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Spatiotemporal epidemiology of indigenous and imported malaria cases in Goa, western India

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Abstract

Background The state of Goa in western India is world-renowned for its coastline and attracts millions of tourists across the world. Historically, Goa was among the malaria-endemic states in India, with *Plasmodium vivax* contributing to the majority of the cases. Past malaria outbreaks in Goa have been linked to construction activities, and imported malaria cases threaten malaria elimination efforts in the state.

Methods The malaria data from the National Centre for Vector Borne Disease Control (NCVBDC) and the Directorate of Health Services, Goa was used to study the spatiotemporal dynamics of *Plasmodium falciparum*, *P. vivax*, and mixed infection in Goa from 2000–2023. The spatiotemporal distribution of indigenous and imported malaria cases from 2014–2023 in the different primary/urban/community health centres (PHC/UHC/CHCs) of Goa was analysed using GIS. The spatiotemporal changes of the last three decades in Goa's land use/land cover (LU/LC) were assessed using Landsat satellite images, and its effect on malaria distribution was analysed.

Results Over the study period (2000–2023), *P. vivax* contributed to 78.2% of the caseload. The malaria trend fluctuated from 2000 to 2008, with a steep decline observed from 2009 onwards, and in 2023, zero indigenous cases were reported. The six health centres of Candolim, Margao, Siolim, Vasco, Mapusa, and Panaji reported 57.8% of the total indigenous and imported malaria cases in Goa during 2014–2023. With 292 cases in 2023, the Porvorim UHC has emerged as a new hotspot of imported malaria cases. The LU/LC change analysis shows a four-fold increase of built-up area, from ~ 70 sq. km in 1991 to 260 sq. km in 2024, with strong spatial overlap between new built-up areas and malaria cases.

Conclusion Due to the concerted parasite and vector control strategies of the state health department, Goa has achieved the target of zero indigenous malaria cases in 2023. Despite achieving this milestone, the threat of imported malaria cases leading to local outbreaks remains a serious concern.

Keywords Goa, Malaria, Imported cases, Indigenous cases, Epidemiology

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Background

India has made significant strides in its efforts to eliminate malaria by 2030; there has been a tenfold decrease in malaria cases from 2.09 million in 2001 to 0.2 million in 2023 [1]. One of the important challenges India faces in its malaria elimination efforts is the threat of migrant workers re-introducing malaria in areas of declining malaria transmission.

Goa, the smallest state in India, is located in the western coast within the Konkan region. Post-liberation from the Portuguese in 1961, Goa has undergone drastic ecological, demographical changes, and rapid urbanization (35% increase in the urban population in the last decade) to support tourism, which is the major source of revenue for the state [2, 3]. Goa attracts millions of visitors every year to its beaches; from 0.9 million in 1997, the number of visitors has increased to ~ 7 million in 2022 [4]. The rapid increase in tourism due to national and international travellers has fuelled Goa's construction boom [5]. Thousands of skilled and unskilled migrant workers, arriving from many malaria-endemic sites, including East and North East India, have been employed in Goa's construction activities [6]. Ever since the major malaria outbreak in Panjim, Goa's capital city, in 1986 [7], malaria continues to be a major public health concern in the state. Past malaria outbreaks in Goa have been associated with sites, with accelerated construction activities [8, 9]. The migrant workers from high transmission settings could be asymptomatic carriers and the source for local malaria outbreaks in Goa's low transmission malaria settings. A greater concern is these construction workers could facilitate the migration of drug-resistant parasites from east and northeast to the urban centres in the west and southwest India [10–12]. Goa's tropical climate (temperature:18–36.2°C, relative humidity: 75–95%, and annual rainfall: 2500-3500mm, mostly from May to October) favours perennial malaria transmission [13]. *Anopheles stephensi* is the major urban malaria vector in Goa [14]. The curing water in construction sites is a major breeding site for *An. stephensi* in Goa [15]. In the last decade, *Anopheles subpictus* has emerged as a secondary malaria vector in Goa, especially during the dry season [14, 16].

India is targeting zero indigenous malaria cases by 2027 and certification of malaria elimination by 2030 [17]. To achieve the target, India has developed a "National Strategic Plan for malaria elimination 2023–27 program" focusing on malaria elimination efforts at the district level [18]. Goa is in the list of category 1 states, where API is < 1, and is approaching malaria elimination [18]. Goa was expected to achieve malaria elimination by 2020 [19]. However, because of the Covid-19 pandemic, Goa's malaria elimination target was extended till 2023 [20]. In the last decade, Goa has seen a steep decrease in malaria cases, especially among the native Goans [21]. Despite the overall decrease in the malaria caseload, the imported malaria cases due to the migrant workers pose a huge challenge to malaria elimination efforts in Goa. Here, the spatiotemporal distribution of Goa's malaria cases in the last decade (2014–23) was mapped at the level of primary/urban/community health centres (PHCs/UHCs/CHCs) to highlight the enormous malaria burden posed by migrant workers. Furthermore, the effect of land use/land cover (LU/LC) changes on malaria distribution in the contiguous urban centres of Goa is analysed. As Goa is pushing towards the final phase of malaria elimination, this analysis details the space–time trend of malaria epidemiology in the state, and the challenges that lie ahead in eliminating malaria and preventing its re-establishment.

Methods

Study site

Goa, bound by latitudes 14° 53′ 57″ N to 15° 47′ 59″ N and longitudes 73° 40′ 54″ E to 74° 20′ 11″ E, covers an area of 3,702 square kilometres with a coastline stretching 105 km. Goa's population is ~ 1.5 million, and ~ 62% of the people reside in urban areas. Goa has two districts and 12 talukas. The North-Goa district has 15 PHCs, 2 UHCs, and one district hospital. The South-Goa district has 15 PHCs, 2 UHCs, and one district hospital. The spatial distribution of Goa's population (2011 census) and PHC/UHC/CHCs are shown in Fig. 1. The population density is high (> 25,000) in the cities of Panaji, Vasco, Mapusa, and Margao. The villages in the eastern part of the state are less populated (< 5000).

Malaria data

The 2000–23 malaria data of the two districts were obtained from the National Centre for Vector Borne Disease Control (NCVBDC). The PHC/UHC/CHC wise indigenous and imported malaria cases data was obtained from the National Vector Borne Disease Control Programme (NVBDCP), Directorate of Health Services, Goa. The data includes total malaria cases, *Plasmodium falciparum*, *Plasmodium vivax*, mixed infection cases (coinfections with *Pf* and *Pv)*, and deaths due to malaria cases. The malariometric indices—annual parasite incidence (API) [(annual malaria cases/population) × 1000], annual falciparum incidence (AFI) [(Annual *P. falciparum* cases/population) × 1000], yearly slide falciparum rate (SFR) [(slides positive for *P. falciparum* in a year/ blood slides examined) × 100] and yearly slide vivax rate (SVR) [(slides positive for *P. vivax* in a year/ blood slides examined) × 100] in North and South Goa districts for 2000–2010, 2011–2019 and 2020–2023 were calculated

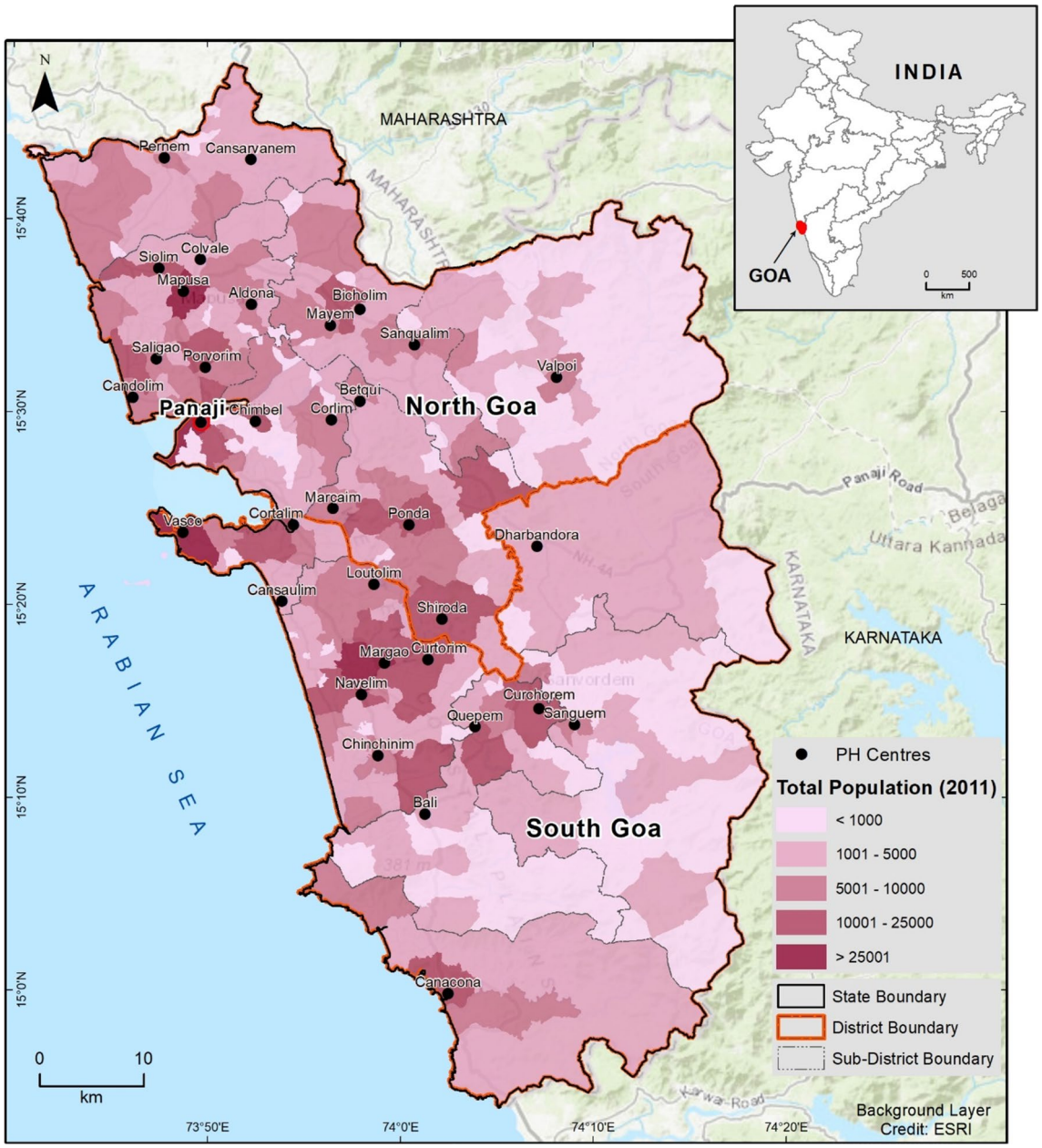

Fig. 1 Location of Goa state and the administrative units. Location of Goa state (inset map) and the administrative units (state, districts, sub-districts and villages). The village-wise distribution of the total population, as per Census 2011, is shown with a gradual colour ramp (dark shade represents population density > 25,000). The locations and names of the state's capital (Panaji) and PHCs are overlaid. The background map represents the topography of the area

from population data as per the census 2001 [22], census 2011 [23], and the projected population for 2020 by the International Institute for Population Science [24], respectively.

Malaria cases were classified as either indigenous or imported according to the National Centre for Vector Borne Disease Control guidelines [18, 25]. Briefly, a case is considered imported when *Plasmodium* infection was contracted outside Goa, while indigenous denotes the infection was acquired in Goa, with no evidence of being imported or being directly linked to an imported case [25]. Introduced case is a locally contracted case that has solid epidemiological evidence connecting it to a known imported case (first-generation local transmission) [18]. Any migrant worker from a malaria-endemic region who tests positive for malaria within fourteen days of arrival

to Goa is categorized as an imported case [26]. The medical officer in the health centre categorizes each case after getting detailed information on the patient's socio-demographic profile, travel history, medical history related to the current illness, diagnostic test results, treatment provided, potential sources of infection, and recent contacts who may have been exposed to malaria. From 2014 to 2022, indigenous and imported were the only two categories listed. In 2023, 77 introduced cases were reported but were not included under the imported cases to maintain uniformity.

Spatiotemporal mapping

Data of indigenous and imported malaria cases from 2014 to 2023 in the different health centres of Goa were added as attributes to the PHC/UHC/CHC locations and choropleth maps were prepared using the ArcGIS 10.4 software (https://desktop.arcgis.com).

LU/LC assessment

The long-term spatiotemporal changes in the LU/LC in Goa were assessed through the satellite images obtained from the USGS Earth Explorer site (https://earthexplorer.usgs.gov/). As the periods 1990–1991 and 2023–2024 fall under normal rainfall and vegetation conditions, and the month of February usually has clear skies, the Landsat 5 images for February 1991 and the Landsat 9 images for February 2024 were selected for the analysis of LU/LC change. The metadata of the satellite data used in the study is presented in the Supplementary table S1. The satellite images were processed through an unsupervised classification algorithm (K-means classifier) with 120 classes and a maximum of 12 iterations. The clusters identified through the spectral signatures of the images were evaluated and assigned suitable LU/LC classes based on the level-1 classification scheme. The accuracy of the classified LU/LC classes was corroborated by incorporating high-resolution Google Earth imagery, topographic information, and published Google maps. A total of 80 random points equally distributed across classes were selected to evaluate the classification accuracy. Accuracy assessments yielded an overall accuracy (Kappa Statistic) of 88.57% (0.87) for 1991 and 92.50% (0.91) for 2024 (Supplementary table S2, S3, and S4).

Results

Epidemiology of malaria cases in Goa (2000–2023)

From 2000–2013, malaria cases in Goa were not segregated as indigenous and imported. The segregation happened from 2014 onwards, and the cases shown from 2014 to 2023 are indigenous cases (Fig. 2 and Table 1). From 2000 to 2009, Goa consistently reported greater than 1000 cases/year, with an API of > 2. In the study period, the highest number of malaria cases (16,818 cases) was reported in 2002, with an API of 12.48. The cases declined in the subsequent years, but an upsurge in cases was observed in 2007 (9755 cases) and 2008 (9822 cases), with an API of 7.24 and 7.29, respectively. North Goa reported near about double the cases of South Goa until 2008. Thereafter, the difference between the two districts has narrowed as the malaria cases decreased in North Goa. The malaria trend fluctuated from 2000 to 2008, and a steep decline was observed from 2009 onwards. In 2011 and 2012, the malaria cases and API

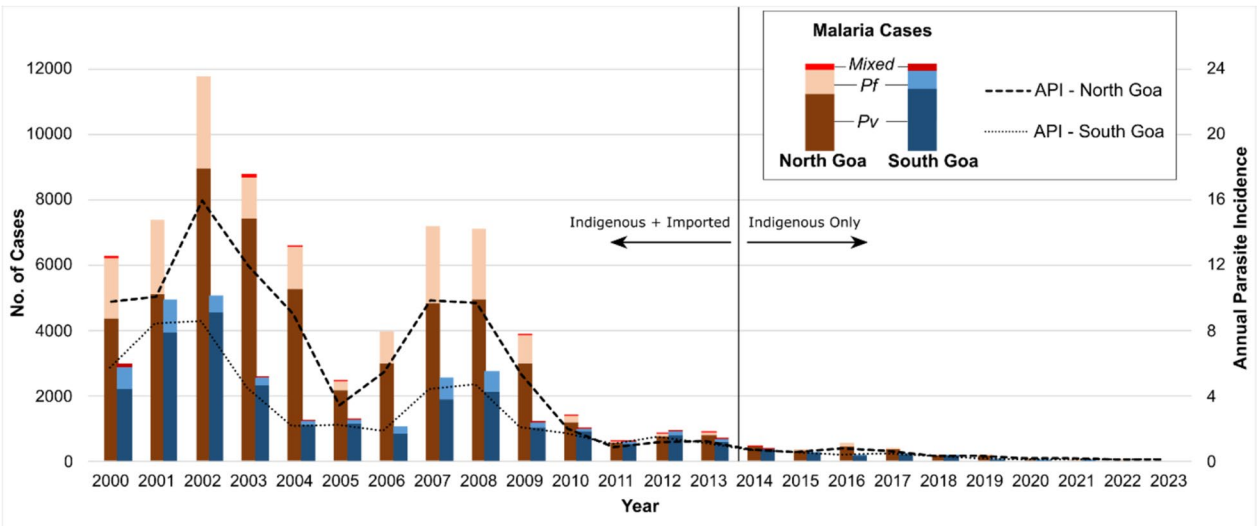

Fig. 2 Trends of malaria cases and API in North Goa and South Goa from 2000–2023. The bar graph represents the species-wise malaria cases in North Goa and South Goa. The API is represented by a dotted line for South Goa and a dashed line for North Goa. *Pf- P. falciparum, Pv- P. vivax*

Table 1 Distribution of Annual malaria cases in Goa from 2000 to 2023

Year	Malaria cases			*P. falciparum*		*P. vivax*		Mixed Infections		ABER		SPR		SFR		SVR		API		AFI		Malaria deaths	
	North Goa	South Goa	Total Cases	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa	North Goa	South Goa
2000	6276	2888	9164	1844	656	4360	2206	72	26	27.69	19.25	3.41	2.97	1	0.67	2.37	2.27	8.27	4.9	2.43	1.11	NA	NA
2001	7384	4947	12,331	2264	1046	5120	3901	NA	NA	21.81	18.98	4.46	4.42	1.37	0.94	3.09	3.49	9.73	8.4	2.98	1.78	NA	NA
2002	11,756	5062	16,818	2821	527	8935	4535	NA	NA	21.23	19.08	7.3	4.5	1.75	0.47	5.55	4.04	15.5	8.59	3.72	0.89	NA	NA
2003	8780	2590	11,370	1263	240	7428	2304	89	46	22.35	18.52	5.18	2.37	0.74	0.22	4.38	2.11	11.57	4.4	1.66	0.41	0	1
2004	6611	1228	7839	1298	89	5255	1113	58	26	19.37	15.64	4.5	1.33	0.88	0.1	3.58	1.21	8.72	2.08	1.71	0.15	6	1
2005	2478	1269	3747	290	140	2162	1117	26	12	21.99	16.52	1.49	1.3	0.17	0.14	1.3	1.15	3.27	2.15	0.38	0.24	1	0
2006	3966	1044	5010	977	219	2989	825	0	0	22.7	17.96	2.3	0.99	0.57	0.21	1.74	0.78	5.23	1.77	1.29	0.37	5	2
2007	7199	2556	9755	2381	666	4818	1890	0	0	30.3	21.34	3.13	2.03	1.04	0.53	2.1	1.5	9.49	4.34	3.14	1.13	7	4
2008	7100	2722	9822	2134	593	4966	2129	0	0	32.04	26.19	2.92	1.76	0.88	0.38	2.04	1.38	9.36	4.62	2.81	1.01	13	8
2009	3867	1189	5056	875	171	2984	1016	8	2	33.98	27.05	1.5	0.75	0.34	0.11	1.16	0.64	5.1	2.02	1.15	0.29	3	7
2010	1395	973	2368	186	86	1207	886	2	1	37.22	30.14	0.49	0.55	0.07	0.05	0.43	0.5	1.84	1.65	0.25	0.15	0	1
2011	586	601	1187	37	95	548	504	1	2	31.37	25.31	0.23	0.37	0.01	0.06	0.21	0.31	0.72	0.94	0.05	0.15	0	3
2012	826	888	1714	58	107	766	778	2	3	34.25	25.79	0.29	0.54	0.02	0.06	0.27	0.47	1.01	1.39	0.07	0.17	0	0
2013	881	649	1530	66	60	812	587	3	2	33.68	25.74	0.32	0.39	0.02	0.04	0.29	0.36	1.08	1.01	0.08	0.09	0	0
2014	458	366	824	18	20	438	344	2	2	33.96	24.04	0.16	0.24	0.01	0.01	0.16	0.22	0.56	0.57	0.02	0.03	0	0
2015	379	272	651	45	30	334	242	0	0	33.93	23.41	0.14	0.18	0.02	0.02	0.12	0.16	0.46	0.42	0.06	0.05	0	1
2016	554	188	742	102	28	452	160	0	0	32.71	23.14	0.21	0.13	0.04	0.02	0.17	0.11	0.68	0.29	0.12	0.04	0	0
2017	417	236	653	38	37	379	199	0	0	28.64	22.28	0.18	0.17	0.02	0.03	0.16	0.14	0.51	0.37	0.05	0.06	1	0
2018	215	162	377	26	24	189	138	0	0	26.8	21.42	0.1	0.12	0.01	0.02	0.09	0.1	0.26	0.25	0.03	0.04	0	0
2019	205	67	272	42	12	163	55	0	0	26.17	20.33	0.1	0.05	0.02	0.01	0.08	0.04	0.26	0.1	0.05	0.02	0	0
2020	80	22	102	23	9	57	13	0	0	12.98	9.2	0.08	0.04	0.02	0.02	0.05	0.02	0.1	0.03	0.03	0.01	0	0
2021	70	20	90	38	10	32	10	0	0	12.86	8.63	0.06	0.03	0.03	0.02	0.03	0.02	0.08	0.03	0.04	0.01	0	0
2022	2	0	2	1	0	1	0	0	0	17.88	12.83	0	0	0	0	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0	0	22.89	16.79	0	0	0	0	0	0	0	0	0	0	0	0

The above malariometic indices for North and South Goa districts for 2000–2010, 2011–2019 and 2020–2023 were calculated from population data as per the census 2001 [22], census 2011 [23], and the projected population for 2020 by the International Institute for Population Science [24], respectively

ABER annual blood examination rate; *SPR* slide positivity rate; *SFR* slide falciparum rate; *SVR* slide *vivax* rate, *API* annual parasite incidence; *AFI* annual falciparum incidence, *NA* not available

were slightly higher in South Goa. From 2010–2013, the API hovered between 1 and 2, and from 2014 onwards, the API was < 1, and in 2023, the API was zero. *P. vivax* was the predominant malaria parasite in both districts; the ratio of *P. falciparum*: *P. vivax* over the study period was ~2:7. The variation of *P. falciparum* and *P. vivax* ratio in both districts followed a similar trend. After 2010, the *P. falciparum*: *P. vivax* ratio declined along with the API in both districts. However, from 2020 onwards, as the total malaria cases reached 2 digits, the *P. falciparum*: *P. vivax* ratio tends towards equality. Similar down trends were seen with slide positivity rate (SPR), slide falciparum rate (SFR), and slide vivax rate (SVR) (Table 1).

Spatiotemporal distribution of indigenous and imported malaria cases (2014–2023)

The spatiotemporal distribution of indigenous and imported malaria cases from 2014 to 2023 in the different health centres of Goa are shown in Figs. 3 and 4, respectively. The indigenous and imported cases were detected by active and passive surveillance (Supplementary Table S5). Until 2016, four to five health centres reported > 50 indigenous malaria cases per year; it reduced to two in 2019 and none afterwards. The PHC/UHC of Candolim, Panaji, and Margao frequently reported > 50 indigenous malaria cases annually. Panaji UHC is the only centre to report > 20 indigenous cases after 2020. The number of PHCs/UHCs with > 100 imported malaria cases per year was 8 until 2018, and it reduced to five in 2019 and zero in 2020. However, in 2023, only three health centres in North Goa reported ≥ 100 imported malaria cases. The PHCs/UHCs that reported more indigenous malaria cases—Candolim, Panaji, and Margao, also consistently reported more imported malaria cases. In addition, the health centres of Vasco, Siolim, and Mapusa also frequently reported > 100 imported malaria cases annually. In 2023, the Candolim, Porvorim, and Siolim health centres reported ≥ 100 imported malaria cases; Porvorim has emerged as a new hotspot with 292 cases. At Porvorim UHC, the total number of imported cases reported during 2014–2023 was 673, and 43% of the cases were reported in 2023 alone. (Supplementary Table S6 & S7).

Compared to the South Goa district, the North Goa district reported substantially higher malaria cases, both indigenous and imported. Candolim PHC in the coastal North Goa reported the highest number (3,458 cases) of indigenous and imported malaria cases and was followed by Margao in the South Goa district with 3,070 cases. These two are followed by the PHCs/UHCs of

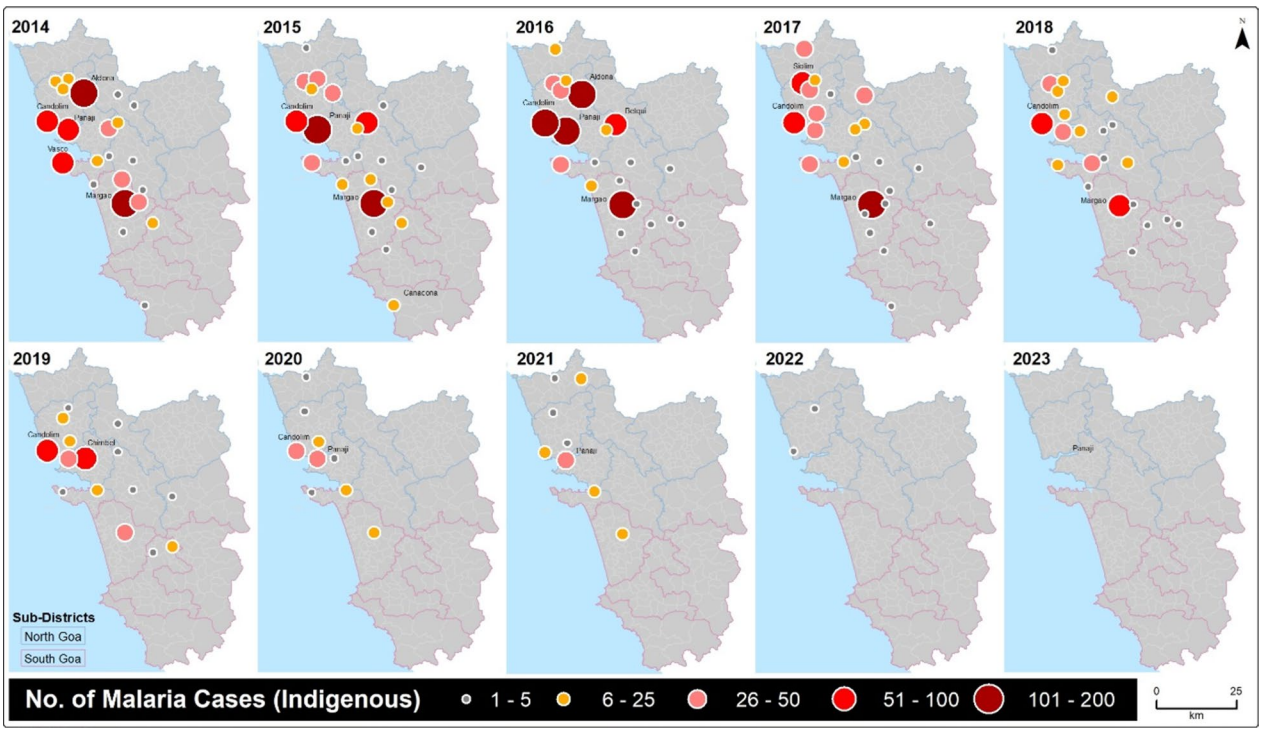

Fig. 3 Spatiotemporal distribution of indigenous malaria cases in different health centre's of Goa from 2014 to 2023. The size and colour of the circles denote the number of malaria cases; larger and darker circles denote a higher caseload. The PHCs with high caseloads are labelled. The districts of North and South Goa are shown by blue and purple boundaries, respectively

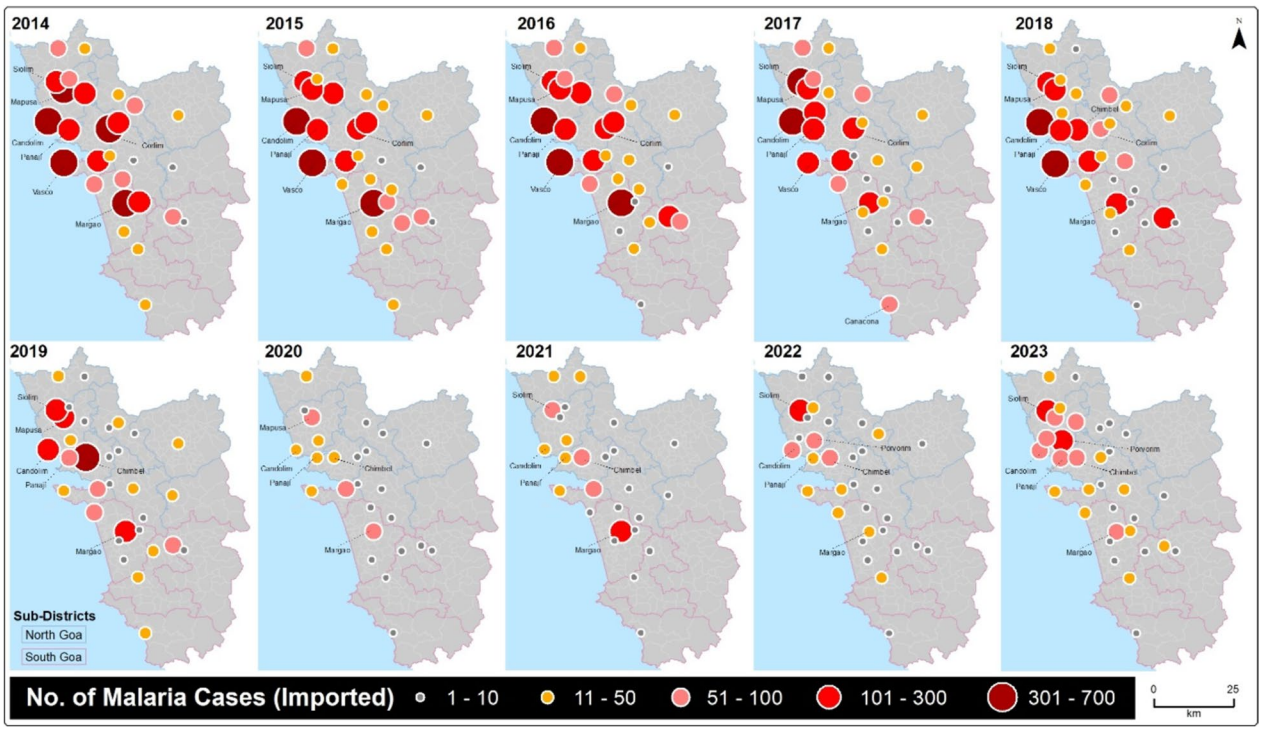

Fig. 4 Spatiotemporal distribution of imported malaria cases in different health centre's of Goa from 2014 to 2023. The size and colour of the circles denote the number of malaria cases; larger and darker circles denote a higher caseload. The PHCs with high caseloads are labelled. The districts of North and South Goa are shown by blue and purple boundaries, respectively

Vasco (2,244 cases), Siolim (2,117 cases), Mapusa (1,633 cases), and Panaji (1,587 cases) in North Goa; altogether these six PHCs reported ~ 57.8% of the total indigenous and imported malaria cases in Goa with indigenous cases being always on the lower side during the entire study period 2014–2023 (Fig. 5).

From 2018 to 2023, the percentage of *P. falciparum* and *P. vivax* among the imported cases were 22.3% (1692 cases) and 77.6% (5894 cases), respectively. The distribution of *P. falciparum* and *P. vivax* among the imported cases in the different health centres are shown in Supplementary Table S8.

LU/LC changes

The comparison of LU/LC between February 1991 and February 2024 shows notable changes in a few classes. Forest was the dominant LU/LC class in 1991 and 2024 with 68 and 67%, respectively. Even though the overall proportion showed only a minor change (~ 1%), the forest cover along the coastlines has changed considerably. Most of the forest cover along the coastline (beaches) was converted into built-up areas, while the forest cover bordering the eastern state boundary was intact. The areas between the core forests areas and built-up regions saw improvements in the forest cover; the scrublands with trees and open spaces were converted into thick forest cover. The proportion of scrublands and croplands has drastically reduced in and around the built-up regions/settlements in the North Goa district. In 1991, the total built-up area of Goa was ~ 70 sq. km (~ 2% of the total area), which increased four-fold to ~ 260 sq. km (~ 7% of the total area) in 2024. The new built-up areas are predominantly along the coastlines and arterial roads that connect coasts to the interior of the North Goa district; there is a strong spatial overlap between these new built-up areas and malaria cases. Similarly, the proportion of mining pits has also increased seven-fold from 0.7 sq. km. in 1991 to 4.7 sq. km. in 2024. Compared to 1991, the proportions of wetlands and croplands have decreased while the areas under the barren, fallow, or wasteland (these termed as miscellaneous) have considerably increased in the North Goa district.

The changes in LU/LC classes (in %) from a) 1991 (left) to b) 2024 (right) are overlaid on the map as a pie chart with the same colour codes. Forest (dark green) is the dominant LU/LC class (68% in 1991 and 67% in 2024). The built-up (red) class shows substantial changes from 1991 to 2024, both spatially and temporally. The PHC-wise total malaria cases (2014–2023) is overlaid on the 2024 image as black circles to understand the relative

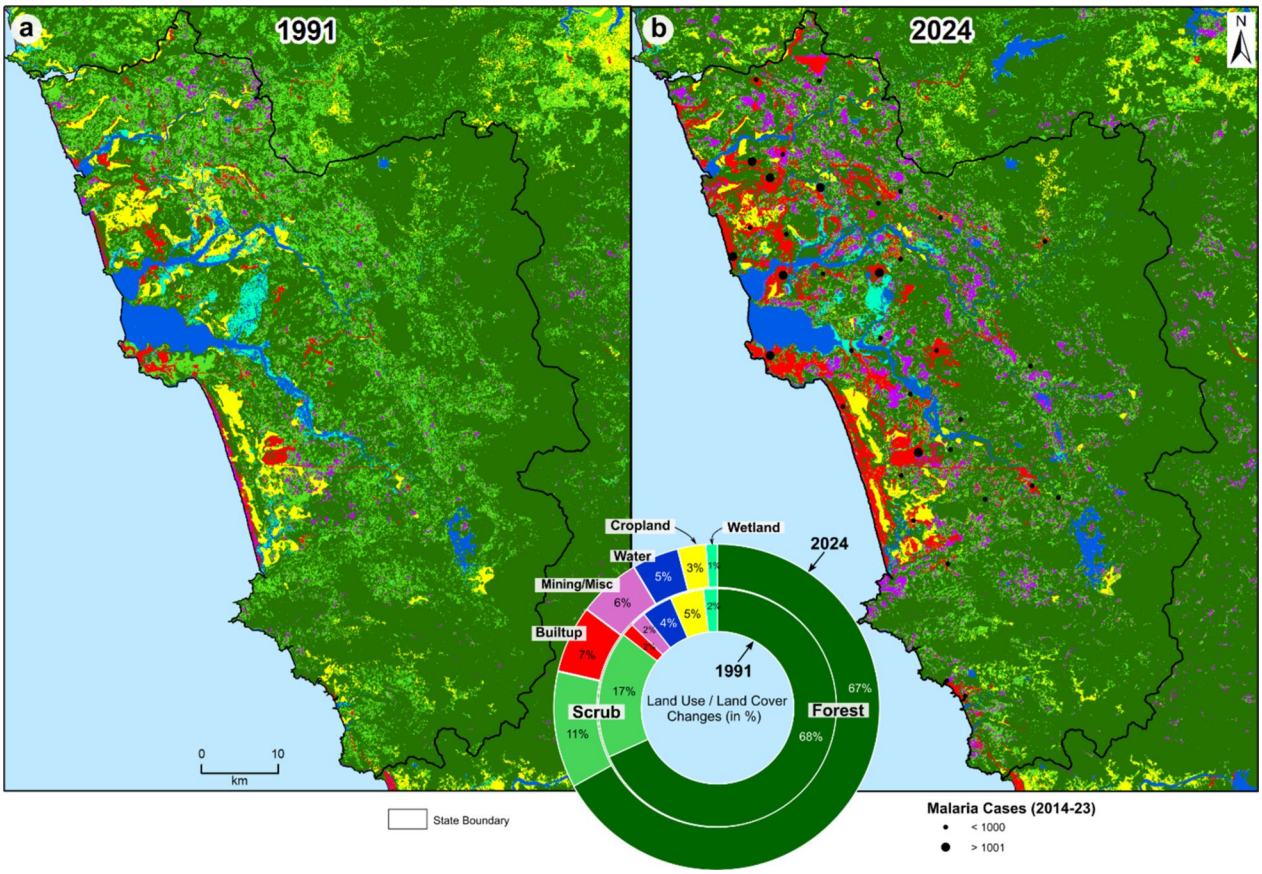

Fig. 5 Long-term changes (1991–2024) in land use/land cover (LU/LC) in Goa. The changes in LU/LC classes (in %) from a) 1991 (left) to b) 2024 (right) are overlaid on the map as a pie chart with the same colour codes. Forest (dark green) is the dominant LU/LC class (68% in 1991 and 67% in 2024). The built-up (red) class shows substantial changes from 1991 to 2024, both spatially and temporally. The PHC-wise total malaria cases (2014–2023) is overlaid on the 2024 image as black circles to understand the relative influence of new built-up class on malaria cases. The state boundary is demarcated by a black line

influence of new built-up class on malaria cases. The state boundary is demarcated by a black line.

Discussion

Goa's tropical climate with heavy rainfall due to the southwest monsoon provides an ideal ecological niche for Anopheline vectors and malaria transmission. *Anopheles stephensi* is the major vector in Goa's contiguous urban centres, especially during the monsoon season (May to October) [16]. In the drier months (November to April), *An. subpictus* sustains malaria transmission in the state [16].

In the last decade, indigenous malaria transmission in Goa has declined steeply, and the state appears to be on track to achieve its goal of malaria elimination. Despite the steep decline in indigenous cases, imported malaria cases continue to pose a significant threat to sustaining the progress. Malaria control in Goa is of regional, national and international importance. Under the National Strategic Plan for Malaria Elimination (2023–2027), Goa comes under category 1—states with an API of < 1 in all the districts [18]. In 2023, Goa joined the states and union territory under category 0—states with zero indigenous cases [27]. As an international tourist destination, Goa is an important source of imported malaria to travellers from Europe [28, 29]. Attaining and maintaining malaria-free status could boost the state's tourism and economy.

Goa's beaches attract millions of domestic and international travellers every year. To sustain tourism in Goa, scores of migrants are employed in construction activities throughout the year. The high demand and wages attract migrants from socioeconomically disadvantaged states to Goa to the construction industry and to a lesser extent to the hospitality sector [5, 30]. In the spatial analysis, clusters of high imported malaria cases in North Goa's Panaji, Aldona, Porvorim, Betqui, Candolim, and Siolim, and South Goa's Margao; these cities are the hub

of continuous construction activities and have high built-up areas. The imported malaria cases in these cities are largely attributable to the migrant construction workers [21, 31]; more than half of the malaria-positive cases in Goa Medical College (GMC) were migrant construction workers from the malaria-endemic north-central, eastern and northeastern states [31, 32].

In the malaria-endemic regions, due to high protective immunity, asymptomatic carriers of malaria are common [33, 34]. As many of the migrant workers visiting Goa are from the malaria-endemic states, a proportion of them could be asymptomatic carriers [35–38] and could harbour very low levels of gametocytes that can be detected only by molecular tools [39]. In a longitudinal study among asymptomatic individuals, gametocytes were found in 36.3% of asymptomatic carriers at least once before the parasite clearance [40]. A decade-long hospital-based study of malaria patients in Goa Medical College, Goa, showed a steep decrease in parasitaemia from 2% in 2012 to 0.35% in 2021, while the gametocyte density has increased from 146 to 385/uL, suggesting an increasing trend towards submicroscopic infections and transmission commitment, characteristic of low-transmission settings [21].

The Goa Public Health Act (1985), implemented by the directorate of health services, mandates contractors to screen the hired migrants for malaria by rapid diagnostic test (RDT) or microscopy at the local PHC so that a health card can be prepared within 24–48 h after their arrival in Goa [41]. A major limitation of malarial screening by RDT or microscopy is they cannot detect sub-microscopic infections with very low levels of parasites. Studies have shown even microscopically undetectable levels of gametocytes can be infective to mosquitoes [42–44]. The ongoing controlled feeding experiments at the National Institute of Malaria Research-Goa, show blood from asymptomatic carriers, including one from a patient who was microscopy negative but PCR positive, were infective to mosquitoes (unpublished data). The construction workers are housed in temporary shelters near the building sites. Among these workers, the undetected low-density gametocyte carriers could serve as key reservoirs for malaria transmission among workers and the local population living near the construction sites. The curing water in the construction sites is a preferred breeding ground of *An. stephensi*, the dominant malaria vector in Goa [45, 46].

In addition to the risk of local malaria transmission, these migrant workers can also introduce drug-resistant malaria parasites from NE, especially parasites resistant to sulfadoxine-pyrimethamine (SP), to the urban centres of Goa [11, 47]. In the North-East, due to resistance to SP [11, 48], lumefantrine is the recommended partner to artemether in the artemisinin-based combination therapy (ACT), while in the rest of India, the first-line anti-malarial is artesunate (AS) plus SP [49]. In Goa, treating SP-resistant parasites from NE with AS-SP might increase the pressure on artemisinin. Already, reduced sensitivity to dihydroartemisinin has been reported in isolates from several states in India, including Goa [50, 51].

In the last three decades, Goa has undergone significant changes in its LU/LC, especially in its built-up area and mining pits, which increased by four and seven-fold, respectively, from 1991–2024. Most of the built-up area and accompanying settlements, especially in the coastal parts of the North Goa district, contain a large number of water bodies, wetlands, and mining pits (fresh water collects in these pits), which serve as breeding grounds for mosquito vectors. In the last decade, Goa has seen the emergence of a new secondary malaria vector—*An. subpictus* B [16]. Recently in Goa, *Anopheles jamesii*, considered a non-malaria vector was found positive for *Plasmodium* carriage in longitudinal mosquito surveys and was shown to support sporozoite development in vitro [52]. The emergence of new vectors could be attributable to the ecological changes that have taken place in the last three decades; increasing human settlements near water bodies may have led to their increased anthropophilic behaviour. Furthermore, sustained vector-control efforts to contain *An. stephensi*, the established vector, in this region may have led to the emergence of new vectors.

With no indigenous malaria case reported in 2023, Goa is close to its malaria elimination end-game. The steep decline in malaria cases is attributable to the preventive measures implemented by the state government such as: 1) Active surveillance of malaria cases in high-risk areas such as construction sites; from 2007–2022; Goa and Mizoram are the only two states where the average annual blood examination rates surpassed 20% nationally [32], 2) Cleanliness drive and source reduction—routine screening and application of insecticides/pesticides in construction sites and anthropogenic water bodies near transmission-receptive settings, 3) Distribution of long lasting insecticidal nets to migrant workers and local vulnerable population below the poverty line, especially those living near the construction sites, 4) Screening of migrant construction workers for malaria and issuance of health cards on arrival to Goa; a fine of Rs. 10,000 per head would be imposed on the contractor if any of his workers do not have the health card as per Goa Public Health Act 1985 [53] and 5) Implementation of information, education and communication strategies such as educating the migrant workers about malaria and importance of early diagnosis and treatment, and informing the contractors/engineers to use larvicides in curing sites

and water-containers at construction sites. Goa reported zero malaria cases in the first half of the 1980s. However, malaria rebounded in the subsequent years. Even though no indigenous cases were reported in 2023, the imported cases have more than doubled from 585 in 2022 to 1,209 in 2023. From 2012–2021, the patients' profile at GMC shows that only ~ 10% of the cases are malaria-positive within one month of their arrival to Goa, indicating substantial local transmission among migrant workers [21]. As the imported malaria cases are increasing in recent years, it is a question of when and not if indigenous cases will be reported. In the long run, the current decline in indigenous cases can be sustained only when the submicroscopic gametocyte carriers are identified and treated. The migrant workers and the local vulnerable population residing closer to the construction sites should be periodically screened for submicroscopic gametocyte infections by quantitative real-time PCR (qPCR). Furthermore, migrant construction workers negative for RDT and/or microscopy should be screened by qPCR on their arrival to Goa. As the malaria cases decrease in the local population, there will be a decrease in protective immunity, and local outbreaks could lead to severe symptoms. The study by Chakrabarti et al. has shown that despite the decline in uncomplicated and severe malaria cases over the last decade, the proportion of severe malaria cases has increased in Goa [21].

The study has several limitations. The data on the socio-demographic profile of the imported malaria cases are not available, which makes it impossible to quantify the proportion of construction workers among the imported malaria cases. The lack of species wise segregation until 2017 makes it hard to assess the true proportion of *P. vivax* and *P. falciparum* among imported cases in the last decade. Active surveillance data on malaria-positive febrile and non-febrile cases in high-risk areas would have given important insights into the proportion of asymptomatic cases. Furthermore, the statistical association between malaria cases and LULC changes could not be studied due to the lack of details on patient's locations.

Conclusions

For the first time in the last two decades, Goa reported zero indigenous malaria cases in 2023. Despite the steep fall in indigenous cases, imported malaria cases have continued to rise in recent years, indicating the continuous arrival of high-risk groups positive for malaria. Continuous active surveillance, early detection and prompt treatment of migrant workers and vulnerable local population, and sustaining the ongoing parasite and vector control strategies, are key to maintaining the malaria-free status in Goa.

Abbreviations

NCVBDC	National Centre for Vector Borne Disease Control
PHC	Primary health centre
UHC	Urban health centre
CHC	Community health centre
GIS	Geographic information systems
LU/LC	Land use/ Land cover
API	Annual parasite incidence
AFI	Annual falciparum incidence
SFR	Yearly slide falciparum rate
SVR	Yearly slide vivax rate
AS	Artesunate
SP	Sulfadoxine-Pyrimethamine
ACT	Artemisinin-based combination therapy

Supplementary Information

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Supplementary material 1

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Author contributions
PBN and AKM conceptualized, designed, and wrote the first draft of the manuscript. AN, AG, and DM contributed to the literature search. SS, KM, PKB, and KB contributed to the review and editing of the manuscript. AG and PTP analysed the data, and KB made the figure. All authors have read and agreed to the final version of the manuscript.

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The authors declare that they have no competing interests.

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References

1. National Center for Vector Borne Diseases Control (NCVBDC). Magnitude of the Problem. Available from: https://ncvbdc.mohfw.gov.in/index4.php?lang=1&level=0&linkid=420&lid=3699
2. Vaz E, Taubenböck H, Kotha M, Arsanjani JJ. Urban change in Goa. India Habitat Int. 2017;68:24–9.
3. Government of Goa. Statistical Hand Book of Goa 2018–19. Panaji: Directorate of Planning, Statistics, and Evaluation; 2020. Available from: https://www.goa.gov.in/wp-content/uploads/2020/11/Statistical-Hand-Book-of-Goa-2018-19.pdf.
4. CEIC. India. Resident Visits: by States. Available from: https://www.ceicdata.com/en/india/resident-visits-by-states.
5. Fernandes D, Paul GD. Social Networks of Migrant Construction Workers in Goa. Indian J Ind Relat. 2011;47:65–77.
6. Pai M, Zachariah A, Rose W, Satyajit S, Verghese S, Joseph A. Malaria and migrant labourers: socio-epidemiological inquiry. Econ Polit Wkly. 1997;32:839–42.
7. Narasimham MV, Khamre JS. Epidemiological and entomological aspects of malaria outbreak during 1986–87 in Panaji. Goa J Commun Dis. 1987;19:117–20.
8. Kumar A, Sharma VP, Thavaselvam D. Malaria related to constructions in Panaji. Goa Indian J Malariol. 1991;28:219–25.
9. Rahul R, Dhupdale N. The trend of malaria in Goa (India): retrospective record based study. J Evol Med Dent Sci. 2015;4:14609–19.
10. Sharma J, Dutta P, Khan SA, Soni M, Dey D, Mahanta J. Genetic polymorphisms associated with sulphadoxine-pyrimethamine drug resistance among *Plasmodium falciparum* field isolates in malaria endemic areas of Assam. J Postgrad Med. 2015;61:9–14.
11. Mohapatra PK, Sarma DK, Prakash A, Bora K, Ahmed MdA, Sarma B, et al. Molecular evidence of increased resistance to anti-folate drugs in *Plasmodium falciparum* in North-East India: a signal for potential failure of artemisinin plus sulphadoxine-pyrimethamine combination therapy. PLoS ONE. 2014;9:e105562.
12. Shah NK, Dhillon GPS, Dash AP, Arora U, Meshnick SR, Valecha N. Antimalarial drug resistance of *Plasmodium falciparum* in India: changes over time and space. Lancet Infect Dis. 2011;11:57–64.
13. Department of Information and Publicity. Available from: https://dip.goa.gov.in/climate/.
14. Sumodan PK, Kumar A, Yadav RS. Resting behavior and malaria vector incrimination of *Anopheles stephensi* in Goa. India J Am Mosq Control Assoc. 2004;20:317–8.
15. Kumar A, Thavaselvam D. Breeding habitats and their contribution to *Anopheles stephensi* in Panaji. Indian J Malariol. 1992;29:35–40.
16. Kumar A, Hosmani R, Jadhav S, de Sousa T, Mohanty A, Naik M, et al. *Anopheles subpictus* carry human malaria parasites in an urban area of Western India and may facilitate perennial malaria transmission. Malar J. 2016;15:124.
17. National Vector Borne Disease Control Programme. National framework for malaria elimination in India 2016–2030. Available from: https://ncvbdc.mohfw.gov.in/WriteReadData/l892s/National-framework-for-malaria-elimination-in-India-2016%E2%80%932030.pdf.
18. National Vector Borne Disease Control Programme. National Strategic Plan for Malaria 2023–27. Available from: https://ncvbdc.mohfw.gov.in/Doc/National-Strategic-Plan-Malaria-2023-27.pdf.
19. Times of India. State for zero malaria transmission by 2020. Times India. 2018 Feb 26. Available from: https://timesofindia.indiatimes.com/city/goa/state-for-zero-malaria-transmission-by-2020/articleshow/63071578.cms.
20. National Vector Borne Disease Control Programme. Available from: https://dhsgoa.gov.in/wp-content/uploads/2023/01/National-Vector-Borne-Disease-Control-Programme.pdf.
21. Chakrabarti R, Gillespie K, Walke JT, Fernandes M, Almeida A, Chery-Karschney L, et al. Descriptive, hospital-based, 10-year study of malaria transmission in Goa, a Southwest Indian State in the malaria elimination phase. Am J Trop Med Hyg. 2024;111:11–25.
22. Census India. India - A-01: Number of villages, towns, households, population and area - 2001. Available from: https://censusindia.gov.in/nada/index.php/catalog/20028.
23. Census India. India - A-01: Number of villages, towns, households, population and area - 2011. Available from: https://censusindia.gov.in/nada/index.php/catalog/42526.
24. International Institute for Population Sciences. Full report with final tables. Available from: https://www.iipsindia.ac.in/sites/default/files/FULL_REPORT_WITH_FINAL_TABLES.pdf.
25. National Vector Borne Disease Control Programme. Operational manual for malaria elimination in India 2016. Available from: https://ncvbdc.mohfw.gov.in/WriteReadData/l892s/5232542721532941542.pdf.
26. Times of India. South Goa district heading towards malaria-free tag. Goa News - Times of India. Available from: https://timesofindia.indiatimes.com/city/goa/south-goa-district-heading-towards-malaria-free-tag/articleshow/105867906.cms.
27. National Vector Borne Disease Control Programme. Malaria Annual Report 2023. Available from: https://ncvbdc.mohfw.gov.in/Doc/Malaria-AnnualReport-2023.pdf.
28. Jelinek T, Behrens R, Bisoffi Z, Bjorkmann A, Gascon J, Hellgren U, et al. Recent cases of falciparum malaria imported to Europe from Goa, India, December 2006-January 2007. Euro Surveill. 2007;12:E070111.1.
29. Jelinek T, European Network on Imported Infectious Disease Surveillance. Continuing importation of falciparum malaria from Goa into Europe. Euro Surveill. 2008;13:8028.
30. Kadam DPV. Socio-economic analysis of the migrants of select hotels in North Goa. PalArch. 2020;17:9178–91.
31. Chery L, Maki JN, Mascarenhas A, Walke JT, Gawas P, Almeida A, et al. Demographic and clinical profiles of *Plasmodium falciparum* and *Plasmodium vivax* patients at a tertiary care centre in southwestern India. Malar J. 2016;15:569.
32. Balasubramani K, Bharti PK, Amarthaluri C, Chellappan S, Behera SK, Mohanty AK, et al. Spatiotemporal epidemiology of malaria in India from 2007 to 2022. Am J Trop Med Hyg. 2024;111:26–34.
33. Okell LC, Bousema T, Griffin JT, Ouédraogo AL, Ghani AC, Drakeley CJ. Factors determining the occurrence of submicroscopic malaria infections and their relevance for control. Nat Commun. 2012;3:1237.
34. Das MK, Prajapati BK, Tiendrebeogo RW, Ranjan K, Adu B, Srivastava A, et al. Malaria epidemiology in an area of stable transmission in tribal population of Jharkhand. India Malar J. 2017;16:181.
35. Kumari P, Sinha S, Gahtori R, Yadav CP, Pradhan MM, Rahi M, et al. Prevalence of asymptomatic malaria parasitemia in Odisha, India: a challenge to malaria elimination. Am J Trop Med Hyg. 2020;103:1510–6.
36. Ganguly S, Saha P, Guha SK, Biswas A, Das S, Kundu PK, et al. High Prevalence of asymptomatic malaria in a tribal population in Eastern India. J Clin Microbiol. 2020;51:1439–44.
37. Sarkar R, Kessler A, Mawkhlieng B, Sullivan SA, Wilson ML, Carlton JM, et al. Household and individual level risk factors associated with declining malaria incidence in Meghalaya, India: implications for malaria elimination in low-endemic settings. Malar J. 2021;20:460.
38. Das NG, Dhiman S, Talukdar PK, Goswami D, Rabha B, Baruah I, et al. Role of asymptomatic carriers and weather variables in persistent transmission of malaria in an endemic district of Assam. India Infect Ecol Epidemiol. 2015;5:25442.
39. Das R, Vashisht K, Kori L, Singh K, Kumar G, Hasan I, et al. Detection of the infective *Plasmodium falciparum* gametocytes by RT-qPCR assay from malaria endemic region of Northeastern India. Front Trop Dis. 2024;5:1366462.
40. Andolina C, Ramjith J, Rek J, Lanke K, Okoth J, Grignard L, et al. *Plasmodium falciparum* gametocyte carriage in longitudinally monitored incident infections is associated with duration of infection and human host factors. Sci Rep. 2023;13:7072.
41. Government of Goa. Goa Public Health Act 1985 and Rules 1987. Available from: https://www.goa.gov.in/wp-content/uploads/2021/06/Goa-Public-Health-Act-1985-and-Rules1987-Rules.pdf.
42. Lindblade KA, Steinhardt L, Samuels A, Kachur SP, Slutsker L. The silent threat: asymptomatic parasitemia and malaria transmission. Expert Rev Anti Infect Ther. 2013;11:623–39.
43. Schneider P, Bousema JT, Gouagna LC, Otieno S, van de Vegte-Bolmer M, Omar SA, et al. Submicroscopic *Plasmodium falciparum* gametocyte densities frequently result in mosquito infection. Am J Trop Med Hyg. 2007;76:470–4.
44. Jeffery GM, Eyles DE. Infectivity to mosquitoes of *Plasmodium falciparum* as related to gametocyte density and duration of infection. Am J Trop Med Hyg. 1955;4:781–9.
45. Thomas S, Ravishankaran S, Justin JA, Asokan A, Mathai MT, Valecha N, et al. Overhead tank is the potential breeding habitat of *Anopheles*

stephensi in an urban transmission setting of Chennai. India Malar J. 2016;15:274.
46. Davidson G. The anophelines of India. T. Ramachandra Rao. Indian Council of Medical Research. Malaria Research Centre. revised edition. Trans R Soc Trop Med Hyg. 1984;1984(78):630.
47. Mohapatra PK, Prakash A, Taison K, Negmu K, Gohain AC, Namchoom NS, et al. Evaluation of chloroquine (CQ) and sulphadoxine/pyrimethamine (SP) therapy in uncomplicated falciparum malaria in Indo-Myanmar border areas. Trop Med Int Health. 2005;10:478–83.
48. Mishra N, Kaitholia K, Srivastava B, Shah NK, Narayan JP, Dev V, et al. Declining efficacy of artesunate plus sulphadoxine-pyrimethamine in northeastern India. Malar J. 2014;13:284.
49. National Vector Borne Disease Control Programme. National Drug Policy 2013. Available from: https://ncvbdc.mohfw.gov.in/Doc/National-Drug-Policy-2013.pdf.
50. Chakrabarti R, White J, Babar PH, Kumar S, Mudeppa DG, Mascarenhas A, et al. Decreased in vitro artemisinin sensitivity of *Plasmodium falciparum* across India. Antimicrob Agents Chemother. 2019;63:e00101-e119.
51. Das S, Kar A, Manna S, et al. Artemisinin combination therapy fails even in the absence of *Plasmodium falciparum* kelch13 gene polymorphism in Central India. Sci Rep. 2021;11:9946.
52. Mohanty AK, Mazumdar D, Govekar A, De'souza C, Mohapatra A, Balabaskaran Nina P. *Anopheles jamesii* supports *Plasmodium vivax* sporogony under laboratory conditions. Am J Trop Med Hyg. 2024;111:984–7.
53. Times of India. Goa looks to eliminate malaria by 2022. Goa News - Times of India. Available from: https://timesofindia.indiatimes.com/city/goa/goa-looks-to-eliminate-malaria-by-2022/articleshow/87560382.cms

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