 12-, and 24-months, chemical analysis was conducted by the CDC in the United States. Endline chemical analysis was conducted by the Centre Wallon de Recherches Agronomiques (CRA-W) in Belgium. Both laboratories followed the same procedures. Eight pyr + PBO and four pyr + CFP ITN samples measuring 30 cm x 30 cm were cut from each ITN at CRID from areas adjacent to those used for bioassays, packaged individually in foil, labelled, and sent to the testing laboratory (29, 30). Active ingredients (AIs) were extracted from samples using the Collaborative International Pesticide Analytical Council method (454/LN/M/3.2) (32).

Data management

Household survey data were exported to a secure online database each evening or when data collection teams had access to an internet connection. Data were accessible to the research personnel only. After data collection was completed, files were

imported into Stata where do-files used in standard durability monitoring were adapted to the SDM methodology and used for analysis.

Bioassay and chemical residue data were shared by partner laboratories in Excel format then imported into Stata 18 (StataCorp, College Station, Texas, USA) and R (4.5.2) by the PSI research team for analysis and visualization. As the analysis mirrored that of standard durability monitoring assessments (11, 27), existing Stata do-files were modified to the Cameroonian context and used to manage and analyze the data.

Outcomes of interest

Bioefficacy testing

The primary DNP bioassay outcome of interest was 24-hour mortality, measured as the number of mosquitoes dead after 24 hours over total exposed mosquitoes, multiplied by 100. The primary IG2 bioefficacy outcome of interest was 72-hour mortality, measured as the number of dead mosquitoes after 72 hours over total exposed mosquitoes, multiplied by 100. A secondary bioefficacy outcome of interest for IG2 ITNs was blood-feeding inhibition (BFI), calculated as the difference between the proportion of mosquitoes blood-fed on the negative control and the proportion blood-fed on the field sample, divided by the proportion blood-fed on the negative control and multiplied by 100.

Chemical content

The primary outcome of chemical testing was mean insecticide content, measured in g/kg. A secondary outcome was the proportion of ITNs with mean insecticide content for each AI falling outside ± 20% of the manufacturer's target dose.

Estimates of ITN attrition and attrition due to wear and tear were calculated at each round using a simple Excel analysis template, available with calculation instructions in supplementary materials (33). At 12-months, attrition was calculated as the number of ITNs reportedly received from the mass campaign distribution and no longer present in households divided by the total number of ITNs reportedly received from the campaign. For 24- and 36-months, attrition was estimated based on the number of ITNs in the sample that had to be solicited before a full contingent of 30 ITNs per site was identified as present in households. ITN attrition due to wear and tear was estimated in a comparable way, restricting the numerator to ITNs that were destroyed, discarded or used for other purposes per the standard durability monitoring definition of "wear and tear".

Percentage of ITNs in serviceable condition was defined as the percentage of sampled nets that are still in serviceable physical condition (good or damaged), specifically, with a proportionate hole index (pHI) of 642 or less. The pHI calculation methodology is explained in the literature (11, 27).

Statistical analyses

Statistical analyses were conducted to describe household contexts and ITN use behaviors across rounds, and to assess factors potentially influencing bioassay performance and chemical content.

For continuous variables, such as the mean number of washes, distributional assumptions were first evaluated using the Shapiro–Wilk test. When normality assumptions were satisfied, differences in means across survey rounds were examined using one-way analysis of variance (ANOVA). If normality was not met in at least one group, the non-parametric Kruskal–Wallis test was applied. Categorical variables were recoded into binary indicators prior to analysis, and differences in proportions were assessed using logistic regression models, with the binary variables specified as outcomes and survey round included as a categorical explanatory variable.

Statistical significance across rounds was determined based on the overall p-value for trends across rounds. All analyses were conducted separately within each district. Variables demonstrating significant differences across assessment rounds were further examined for their association with mean chemical content to explore potential contributors to the observed decline in insecticide concentration. Linear regression models were used to quantify associations between statistically significant factors and mean chemical content, with variables showing variation across survey rounds included simultaneously in the model, along with survey rounds.

Survey design was not applied in the analysis assessing ITN care behaviors on chemical content, as clustering was not explicitly modeled due to the small number of observations within clusters. Robust standard errors were used in the regression models to address the sampling design.

Selected explanatory variables included reported net use, drying practices, physical integrity status, history of washing (ever washed as a binary variable and number of washes as a continuous variable), and reported use of detergent or bleach during washing.

Ethical considerations

This study received ethical approval from the National Ethical Committee for Research on Human Health, based within the Ministry of Public Health in Cameroon (N 2023/09/1567/CE/CNERSH/SP). Ethical approval was renewed by this body each year throughout the assessment.

Written informed consent from heads of households or their representative was obtained prior to including household details in the sampling frame during net listing. Respondents in households with ITNs sampled for withdrawal provided written consent prior to being interviewed.

Results

In total, 813 ITNs (432 in Lagdo and 381 in Pitoa) reportedly received from the campaign were enumerated at 12 months (Table 1), of which 703 (356 and 347, respectively) were present and included in the primary sampling frame. At 12 months, 30 ITNs per site were sampled from the primary frame and withdrawn (i.e. all were still available in study households). In Lagdo, field teams had to sample 98 ITNs at 24 months and 104 ITNs at 36 months before achieving a full complement of 30 present ITNs withdrawn for study. In Pitoa, teams had to sample 109 ITNs at 24 months and 121 ITNs at 36 months to achieve the required 30 ITNs per round.

All-cause attrition at 12-months was estimated as 14% in Lagdo and 6% in Pitoa, increasing to 43% and 51%, respectively, at endline. Endline attrition due to wear and tear was estimated at 32% in Lagdo and 35% in Pitoa.

[Table 1: Attrition calculation table]

Strain characterization

Strains were characterized prior to bioassay testing at each round (Table 2, Additional Information). Mortality of the susceptible *An. gambiae* Kisumu colony was above 96% in alpha-cypermethrin (0.05%) WHO tube tests. Susceptibility to CFP was confirmed, with 72-hour mortality registered at 100% across all rounds, including pre-distribution. No 995F- or 995S-kdr resistant alleles were detected.

Wild caught mosquitoes collected from the PMI sentinel site in Monatélé were composed of *An. gambiae* s.s. (95%–97%) and *An. coluzzii (*3%–5%) throughout the assessment period. WHO tube bioassays confirmed this population was highly resistant to alpha-cypermethrin alone, with 24-hour mortality ranging between 0% and 14%. When mosquitoes were pre-exposed to PBO prior to alpha-cypermethrin, 24-hour mortality ranged from 61% to 66% across all time points. Susceptibility to CFP was confirmed across all rounds, with 72-hour mortality stable at 97%. Over the three-year assessment period, the 995F-kdr resistant allele was fixed within 100% of the population, whereas the 9995S-krdr resistant allele was detected in just 3.3% of the time.

DNP bioassays and chemical results

Mortality after 24 hours was consistently high (>92%) against the susceptible strain across all survey rounds in field samples and positive controls (Table 3, Additional Information). Bioassays against the resistant strain showed substantially lower 24-hour mortality in field samples, ranging from 23% at pre-distribution to 5% at endline. Mortality after 24 hours observed in positive

control samples was similarly low, measured at 5% at pre-distribution and ranging from 24% at 12 months to 9% at endline against the resistant strain.

Alpha-cypermethrin content decreased from 5.8 g/kg at pre-distribution to 2.4 g/kg at endline, which corresponded to a chemical content loss of 3% at pre-distribution to 60% at endline compared to the manufacturer's target dose of 6 g/kg (Figure 4). From 12 months onwards, median of alpha-cypermethrin content was at least 20% below the manufacturer's target dose. PBO content decreased from 2.0 g/kg at pre-distribution to 0.4 g/kg at endline, which corresponded to losses of 9% at pre-distribution to 82% at endline, compared to the manufacturer's target dose of 2.2 g/kg. Mean PBO content was below the lower limit of the manufacturer target range for all ITN samples at endline (Figure 4).

Figure 3: Box plot of DuraNet® Plus cone bioassay results for residual efficacy of pyr and PBO

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles), and for each legend, orange dashed line represents WHO optimal effectiveness thresholds for mortality 80%.

Figure 4: Box plot of DuraNet® Plus chemical content results of pyr and PBO

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles). Shaded bands represent the manufacturer-specified target dose ±20% (acceptable range), while dashed horizontal lines indicate the manufacturer target dose.

IG2 bioassays and chemical results

Susceptible laboratory strain 72-hour mortality against field IG2 ITN samples ranged from 94% at pre-distribution to 81% at endline (Table 4, Additional Information). Against positive control ITNs, susceptible strain 72-hour mortality ranged from 95% to 100% across rounds. Against the resistant strain, 72-hour mortality in field IG2 ITN samples declined from 87% at pre-distribution to 55% at endline whereas against positive controls it ranged from 61%-69% across rounds.

BFI against the susceptible strain remained generally high against field samples but varied over time, declining from 84% at pre-distribution to 60% at endline. BFI in positive control samples was similarly high, ranging between 74% and 86%. BFI against the resistant strain was measured at 90% at pre-distribution but declined to just 9% by endline whereas BFI measured against positive control samples ranged between 100% to 66% against the resistant strain.

Mean alpha-cypermethrin content declined from 2.2 g/kg at pre-distribution to 0.9 g/kg at endline, corresponding to a chemical content loss of 8% at pre-distribution and 63% at endline, compared to the manufacturer's target dose of 2.4 g/kg. At 24- and 36-months, median alpha-cypermethrin content was measured at least 20% below the manufacturer's target dose. Mean CFP content declined from 4.0 g/kg at pre-distribution to 1.0 g/kg at endline, corresponding to a loss of 17% at pre-distribution and 79% at endline, compared to the manufacturer's target dose of 4.8 g/kg. At endline, the CFP content of 27 out of 30 endline field ITN samples fell below the lower bound of the manufacturer's specified range (Figure 6). Consistent with this finding, median CFP content was below the lower limit of the manufacturer's target range, at least 20% less than the manufacturer's target dose for 12-, 24- and 36-month survey rounds.

Figure 5: Box plot of Interceptor® G2 tunnel bioassay results for residual efficacy of pyr and CFP

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers) and outlier (circle).

Figure 6: Box plot of Interceptor® G2 chemical content results of pyr and CFP

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles). Shaded bands represent the manufacturer-specified target dose ±20% (acceptable range), while dashed horizontal lines indicate the manufacturer target dose.

Impact of ITN care behaviors on chemical content

Tables 5-8 (Additional Information) summarize ITN handling use and care behaviors for the two sites over time.

Table 9: Identification of significant (p<0.05) net use and maintenance risk factors on reduction in chemical content across three rounds within each district

Indicator	Lagdo (p-value)	Pitoa (p-value)
Net use		
Every night (7 nights) in the past week	0.1923	0.0043
Every night (7 nights) or most nights (5-6 nights) in the past week	0.6805	0.0436
At least once in the past week	0.3716	0.0163
Drying nets under the sun	0.0762	0.0314
Integrity (serviceable)	0.0447	0.9022
Ever washed	0.0108	0.4456
Use of detergent or bleach during washing	0.0093	0.0314
Mean number of washings	0.4319	0.0056

Lagdo, ANOVA applied
Pitoa, Kruskal–Wallis applied.

Table 10. Association between significant net use and maintenance risk factors identified in Table 9 and mean chemical content reduction after adjustment for survey rounds

Indicator	Lagdo (p-value)	Pitoa (p-value)
Net use		
Every night (7 nights) in the past week	N/A	0.8888
Every night (7 nights) or most nights (5-6 nights) in the past week	N/A	0.5329
At least once in the past week	N/A	0.8030
Drying nets under the sun	N/A	0.3514
Integrity (serviceable)	0.0042	N/A
Ever washed	0.0462	N/A
Use of detergent or bleach during washing	0.0092	0.9772
Mean number of washings	N/A	0.9293

N/A: Not Applicable

Note: In this table, chemical content refers to chlorfenapyr content in Lagdo and PBO content in Pitoa. Only factors identified as significant in Table 9 were included in the adjusted models

In Lagdo, the proportion of serviceable nets significantly declined each round, suggesting progressive deterioration in physical integrity over time (p=0.04). The proportion of nets ever washed significantly increased from round to round, reflecting the increasing number of washing exposures as nets aged (p=0.01). The use of detergent or bleach during washing significantly changed across rounds, indicating variation in the products used to wash nets (p=0.009). Using linear regression analysis,

washing practices (ever washed, p=0.046; use of detergent or bleach during washing, p=0.009) and net physical integrity, which may reflect more consistent net use or generally higher exposure to physical damage (p=0.004), were significantly associated with decline in mean chemical content over time. Other variables assessed did not show statistically significant differences across survey rounds.

In Pitoa, the proportion of nets used every night (p=0.004), every night or most nights (p=0.044), and at least once in the past week (p=0.02) varied significantly across rounds, suggesting changes in net use patterns over time. The proportion of nets dried under the sun varied significantly across rounds (p=0.03), as did the proportion of nets washed using detergent or bleach (p=0.03) and the mean number of washings (p=0.006). Although several handling factors showed significant differences across assessment rounds in Pitoa, linear regression analysis indicated that none were significantly associated with decline in mean chemical content over time. Other variables assessed did not show statistically significant differences across survey rounds.

Discussion

This is the first paper to describe the SDM methodology. We monitored the field performance of pyr + PBO DNP and pyr + CFP IG2 ITNs in bordering districts of Cameroon's Northern Region. Random samples of ITNs were assessed prior to a mass campaign in 2022 and again approximately 12, 24, and 36 months after their distribution. In Pitoa district, pyr-resistant strain 24-hour mosquito mortality was consistently and concerningly low against DNP field samples. Before ITNs had left the regional warehouse for distribution, only 23% of tested mosquitoes were killed after 24-hours of exposure. This was lower than resistant strain cone bioassay 24-hour mortality for DNP ITNs measured prior to experimental hut trials in Cameroon, Benin, and Cote d'Ivoire (40%-45%) (34). By study endline, 24-hour mortality decreased to just 5%, indicating that three years post-distribution, assessment ITNs served as little more than a physical barrier between resistant mosquitoes and their would-be hosts. In this context, stakeholders would be justified in questioning if the additional insecticidal benefit purported by manufacturers of DNP ITNs was worth the additional cost compared to standard pyr-only ITNs.

Mean PBO content was within the standard ± 20% of the manufacturer target dose (2.2 g/kg) at pre-distribution. However, across the three assessment rounds, mean PBO content dropped to between 59% and 82% compared to the manufacturer's target dose. Mean alpha-cypermethrin content of assessed DNP ITNs decreased by 60% by study endline. This is a higher loss than that of alpha-cypermethrin-only DuraNet ITNs studied in Grand Gedeh (17%) and Lofa (21%), Liberia, but lower than alpha-cypermethrin-only Interceptor ITNs assessed in Gaoua, Burkina Faso (84%) (11, 35). Our bioassay and chemical data should be compared to a forthcoming durability monitoring assessment of DNP ITNs being conducted in Tanzania (17).

In Lagdo, 72-hour resistant strain mortality of IG2 ITN field samples declined from 87% at pre-distribution to 55% at endline. This corresponds to losses of CFP content, which rose from 17% at pre-distribution to 79% at endline against the manufacturer's target dose of 4.8 g/kg. Reported washing practices and consistent net use were shown to have a significant effect on chemical content results. Mortality and chemical residue results are broadly similar to those seen in a standard durability monitoring assessments in Burkina Faso(11), where endline resistant strain mortality was 51% and reduction in CFP was 76%, and Benin (16), where endline resistant strain mortality was 60% and reduction in CFP was 85%.

Unlike standard durability monitoring, SDM does not follow a cohort of ITNs over three years. Therefore, SDM does not produce physical durability measures like survival curves and risk modeling. Still the generation of the SDM sampling frame means that researchers can be certain that withdrawn ITNs came from a single campaign. The sampling frame also allows for annual snapshots of valuable field performance indicators related to net handling and use. SDM is particularly useful in countries that have previously collected standard durability monitoring data and are focused primarily on bioefficacy data for pyr-PBO and pyr-CFP ITNs. Anecdotally, SDM implementation costs are lower than those of standard durability monitoring. However, no formal cost analysis has been conducted. While SDM includes shorter household surveys and a limited sampling approach, the major cost-drivers of durability monitoring – bioefficacy and chemical residue testing – remain.

A key challenge in conducting the Cameroon SDM assessment was the cancellation of the ITN durability monitoring studies that had been supported by the PMI Evolve project. This cancellation occurred in 2025 when United States Agency for International Development (USAID) projects were transitioned to the US Department of State and meant that the Cameroon SDM assessment was halted between the 24- and 36-month rounds. In April 2025, another funder, GiveWell, stepped in to support the endline survey

round of data collection in Cameroon, as well as endline bioassay and chemical residue analysis (36), allowing the assessment to be completed without disruption.

This was an implementation science assessment, designed to leverage a planned mass campaign of ITNs. The two ITN brands under study were not distributed in a single district, which could have introduced inter-district confounding (37). To mitigate this concern, two neighboring districts in the same region with similar climatic, socioeconomic, and malaria epidemiology profiles were selected. The Hawthorne effect may have been introduced as those who were aware that their ITN use and handling were being assessed may have altered their behaviors.

Per WHO guidelines, pyr + PBO ITNs should undergo tunnel testing after failing cone bioassays. This procedure was not included in our study protocol to reduce costs. This means that while the DNP ITNs performed poorly on cone bioassays, they have not been subjected to the full WHO-recommended lab testing regime.

Conclusions

These are the first SDM data to be reported widely. Results from this assessment contribute to the expanding literature on pyr + PBO and pyr + CFP ITN durability. IG2 ITNs in Lagdo district outperformed DNP ITNs in Pitoa district on measures of pyr-resistant strain mortality and chemical residue loss over the three-year assessment period. In Cameroon therefore, IG2 ITNs should be considered for deployment in areas of confirmed pyr-resistance over DNP ITNs. Washing practices, along with consistent net use, were shown to significantly reduce chemical content on IG2 ITNs. While use should remain consistent, bespoke social behavior change interventions could target appropriate net washing practices in Lagdo to extend chemical content. Additional data from other study sites is required to identify trends in chemical durability of DNP ITNs.

Abbreviations

AI
Active Ingredient
ANOVA
Analysis of Variance
BFI
Blood-Feeding Inhibition
CDC
Centers for Disease Control and Prevention
CI
Confidence Interval
CRA-W
Centre Wallon de Recherches Agronomiques
CRID
Centre for Research in Infectious Diseases
CFP
Chlorfenapyr
DNP
DuraNet® Plus
IG2
Interceptor® G2
IQR
Interquartile Range
ITN
Insecticide-Treated Nets
kdr
Knockdown resistance

NMCP
National Malaria Control Program
PBO
Piperonyl Butoxide
PCR
Polymerase Chain Reaction
pHI
Proportionate Hole Index
PMI
U.S. President's Malaria Initiative
pry
Pyrethroid
PSI
Population Services International
SD
Standard Deviation
SDM
Streamlined Durability Monitoring
TOT
Training-of-Trainers
USAID
United States Agency for International Development
WHO
World Health Organization

Declarations

Ethics declarations

This study received ethical approval from the National Ethical Committee for Research on Human Health, based within the Ministry of Public Health in Cameroon (N 2023/09/1567/CE/CNERSH/SP). Ethical approval was renewed by this body each year throughout the assessment.

Availability of data and materials

Data used for this analysis is available on www.durabilitymonitoring.org.

Competing interests

The authors declare no competing interests.

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Authors' contributions

KE and CW were co-principal investigators for this assessment. KE led the drafting of this manuscript with significant contributions from JR and SP. JR led data analysis with support from SP. Y-FT, RT, SN, DN, EF, JC, SZ, IS, CM, SV, and MB all

reviewed and improved the contents of this manuscript.

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Tables

Tables 1 to 8 are available in the supplementary files section

Figures

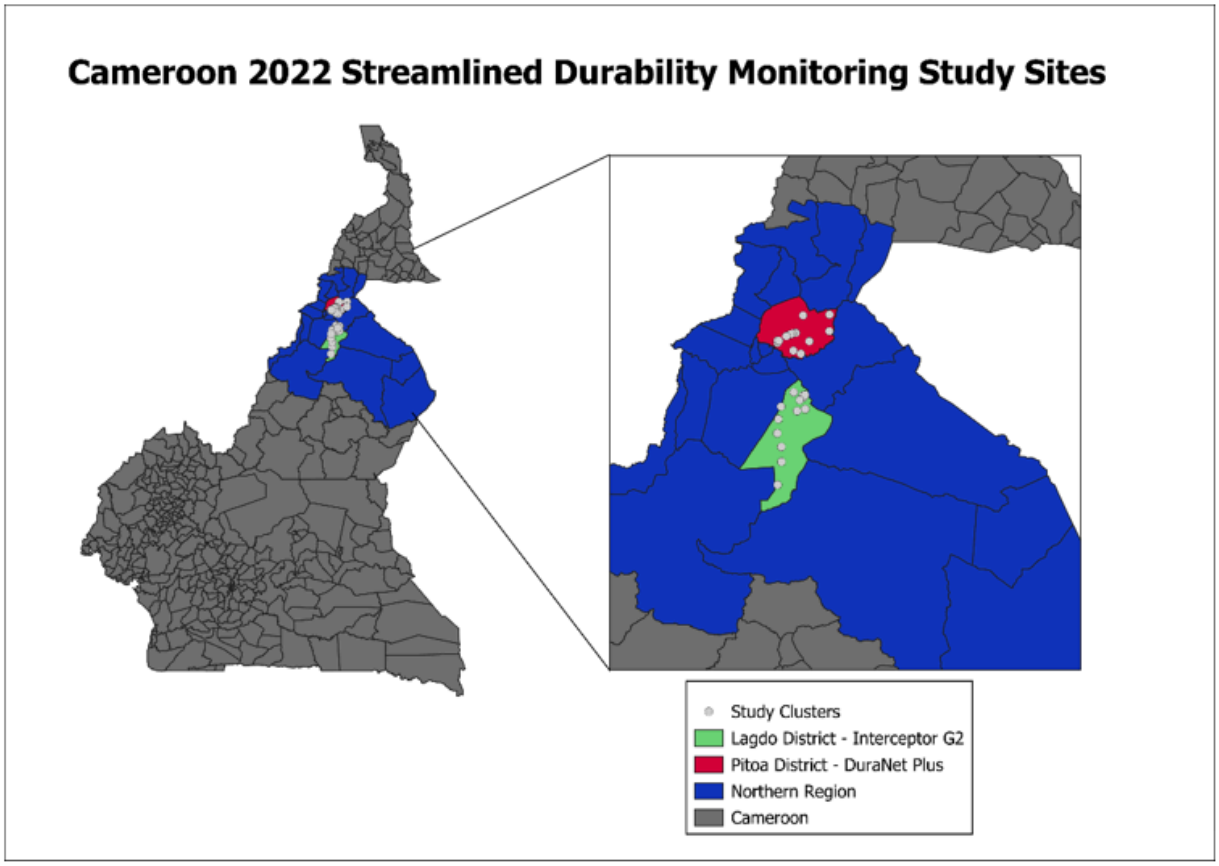


Figure 1

Study sites

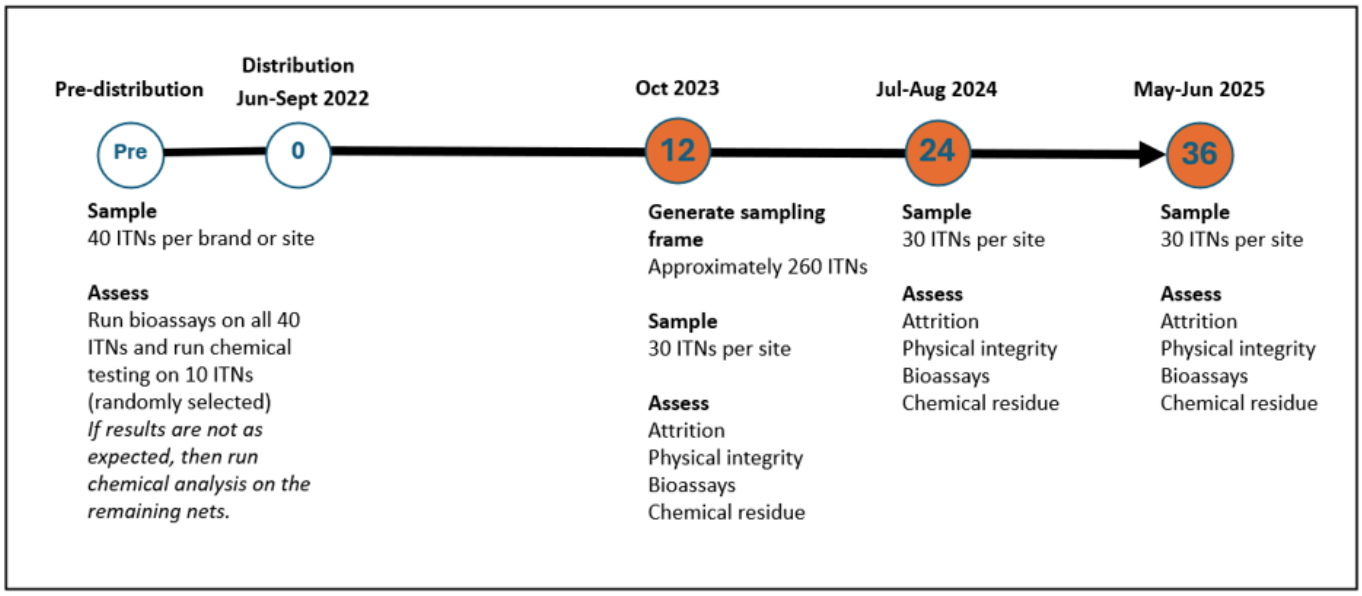
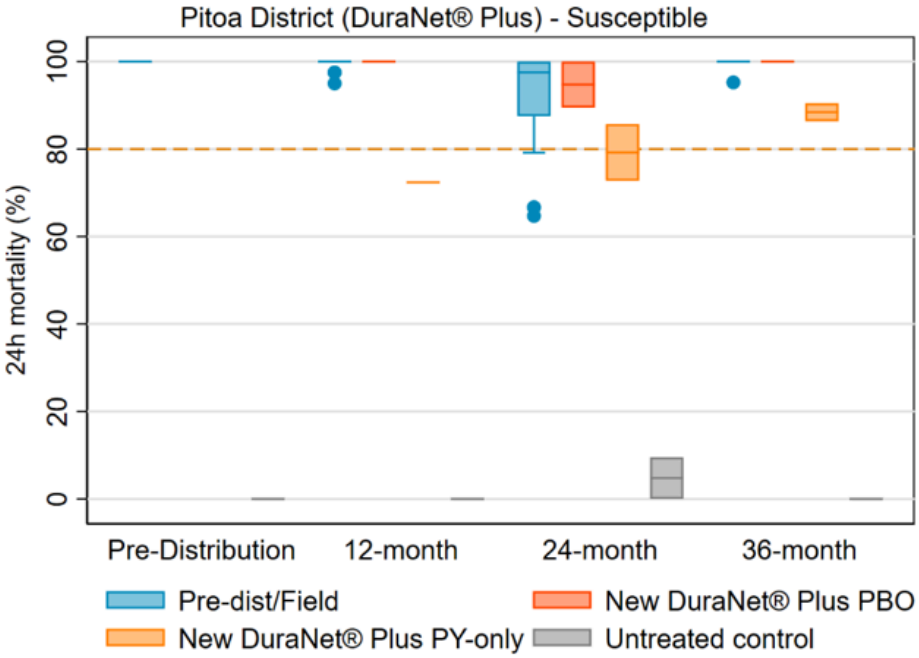


Figure 2

Overview of Cameroon study design for SDM



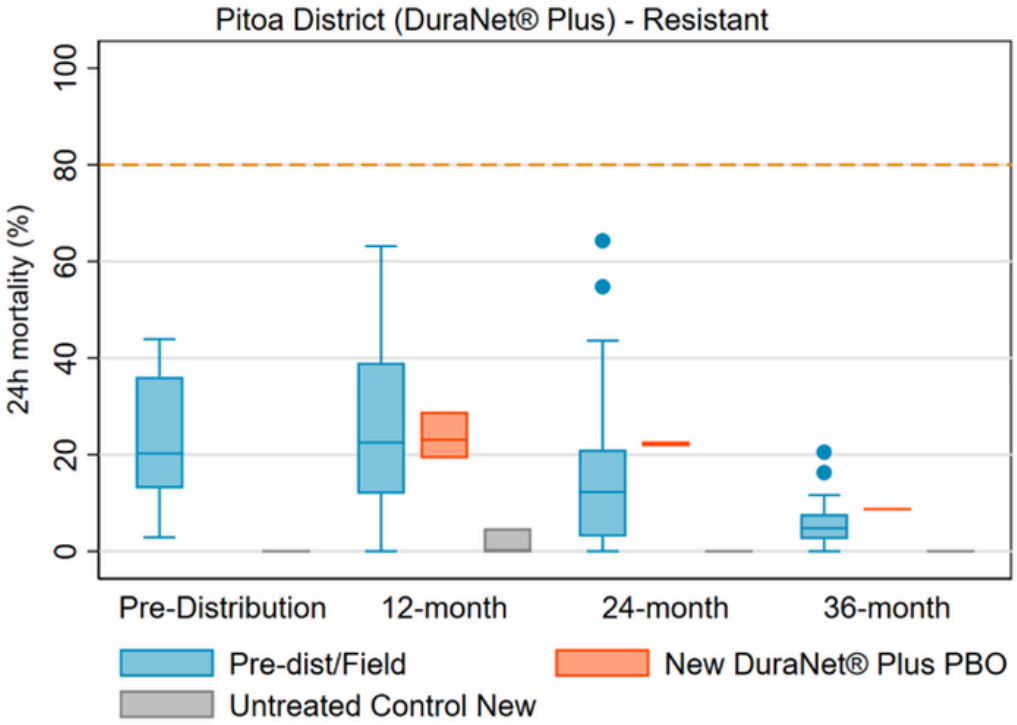


Figure 3

Box plot of DuraNet® Plus cone bioassay results for residual efficacy of pyr and PBO

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles), and for each legend, orange dashed line represents WHO optimal effectiveness thresholds for mortality 80%.

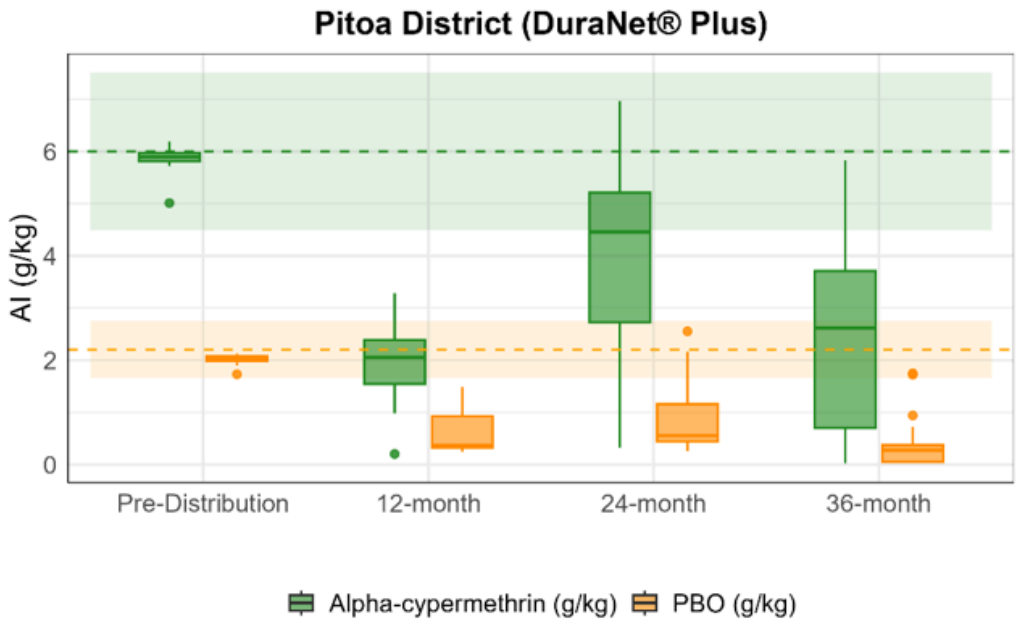
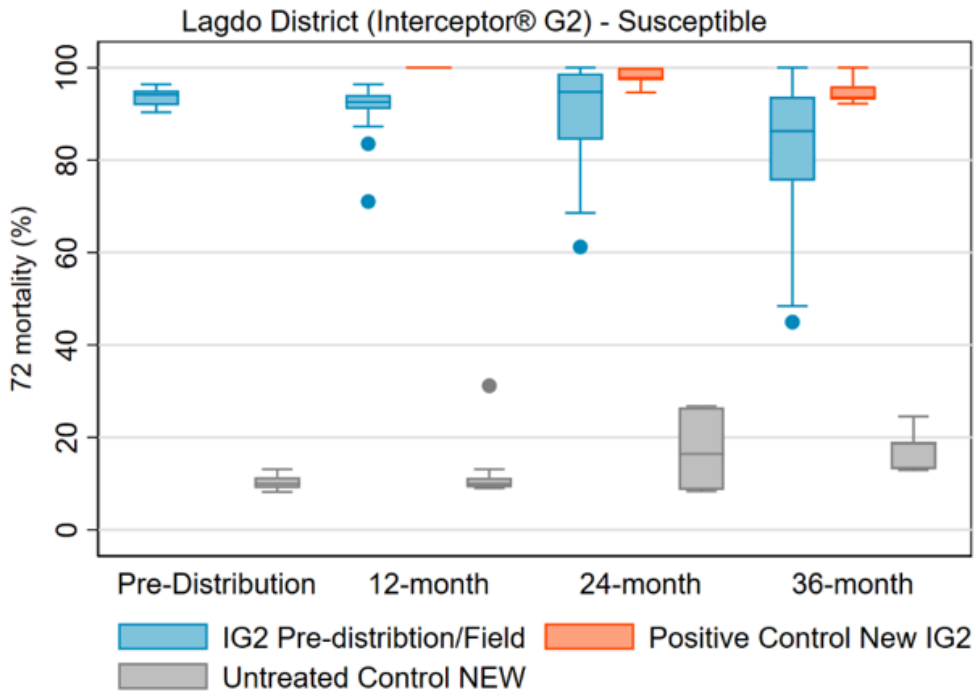


Figure 4

Box plot of DuraNet® Plus chemical content results of pyr and PBO

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles). Shaded bands represent the manufacturer-specified target dose ±20% (acceptable range), while dashed horizontal lines indicate the manufacturer target dose.



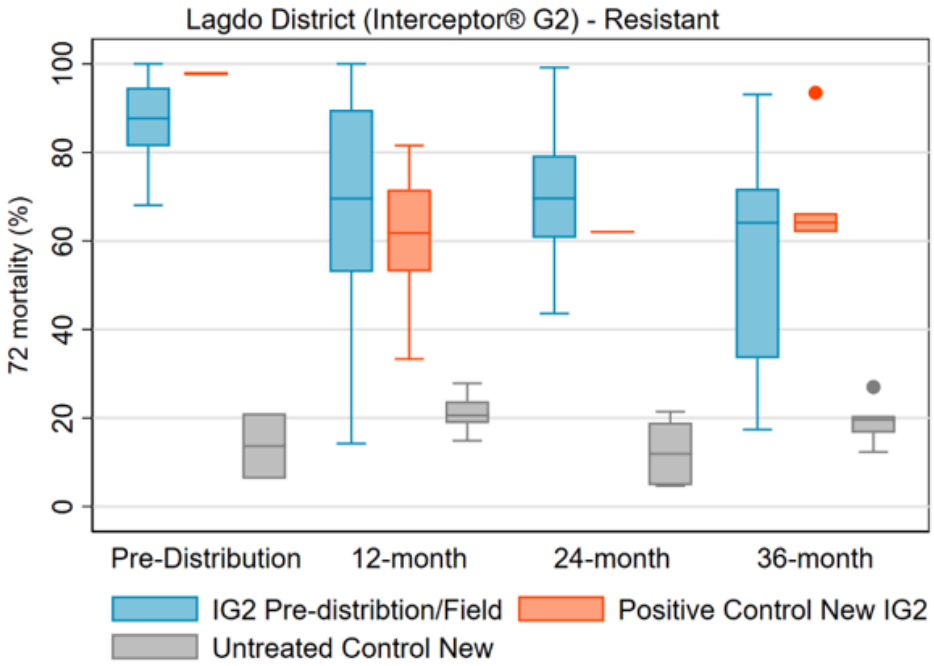


Figure 5

Box plot of Interceptor® G2 tunnel bioassay results for residual efficacy of pyr and CFP

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers) and outlier (circle).

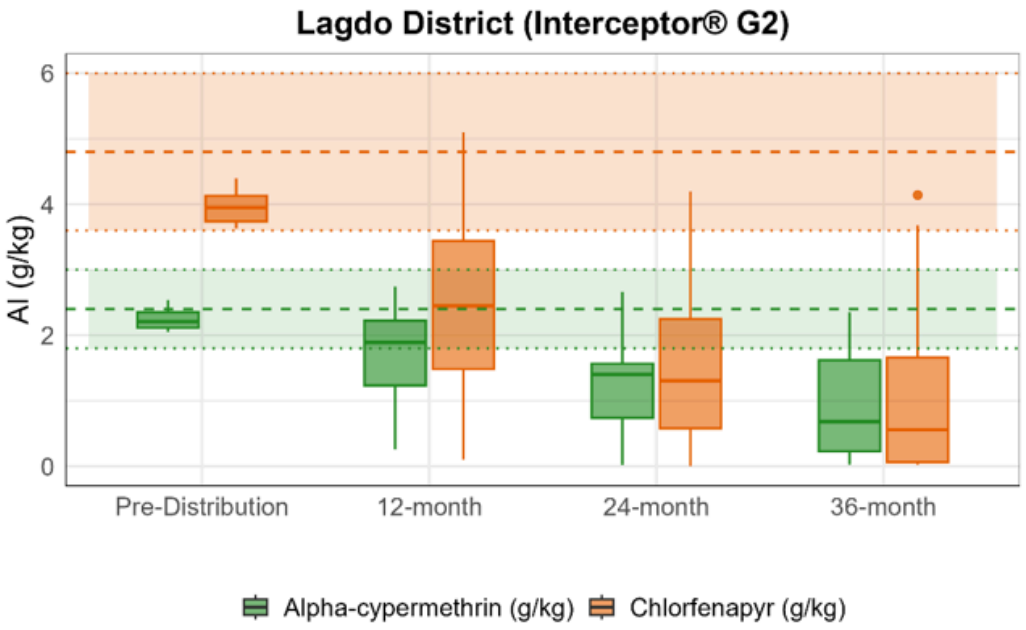


Figure 6

Box plot of Interceptor® G2 chemical content results of pyr and CFP

Box plot shows the median (horizontal line), interquartile range (box), adjacent values (whiskers), outliers (circles). Shaded bands represent the manufacturer-specified target dose ±20% (acceptable range), while dashed horizontal lines indicate the manufacturer target dose.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx