IJID Regions 14 (2025) 100574

Contents lists available at ScienceDirect

IJID Regions

journal homepage: www.elsevier.com/locate/ijregi

Factors predictive of epidemic waves of COVID-19 in Africa during the first 2 years of the pandemic

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ARTICLE INFO

Keywords:
Predictive factors
COVID-19 waves
Climate impact
Economic indicators
Africa

ABSTRACT

Objectives: The objective was to study the epidemic wave curves, according to the characteristics of the countries, to identify the differences and the predictive factors of evolution.

Methods: We have carried out modeling of the COVID-19 epidemic data from validated databases for 53 African countries.

Results: All countries recorded at least four waves. The duration of the waves had decreased over time (P <0.001) and extended with the rainy season (P = 0.03). The incidence rates were higher for countries with the best development indicators (P <0.001). Positive spatial autocorrelation was significant for all wave characteristics, except for relative amplitude at the end of the wave. The time-adjusted multivariate analysis identified seasons for duration (P = 0.017) and human development index for peak incidence rate (P <0.001) and relative amplitude at the end of the wave (P = 0.041) as predictors of wave characteristics.

Conclusions: The duration of the waves was influenced by the seasons and the study periods, the incidences by the economic development, and health indicators. The appearance of new variants seemed associated with the start of the waves. None of the factors studied is associated with an inflection and a decrease in the curve.

Introduction

The COVID-19 epidemic was marked by several waves of recrudescence, with different characteristics regarding the beginning, the peak and the end [1,2]. These variations are reflected in epidemic curves specific to each country [3].

In high-income countries, the predictive factors of the evolution of the epidemic curve were the barrier measures [4], vaccination [5], new variants [6], and the seasons [7].These factors do not appear to be sufficient to explain the occurrence of waves in Africa.

Indeed, (i) the barrier measures decreed quite late [8] were not observed, despite their implementation by governments [9,10]. (ii) The proportion of the population vaccinated remains very low compared with the rest of the world due to low acceptance by the population and lack of access to vaccines [11].

When viral identification was possible, the same variants as in high-income countries were identified in Africa during the same periods [12].

Environmental factors have been suggested as the explanation for the epidemic variations of COVID-19 in Africa [13]. Africa has a dry season and a wet season (rains), 80% of which are located in the tropical zone, crossed by the equator. Its northern and southern borders are in temperate zones, with large temperature variations between summer and winter. In the tropical zone, on the other hand, these variations remain low [14]. These factors could play a role in epidemic waves. The other hypothesis is that the level of economic development of a country would impact the evolution of the epidemic.

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https://doi.org/10.1016/j.ijregi.2025.100574
Received 28 June 2024; Received in revised form 15 January 2025; Accepted 16 January 2025

The objective of this study was to characterize the epidemic waves occurring in Africa during the four semesters of 2020 and 2021 and analyze the epidemic curves according to the factors studied and the appearance of new variants.

Methods

Study population and cases of COVID-19

The study concerned 53 of the 54 African countries; Tanzania did not collect cases. The data on COVID-19 outbreaks were obtained from the Oxford Martin Programme on Global Development database at the University of Oxford from February 07, 2020 to March 06, 2022. For each country, the number of new cases of COVID-19, confirmed by an antigenic test or polymerase chain reaction, as recommended by the World Health Organization (WHO) [15], was collected. The collection of cases was done daily. Weekly incidence per country was calculated by summing new cases over the course of a week. Weekly incidence was smoothed using the moving average method over a 7-week interval.

Covariate data collection

Development indicators

Development indicators were collected from the World Bank database [16] which are the following: (i) annual infant mortality (children under 1 year of age) per 1000 live births, (ii) Gross domestic product per capita, (iii) life expectancy at birth, (iv) human development index, and (v) annual crude mortality per 1000 inhabitants. Each indicator was classified into one of three categories (low, medium, and high), as described by WHO and the World Bank, as follows: 9.43 to 21, 21 to 41, and 41 to 50 for the annual crude mortality per 1000 births; 228 to 2900, 2900 to 5000, and 5000 to 10,000 for the gross domestic product per capita (in US$); 52.78 to 60.03, 60.03 to 70.81, and 70.81 to 82.78 for life expectancy at birth (in years); 0.385 to 0.550, 0.550 to 0.713, and 0.713 to 0.802 for the human development index; and 2.5 to 7, 7 to 9, and 9 to 14 for the annual crude mortality (per 1000 inhabitants).

Environmental factors

The environmental data, climate, and seasons were collected from the Climat et Voyages website [17]. The climate of the capital city was used as a reference for each country. Following the criteria of the World Meteorological Organization, the countries were classified into two categories: temperate zone and tropical zone. For the season, the date of the dry (dry season) and wet (rainy season) seasons were also collected. The season type for each wave was defined as the season type at the start date of the corresponding wave.

Proximity between countries

A first-order country proximity matrix was built: two countries were considered close if they shared a border.

Variant identification

Because the date of occurrence of virus variants has not been systematically identified on the continent, the detection dates of variants identified worldwide, defined by the WHO Technical Advisory Group on SARS-CoV-2 Virus Evolution [18], was considered: Alpha (United Kingdom, September 2020), Beta (South Africa, May 2020), Gamma (Brazil, November 2020), Delta (India, October 2020), and Omicron (many countries, November 2021).

Statistical analysis

To characterize the different waves, four periods corresponding to the four semesters of 2020 and 2021 were defined, with the start date of the semester as a reference.

Wave identification

The different waves in each country were identified using the relative growth rates. First, the weekly incidence for each country was smoothed using the moving average method centered on a 7-week interval to avoid bias linked to fluctuations [19]. Then, the relative growth rate at a given week was calculated as the ratio of the difference in incidence between the current week and 2 weeks earlier, divided by the latter. It corresponds to the change in weekly incidence compared with the 2 previous weeks.

Each wave was defined by a start date, a peak date, and an end date defined as follows:

- The start date was set at 2 weeks before an increase in smoothed weekly incidence, resulting in an increase of 10% or more in the relative growth rate, followed by a further increase in the growth rate for at least 2 weeks.
- The peak date was determined from the week when the growth rate became negative and remained negative for at least the next week. The peak date corresponds to 2 weeks before these successive weeks of decreasing incidence.
- The end-of-wave date corresponds to 2 weeks before the growth rate decreases below 10%.

Wave characterization

Each wave was characterized in terms of chronology and amplitude.

Chronology

- Peak delay is the time elapsed between the wave start date (included) and the wave peak date (excluded).
- The delay between peak and wave end defines the time elapsed between the peak date (included) and the wave end date (excluded).
- Wave duration is the time elapsed between wave start date (included) and wave end date (excluded).

Amplitudes

- Peak incidence rate: the incidence at the time of the peak, divided by the country's population (number of new cases per 100,000 population)
- Relative amplitude at the end of the wave: the amplitude at the end of the wave divided by that of the peak.

The distribution of each wave characteristic according to the countries was described using the median and interquartile range for each period. An analysis of variance was then used to compare the mean of the wave characteristics between the periods. The same description was performed over all countries and over the four periods in the sub-groups defined by the development and the environmental indicators defined above.

Spatial autocorrelation of the wave characteristics over all four periods was estimated using the Moran index and tested using the Monte Carlo method [20].

Multivariate analysis

Linear regression models adjusted for the periods of the study were used to identify the indicators associated to the wave characteristics. We started with a complete model, including all indicators as categorical variables. We then eliminated non-significant variables at each step to end up with a parsimonious model, retaining only the significant variables. When no variable reached the significance threshold (P <0.05), we retained the one with the smallest P-value less than 0.10.

The statistical analyses were performed using R software (Version 4.1.3). The significance level was set at 5%.

Results

A total of 53 countries on the African continent were studied in this work to analyze the curves of the COVID-19 epidemic. The variations

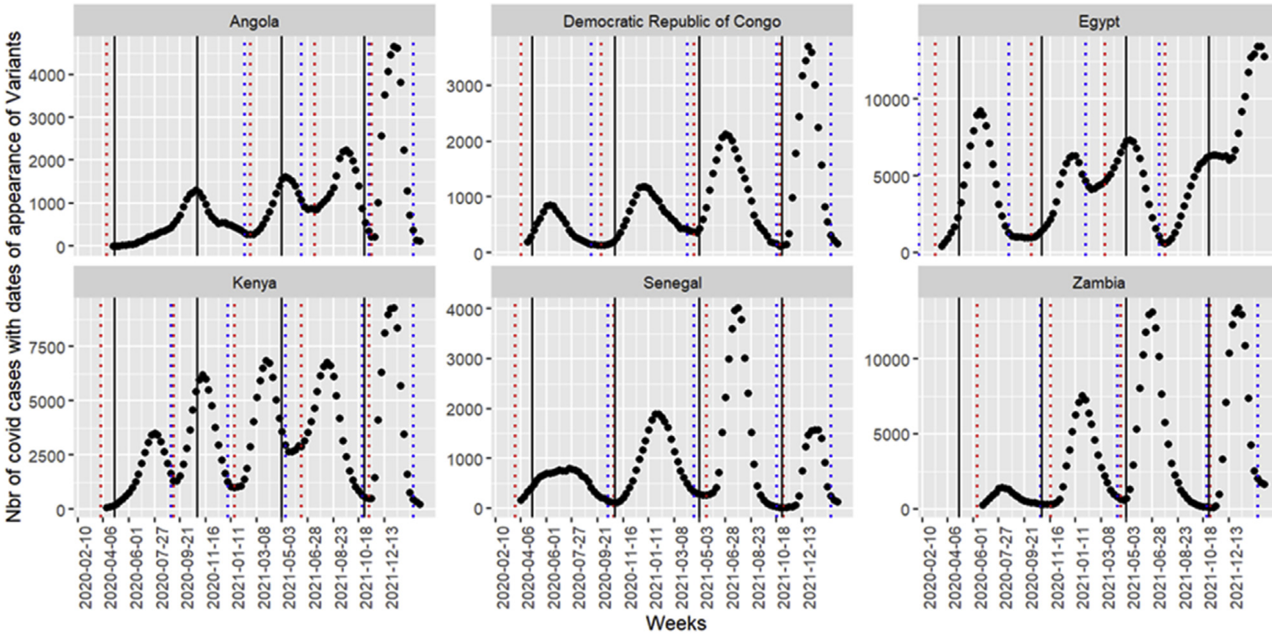

Figure 1. Time-smoothed incidence curves for Angola, Democratic Republic of Congo, Egypt, Kenya, Senegal, and Zambia (wave start date: red line, wave end date: blue line, date of first variant identification: black line). These six countries were taken as typical examples, showing the diversity of timeframes, growth rates, maximum levels, and forms of decline.

Table 1
Evolution of wave characteristics according to the four study periods.

Wave characteristics	Periods				Median (Q_1; Q_3)	*P-value*
	1	2	3	4		
Delay between peak and start of wave (in days)	91	84	70	56[a]	70 (56;91)[b]	< 0.001[c]
Peak incidence rate (per 100,000)	5.89	9.92	12.83	14.13	10.04 (4.59;36.06)	0.4
Time between peak and end of wave (days)	77	77	70	49	66.5 (49;91)	<0.001
Relative amplitude at the end of the wave (%)	0.165	0.15	0.08	0.07	10.5 (5;24)	0.008
Wave duration (in days)	178.5	161	154	105	154 (112;183.8)	<0.001

[a] Median for all countries over the period.
[b] Overall median, for all countries over the four periods, with the first (Q_1) and third (Q_3) quartiles.
[c] Analysis of variance with period as factor.

of the curves were compared between different countries. We observed the behavior of epidemic curves as a function of variables identified as predictive of the evolution of the epidemic.

Waves characterization

The smoothed incidence curves over all periods, with the dates of appearance of the variants, are presented in Appendix 2 (Figures S1 to S3). Of the 53 countries included in our study, six countries (Egypt, Senegal, Kenya, Angola, Democratic Republic of Congo, and Zambia) were selected in each region (northern, western, eastern, central, and southern) for illustration (Figure 1). All the countries taken as examples presented four epidemic waves, except for Kenya. There are differences in the characteristics between waves: in the first wave, the time to peak appears shorter in Egypt than in Angola; the amplitude of the peak is greater in the last wave than in previous waves, except in Senegal; the amplitude at the end of the second wave is higher in Egypt than in other countries; and the duration of the second wave in Senegal is 6 months, longer than the third.

The peak delay, the delay between the peak and the wave end, the relative amplitude at the end of the wave, and the duration of the wave presented a statistically significant decrease over time in all countries (Table 1). For the first two characteristics, the decrease mainly concerned the last wave. The relative amplitude at the end of the wave decreased from the third period onward. Wave duration decreased progressively from the first to the fourth period. The peak incidence rate seemed to increase, but this increase was not statistically significant.

Observation of the behavior of the curves at the time of the appearance of the variants revealed that this coincided each time with the start of the wave (Figures S1 to S2).

Waves characterization in the sub-group of the development and environmental indicators

Wave amplitude parameters were significantly different according to the development indicators (Tables S1 and S2). The peak incidence rate decreased with increasing annual infant mortality (P <0.001) and increased with gross domestic product per capita (P <0.001), life expectancy at birth (P <0.001), and the human development index (P <0.001). The amplitude at the end of the wave decreased when annual infant mortality increased (P = 0.002) and increased when life expectancy at birth and the human development index increased (P <0.001). Chronologic parameters were not influenced by development indicators. Only the time between the peak and the end of the wave presented P-values close to significance. However, the variations observed did not make it possible to identify a trend. Annual crude mortality per 1000 inhabitants was not associated with any of the wave characteristics.

We observed significantly higher wave duration during the rainy season. Wave amplitude was also different depending on climate type,

Table 2
Wave characteristics as a function of climate and season.

Wave characteristics	Climate			Seasons		
	Temperate	Tropical	***P-value***	Dry	Rain	***P-value***
Delay between peak and start of wave (in days)	77	70	0.96	70	77	0.09
Peak incidence rate (per 100,000)	58.99	8.22	0.01	10.48	8.79	0.79
Time between peak and end of wave (days)	56	70	0.13	63	70	0.17
Relative amplitude at the end of the wave (%)	0.17	0.1	0.03	0.14	0.09	0.34
Wave duration (in days)	147	154	0.39	147	161	0.03

The parameters presented in Table 2 show a significantly higher wave duration during the rainy season. Wave amplitude was also significantly different by climate type, with significantly higher values for the "temperate" climate than for the "tropical" climate.

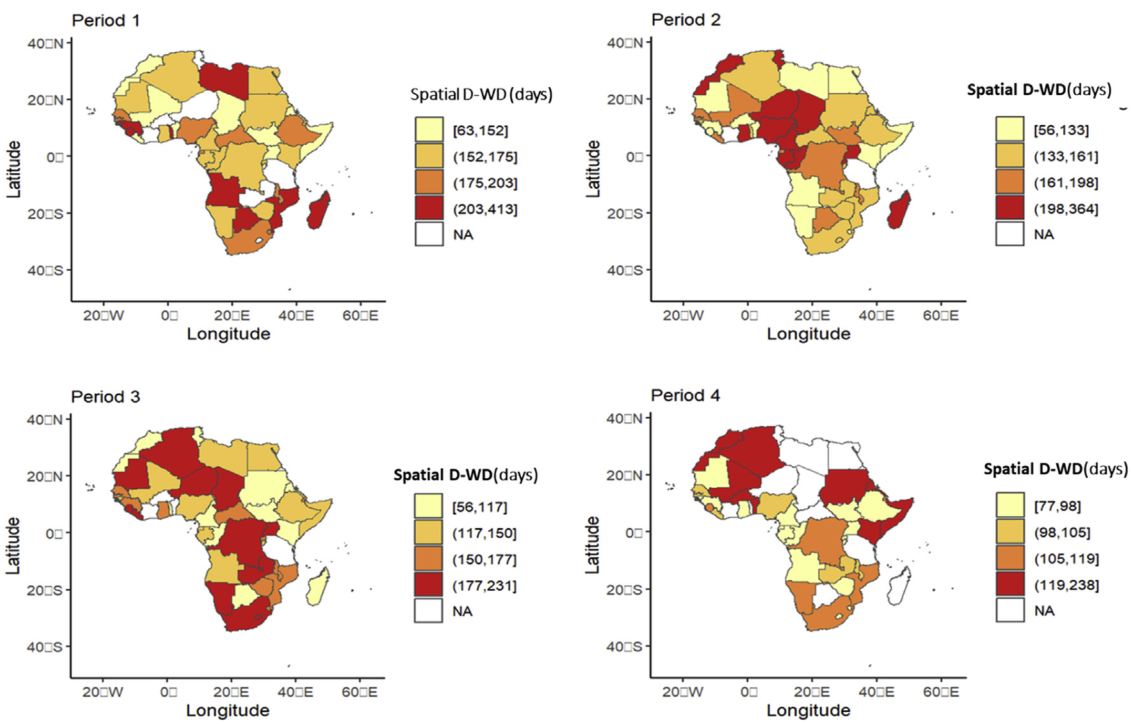

Figure 2. Spatial D-WD in days according to the study period.
Each study period corresponds to one semester of the year. D-WD, distribution of wave duration. Note: please keep the same colors for the figures.

with significantly higher values for the "temperate" climate than for the "tropical" climate (Table 2).

The mapping highlights the similarities and differences in the wave characteristics between neighboring countries. The maps in Figure 2 present the duration of the waves taken as an example; we note the grouping of light and dark colors moving from one period to another. These color groupings reflect the existence of spatial autocorrelation of wave characteristics. These trends are confirmed by the values of the estimated Moran index (Table S3). We found a statistically significant Moran index of 0.23 (P = 0.02) for the total duration of the wave and its two components: the peak delay and the delay between peak and wave. Peak incidence rates were also significantly correlated between neighboring countries.

This means that neighboring countries tended to have similar peak incidence rates and wave durations.

Study of predictive factors in multivariate analysis

The results of the parsimonious models shown in Table 3 were obtained after multivariate regression adjusted for the periods of the study. We noticed that the peak incidence rate increased significantly with increasing gross domestic product per capita (P <0.001) and human development index (P <0.001); the relative amplitude at the end of the wave increased with increasing life expectancy (P = 0.01) and human development index (P = 0.04); the time between the peak and the end of the wave seemed to correlate with the human development index. It decreased by 7 days when the development index increased by one unit. This effect was borderline statistically significant (P = 0.085); the dry season predicted shorter wave duration compared to the rainy season (P = 0.017). It was associated with a decrease in the time between wave onset and peak, although this effect was not statistically significant (P = 0.085).

Discussion

In this study of African countries, the factors predictive of the wave characteristics of the COVID-19 epidemic were investigated. The African continent is of particular scientific interest because of the epidemic's evolution virtually without optimal barrier measures [9].

All countries recorded epidemic waves. Despite the absence of the barrier measures that are known to affect wave evolution, these waves show a classic bell-shaped evolutionary pattern. Although the appearance of new variants may justify the start of a new wave, questions remain as to what justifies the amplitude of waves, as well as their decay and end.

Waves were analyzed according to intensity and duration. A shortening of wave duration was observed over time from one period to the next. Short wave durations were also associated with the continent's

Table 3
Multivariate analysis, adjusted for the study period, of factors predicting wave characteristics.

Wave characteristics	Gross domestic product per capita	Life expectancy at birth	Human development index	Season dry vs rainy
Delay between peak and start of wave (in days)				−11.88 (−25.44;1.67) P = 0.085
Peak incidence rate (per 100,000)	37.97 (22.44;53.49) ***P* <0.001**		30.75 (14.89;46.61) ***P* <0.001**	
Time between peak and end of wave (days)			−7.35 (−15.73;1.03) P = 0.085	
Relative amplitude at the end of the wave (%)		7 (2;13) ***P* = 0.013**	5 (0;10) ***P* = 0.041**	
Wave duration (in days)				−19.07 (−34.74;−3.39) ***P* = 0.017**

tropical zone and the dry season. No association was observed between wave duration and development indicators. Variations in wave intensity were associated with development indicators. Countries with the best indicators showed higher incidence rates at peak and higher relative amplitudes at the end of waves. Positive Moran spatial autocorrelation indexes were significantly observed for all wave characteristics, except relative amplitude at the end of the wave. Period-adjusted multivariate analysis identified seasonality and human development index as the factors best explaining the variations in wave characteristics.

Waves characterization

All chronologic wave characteristics decreased with time. This resulted in increasingly shorter waves. We observed better epidemic clearance with increasingly lower relative amplitudes at the end of the waves. This could be a reflection of three factors: an optimization of the management of the epidemic by health systems, an adaptation of the population to the lifestyle imposed by the presence of the epidemic, and an acquisition of individual immunity and collective [21,22]. Indeed, if the start of a wave can be attributed to the appearance of a new variant, we have not found, in the absence of vaccination and effective barrier measures, arguments to justify the inflection then the decline of the curve, apart from a possible acquired collective immunity. However, it remains obvious that the shape and appearance of each wave reflect the isolated or combined biological and epidemiologic characteristics of the variants of the virus in circulation.

Prediction of wave characteristics by development indicators

The effect of development indicators was mainly on wave intensity parameters. A country's high level of development was significantly associated with high incidence rates at the peak and the end of the wave. The role of development indicators has been analyzed by several teams but only regarding wave intensities [23,24]. Our study shows no effect of a country's level of development on wave duration. However, countries with lower incomes reported fewer cases. This may be justified by the country's ability to provide the diagnostic facilities needed to detect a greater number of cases, as well as the population's acceptance of screening [25]. Developed countries also have an optimized health care system, with access to care for the majority of the population. The country's development is also a guarantee of a better reporting and data archiving system.

Prediction of wave characteristics by environmental factors

The role of climate has been suggested by authors; however, no specific trend has emerged [26]. Our results showed a significant positive association of temperate climate with peak incidence rate (P <0.01) and relative amplitude at the end of the wave (P = 0.03). This could be linked to the difference in levels of development between the two zones, with temperate continental countries having relatively better overall development indicators than tropical countries.

The seasonal analysis showed a longer wave duration in the rainy season (P = 0.03). This is even more interesting because the season parameter in our study reflects the difference in humidity level, which was mentioned by Diouf et al. [27] as one of the most influential factors in the COVID-19 epidemic. There was no correlation between seasons and wave intensities, which contradicts all previous observations. However, as we have said, wave intensity is poorly known, being mainly a reflection of the variable quality of reporting in a context of scarce resources.

Prediction of wave characteristics based on proximity between countries

The Moran indexes show a positive spatial autocorrelation of country neighborhoods with incidence rates and peak durations. Similar trends have been described by Kianfar and Mesgari [28] in Europe and Sandar et al. [29] in Thailand.

Study of predictive factors in multivariate analysis

Adjusted over time, the regressions ultimately showed that the human development index (P <0.001), gross domestic product per capita (P <0.001), and life expectancy at birth (P = 0.013) were the most significant predictors of variations in wave characteristics. These indicators were positively associated with wave amplitudes. In addition, to confirm the positive association between the human development index and the prevalence of COVID-19 cases, our results allowed us to differentiate the roles of each of the human development index components considered. The positive association between gross domestic product per capita and peak incidence rate showed that the economic development of each country was a guarantee of better detection capacities during periods of epidemic rise. This is in line with observations made by Heo et al. [23]. Life expectancy at birth specifically reflects the development of the health system. It was positively associated only with the relative amplitude at the end of the wave. Therefore, to detect and confront an epidemic, a combination of economic development and a solid health system is required.

The multivariate analysis also confirmed the positive association between rainy season and wave duration (P = 0.017). Waves occurring in the dry season were significantly shorter than those in the rainy season. The impact of climate on the COVID-19 epidemic has been studied in particular by Diouf et al. [27] and Wang et al. [17]. These studies, limited to small climatic zones, only assessed wave amplitudes. Our study had the dual advantage of being more extensive and including wave durations.

Limitations of the study

A limitation of our study is the lack of precise information on the date of appearance of the variants in each country. However, this does not affect the interpretation because what was studied was the overall shape of the epidemic curve.

Another limitation is the absence of comparisons with high-income countries, particularly, in other continents. However, the difference in levels of development between the various countries provides sufficient contrast to assess the impact significantly. In the absence of a sufficient temperature margin, the difference in humidity levels between the rainy and dry seasons provides sufficient contrast to assess the impact.

Conclusion

This study focused on the analysis of epidemic waves of COVID-19 in a context of minimal application of barrier measures.

At least four epidemic waves were observed in each country. The waves lasted the longest in wet weather during the rainy season; however, this duration decreased overall from one period to the next as the epidemic was managed, with positive spatial autocorrelation. The human development index was significantly positively associated with wave amplitudes but not with wave duration.

Optimized economic and health development indicators are necessary to enable countries to put in place diagnostic resources and measures to combat epidemics. These control measures should be reinforced during the rainy season. Finally, it is necessary to strengthen reporting systems at all levels to minimize artifacts in the wave comparisons needed for the next pandemic.

Declarations of competing interest

The authors have no competing interests to declare.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethics approval and consent to participate

All methods were carried out in accordance with the relevant guidelines and regulations. Because the study involved established databases, it did not require informed consent from participants.

Acknowledgments

Not applicable.

Author contributions

Conception and design of the study, or acquisition of data, or analysis and interpretation of data: PW, AD, AK, RE, and MR. Drafting the article or revising it critically for important intellectual content: PW, AD, AK, RE, MR LT, JI, JFE, and PV. Final approval of the version to be submitted: PW, AD, AK, RE, MR, LT, JI, JFE, and PV.

Data availability

The data sets generated and/or analyzed during the study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijregi.2025.100574.

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