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CLIMATIC DETERMINANTS OF MALARIA INCIDENCE IN BOKKOS TOWN, PLATEAU STATE, NIGERIA

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Background: Human health is significantly dependent on natural environmental factors, including air temperature, precipitation amount and relative humidity. Under global climate change, the variability of these parameters is increasing, leading to increased extreme weather events and altered seasonal disease patterns, particularly in countries with limited adaptive resources. One of the most climate-sensitive infectious diseases is malaria, a life-threatening disease caused by parasites of the genus *Plasmodium*, transmitted through the bites of infected female *Anopheles* mosquitoes. Recent research confirms that climate warming is shifting malaria risk zones to higher latitudes and altitudes, complicating disease forecasting and control. Understanding relationships of climatic factors and biological mechanisms is key to developing effective epidemiological surveillance strategies, climate-sensitive forecasting models, and resilient public health adaptation measures in the face of ongoing climate change. Despite compelling global and national evidence confirming the crucial role of temperature, precipitation, and relative humidity in controlling malaria transmission, detailed empirical studies quantifying the impact of these climatic factors on the seasonal and interannual dynamics of malaria incidence in Bokkos remain lacking. **Objectives:** Bokkos represents a unique natural-climatic laboratory for studying climate-driven changes in malaria epidemiology in the highlands of Nigeria. The objective of this study is to identify and quantify the relationships between climatic factors such as ambient temperature, precipitation, and relative humidity and malaria incidence dynamics in Bokkos from 2014 to 2023. Unlike previous studies, which have primarily focused on lowland or regionally aggregated data, this work aims to provide new empirical evidence reflecting the specificity of high-altitude conditions and their transformation under climate change. The study is based on the hypothesis that rising temperatures and changing precipitation patterns over the past decade have led to an extension of the malaria transmission season and an increase in seasonal peaks in Bokkos. **Methods:** The study was conducted in Bokkos Local Government Area located in the central part of Plateau State, Nigeria. Data on *Plasmodium* malaria cases were obtained from the medical registries of Bokkos Cottage Hospital, located in the study area. Records covered the period from March 1, 2014, to March 31, 2023, and included aggregated monthly data on the number of confirmed cases. All climate data were obtained from the Nigerian Meteorological Agency (NiMet) based on observations conducted at the Yakubu Gowon Airport weather station. The study had an observational design using retrospective medical and climate data, supplemented by questionnaire. The sample size for the socio-demographic component of the study was determined using the Cochran formula and there were 150 respondents. Quantitative data were analysed using SPSS and Microsoft Excel software. Inferential statistics, including the Pearson correlation coefficient, were used to assess the relationships between climate variables (temperature, precipitation, relative humidity) and malaria incidence. Research framework views malaria incidence in Bokkos as the result of complex interactions between climatic elements and the local ecosystem. **Results:** It was found that during the study period malaria was the most prevalent disease, accounting for 53% of all recorded cases. Typhoid fever ranked second (22%), followed by diarrhoeal diseases (14%), while respiratory diseases showed the lowest incidence (11%). The year-round persistence of malaria transmission with pronounced seasonal peaks is supported by the frequency of visits to medical canters: 44% of respondents visited more than three times per year, 31% visited two to three times, and 25% visited once per year. Precipitation showed a positive and statistically significant association with malaria incidence ($r = 0.646$, $p < 0.05$). Relative humidity was found to have an even stronger association with malaria incidence ($r = 0.852$, $p < 0.01$). **Conclusion:** This study confirmed that malaria remains the dominant infectious disease in Bokkos, affecting more than half of the residents surveyed between 2014 and 2023. The study supported the hypothesis that changes in rainfall patterns and high relative humidity contributed to the extension of the malaria transmission season and increased seasonal peaks of disease incidence. Relative humidity proved to be a key factor, increasing adult mosquito survival and bite frequency, while significant rainfall creates favourable conditions for vector breeding. It is shown for the first time that in a high-altitude tropical climate, humidity and precipitation are decisive factors determining the seasonality and intensity of malaria outbreaks, while temperature plays a secondary role. This fills a gap in knowledge about the local determinants of malaria transmission in the highlands of Nigeria, where only generalized regional models previously existed.

Keywords: malaria; health risks; SDG 3; rainfall; relative humidity; temperature; season; highland area; West Africa.

INTRODUCTION

Climate plays a key role in shaping the conditions that determine population health and disease prevalence, serving as important environmental and social determinants of human health (Ezzati et al., 2004). Climate has a systemic influence on patterns of human activity and behaviour, including seasonal employment, migration patterns, winter and summer lifestyle patterns, and the level and nature of physical activity. These behavioural adaptations, in turn, can significantly modify the mechanisms and intensity of transmission of infectious and non-communicable diseases (Kuhn et al., 2003; Tsui et al., 2024).

Human health is significantly dependent on natural environmental factors, including air temperature, precipitation amount and distribution, and relative and absolute humidity (Wuyep & Madaki, 2020; Ezzati et al., 2004). Under global climate change, the variability of these parameters is increasing, leading to increased extreme weather events and altered seasonal disease patterns, particularly in countries with limited adaptive resources (Romanello et al., 2024; Ezzati et al., 2004).

One of the most climate-sensitive infectious diseases is malaria, a life-threatening disease caused by parasites of the genus *Plasmodium*, transmitted through the bites of infected female *Anopheles* mosquitoes (Wilkinson, 2006; Paaijmans, Imbahale, Thomas, & Takken, 2010). According to the World Health Organization (Ezzati et al., 2004), approximately 263 million cases of malaria and 597,000 deaths were reported worldwide in 2023, with sub-Saharan Africa bearing the overwhelming share of the global disease burden. The World Malaria Report 2024 indicates that Nigeria accounted for approximately 40% of all cases and 46% of deaths among the ten highest-risk countries in 2023 (Ezzati et al., 2004). Malaria remains not only a serious public health problem but also a significant socioeconomic burden. The disease is a major source of human and economic losses for households, as well as for local, state, and federal governments in Nigeria. The Federal Ministry of Health, Nigeria (FMH, 2020), estimates that annual economic losses due to treatment, burden on the healthcare system, and lost productivity exceed $190 billion.

Climate has a decisive influence on the survival, reproduction, and spatial distribution of mosquito vectors, as well as the development of the malaria parasite within the vector (Epstein et al., 1993; Wuyep & Daloeng, 2020; Ezzati et al., 2004). Temperature directly influences the rate of *Plasmodium* extrusion in the mosquito body and the frequency of blood feeding, with higher temperatures accelerating parasite development and increasing the likelihood of transmission to humans (Epstein et al., 1993; Mordecai et al., 2020).

Rainfall is one of the most significant climatic factors in malaria transmission, as it creates temporary and permanent pools of water essential for mosquito breeding. In African regions, even small changes in the amount and seasonality of rainfall can cause dramatic fluctuations in malaria incidence (Talla et al., 2025; Chapoterera et al., 2025). Typically, an increase in malaria cases is observed one to two months after the onset of intense rainfall, reflecting the biological cycle of mosquitoes and the parasite (Assefa et al., 2025).

However, the effect of precipitation is nonlinear: excessive rainfall can wash out larvae and destroy breeding sites, while prolonged dry periods lead to a reduction in mosquito populations (Talla et al., 2025). Relative humidity also plays a significant role, as mosquito survival is significantly higher at humidity levels above 60% (Neddermeyer et al., 2023; Masse et al., 2025). During the harmattan period in northern Nigeria, low humidity and high dust concentrations reduce mosquito lifespan and, consequently, malaria transmission, whereas with the return of rains, a sharp increase in malaria incidence is observed (Wuyep & Daloeng, 2020).

Current climate change is already leading to increased temperatures and changing rainfall patterns in various regions of Nigeria, including Plateau State, making malaria transmission seasons longer, more intense, and less predictable (IPCC, 2007; Babaie et al., 2018). Recent research confirms that climate warming is shifting malaria risk zones to higher latitudes and altitudes, complicating disease forecasting and control (Rocklöv & Dubrow, 2020; Ryan et al., 2023).

Thus, malaria represents a clear example of a disease in which the interaction of climatic factors, biological mechanisms, and socioeconomic conditions forms a complex and dynamic system of risks. Understanding these relationships is key to developing effective epidemiological surveillance strategies, climate-sensitive forecasting models, and resilient public health adaptation measures in the face of ongoing climate change (Ezzati et al., 2004; Romanello et al., 2024).

Bokkos Town, located in Bokkos Local Government Area of Plateau State, Nigeria, is located at an altitude of approximately 1,400 m above sea level and is characterized by a distinct seasonal climate, including a rainy season (April – October) and a dry season (November – March) (NiMet, 2020). The area has a tropical savanna climate, but the relatively cool temperatures associated with the high altitude have traditionally been considered a limiting factor for the survival and reproduction of mosquito vectors compared to lowland areas.

In recent years, however, observed temperature changes indicate an increase in the climatic suitability of high altitude areas for *Anopheles* mosquito populations. Recent research suggests that climate warming is expanding the altitudinal range of vectors and increasing the risk of malaria transmission in previously less affected areas (Megersa & Luo, 2025). In this context, Bokkos represents a unique natural-climatic laboratory for studying climate-driven changes in malaria epidemiology in the highlands of Nigeria.

Despite compelling global and national evidence confirming the crucial role of temperature, precipitation, and relative humidity in controlling malaria transmission, detailed empirical studies quantifying the impact of these climatic factors on the seasonal and interannual dynamics of malaria incidence in Bokkos remain lacking. Specifically, how variations in climatic parameters shape annual malaria peaks in high-altitude climates remains understudied. This knowledge gap limits the ability of health workers and public health authorities to predict outbreaks early and plan preventive and control measures in a timely manner.

The objective of this study is to identify and quantify the relationships between climatic factors such as ambient temperature, precipitation, and relative humidity and malaria incidence dynamics in Bokkos from 2014 to 2023. Unlike previous studies, which have primarily focused on lowland or regionally aggregated data, this work aims to provide new empirical evidence reflecting the specificity of high-altitude conditions and their transformation under climate change.

The study is based on the hypothesis that rising temperatures and changing precipitation patterns over the past decade have led to an extension of the malaria transmission season and an increase in seasonal peaks in Bokkos. It is hypothesized that the combination of elevated temperatures and high relative humidity after the onset of the rainy season creates optimal conditions for mosquito survival and accelerated *Plasmodium* development, which is reflected in a statistically significant increase in the number of registered cases with a time lag of several weeks.

MATERIALS AND METHODS

Study area description

Bokkos Local Government Area (L.G.A.) is located in Plateau State, Nigeria, in the central part of the state (Figure 1). The district's capital is Bokkos Town, which is located at approximately 9°15′ north latitude and 8°53′ east longitude (Wuyep et al., 2022). The local government area covers an area of approximately 1,682 – 1,700 km^2 and borders Mangu District to the east, Barkin Ladi to the north, Kuan Pan to the south, and Nasarawa State to the west (NPC, 2006).

Due to its high altitude, Bokkos and the surrounding areas are characterized by moderate temperatures, with maximum temperatures around 20 °C and average minimum temperatures of approximately 18 °C. The climate of the area is clearly divided into two main seasons: wet and dry. The rainy season lasts from April to October, while the dry season coincides with the harmattan period, which is accompanied by dry and dusty north-easterly winds coming from the Sahara Desert and lasts from November to March each year. Overall, weather conditions in Bokkos are relatively cool, especially from July to August and from November to February.

Relative humidity in Bokkos is closely related to temperature, with rising temperatures contributing to increased atmospheric water vapor. The area is characterized by pronounced seasonality, with approximately 5 – 6 months of predominantly rainfall alternating with dry periods throughout the year (Wuyep et al., 2022).

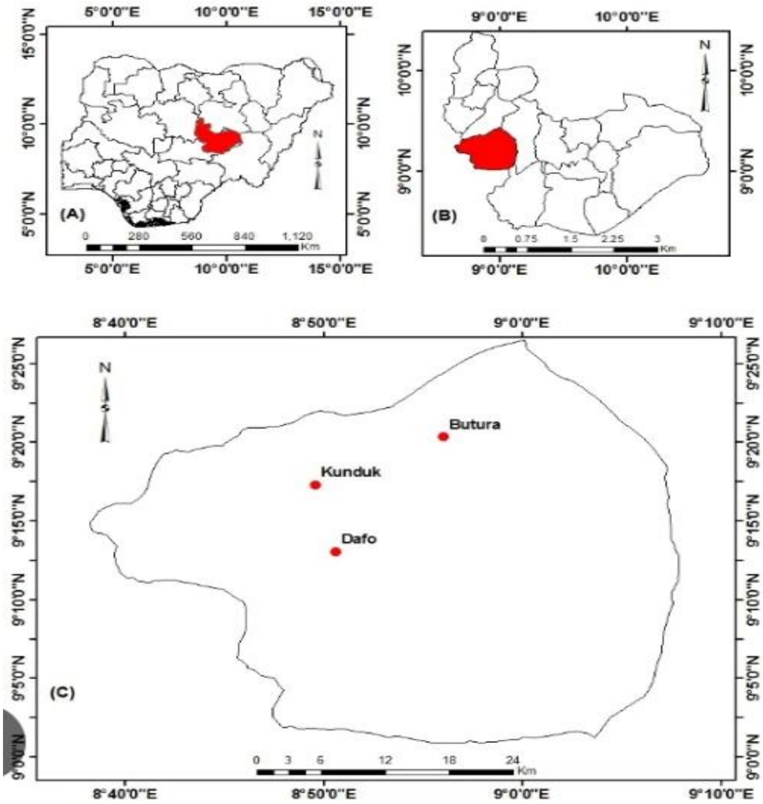


Figure 1. Map of study area

The economic activity of the people of Bokkos is primarily focused on agriculture and related "green economy" activities (Ogbole et al., 2024). The soil cover is predominantly acidic soils, including Ultisols, Alfisols, and Inceptisols, and the vegetation is characterized by a combination of montane grasslands and patches of sparse forest (Wuyep et al., 2024). According to the 2022 census, the population of the district is approximately 264,100 and is predominantly made up of the Rone, Kulere, and Musher ethnic groups, who rely heavily on rain-dependent agriculture, including the cultivation of Irish potatoes, maize, and vegetable crops (Wuyep et al., 2022).

Data sources

Malaria incidence data

Data on *Plasmodium* malaria cases were obtained from the medical registries of Bokkos Cottage Hospital, located in the study area. All registered cases were laboratory confirmed using either light microscopy of blood smears or rapid diagnostic tests (RDTs), which comply with standard malaria diagnostic protocols in endemic areas.

Records covered the period from March 1, 2014, to March 31, 2023, and included aggregated monthly data on the number of confirmed cases. Medical information collected at the facility level undergoes multi-level consolidation, verification, and validation within the hierarchical structure of the health system to ensure data completeness, consistency, and quality.

Meteorological data

Meteorological data were obtained from the Nigerian Meteorological Agency (NiMet) based on observations conducted at the Yakubu Gowon Airport weather station. Climate parameters included monthly minimum and maximum air temperatures (°C), precipitation (mm), and relative humidity (%) for the period from March 2014 to March 2023, covering the town of Bokkos.

Using official meteorological service data ensures representativeness and comparability, and is consistent with approaches widely used in modern climate-epidemiological studies analysing the impact of climate variability on the dynamics of vector-borne diseases.

Study design, sample size determination and analysis

The study had an observational design using retrospective medical and climate data, supplemented by a population questionnaire. The sample size for the sociodemographic component of the study was determined using the Cochran formula (1977) and was 150 respondents.

Participants were selected using a multistage sampling procedure. First, the town of Bokkos was divided into administrative districts, after which households in each district were selected using simple random sampling. As a result, 150 questionnaires were collected and validated from respondents living in the selected districts. Additional data on malaria incidence were obtained from the medical records of Bokkos Cottage Hospital.

Quantitative data were analysed using SPSS and Microsoft Excel software. Descriptive statistics were used to summarize climate parameters and malaria incidence rates, including means, standard deviations, and seasonal distributions. Inferential statistics, including the Pearson correlation coefficient, were used to assess the relationships between climate variables (temperature, precipitation, relative humidity) and malaria incidence. This approach is widely used in empirical studies aimed at identifying climate-related patterns of malaria transmission at the local and regional levels.

2.2.4 Ethical approval and consent to participate

The study was conducted in compliance with ethical principles applicable to research involving human subjects. Appropriate ethical approval was obtained, and informed consent was provided by all survey participants. Confidentiality of personal data was strictly maintained, and participants were guaranteed the right to withdraw from the study at any stage without any consequences.

Theoretical framework

The study draws on a unified conceptual framework, drawing primarily on weather-disease theory and ecological health theory (Perera et al., 2025; Eyzaguirre et al., 2025), complemented by principles of environmental determinism (McMichael et al., 2006). This framework views malaria incidence in Bokkos as the result of complex interactions between climatic elements and the local ecosystem.

According to Bouma & van der Kaay (2003), weather conditions control the reproduction, survival, and development of mosquitoes, the primary vectors of malaria. Meanwhile, Martens et al. (1995) emphasize that human health is closely interrelated with the ecosystem, since changes in environmental climatic parameters can contribute to an increase in the number and size of mosquito breeding sites, an acceleration of the incubation period and the lifespan of malaria carriers, directly affecting the transmission of diseases. The environmental determinism approach proposed by McMichael et al. (2006) confirms that the physical environment, including the high altitude and highly seasonal climate of Bokkos, shapes both the population's exposure to and vulnerability to malaria. Together, this theoretical framework explains the observed seasonal fluctuations in malaria incidence: a sharp increase in cases after the onset of the rains and a decline during the dry Harmattan season. Thus, this conceptual framework provides a solid theoretical foundation for analysing the relationship between climatic factors and malaria incidence in the study area.

RESULTS AND DISCUSSION

Morbidity rates in the study area

Table 1 shows the distribution of disease incidence in the study area for the period 2014 – 2023. Based on medical records, malaria was the most common disease, accounting for 53% of all reported cases. Typhoid fever was second (22%), followed by diarrhoea (14%), and respiratory diseases had the lowest incidence (11%). These data confirm earlier findings by Nanvyat et al. (2018), who noted that malaria remains the main climate-sensitive disease in the highlands of Plateau State.

Table 1. Disease incidences (2014 – 2023)

Variables	Frequency	Percentage, %
Malaria	80	53
Respiratory infection	16	11
Typhoid	33	22
Diarrhoea disease	21	14
Total	**150**	**100**

The results highlight that malaria continues to be the leading cause of health care seeking, consistent with the overall global pattern of climate-related infectious diseases (Ezzati et al., 2004; Liu et al., 2021).

Frequency of visits to medical institutions

Figure 2 shows the distribution of frequency of visits to health facilities by respondents during the period 2014 – 2023. Forty-four percent (44%) of respondents visited health centres more than three times a year, 31% two to three times, and 25% once a year. These data indicate persistent year-round malaria transmission with pronounced seasonal peaks, which is consistent with the observations of Abeku (2007) and Daloeng (2019), who emphasize that epidemics typically follow periods of abnormal weather activity due to the potential for infection to spread in populations without robust immunity (Abeku, 2007), and that peaks in incidence are often delayed by climate change, suggesting that climate variation is a key driver of seasonal malaria peaks in some parts of Nigeria (Daloeng, 2019). Climatic variability, including variations in rainfall and temperature, contributes to the prolongation of the malaria transmission season (Paaijmans et al., 2010).

Respondents' perception of climate

Table 2 shows that 77% of respondents noted changes in weather conditions over the past ten years, while 23% either did not notice any changes or could not describe them. These data indicate a high level of awareness of climate change among the local population, but with varying levels of perception. The results are consistent with the findings of Emmanuel et al. (2024), according to which over 70% of respondents in Jos south identify increased and variable rainfall as a key indicator of climate change.

Observed changes in climate elements

Table 3 shows that precipitation variability explains approximately 57% of the variation in observed weather patterns, while temperature variations account for 14% and extreme weather events account for 29%. These findings support the findings of Riley et al. (2021), who note that precipitation variability is a key climate signal for high-mountain communities.

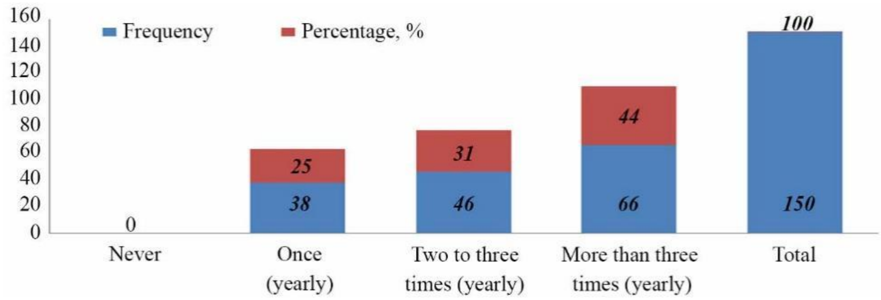


Figure 2. Treatment periods

Table 2. Climate perception of respondents (2014 – 2023)

Variables	Frequency	Percentage, %
Noticed changes in the weather patterns over 10 years	115.5	77
Do not perceive or not aware of climate change pattern	34.5	23
Total	**150**	**100**

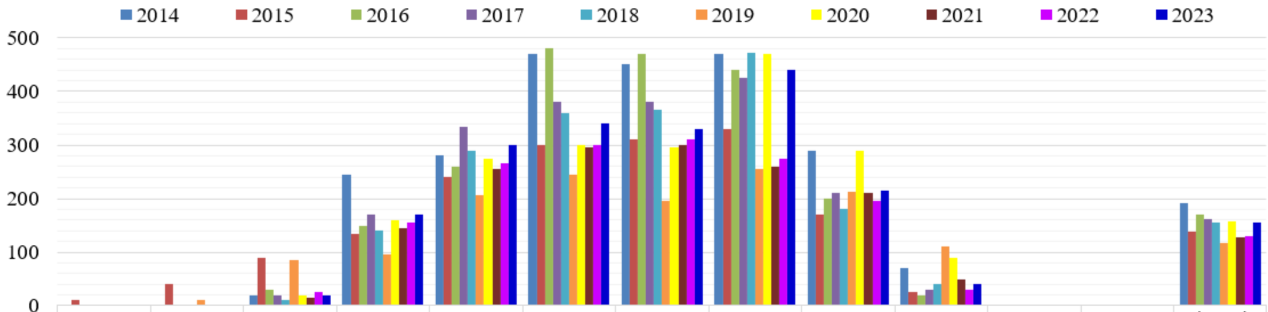
Table 3. Observed changes on climate elements

Variables	Frequency	Percentage, %
Temperature	21	14
Irregular rainfall	85	57
More extreme weather event	44	29
Total	**150**	**100**

Trends of rainfall (2014 – 2023)

Figure 3 shows that rainfall fluctuates in Bokkos, with a decreasing trend in overall rainfall regularity, as evidenced by the linear trend line. The decrease in rainfall may be related to climate change, defined as the long-term statistical variation in weather patterns that persists for decades (IPCC, 2001; Wuyep et al., 2022). This trend supports the findings of Yamba et al. (2023), who showed that malaria transmission in Africa is dependent on the timing and intensity of rainfall rather than the annual amount of rainfall.

Daloeng (2019) noted that increased rainfall expands existing mosquito habitats and creates new ones, leading to increased disease incidence, especially in the absence of preventive measures.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
2014	0	0	20	245	280	470	450	470	290	70	0	0	191.25
2015	10	40	90	135	240	300	310	330	170	25.1	0	0	137.51
2016	0	0	30	150	260	480	470	440	200	20	0	0	170.83
2017	0	0	20	170	335	380	380	425	210	30	0	0	162.5
2018	0	0	10	140	290	360	365	472.6	180	40	0	0	154.8
2019	0	10	85	95.9	205.4	245.7	195.1	255	213.3	110	0	0	117.95
2020	0	0	20	160	275	300	295	470	290	90	0	0	158.33
2021	0	0	15	145	255	295	300	260	210	50	0	0	127.5
2022	0	0	25	155	265	300	310	275	195	30	0	0	129.58
2023	0	0	20	170	300	340	330	440	215	40	0	0	154.58

Figure 3. Trends of rainfall (2014 – 2023) (NiMet office, Jos, 2024)

According to Stensgaard et al. (2016), a minimum average rainfall of 1.5 mm/day is necessary to maintain the aquatic stage of the *Anopheles* mosquito life cycle, highlighting the key role of rainfall in malaria epidemiology.

Trends in temperature distribution (2014 – 2023)

Figure 4 shows that temperature fluctuates in the study area, but not as significantly as precipitation. The highest temperatures were observed in 2015, and the lowest in 2020. Increasing temperature reduces the incubation period of *Plasmodium* falciparum in *Anopheles* mosquitoes from approximately 26 days at 20 °C to 12 days at 25 °C (Megersa & Luo, 2025). This explains the stable presence of malaria even at an altitude of 1,400 m above sea level in Bokkos.

Recent research shows that increasing temperature can both accelerate malaria transmission and limit mosquito dispersal at extremely high temperatures (>38 °C), highlighting the complex nonlinear relationship between temperature and disease incidence (Talla et al., 2025; Murugan & Shrivastav, 2025).

Trends in the distribution of relative humidity (2014 – 2023)

Figure 5 shows that relative humidity fluctuated over the study period, with minimum values in 2020 and a peak in 2023. During most rainy seasons, relative humidity exceeded 60%, which promotes adult mosquito survival and increases biting frequency (Liu, 2021; Megersa & Luo, 2025).

The increase in relative humidity in 2023 coincided with record malaria incidence, highlighting the critical role of humidity in

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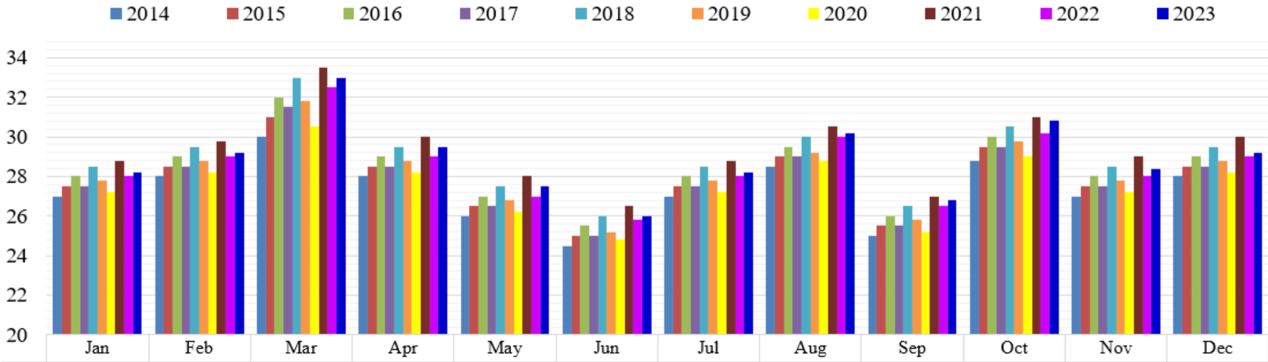
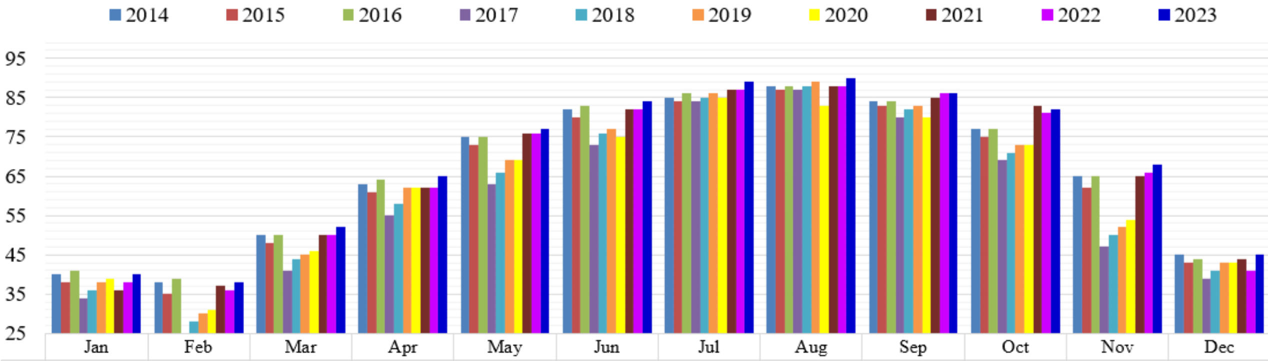
controlling transmission. These results are consistent with studies by Neddermeyer et al. (2023), which showed that high humidity prolongs mosquito lifespan and increases malaria transmission. Recent reviews and studies also confirm that high humidity promotes mosquito survival and biting activity, thereby increasing the potential for malaria transmission by extending vector lifespan and population density (Megersa & Luo, 2025).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2014	27	28	30	28	26	24.5	27	28.5	25	28.8	27	28
2015	27.5	28.5	31	28.5	26.5	25	27.5	29	25.5	29.5	27.5	28.5
2016	28	29	32	29	27	25.5	28	29.5	26	30	28	29
2017	27.5	28.5	31.5	28.5	26.5	25	27.5	29	25.5	29.5	27.5	28.5
2018	28.5	29.5	33	29.5	27.5	26	28.5	30	26.5	30.5	28.5	29.5
2019	27.8	28.8	31.8	28.8	26.8	25.2	27.8	29.2	25.8	29.8	27.8	28.8
2020	27.2	28.2	30.5	28.2	26.2	24.8	27.2	28.8	25.2	29	27.2	28.2
2021	28.8	29.8	33.5	30	28	26.5	28.8	30.5	27	31	29	30
2022	28	29	32.5	29	27	25.8	28	30	26.5	30.2	28	29
2023	28.2	29.2	33	29.5	27.5	26	28.2	30.2	26.8	30.8	28.4	29.2

Figure 4. Trend in temperature distribution (2014 – 2023) (NiMet office, Jos, 2024)

Humidity, in combination with temperature and precipitation, exerts the most significant influence on malaria transmission. Specifically, relative humidity levels between 66% and 81%, coupled with temperatures ranging from 20 °C to 33 °C, create a favourable warm and moist environment that supports mosquito development, parasite maturation, and enhanced malaria transmission (Wu & Huang, 2022). A similar pattern was observed in the seasonal dynamics of *Anopheles* mosquitoes in Zambia, where periods of sustained high humidity were associated with peaks in mosquito activity and survival, potentially increasing malaria incidence (Duque et al., 2022). However, heavy rainfall can disrupt breeding sites by washing away larvae, while prolonged dry conditions can limit mosquito populations due to the lack of standing water (Talla et al., 2025).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2014	40	38	50	63	75	82	85	88	84	77	65	45
2015	38	35	48	61	73	80	84	87	83	75	62	43
2016	41	39	50	64	75	83	86	88	84	77	65	44
2017	34	25	41	55	63	73	84	87	80	69	47	39
2018	36	28	44	58	66	76	85	88	82	71	50	41
2019	38	30	45	62	69	77	86	89	83	73	52	43
2020	39	31	46	62	69	75	85	83	80	73	54	43
2021	36	37	50	62	76	82	87	88	85	83	65	44
2022	38	36	50	62	76	82	87	88	86	81	66	41
2023	40	38	52	65	77	84	89	90	86	82	68	45

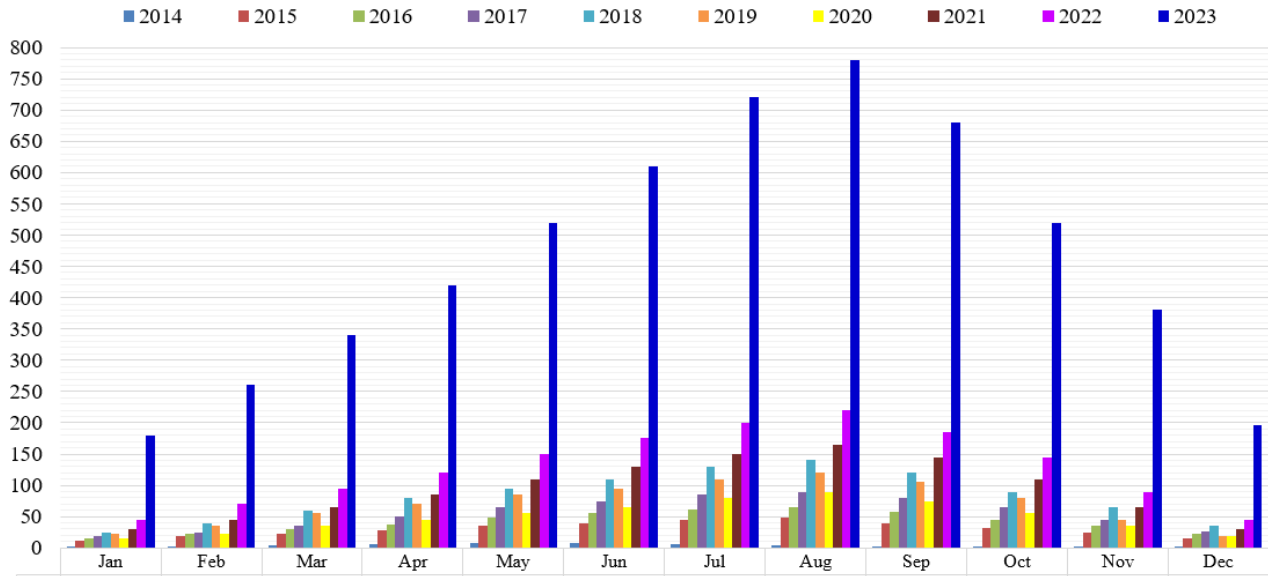
Figure 5. Trend in the distribution of relative humidity (2014 – 2023) (NiMet office, Jos, 2024)

Trends on the incidences of malaria (2014 – 2023)

Analysis of malaria incidence (Figure 6) demonstrates a pronounced increase in the number of reported cases over the period from 2014 to 2023, rising from 48 cases recorded during the cold dry season of 2014 to 5,127 cases in 2023. Distinct peaks in malaria incidence are observed approximately one to two months following the rainy season (October – November), thereby confirming the classical time-lag effect described by Abeku (2007) and Thomas et al. (2025). Similarly, Tariq et al. (2025) identified time lags between malaria incidence and rainfall ranging from 7 to 15 weeks. At a time lag of 15 weeks, a stable relationship between rainfall and malaria cases was identified until rainfall amounts reached 120 – 150 mm, while the relationship between malaria incidence and temperature was observed to peak within the range of 22 – 30 °C.

High malaria incidence is strongly associated with increased rainfall levels, which promote the formation of stagnant water and create favourable environmental conditions for mosquito breeding. During the rainy season, female *Anopheles* mosquitoes deposit their eggs, resulting in a subsequent increase in the adult vector population. These findings are in consistent with malaria transmission models proposed by Pascual et al. (2008) and Talla et al. (2025), and they confirm that the rainy season, together with associated climatic variability, remains a principal determinant of malaria transmission in high-altitude regions.

Consequently, the results of this study demonstrate that the interaction between precipitation, temperature, and relative humidity, in combination with the biological characteristics of both the mosquito vector and the malaria parasite, directly governs the seasonality and dynamics of malaria incidence in Bokkos. This evidence provides an important scientific basis for the development of effective malaria prevention strategies and the planning of early warning and surveillance activities.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2014	2	3	4	6	7	8	6	4	3	2	2	1
2015	12	18	22	28	35	40	45	48	40	32	25	15
2016	15	22	30	38	48	55	62	65	58	45	35	22
2017	18	25	35	50	65	75	85	90	80	65	45	27
2018	25	40	60	80	95	110	130	140	120	90	65	35
2019	22	35	55	70	85	95	110	120	105	80	45	18
2020	15	22	35	45	55	65	80	90	75	55	35	18
2021	30	45	65	85	110	130	150	165	145	110	65	30
2022	45	70	95	120	150	175	200	220	185	145	90	45
2023	180	260	340	420	520	610	720	780	680	520	380	197

Figure 6. Trend on the incidences of malaria (2014 – 2023) (Primary Health Care, Bokkos, 2024)

Relationship between precipitation, relative humidity and temperature on malaria incidence

An analysis of correlations between climate variables and malaria incidence in Bokkos revealed that precipitation and relative humidity had the most significant impact, while temperature showed a weak and negative correlation Table 4.

Precipitation showed a positive and significant association with malaria incidence ($r = 0.646$, $p < 0.05$, Table 4). This indicates that increased precipitation is directly associated with increased malaria cases. The results are consistent with the findings of Bationo et al. (2021), the World Bank Group (2022), and Ekpa et al. (2023), who found a positive correlation between precipitation and malaria incidence in similar African highlands. The mechanism behind this effect is explained by mosquito biology: rainfall creates stagnant water necessary for the development of *Anopheles* larvae, increasing vector density and promoting malaria transmission (Pascual et al., 2008; Paaijmans et al., 2010).

Relative humidity was found to be even more strongly associated with malaria incidence ($r = 0.852$, $p < 0.01$, Table 4). High humidity increases the lifespan of adult mosquitoes and the frequency of bites, creating favourable conditions for *Plasmodium* transmission. These results support Bouma (2003) and Liu (2021), who showed that humidity is a key factor in the survival of malaria vectors, especially during the rainy season, when the number of aquatic habitats for mosquitoes increases.

Temperature in the study area showed a weak negative correlation with malaria incidence ($r = -0.194$), which is not statistically significant. This result highlights the complex and nonlinear nature of the effect of temperature on malaria transmission. The results are consistent with the observations of Sissoko et al. (2017) and Ouedraogo et al. (2018) who noted a gradual increase in malaria incidence with moderate temperature increases and a decrease at extremely high temperatures. The mechanism for this phenomenon is linked to mosquito biology: *Anopheles* gambiae, the main vector in the region, exhibits increased mortality at temperatures above 35 °C, limiting malaria transmission intensity (Christiansen-Jucht et al., 2014).

Interpretation considering the time-lag effect

It is important to emphasize that the analysis conducted in the present study did not explicitly account for time lags between changes in climatic factors and malaria incidence. The literature indicates that seasonal peaks in malaria incidence often occur no earlier than four weeks following periods of intense rainfall or high humidity (Abeku, 2007). These time lags can be explained by the biological cycle of mosquitoes and the incubation period of *Plasmodium* within the vectors (Paaijmans et al., 2010; Megersa & Luo, 2025). Therefore, future studies should incorporate climatic time lags to more accurately model and predict seasonal fluctuations in malaria incidence, particularly in high-altitude regions where ecosystem responses to climatic variations may be delayed.

Table 4. Statistical analysis results: Pearson correlation, 2014 – 2023 monthly data

Climate element	r-value	p-value	Interpretation
Rainfall	0.646	< 0.05	Strong positive significant relationship
Relative humidity	0.852	< 0.01	Very strong positive highly significant relationship
Temperature	-0.194	> 0.05	Weak, non-significant relationship

Overall, the findings of this study provide direct support for the weather-disease theory (Zong et al., 2024), the ecological theory of health (Eyzaguirre et al., 2025), and regional empirical observations by Zong et al. (2024), which collectively demonstrate that precipitation and humidity are key climatic determinants of malaria transmission in the African highlands. At the same time, the observed weak influence of temperature underscores the importance of adopting a comprehensive approach that considers not only average climatic parameters but also their variability, extreme events, and lag effects. Such an approach is critical for developing early warning systems and planning effective preventive interventions.

As several earlier studies have shown, mosquito adaptation is strongly influenced by both humidity and temperature, with high humidity promoting vector survival and feeding behaviour. Therefore, malaria prevention strategies should explicitly consider humidity-related factors to better forecast transmission patterns and enhance vector control measures. Proactive measures can be implemented to predict outbreaks, optimize the allocation of resources for vector management, and prepare for potential future increases in case numbers. This approach enables timely interventions before climate-driven rises in malaria incidence occur, thereby improving both prevention and treatment outcomes (Talla et al., 2025).

Possible approaches to addressing the problem

The implementation of a malaria early warning system using NiMet forecasts of rainfall, temperature, and relative humidity could significantly improve the effectiveness of preventive measures in Bokkos. Such forecasts would enable the distribution of antimalarial drugs and long-lasting insecticidal nets (LLINs) and the mobilization of rapid response teams 4 – 15 weeks before expected seasonal peaks. Scientific evidence shows that malaria episodes in highlands, including Bokkos, an increase in malaria cases is observed about a month after the rains begin, making advance planning crucial to reduce the incidence (Abeku, 2007; Paaijmans et al., 2010).

Pre-season drainage and watercourse cleaning campaigns, jointly implemented by the Bokkos LGA Environmental Health Unit and local community development associations, can minimize the formation of stagnant water, which serves as a breeding ground for mosquitoes. This approach will reduce the intensity of seasonal malaria outbreaks, which is supported by empirical data on the influence of aquatic habitats on *Anopheles* mosquitoes (Stensgaard et al., 2016; Daloeng, 2019).

Continuing and expanding the free distribution of long-lasting insecticidal nets (LLINs) with enhanced community mobilization will reach agricultural households and schools and maintain net uptake at >85%. Continued use of LLINs has been shown to reduce malaria incidence in highland areas and is a key component of integrated prevention (Bouma, 2003).

Regular educational programs delivered through local radio stations, traditional leaders, churches, and schools can increase public awareness of the link between climate factors such as irregular rainfall, stagnant water, and high relative humidity and malaria risk. Such programs can encourage early treatment seeking, increased use of nets, and environmental sanitation. Particular attention should be paid to linguistic and cultural aspects, given that 23% of study respondents do not fully understand the impact of climate change on malaria (Emmanuel et al., 2024).

Overall, the comprehensive implementation of these evidence-based interventions has the potential to significantly reduce the preventable burden of malaria in Bokkos, including reducing the number of cases and associated economic and social losses. This integrated approach is consistent with current WHO recommendations and recent research findings in similar settings (Bationo et al., 2021; Ekpa et al., 2023).

CONCLUSION

This study confirmed that malaria remains the dominant infectious disease in Bokkos, affecting more than half of the residents surveyed between 2014 and 2023. The analysis revealed a clear seasonal pattern: the number of cases increases sharply 1 – 2 months after the onset of the rainy season, which is associated with mosquito breeding in stagnant water.

These data support part of the original hypothesis: changing rainfall patterns and high relative humidity contributed to the extension of the malaria transmission season and increased seasonal peaks in incidence. Relative humidity proved to be a key factor, increasing adult mosquito survival and bite frequency, while significant rainfall creates favourable conditions for vector breeding. Thus, the extension of the transmission season and increased peaks in incidence are explained by climate change, primarily related to water conditions and humidity.

At the same time, rising temperatures within the cool, high-altitude range of Bokkos did not show a statistically significant direct effect on malaria incidence. This suggests that at high altitudes, water availability and high humidity outweigh the effects of temperature. Thus, the study found that the role of temperature as a determinant of malaria transmission in high-altitude zones may be limited.

The novelty of this study lies in its detailed quantitative analysis of the relationship between climate elements and malaria incidence in the highland town of Bokkos over a ten-year period. It is shown for the first time that in a high-altitude tropical climate, humidity and precipitation are decisive factors determining the seasonality and intensity of malaria outbreaks, while temperature plays a secondary role. This fills a gap in knowledge about the local determinants of malaria transmission in the highlands of Nigeria, where only generalized regional models previously existed.

The results open up prospects for accurately predicting seasonal peaks in malaria incidence and developing targeted preventive strategies, including pre-season distribution of insecticidal nets, sanitation measures, and educational programs. Thus, the study not only confirmed the initial hypothesis but also contributed new empirical data on the local climatic determinants of malaria transmission in highland conditions.

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Author's statements

Contributions

All authors contributed to the study's conception and design. Conceptualization: W.S.Z.; Data curation: I.P.A.; Formal analysis: D.H.M.; Investigation: W.S.Z.; Methodology: D.H.M.; Project administration: I.P.A.; Writing – original draft: W.S.Z.; Writing – review & editing: D.H.M.

Declaration of conflicting interest

The authors declare no competing interests.

Financial interests

The authors declare they have no financial interests.

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Data availability statement

Data used for the study would be made available on request.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

This study adhered to ethical guidelines for research involving human participants, as approved by the Institutional Research Committee. Informed consent was obtained from all individuals who participated in the study.

Additional information

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