

Prevalence and Risk Factors of Baseline Plasmodium Infection before the First Seasonal Malaria Chemoprevention Round in Burkina Faso: A Cross-Sectional Study

Toussaint Rouamba^{1,2,3*}, Berenger Kabore¹, Paul Sondo¹, Ismaïla Bouda¹, Franck So-vii Hien¹, Wendmanegda Geneviève Maïga¹, Solange Kié Millogo¹, Ipéné Mylène Carenne Bayala¹, Ange Evodie Tapsoba¹, Eulalie Wendingouda Compaore¹, Karim Derra¹, Smaila Ouedraogo², Halidou Tinto¹

¹CNRST/IRSS-Unité de Recherche Clinique de Nanoro, Nanoro, Burkina Faso

²Department of Public Health Laboratory, Faculty of Health Sciences Training and Research, University Joseph Ki-Zerbo, Ouagadougou, Burkina Faso

³Centre de Recherche en Epidémiologie, Biostatistiques et Recherche Clinique, Ecole de Santé Publique, Université libre de Bruxelles, Brussels, Belgium

Email: *rouambatoussaint@gmail.com

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Abstract

Background: Malaria parasite carriage represents a hidden reservoir that sustains transmission and may undermine the effectiveness of control strategies such as seasonal malaria chemoprevention (SMC). Quantifying the prevalence and risk factors of parasite carriage prior to SMC delivery could provide essential baseline data for assessing the impact of the intervention and optimizing its implementation. **Methods:** A cross-sectional survey was conducted in July 2025, 0 to 4 days before delivery of the first round of SMC. Children were randomly selected from ten villages in the Nanoro Health and Demographic Surveillance System (HDSS). Capillary blood was collected by finger prick to prepare thick and thin blood smears, which were examined later by light microscopy to detect *Plasmodium* species carriage. Socio-demographic and household characteristics were extracted from the HDSS database. Associations between covariates including child age, sex, mid upper arm circumference, household head education, malaria prevention practices, and household wealth quintile and *Plasmodium* carriage were assessed using modified Poisson regression with robust variance, fitted with generalized estimating equations to estimate prevalence ratios and 95% confidence intervals. An exchangeable working correlation structure was specified, with clustering at the household level to account for intra household intra correlation. **Results:**

Among 1,643 enrolled children with microscopy results, the prevalence of *Plasmodium* carriage was 25.5% (95% CI: 23.5% - 27.7%) and that of gametocyte carriage was 2.2% (95% CI: 1.6 - 3.1). Compared to children aged < 1 year, the risk of carriage was higher in those aged 2 - 3 years (aPR 3.03; 95% CI: 1.98 - 4.63), and 3 - 4 years (aPR 3.43; 95% CI: 2.25 - 5.23). Male children had higher prevalence ratio than females (aPR = 1.21; 95% CI: 1.03 - 1.42). **Conclusion:** Prior to SMC campaign, *Plasmodium* carriage was prevalent among children in Nanoro, with older children exhibiting significantly higher risk. These findings emphasize the relevance of SMC intervention at that period of the year and complementary interventions, such as vaccination and targeted health education, alongside the SMC implementation. This baseline data informs tailored strategies in high-transmission settings.

Keywords

Malaria, *Plasmodium* Infections, Seasonal Malaria Chemoprevention, Prevalence, Determinants, Burkina Faso

1. Introduction

Malaria remains one of the leading causes of morbidity and mortality in sub-Saharan Africa, disproportionately affecting children under five years of age. In 2024, the World Health Organization (WHO) reported an estimated 249 million malaria cases and 608,000 deaths, with more than 94% occurring in Africa [1]. Burkina Faso is among the highest-burden countries, reporting an incidence of approximately 400 cases per 1000 population per year, and malaria continues to be the primary cause of outpatient consultations and childhood mortality [1] [2].

Over the past two decades, Burkina Faso has introduced multiple malaria control strategies to reduce transmission. These include the large-scale deployment of long-lasting insecticide-treated nets (LLITNs), expanded access to rapid diagnostic tests (RDTs), artemisinin-based combination therapies (ACTs), and the implementation of seasonal malaria chemoprevention (SMC) for children aged 3 - 59 months since 2014 [3] [4]. The latter has demonstrated high protective efficacy, reducing clinical malaria episodes by up to 75% when correctly administered [5]. In addition, malaria vaccination (RTS, S and R21) is now part of the national malaria control tools [6] [7]. Importantly, combining the malaria vaccine with SMC has been shown to yield greater protection than either intervention alone, reducing clinical malaria by 62% and severe malaria by 70% in a West African trial [8].

Despite these advances, *Plasmodium* infections remain widespread. These silent infections, common among young children in the Sahel, can account for 20% - 40% parasite prevalence at the onset of the rainy season [9]-[12]. Children who carry parasites contribute to the sustainability of malaria transmission and may experience breakthrough infections [13] despite the deployment of preventive

measures. When SMC is not effective in clearing parasites, either because of poor adherence or non-compliance, these persistent infections may progress to clinical malaria [14] [15], which, if not promptly treated, can evolve into severe disease with life-threatening consequences [16] [17]. Such residual carriage may ultimately reduce the apparent impact of SMC or vaccination by sustaining the parasite reservoir and enabling progression to illness [16].

Understanding the prevalence and determinants of *Plasmodium* parasite carriage (*Plasmodium* infection) prior to SMC campaigns is therefore critical. Baseline parasitemia may be useful for understanding short-term SMC effectiveness, identifying higher-risk groups such as older preschool children, and informing the integration of emerging tools, including malaria vaccines, into national malaria control strategies. In fact, a recent study in Northern Cameroon and southern Senegal reported a high baseline prevalence of RDT-confirmed asymptomatic *P. falciparum* infections prior to the SMC implementation [18]. In the context of large-scale SMC deployment, the protective impact against clinical malaria was high when coverage was adequate, but real-world constraints may reduce the effectiveness and maintain a reservoir of asymptomatic infections [19].

This study aimed to estimate the prevalence of *Plasmodium* infection by microscopy among children (6 to 59 months) prior to the first SMC round and to identify demographic and household determinants of *Plasmodium* infections.

2. Methods

2.1. Study Design and Setting

A cross-sectional survey was conducted in July 2025, within 0 - 4 days preceding the first Seasonal Malaria Chemoprevention (SMC) round. The study was carried out in the Nanoro Health District in Burkina Faso, an area of intense seasonal malaria transmission with peaks between July and October. Ten villages from Soaw department located in the Nanoro Health and Demographic Surveillance System (HDSS) catchment area were included. This survey was nested within the MalNut Project, a multi-component randomized controlled trial designed to prevent malnutrition and malaria in children aged 6 to 59 months in Burkina Faso by combining SMC with nutritional supplementation (PACTR202507830860741). In the parent trial, eligible children were to be randomly allocated to receive either SMC + Plumpy Doz[®], SMC + Nutributter Plus[®], or standard intervention (only SMC).

2.2. Study Population and Sampling

Prior to treatment allocation and initiation of the intervention, households were identified from the HDSS database and screened for eligibility. Following the recruitment strategy of the parent trial, households with one eligible child (6 - 59 months) were selected first; if the target sample size for the main trial had not yet been reached, households with two eligible children were subsequently included until the required sample size was attained. During the household visit, all eligible

children present in the selected households were assessed. For children presenting with malaria-related symptoms, a blood smear was collected before referral to the nearest health facility for clinical evaluation and appropriate management.

2.3. Data Collection

Data were collected using a structured electronic questionnaire developed in REDCap (Research Electronic Data Capture), administered by trained field workers during household visits. Socio-demographic and household variables, including household head education and occupation, household wealth quintile, and geographical coordinates, were extracted from the HDSS database.

Information on malaria prevention practices (use of insecticide-treated nets, mosquito coil burning, and indoor insecticide spraying), anthropometric measurements (mid-upper arm circumference, weight, height), and axillary temperature were collected during the home visit.

Capillary blood was collected by trained nurses to prepare thick smears and to measure hemoglobin concentration. Microscopy slides were read independently by two certified microscopists, and any discrepancies were resolved by a senior expert reader.

2.4. Variables Definition

Primary outcome

The primary outcome was asymptomatic *Plasmodium* infection, defined as the detection of asexual parasites by microscopy in the absence of declared malaria-related symptoms. Because all blood smears were collected during household visits, outside of health facilities, and without care-seeking by participants, all microscopy-positive cases identified in the survey were classified as asymptomatic carriers. Secondary outcome was the prevalence of gametocyte carriage.

Exposure variables

The main exposure variables included child age and sex, household wealth quintile, head-of-household occupation, and education. Household wealth quintiles were derived from HDSS socioeconomic data using a routine asset-based household wealth index and classified into five ordered categories, from lowest to highest.

2.5. Statistical Analysis

Descriptive statistics were used to summarize household and participant characteristics, malaria-prevention practices, and the prevalence of asymptomatic infection with corresponding 95% confidence intervals (95% CI). To assess factors associated with asymptomatic *Plasmodium* infection, modified Poisson regression with robust variance estimation, implemented through generalized estimating equations (GEE) was used to estimate prevalence ratios and their 95% confidence intervals. This approach was selected because the outcome (asymptomatic infection) was relatively common in the study population, and logistic regression

would therefore overestimate the risk by yielding odds ratios that diverge from the true risk ratio. The modified Poisson model, as described by Zou (2004), provides direct and interpretable estimates of prevalence ratios, which are more appropriate than odds ratios for cross-sectional studies with binary outcomes. The use of a robust sandwich variance estimator corrects for potential misspecification of the Poisson variance structure, ensuring valid standard errors even when the equidispersion assumption is not met. Because children were clustered within both households and villages, correlation was assessed at both levels. The intravillage correlation was low (ICC = 0.008), whereas the intrahousehold correlation was more substantial (ICC = 0.156). Therefore, the primary analysis accounted for clustering at the household level using a GEE framework with an exchangeable working correlation structure. The model was adjusted with number of prevention practices, mid-upper arm circumference (MUAC), village, number of households, and household size. All analyses were conducted using R version 4.5.1 (2025-06-13 ucrt).

3. Results

3.1. Household Characteristics of Enrolled Children

Most households had one infant (910, 73.7%), followed by two infants (246, 19.9%), three infants (60, 4.9%), four infants (15, 1.2%), and five infants (4, 0.3%), indicating that households with multiple infants were relatively uncommon. Household characteristics ($n = 1235$) were broadly similar across all age groups. Children lived in large households, with a median of 10 members overall. Wealth distribution was balanced across age categories, with most of the households falling into the middle and upper wealth quintiles. The majority of household heads were engaged in agriculture (77.2%), and formal employment (*i.e.* Commerce, Crafts, Farming) was rare (2.3%). Educational attainment was low across all groups, with approximately 89.7% of household heads having no formal schooling. Overall, the socioeconomic profile of participating households was relatively homogeneous (Table 1).

Table 1. Household characteristics of enrolled children by age category.

Characteristic	<1 year	[1 - 2] years	[2 - 3] years	[3 - 4] years	Overall
	(N = 88)	(N = 343)	(N = 398)	(N = 406)	(N = 1235)
Number of households within the compound					
Mean (SD)	2.74 (1.83)	2.92 (2.14)	3.02 (2.53)	3.14 (2.34)	3.01 (2.32)
Median [Min, Max]	2.93 [1.00, 11.0]	2.93 [1.00, 17.0]	2.00 [1.00, 17.0]	2.93 [1.00, 17.0]	2.93 [1.00, 17.0]
Number of members per household					
Mean (SD)	10.8 (5.75)	9.90 (6.59)	10.5 (6.94)	10.7 (6.67)	10.4 (6.68)
Median [Min, Max]	11.5 [1.00, 32.0]	10.0 [1.00, 65.0]	10.0 [1.00, 70.0]	10.0 [1.00, 39.0]	10.0 [1.00, 70.0]

Continued

Wealth quintile					
Lowest	27 (30.7%)	80 (23.3%)	64 (16.1%)	62 (15.3%)	233 (18.9%)
Second	13 (14.8%)	44 (12.8%)	57 (14.3%)	44 (10.8%)	158 (12.8%)
Third	13 (14.8%)	52 (15.2%)	74 (18.6%)	75 (18.5%)	214 (17.3%)
Fourth	18 (20.5%)	87 (25.4%)	114 (28.6%)	125 (30.8%)	344 (27.9%)
Highest	17 (19.3%)	80 (23.3%)	89 (22.4%)	100 (24.6%)	286 (23.2%)
Household head occupation					
Agriculture	69 (78.4%)	264 (77.0%)	306 (76.9%)	315 (77.6%)	954 (77.2%)
None/Other	12 (13.6%)	44 (12.8%)	52 (13.1%)	56 (13.8%)	164 (13.3%)
Small-scale work	6 (6.8%)	28 (8.2%)	25 (6.3%)	30 (7.4%)	89 (7.2%)
Formal job	1 (1.1%)	7 (2.0%)	15 (3.8%)	5 (1.2%)	28 (2.3%)
Household head education					
No education	67 (76.1%)	310 (90.4%)	358 (89.9%)	373 (91.9%)	1108 (89.7%)
Primary	15 (17.0%)	16 (4.7%)	18 (4.5%)	21 (5.2%)	70 (5.7%)
Secondary or higher	6 (6.8%)	17 (5.0%)	22 (5.5%)	12 (3.0%)	57 (4.6%)

3.2. Baseline Demographic and Anthropometric Characteristics

Among 1662 children from 1235 household visited before the SMC campaign, anthropometric indicators such as weight, height, and MUAC increased consistently with age, reflecting expected developmental patterns (Table 2). The overall prevalence of fever (axillary temperature ≥ 37.5) was low (2.5%), with minimal variation across age groups, suggesting limited symptomatic infection at baseline.

Table 2. Baseline demographic and anthropometric characteristics of children by age group.

	<1 year (N = 171)	[1 - 2] years (N = 510)	[2 - 3] years (N = 495)	[3 - 4] years (N = 486)	Overall (N = 1662)
Age (months)					
Mean (SD)	0.80 (0.11)	1.51 (0.27)	2.49 (0.28)	3.48 (0.27)	2.31 (0.96)
Median [Min, Max]	0.80 [0.59, 0.99]	1.51 [1.00, 1.99]	2.52 [2.00, 2.99]	3.52 [3.00, 3.99]	2.29 [0.59, 4.00]
Sex					
Female	81 (47.4%)	254 (49.8%)	247 (49.9%)	240 (49.4%)	822 (49.5%)
Male	90 (52.6%)	256 (50.2%)	248 (50.1%)	246 (50.6%)	840 (50.5%)
Temperature (°C)					
Mean (SD)	36.4 (0.544)	36.4 (0.583)	36.3 (0.587)	36.4 (0.602)	36.4 (0.586)
Median [Min, Max]	36.4 [35.0, 37.8]	36.4 [35.0, 39.1]	36.3 [35.0, 39.4]	36.4 [35.0, 39.2]	36.3 [35.0, 39.4]
Fever (Temperature $\geq 37.5^\circ$)					
Fever	3 (1.8%)	15 (2.9%)	11 (2.2%)	12 (2.5%)	41 (2.5%)
No fever	168 (98.2%)	495 (97.1%)	484 (97.8%)	474 (97.5%)	1621 (97.5%)

Continued

Weight (kg)					
Mean (SD)	8.49 (7.84)	9.11 (1.45)	10.8 (1.86)	12.3 (2.21)	10.5 (3.37)
Median [Min, Max]	7.60 [5.20, 109]	9.00 [5.30, 16.6]	10.9 [5.70, 19.0]	12.5 [6.20, 19.9]	10.1 [5.20, 109]
Height (cm)					
Mean (SD)	69.4 (4.86)	75.7 (5.65)	82.5 (6.50)	89.0 (8.09)	81.0 (9.25)
Median [Min, Max]	69.0 [50.0, 88.0]	75.0 [60.0, 97.0]	83.0 [62.0, 102]	91.0 [64.0, 115]	80.0 [50.0, 115]
MUAC (cm)					
Mean (SD)	13.9 (0.937)	14.0 (0.938)	14.4 (0.964)	14.8 (0.954)	14.4 (1.02)
Median [Min, Max]	13.7 [12.0, 17.0]	14.0 [10.1, 17.0]	14.4 [11.0, 18.2]	15.0 [13.0, 18.2]	14.2 [10.1, 18.2]

3.3. Utilization Patterns of Malaria Prevention Tools among Children in Nanoro

Figure 1 shows a strong predominance of insecticide-treated net (ITN) use among children in the study population. ITNs were the most commonly reported malaria prevention tool, with 1367 children using ITNs alone, and 1660 ITN reports overall when combinations with other tools were included. By contrast, the other prevention tools were much less frequently reported, including approximately 285 reports each for coil burning and other tools, 158 for spray use, and 146 for repellent gel cream. This UpSet plot further indicates that the vast majority of children relied on a single prevention method, overwhelmingly ITN use alone, whereas only a small minority reported combinations of multiple tools.

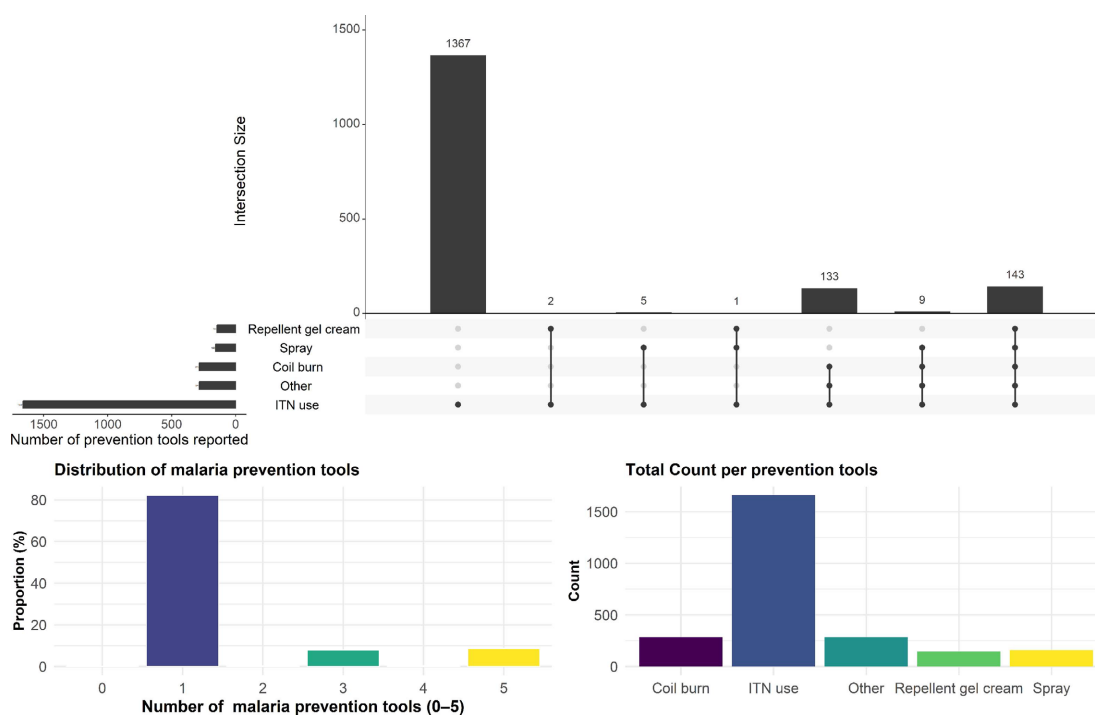


Figure 1. Utilization patterns of malaria prevention tools among children in Nanoro.

3.4. Prevalence of Malaria in the Study Population

The overall prevalence of malaria infection in the study population was 25.5% (95% CI: 23.5% - 27.7%). The prevalence of asymptomatic *Plasmodium* infections increased sharply with age. Infants under 1 year had a relatively low prevalence of 12.3% (95% CI: 8.2% - 18.0%), and children aged 1 - 2 years showed a similar level at 12.9% (95% CI: 10.3% - 16.1%). However, infection prevalence rose noticeably in older age groups. Among children aged 2 - 3 years, nearly one-third were infected (32.7%), and the highest prevalence was observed in those aged 3 - 4 years at 36.0% (Table 3).

Table 3. The prevalence of asymptomatic *Plasmodium* infections according to the age group.

Age category	Positive	Total	Prevalence (95% CI)
All population	424	1662	25.5% (23.5%, 27.7%)
<1 year	21	171	12.3% (8.2%, 18.0%)
[1 - 2) years	66	510	12.9% (10.3%, 16.1%)
[2 - 3) years	162	495	32.7% (28.7%, 37.0%)
[3 - 4] years	175	486	36.0% (31.9%, 40.4%)

Figure 2 shows the distribution of log-transformed parasitemia levels across different age classes among children with positive parasitemia. Overall, parasitemia levels were significantly higher in older age groups. Children aged < 1 year and those between 1 - 2 years had lower median parasite densities compared to children aged 2 - 3 years and 3 - 4 years, who showed markedly higher and more variable parasitemia levels. This trend suggests increasing exposure and parasite burden with age.

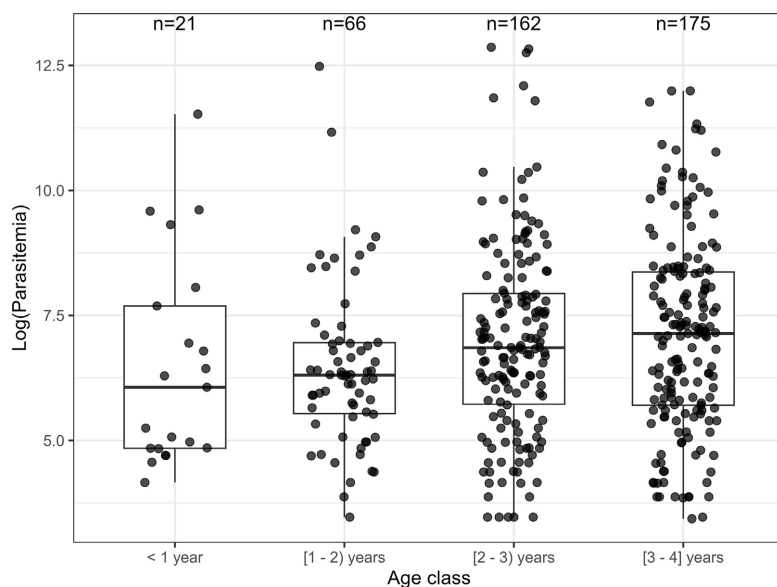


Figure 2. Distribution of log-transformed parasitemia levels across different age classes among children with positive parasitemia.

It was noticeable that gametocyte carriage was detected in 2.2% of the study population (95% CI: 1.6 - 3.1).

3.5. Factors Associated with Malaria Infection

In adjusted analyses, age was the strongest factor associated with parasite prevalence. Compared with infants < 1 year, children aged 1 - 2 years showed no difference in prevalence (PR = 1.14; 95% CI: 0.71 - 1.83), whereas those aged 2 - 3 years (PR = 3.03; 95% CI: 1.98 - 4.63) and 3 - 4 years (PR = 3.43; 95% CI: 2.25 - 5.23) had almost a threefold higher prevalence (**Table 4**). Male children had higher prevalence than females (PR = 1.21; 95% CI: 1.03 - 1.42).

No significant associations were observed for nutritional status (MUAC), household composition (number of households or household size), socioeconomic status (wealth quintile), head-of-household occupation, or education level. Similarly, the number of prevention practices used did not show a measurable association with parasite prevalence.

Table 4. Multivariable modified Poisson regression identifying factors associated with asymptomatic malaria infection.

Characteristic	N	n	PR	95% CI	p-value
Age category					
<1 year (ref)	171	21	1	—	
[1 - 2] years	510	66	1.14	0.71, 1.83	0.6
[2 - 3] years	495	162	3.03	1.98, 4.63	<0.001
[3 - 4] years	486	175	3.43	2.25, 5.23	<0.001
Sex					
Female	822	190	1	—	
Male	840	234	1.21	1.03, 1.42	0.023
Axillary Temperature \geq 37.5					
No	1621	408	1	—	
Yes	41	16	1.49	1.00, 2.24	0.052
Wealth quintile					
Fourth (ref)	468	132	1	—	
Highest	436	108	0.91	0.72, 1.14	0.4
Lowest	277	70	0.98	0.76, 1.27	0.9
Second	194	43	0.82	0.60, 1.13	0.2
Third	287	71	0.85	0.66, 1.11	0.2
Head of household occupation					
Agriculture (ref)	1299	323	1	—	
Formal job	34	10	1.53	0.72, 3.24	0.3
None/Other	214	59	1.07	0.84, 1.37	0.6
Small-scale work	115	32	1.17	0.86, 1.58	0.3

Continued

Head of household education					
No education (ref)	1499	382	1	—	
Primary	94	26	1.17	0.83, 1.63	0.4
Secondary or higher	69	16	0.79	0.42, 1.49	0.5

Adjusted with Village, Number of prevention practices, Mid-upper arm circumference (MUAC), Number of households, and Household size.

4. Discussion

This study shows that the overall prevalence of infections was substantial, and older pre-school children carried a disproportionate burden of asymptomatic parasitemia. Age-related gradients similar to those observed here have been consistently documented across the Sahel region, where parasite carriage typically ranges from 20% to 40% at the start of the rainy season [9]-[12] [20]. Infants exhibited the lowest prevalence, likely reflecting protection from residual maternal antibodies, lower mobility, and closer household head/caregiver protection [21]-[23]. In contrast, increased independence, outdoor activity, and cumulative exposure may explain the sharp increase in infection among children older than two years, consistent with longitudinal studies from several sub-Saharan African countries [20] [24].

The high prevalence of parasitemia observed nearly before the SMC delivery has important operational implications. The protective efficacy of SP-AQ depends on both clearance of existing parasitemia and short-term chemoprophylaxis [19] [25] [26]. A large baseline reservoir may reduce the observable impact of SMC if parasites are not fully cleared due to incomplete adherence, suboptimal dosing, vomiting, or chemoprophylactic failure [25]. Persistent parasitemia at the time of SMC administration has been associated with increased risk of breakthrough malaria during the same transmission season [14]. If untreated, such infections may progress from asymptomatic to clinical malaria, and eventually to severe disease, especially in younger children [14] [15]. These findings highlight the need for improved adherence monitoring, community counselling, and pharmacovigilance during SMC campaigns.

The detection of gametocytes (2.6%) provides further evidence of sustained transmission potential despite preventive measures. Even low-density gametocytemia is sufficient to infect mosquitoes and perpetuate the transmission between SMC cycles [27]. These results support the need to reinforce integrated vector management, particularly ITN durability, replacement campaigns, and complementary strategies addressing outdoor or early-evening biting, which has been increasingly documented in West Africa [28].

Importantly, children older than three years had the highest prevalence and parasite densities, suggesting that this age group represents a particularly important reservoir. Although still eligible for SMC, their increasing exposure and

waning maternal immunity may reduce the relative protection provided by chemoprevention alone. Evidence from recent West African trials shows that combining SMC with malaria vaccination (RTS, S/AS01 or R21/Matrix-M) yields additive protection and substantially reduces clinical malaria by more than 60% [6] [8] [29] [30]. Vaccination of this older pre-school group may therefore enhance protection during the high-risk period when exposure intensifies.

No socioeconomic or household-level characteristics were associated with infection risk, likely reflecting the relative socioeconomic homogeneity of rural Nanoro. The lack of association with malaria prevention practices, dominated by reported ITN use, probably reflects behavioral and entomological factors rather than absence of effect [31]. In Burkina Faso, substantial outdoor and early evening vector biting could limit ITN protection, which is largely confined to indoor sleeping hours. As a result, an estimated 10 percent of malaria transmission persists despite high ITN coverage, occurring when human activity overlaps with vector exposure outside net use [31]. In addition, self-reported ITN use often overestimates actual protection by 8 to 13.6 percent, potentially biasing assessments of ITN effectiveness [32] [33]. These findings highlight the persistence of residual transmission and the need for complementary malaria control strategies.

This study has several strengths. HDSS-linked random sampling ensured strong population representativeness, while data collection conducted immediately prior to the SMC implementation enabled an accurate estimation of baseline infection prevalence. The use of GEE-based modified Poisson regression provided valid population-averaged effect estimates and appropriately accounted for within-village clustering. Nevertheless, some limitations should be considered. Microscopy may have underestimated the true prevalence by missing sub-patent infections detectable only by molecular methods such as PCR. The cross-sectional design captures infection status at a single time point, precluding assessment of temporal dynamics or causality. In addition, malaria prevention practices were self-reported and therefore subject to recall and social desirability bias.

Despite these limitations, the study provides valuable insights into the asymptomatic malaria reservoir in a high-burden Sahelian setting and underscores the need to adapt malaria control strategies, particularly for older pre-school children who remain highly exposed despite their eligibility for seasonal malaria chemoprevention.

5. Conclusions

Asymptomatic *Plasmodium* infections were highly prevalent among children under five in Nanoro immediately before the 2025 SMC cycle, with older pre-school children being the main reservoir of infection and transmission. Age was the main determinant of infection risk, whereas socioeconomic and household characteristics showed no meaningful influence. These findings underscore the need to strengthen malaria control strategies for children aged 2 - 4 years, who experience increasing exposure but remain incompletely protected by SMC alone.

Enhanced community-based surveillance, improved adherence monitoring dur-

ing SMC, and reinforcement of ITN and vector management strategies are essential to reduce the asymptomatic reservoir. Integrating malaria vaccination with SMC could provide additional protection, particularly for older pre-school children who carry the highest burden of the infection. This baseline assessment will be critical for evaluating the impact of the MalNut intervention and guiding future malaria control strategies in Burkina Faso.

Ethics Approval and Consent to Participate

The study was approved by the ethic committee of Burkina Faso (Comité d’Ethique pour la Recherche en Santé, n°2024-10-308). Written informed consent was obtained from parents or legal guardians prior to participation.

Availability of Data and Materials

The datasets generated and/or analysed during the current manuscript are not publicly available due to ethical and confidentiality restrictions but are available from the corresponding author on reasonable request, subject to institutional approval and applicable data-sharing regulations.

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Authors’ Contributions

TR conceived the analysis idea, conducted the statistical analysis, interpreted the data, and drafted the first version of the manuscript. HT, SO, PS and BK contributed to study design and supervision of field implementation. IB, MKS, WEC WGM and KD contributed to data collection and laboratory procedures. HT, PS and BK contributed to data interpretation and critical revision of the manuscript. All authors read and approved the final manuscript.

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Declaration of Generative AI and AI-Assisted Technologies

The authors used ChatGPT (OpenAI) solely for English language editing and im-

provement of writing clarity. All scientific content, interpretation, and conclusions were developed and validated by the authors.

Conflicts of Interest

The authors declare that they have no competing interests.

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