

Predicting the spatiotemporal evolution of HIV/AIDS in Africa: A retrospective analysis of epidemiological trends

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ABSTRACT

Background: Africa bears the highest global burden of HIV, with marked regional inequalities in prevalence, incidence and clinical outcomes. Mapping the spatial and temporal evolution of the epidemic is essential to guide targeted interventions and anticipate future trends.

Methods: We conducted a retrospective analysis of UNAIDS annual estimates for adults aged 15–49 years across 49 African countries (2014–2023). We described spatiotemporal patterns in HIV prevalence, incidence, adults living with HIV (ALHIV) and AIDS-related

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deaths, and quantified temporal trends using annual percentage change and linear regression. For the ten highest-burden countries, we forecast prevalence to 2033 using an ensemble of machine learning models. Hierarchical and k-means clustering, supported by principal component analysis, were applied to identify epidemic archetypes based on average prevalence levels and temporal trajectories.

Results: Southern Africa remained the epicentre of the epidemic, with mean adult prevalence of 19.97% versus <1.3% in Northern and Western Africa. From 2014 to 2023, prevalence and incidence declined in all regions, with the steepest reductions in Southern (prevalence –19.5%; incidence –68.4%) and Eastern Africa (–22.2% and –65.6%, respectively). Despite falling rates, the absolute number of ALHIV increased in several regions, while AIDS-related deaths decreased by more than 44% in Central and Western Africa. Forecasts for the highest-burden countries indicate a continued, gradual decline in prevalence. Cluster analysis identified a hyperendemic group of six Southern African countries (mean prevalence 15.6%) and a second cluster of 41 countries with moderate-to-low prevalence (2.1%) and mainly stable or declining trajectories.

Conclusions: The African HIV epidemic is increasingly heterogeneous and evolving rather than uniformly controlled. Combining machine learning forecasts and clustering with routine surveillance can support differentiated, data-driven strategies that intensify prevention and treatment in hyperendemic settings while sustaining gains elsewhere.

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Abbreviations

AGYW	Adolescent Girls and Young Women
AIDS	Acquired Immunodeficiency Syndrome
ALHIV	Adults Living with HIV
aOR	Adjusted Odds Ratio
APC	Annual Percentage Change
aPR	Adjusted Prevalence Ratio
ART	Antiretroviral Therapy
CAB-LA	Cabotegravir Long-Acting
CI	Confidence Interval
DSD	Differentiated Service Delivery
ECOWAS	Economic Community of West African States
FSW	Female Sex Workers
HIV	Human Immunodeficiency Virus
IPV	Intimate Partner Violence
IRB	Institutional Review Board
LePHIA	Lesotho Population-based HIV Impact Assessment
MAE	Mean Absolute Error
MSM	Men who have Sex with Men
OR	Odds Ratio
PCA	Principal Component Analysis
PEPFAR	President's Emergency Plan for AIDS Relief
PLWHIV	People Living with HIV
PMTCT	Prevention of Mother-to-Child Transmission
PrEP	Pre-Exposure Prophylaxis
PWID	People Who Inject Drugs
R ²	R-squared (coefficient of determination)
SSA	Sub-Saharan Africa
U=U	Undetectable = Untransmittable
UNAIDS	Joint United Nations Programme on HIV/AIDS
WHO	World Health Organization

1. Introduction

The HIV/AIDS epidemic remains one of the most significant global health challenges, affecting millions worldwide. According to recent estimates from the Joint United Nations Programme on HIV/AIDS (UNAIDS), approximately 40.8 million people were living with HIV globally in 2024, of whom 39.4 million were adults aged 15 years or older (WHOa). The burden of disease remains disproportionately concentrated in Sub-Saharan Africa (SSA) (Kharsany & Karim, 2016; Michael et al., 2024), with Southern Africa representing the most affected region: although its countries account for less than 2% of the global population, they bear nearly one-third of all HIV infections. Despite a 40% reduction in global incidence since 2010, with 1.3 million new infections reported in 2024 (WHOb), progress remains uneven, and SSA continues to carry a disproportionately heavy burden.

Mortality patterns further reflect this concentration. While AIDS-related deaths have declined globally by 54% since 2010, reaching 630,000 in 2024 (UNAIDSa), SSA accounted for 60% of all AIDS-related deaths in 2023 (van et al., 2024). These figures underscore the persistent geographic and demographic heterogeneity of the epidemic, emphasizing the need for spatiotemporal analyses to understand localized transmission trends and identify emerging hotspots. Broad regional aggregates, such as “Eastern and Southern Africa”, while useful for global reporting, often mask critical national and subnational variations that demand context-specific interventions.

The introduction of antiretroviral therapy (ART) has transformed HIV management, extending life expectancy and reducing transmission (Ford et al., 2011). The principle “Undetectable = Untransmittable” (U=U) (Orlando et al., 2025) has been central in reinforcing the social and biomedical impact of ART, reducing stigma and encouraging testing among young populations in SSA (Agaku et al., 2022). Nonetheless, significant disparities persist. In 2024, 87% of people living with HIV (PLWHIV) were aware of their HIV status, and 89% of those diagnosed were receiving antiretroviral therapy (ART), reflecting substantial but uneven progress toward the UNAIDS 95–95–95 targets. These targets refer to a sequential cascade of care, whereby 95% of all individuals living with HIV are expected to be diagnosed, 95% of those diagnosed should receive sustained ART, and 95% of those on treatment should achieve viral suppression. Despite overall improvements, important disparities persist across population groups. In 2024, women reached levels of 92–91–95 across the cascade, compared with 84–87–94 among men, while only 63% of children aged 0–14 were aware of their HIV status (UNAIDSa). These gaps highlight structural weaknesses in Prevention of Mother-To-Child Transmission (PMTCT) programs and in linkage to pediatric care (Mukuku & Govender, 2025). Vulnerable populations, including men who have sex with men (MSM), female sex workers (FSW), and people who inject drugs (PWID), face additional barriers to ART access and adherence due to socioeconomic constraints, stigma, and limited healthcare infrastructure (Anderegg et al., 2024; Ochonye et al., 2019).

Recent biomedical innovations offer promising prevention tools. Long-acting injectable PrEP formulations, such as Cabotegravir (CAB-LA) and Lenacapavir, provide more discreet and convenient alternatives to daily oral Pre-Exposure Prophylaxis (PrEP) (HIV and AIDS Resources), with monthly or semi-annual dosing that may enhance adherence and efficacy (ViiV Healthcare). However, their implementation in SSA faces substantial logistical and financial challenges. Even with voluntary licensing agreements and non-profit pricing, access remains limited, as demonstrated by supply disruptions in South Africa (PrEP Watch). International financial support has historically been pivotal. Programs such as President's Emergency Plan for AIDS Relief (PEPFAR), initiated in 2003, have contributed to a 52% reduction in new infections and a 59% decrease in AIDS-related deaths in supported countries since 2010 (HIV and AIDS Resources), and have driven over 90% of global PrEP initiations. However, recent disruptions in US foreign aid in early 2025 (UNAIDSb) highlight the fragility of this progress, threatening access to essential services, including ART, PrEP, and diagnostic testing, in countries such as Malawi and Ethiopia.

The epidemic is further shaped by mobility and urbanization. Labor migration and extended periods away from rural communities are associated with higher-risk sexual behaviors and reduced adherence to care (Camlin & Charlebois, 2019), while key urban and transport nodes, such as Johannesburg, Durban, Cape Town, Lusaka, Ndola, Bulawayo, and Maputo, emerge as persistent transmission hotspots (Bell et al., 2025). These patterns reinforce the need for geographically focused approaches, which can identify structural determinants of transmission and target interventions efficiently (Fox, 2010).

This study provides a detailed overview of the HIV burden across 49 African countries from 2014 to 2023, with three main objectives: (i) to evaluate recent trends in adult HIV prevalence, incidence, and AIDS-related mortality; (ii) to predict the future evolution of HIV prevalence in countries with the highest-burden, applying time series models integrated with machine learning techniques; and (iii) to identify archetypal epidemic profiles to inform targeted, context-specific prevention and treatment strategies. Specifically, Section 2 describes the data sources and details the methodological framework used to model temporal dynamics and perform the clustering analysis. Section 3 presents the major findings, including spatial disparities in HIV prevalence and incidence across African regions, temporal trends over 2014–2023, projected future prevalence in the highest-burden countries, and the identification of archetypal epidemic profiles through cluster analysis. Section 4 discusses implications for policy and targeted interventions. Finally, Section 5 summarizes the main findings and provides recommendations to support long-term HIV epidemic control in Africa.

2. Materials and methods

2.1. Study design and data sources

A retrospective analytical framework was adopted, based on publicly available annual estimates from the Joint United Nations Programme on HIV/AIDS (UNAIDS) for all African countries. Four indicators were analysed as defined by UNAIDS: (i) adult HIV prevalence (%) among individuals aged 15–49 years, (ii) HIV incidence rate per 1000 uninfected adults aged 15–49 years, (iii) estimated adults living with HIV (ALHIV) aged ≥ 15 years, and (iv) AIDS-related deaths among adults aged ≥ 15 years. Age definitions were preserved exactly as provided by UNAIDS without reclassification, and the age basis is explicitly stated for each indicator.

UNAIDS estimates were imported from the `HIV2024Estimates_ByYear` sheet of the “HIV estimates from 1990 to present” Excel dataset. Columns were renamed and cleaned to standardize country names and indicator formats. Censored values reported as inequalities were handled using midpoint substitution, with 0.05 used for values reported as “ < 0.1 ” and 100 for values reported as “ < 200 ”. Missing values were linearly interpolated where necessary. A sensitivity analysis excluding censored entries yielded consistent results, confirming the robustness of the substitution approach.

Countries lacking complete time series for one or more indicators were excluded from the main analyses (Seychelles, Cameroon, Central African Republic, Equatorial Guinea, and São Tomé and Príncipe). For Somalia, Madagascar, and Libya, national incidence series were unavailable; therefore, incidence-related computations were restricted to countries with complete data. Geographic aggregation followed the United Nations geoscheme, dividing the continent into Northern, Western, Central, Eastern, and Southern Africa.

Summary statistics, including mean and standard deviation, were computed over the 2014–2023 period to provide a recent, representative snapshot of HIV burden across African countries, reflecting the last decade of available data and minimizing the influence of earlier historical fluctuations in epidemic dynamics. In contrast, time-series forecasting models utilized the full dataset from 1990 onwards to capture long-term temporal trends, epidemic onset, and structural changes in HIV transmission and management, which are essential for accurate prediction and trend extrapolation. This dual-period approach ensures that descriptive statistics focus on contemporary conditions while forecasting leverages the entire historical record.

All computational workflows were implemented entirely in Python (version 3.11), encompassing data processing, statistical analysis, visualization, and machine learning-based forecasting. The analytical framework integrated ensemble learning algorithms, clustering techniques, and principal component analysis (PCA) to explore temporal and spatial patterns in HIV prevalence. Spatial analyses employed choropleth mapping to visualize regional and national heterogeneity. A single-hue graduated colour scale encoded within-country values, while neutral tones denoted missing data. National boundaries were displayed for all countries, including those without available estimates, and cartographic outputs incorporated north arrows and scale bars to enhance spatial interpretability. All maps were rendered using equal-area projections to ensure accurate representation of areal relationships across the African continent.

2.1.1. Temporal and spatial summary of indicators

For each country i and indicator x , the temporal mean and standard deviation over the 2014–2023 period were computed to summarize both the average burden and interannual variability:

$$\bar{x}_i = \frac{1}{T} \sum_{t=1}^T x_{i,t}, \quad s_i = \sqrt{\frac{1}{T-1} \sum_{t=1}^T (x_{i,t} - \bar{x}_i)^2},$$

where $T = 10$ denotes the number of available years.

To capture regional and continental patterns without conflating rate intensity with population burden, indicators expressed as rates (e.g., prevalence, incidence) were aggregated as unweighted per-country means:

$$\bar{x}_r = \frac{1}{n_r} \sum_{i=1}^{n_r} \bar{x}_i,$$

where n_r is the number of countries in region r . Count-based indicators (adults living with HIV and HIV-related deaths) were aggregated across countries within each region as the sum of national mean annual totals:

$$X_r = \sum_{i=1}^{n_r} \bar{x}_i.$$

For count-based indicators, X_r represents the regional aggregation of national mean annual totals over 2014–2023. This measure reflects the average annual burden at the regional level, rather than a single-year observation or a cumulative multi-year total. It is designed to capture sustained epidemiological burden while preserving comparability across regions with different population sizes and epidemic structures.

Temporal change within countries was quantified using annual percentage change (APC):

$$APC_{i,t} = 100 \times \frac{x_{i,t} - x_{i,t-1}}{x_{i,t-1}},$$

while long-term trends were estimated using ordinary least squares regression:

$$x_{i,t} = \beta_{0,i} + \beta_{1,i} t + \epsilon_{i,t},$$

where $\beta_{1,i}$ represents the annual change in percentage points per year. Countries were ranked by the magnitude $|\beta_{1,i}|$ to identify the strongest trends, and by the sign of $\beta_{1,i}$ to distinguish increasing versus decreasing prevalence trajectories.

Finally, countries were classified according to the direction and magnitude of their linear trend:

$$\text{Trend}_i = \begin{cases} \text{Increasing,} & \beta_{1,i} > 0, \\ \text{Stable,} & |\beta_{1,i}| < 0.05, \\ \text{Declining,} & \beta_{1,i} < 0. \end{cases}$$

This unified approach allows simultaneous assessment of average levels, interannual variability, regional aggregation, and long-term trends in a coherent framework.

2.1.2. Machine learning forecasting

Forecasts were generated for the ten highest-burden African countries using an ensemble of machine learning models, including Random Forest, Gradient Boosting, and Ridge Regression. The ensemble approach was chosen to leverage the complementary strengths of different algorithms: (i) Random Forest captures nonlinear relationships and interactions between temporal features without overfitting, thanks to its averaging of multiple decision trees. (ii) Gradient Boosting sequentially improves predictions by focusing on residual errors of previous models, allowing finer capture of trends and subtle shifts in prevalence. (iii) Ridge Regression provides a regularized linear baseline that stabilizes predictions, mitigating overfitting especially when the number of historical data points is limited.

For each country i , features were derived from historical prevalence $p_{i,t}$:

$$\mathbf{X}_{i,t} = \begin{bmatrix} t, & t^2, & t^3, \\ p_{i,t-1}, & p_{i,t-2}, & p_{i,t-3}, \\ \text{RollingMean}_3, & \text{RollingStd}_3, & \text{RollingMean}_5, \\ \frac{p_{i,t} - p_{i,t-1}}{p_{i,t-1}} \end{bmatrix}$$

where rolling statistics are defined as:

$$\text{RollingMean}_w = \frac{1}{w} \sum_{k=0}^{w-1} p_{i,t-k}, \quad \text{RollingStd}_w = \sqrt{\frac{1}{w-1} \sum_{k=0}^{w-1} (p_{i,t-k} - \text{RollingMean}_w)^2}.$$

Models were trained on 80% of historical data and evaluated on the remaining 20% using:

$$R^2 = 1 - \frac{\sum_t (p_{i,t} - \hat{p}_{i,t})^2}{\sum_t (p_{i,t} - \bar{p}_i)^2}, \quad \text{MAE} = \frac{1}{n} \sum_t |p_{i,t} - \hat{p}_{i,t}|,$$

where $\hat{p}_{i,t}$ is the predicted prevalence and $\bar{p}_i$ the mean observed value.

To provide a conservative assessment of predictive accuracy, adjusted R^2 was also computed as:

$$R^2_{\text{adj}} = 1 - \left[\frac{(1 - R^2)(n - 1)}{n - p - 1} \right],$$

where n denotes the number of observations and p the number of features. In-sample performance metrics (R^2 , adjusted R^2 , and MAE) were computed over the full 1990–2023 time series, whereas out-of-sample metrics were evaluated on the held-out 20% test set corresponding to the 2017–2023 period.

The ensemble prediction was computed as a weighted average:

$$\hat{p}_{i,t}^{\text{ensemble}} = \sum_{m=1}^M w_m \hat{p}_{i,t}^{(m)}, \quad w_m \geq 0, \quad \sum_{m=1}^M w_m = 1,$$

with weights proportional to the positive R^2 of each model on the validation set. Forecast uncertainty was quantified as:

$$\sigma_{i,t} = \sqrt{\frac{1}{M} \sum_{m=1}^M \left(\hat{p}_{i,t}^{(m)} - \hat{p}_{i,t}^{\text{ensemble}} \right)^2}.$$

Forecasts were produced for 10-year horizons (2024–2033) and constrained to non-negative values.

2.1.3. Clustering and pattern analysis

To identify countries with similar epidemic trajectories, standardized prevalence series were clustered. Let $\mathbf{p}_i = [p_{i,t_1}, \dots, p_{i,t_T}]$ and standardize:

$$\tilde{\mathbf{p}}_i = \frac{\mathbf{p}_i - \bar{\mathbf{p}}_i}{s_i}, \quad \bar{\mathbf{p}}_i = \frac{1}{T} \sum_t p_{i,t}, \quad s_i = \sqrt{\frac{1}{T-1} \sum_t (p_{i,t} - \bar{\mathbf{p}}_i)^2}.$$

K-means clustering minimized within-cluster variance:

$$\min_{\{C_k\}} \sum_{k=1}^K \sum_{i \in C_k} \|\tilde{\mathbf{p}}_i - \boldsymbol{\mu}_k\|^2,$$

with $\boldsymbol{\mu}_k$ the cluster centroid. Optimal K was chosen using the silhouette coefficient:

$$s(i) = \frac{b(i) - a(i)}{\max(a(i), b(i))}, \quad s = \frac{1}{N} \sum_i s(i),$$

where $a(i)$ is mean intra-cluster distance and $b(i)$ mean nearest-cluster distance.

To visualize clusters, PCA reduced dimensionality:

$$\mathbf{Z} = \tilde{\mathbf{P}}\mathbf{W}, \quad \mathbf{W} = \operatorname{argmax}_{\mathbf{W}^T \mathbf{W} = \mathbf{I}} \operatorname{Var}(\tilde{\mathbf{P}}\mathbf{W}),$$

where $\tilde{\mathbf{P}}$ is the standardized data matrix and $\mathbf{Z}$ contains the first two principal components.

Clusters were characterized by mean prevalence, temporal trends, and country composition, allowing identification of countries with rising, stable, or declining HIV prevalence patterns. This approach captures multiyear epidemic trajectories, supporting targeted regional interventions.

3. Results

3.1. Spatial and regional distribution of HIV indicators

The spatial maps shown in Fig. 1 highlight substantial geographical variation in key HIV indicators among adults aged 15–49 years across Africa during the period 2014–2023. Fig. 1A shows HIV prevalence, which follows a pronounced south-to-north gradient. Southern Africa is the most affected region, with national averages above 15% and peaks exceeding 25% in Eswatini, Lesotho, and Botswana. In contrast, North Africa (e.g., Algeria, Morocco, Egypt) and much of West Africa (e.g., Niger, Senegal, Mauritania) remain at very low levels, typically below 1%. Fig. 1B presents the average HIV incidence rate, measured as new infections per 1000 uninfected adults. Again, southern Africa has the highest incidence, often exceeding 6–10 per 1000, reflecting ongoing transmission and persistent vulnerability at the community level. North and West Africa show an incidence close to zero, which may be the result of lower baseline prevalence, more effective control of the epidemic, or different transmission dynamics.

Fig. 1C and D shows the average annual number of ALHIV and HIV-related deaths, respectively, further illustrating the demographic and epidemiological burden. The largest ALHIV populations are found in high-prevalence, densely populated countries such as South Africa, Mozambique, Tanzania, and Kenya, where the combination of high incidence and a large adult population accounts for a disproportionate share of the continental burden (Fig. 1C). Mortality patterns mirror this distribution, with HIV-related deaths concentrated in southern and eastern Africa, despite an overall regional decline linked to the expansion of antiretroviral therapy coverage. Central and West Africa, although less affected overall, continue to experience localized pockets of mortality, reflecting structural gaps in access to healthcare and weaknesses in surveillance systems (Fig. 1D). All regional and national data details, are summarized in Tables 1 and 2.

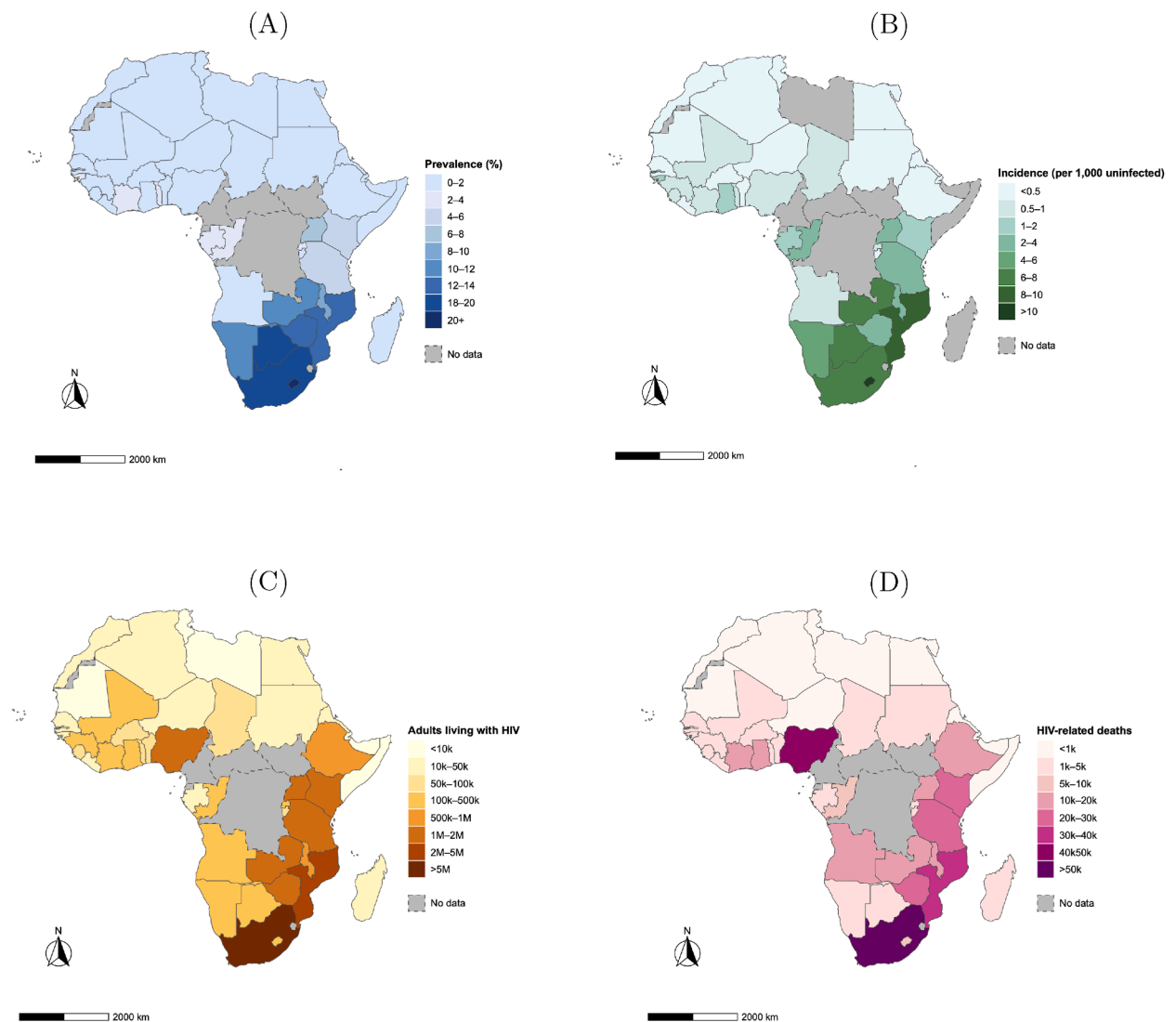


Fig. 1. Country-level HIV indicators in Africa among adults aged 15–49 years over the period 2014–2023. Panel (A) shows HIV prevalence (%), computed as the national mean across the study period. Panel (B) reports HIV incidence rate, defined as the number of new infections per 1000 uninfected adults, averaged over 2014–2023. Panel (C) shows, for each country, the arithmetic mean of the annual estimated totals of adults aged ≥ 15 years living with HIV (ALHIV) across the ten years of the study period (2014–2023); the mapped value therefore represents the average yearly count of ALHIV for that country over the decade, expressed in absolute numbers. Panel (D) reports, analogously, the arithmetic mean of the annual estimated totals of HIV-related deaths among adults aged ≥ 15 years over the same period. Both panels reflect the combined influence of HIV transmission rates, survival under antiretroviral therapy, and population size, and should be interpreted as indicators of absolute epidemiological burden rather than rates.

3.2. Temporal trends and forecasting of HIV prevalence

The temporal trends illustrated in Fig. 2 show a progressive reduction in HIV prevalence and incidence across most African regions between 2014 and 2023, with the most pronounced declines observed in Eastern and Southern Africa. Specifically, prevalence in Southern Africa decreased from 21.7% to 17.4% (–20.0%), while in Eastern Africa it declined from 4.88% to 3.94% (–19.3%). More moderate reductions were observed in Central Africa (from 2.32% to 1.88%, –19.0%) and Western Africa (from 1.50% to 1.08%, –27.9%).

The patterns observed for North Africa in Fig. 2a and d are markedly different from other African regions and require careful interpretation, as they reflect a combination of genuine epidemiological signals, evolving surveillance coverage, and country-specific dynamics rather than a uniform regional trend.

Regarding prevalence (Fig. 2a), North Africa remained stable at approximately 0.07–0.10% from 2014 to 2019, followed by a gradual increase to approximately 0.13% in 2023. This rise is not uniformly distributed across countries. Sudan represents the primary epidemiological driver, with national prevalence increasing from approximately 0.10% to 0.20% between 2014

Table 1

Regional summary of HIV epidemiological indicators among adults in Africa over the period 2014–2023. Values are reported as unweighted per-country means for prevalence (%; ages 15–49) and incidence (per 1000 uninfected adults, ages 15–49), and as mean annual regional totals for adults (aged ≥ 15 years) living with HIV (ALHIV) and HIV-related deaths. Left-censored values were imputed using midpoint substitution (<0.1 replaced with 0.05; <200 replaced with 100). Regional groupings follow the United Nations geoscheme. Incidence data were unavailable for Libya, Madagascar, and Somalia. Countries with incomplete indicator coverage (Seychelles, Cameroon, Central African Republic, Equatorial Guinea, and São Tomé and Príncipe) were excluded from aggregation.

Region	Prevalence (%)	Incidence (per 1000)	ALHIV (≥ 15)	HIV-related deaths (≥ 15)
Southern Africa	19.97	8.94	8,044,000	73,430
Eastern Africa	4.11	2.10	10,695,490	191,006
Central Africa	2.10	1.28	976,700	37,110
Western Africa	1.29	0.63	3,242,100	95,645
Northern Africa	0.07	0.08	106,350	3595
Africa (overall)	4.11	2.02	23,064,640	400,786

Table 2

Country-level mean HIV indicators among adults in Africa over the period 2014–2023. Values are reported as mean $\pm$ standard deviation across the 10-year study period. Indicators include HIV prevalence (%; ages 15–49), incidence rate (new infections per 1000 uninfected adults, ages 15–49), the number of adults (aged ≥ 15 years) living with HIV (ALHIV), and the number of HIV-related deaths among adults (aged ≥ 15 years). Left-censored observations were handled using midpoint substitution (<0.1 replaced with 0.05; <200 replaced with 100). The “All” row reports the unweighted per-country mean $\pm$ standard deviation across countries.

Country	Prevalence (%)	Incidence (per 1000)	ALHIV (≥ 15)	HIV-related deaths (≥ 15)
Algeria	0.05 $\pm$ 0.00	0.05 $\pm$ 0.00	18,100 $\pm$ 3784	500 $\pm$ 0
Angola	1.70 $\pm$ 0.10	1.00 $\pm$ 0.18	277,000 $\pm$ 11,595	10,650 $\pm$ 1086
Benin	0.90 $\pm$ 0.10	0.23 $\pm$ 0.08	60,900 $\pm$ 316	1295 $\pm$ 214
Botswana	19.90 $\pm$ 2.00	6.82 $\pm$ 2.79	349,000 $\pm$ 9944	4240 $\pm$ 201
Burkina Faso	0.80 $\pm$ 0.10	0.15 $\pm$ 0.06	90,800 $\pm$ 3225	2650 $\pm$ 506
Burundi	1.10 $\pm$ 0.20	0.33 $\pm$ 0.13	77,300 $\pm$ 1059	1635 $\pm$ 780
Cape Verde	0.90 $\pm$ 0.10	0.81 $\pm$ 0.05	3210 $\pm$ 472	100 $\pm$ 0
Chad	1.20 $\pm$ 0.20	0.55 $\pm$ 0.13	99,600 $\pm$ 699	3380 $\pm$ 518
Comoros	0.05 $\pm$ 0.00	0.10 $\pm$ 0.00	100 $\pm$ 0	100 $\pm$ 0
Congo	3.30 $\pm$ 0.10	2.87 $\pm$ 0.12	102,000 $\pm$ 7303	5210 $\pm$ 160
Côte d'Ivoire	2.40 $\pm$ 0.40	0.90 $\pm$ 0.29	415,000 $\pm$ 8498	13,730 $\pm$ 4213
DR Congo	0.80 $\pm$ 0.10	0.39 $\pm$ 0.09	449,000 $\pm$ 11,005	16,230 $\pm$ 6608
Djibouti	1.10 $\pm$ 0.20	0.49 $\pm$ 0.08	8200 $\pm$ 949	625 $\pm$ 97
Egypt	0.05 $\pm$ 0.00	0.06 $\pm$ 0.03	22,500 $\pm$ 9778	526 $\pm$ 52
Eritrea	0.70 $\pm$ 0.20	0.16 $\pm$ 0.06	14,300 $\pm$ 1160	520 $\pm$ 45
Eswatini	28.60 $\pm$ 2.00	15.63 $\pm$ 7.80	223,000 $\pm$ 6749	3340 $\pm$ 417
Ethiopia	1.00 $\pm$ 0.20	0.20 $\pm$ 0.07	587,000 $\pm$ 4830	11,450 $\pm$ 1504
Gabon	3.50 $\pm$ 0.30	1.59 $\pm$ 0.24	49,100 $\pm$ 568	1640 $\pm$ 255
Gambia	1.70 $\pm$ 0.20	1.21 $\pm$ 0.27	24,200 $\pm$ 789	1200 $\pm$ 47
Ghana	1.70 $\pm$ 0.10	1.10 $\pm$ 0.11	300,000 $\pm$ 12,472	12,800 $\pm$ 789
Guinea	1.50 $\pm$ 0.10	0.83 $\pm$ 0.22	109,000 $\pm$ 3162	3380 $\pm$ 516
Guinea-Bissau	2.90 $\pm$ 0.40	1.27 $\pm$ 0.43	32,600 $\pm$ 516	1304 $\pm$ 302
Kenya	4.10 $\pm$ 0.60	1.03 $\pm$ 0.47	1,370,000 $\pm$ 48,305	27,200 $\pm$ 5940
Lesotho	21.90 $\pm$ 2.10	10.47 $\pm$ 4.89	275,000 $\pm$ 7071	5080 $\pm$ 1010
Liberia	1.10 $\pm$ 0.20	0.47 $\pm$ 0.18	31,700 $\pm$ 1059	1388 $\pm$ 587
Libya	0.05 $\pm$ 0.00	–	5710 $\pm$ 638	130 $\pm$ 48
Madagascar	0.30 $\pm$ 0.10	–	48,400 $\pm$ 13,729	2180 $\pm$ 322
Malawi	8.50 $\pm$ 1.20	2.56 $\pm$ 1.40	921,000 $\pm$ 19,120	12,660 $\pm$ 2271
Mali	1.00 $\pm$ 0.10	0.54 $\pm$ 0.12	110,000 $\pm$ 0	4130 $\pm$ 452
Mauritania	0.20 $\pm$ 0.10	0.05 $\pm$ 0.00	6190 $\pm$ 363	470 $\pm$ 95
Mauritius	1.40 $\pm$ 0.10	1.28 $\pm$ 0.11	11,600 $\pm$ 699	587 $\pm$ 65
Morocco	0.05 $\pm$ 0.00	0.05 $\pm$ 0.00	20,000 $\pm$ 1491	519 $\pm$ 31
Mozambique	12.30 $\pm$ 0.40	8.24 $\pm$ 2.17	2,050,000 $\pm$ 206,828	39,600 $\pm$ 3307
Namibia	11.20 $\pm$ 1.00	5.06 $\pm$ 1.10	217,000 $\pm$ 4830	3870 $\pm$ 411
Niger	0.20 $\pm$ 0.00	0.05 $\pm$ 0.00	27,600 $\pm$ 516	978 $\pm$ 348
Nigeria	1.60 $\pm$ 0.20	0.76 $\pm$ 0.17	1,830,000 $\pm$ 48,305	46,400 $\pm$ 9857
Rwanda	2.80 $\pm$ 0.40	0.67 $\pm$ 0.29	224,000 $\pm$ 5164	2870 $\pm$ 427
Senegal	0.40 $\pm$ 0.10	0.20 $\pm$ 0.05	37,700 $\pm$ 1889	1060 $\pm$ 283
Sierra Leone	1.40 $\pm$ 0.00	0.86 $\pm$ 0.15	63,600 $\pm$ 5016	1920 $\pm$ 480
Somalia	0.07 $\pm$ 0.05	–	8590 $\pm$ 1018	609 $\pm$ 131
South Africa	18.20 $\pm$ 0.60	6.70 $\pm$ 1.77	6,980,000 $\pm$ 396,653	56,900 $\pm$ 6624
South Sudan	1.80 $\pm$ 0.10	1.37 $\pm$ 0.31	135,000 $\pm$ 8498	7270 $\pm$ 2089
Sudan	0.10 $\pm$ 0.00	0.15 $\pm$ 0.02	33,600 $\pm$ 6114	1420 $\pm$ 140
Tanzania	4.30 $\pm$ 0.30	2.52 $\pm$ 0.59	1,470,000 $\pm$ 141,814	26,600 $\pm$ 3406
Togo	2.00 $\pm$ 0.30	0.67 $\pm$ 0.26	99,600 $\pm$ 516	2840 $\pm$ 923
Tunisia	0.10 $\pm$ 0.00	0.11 $\pm$ 0.01	6440 $\pm$ 809	500 $\pm$ 0
Uganda	6.10 $\pm$ 0.60	2.75 $\pm$ 1.00	1,330,000 $\pm$ 82,327	19,600 $\pm$ 3239
Zambia	11.40 $\pm$ 0.80	6.27 $\pm$ 2.68	1,210,000 $\pm$ 110,050	16,600 $\pm$ 966
Zimbabwe	12.80 $\pm$ 1.50	3.56 $\pm$ 2.16	1,230,000 $\pm$ 48,305	20,900 $\pm$ 2514
All (unweighted per-country)	4.11 $\pm$ 0.35	2.02 $\pm$ 0.69	470,707 $\pm$ 21,307	8179 $\pm$ 1139

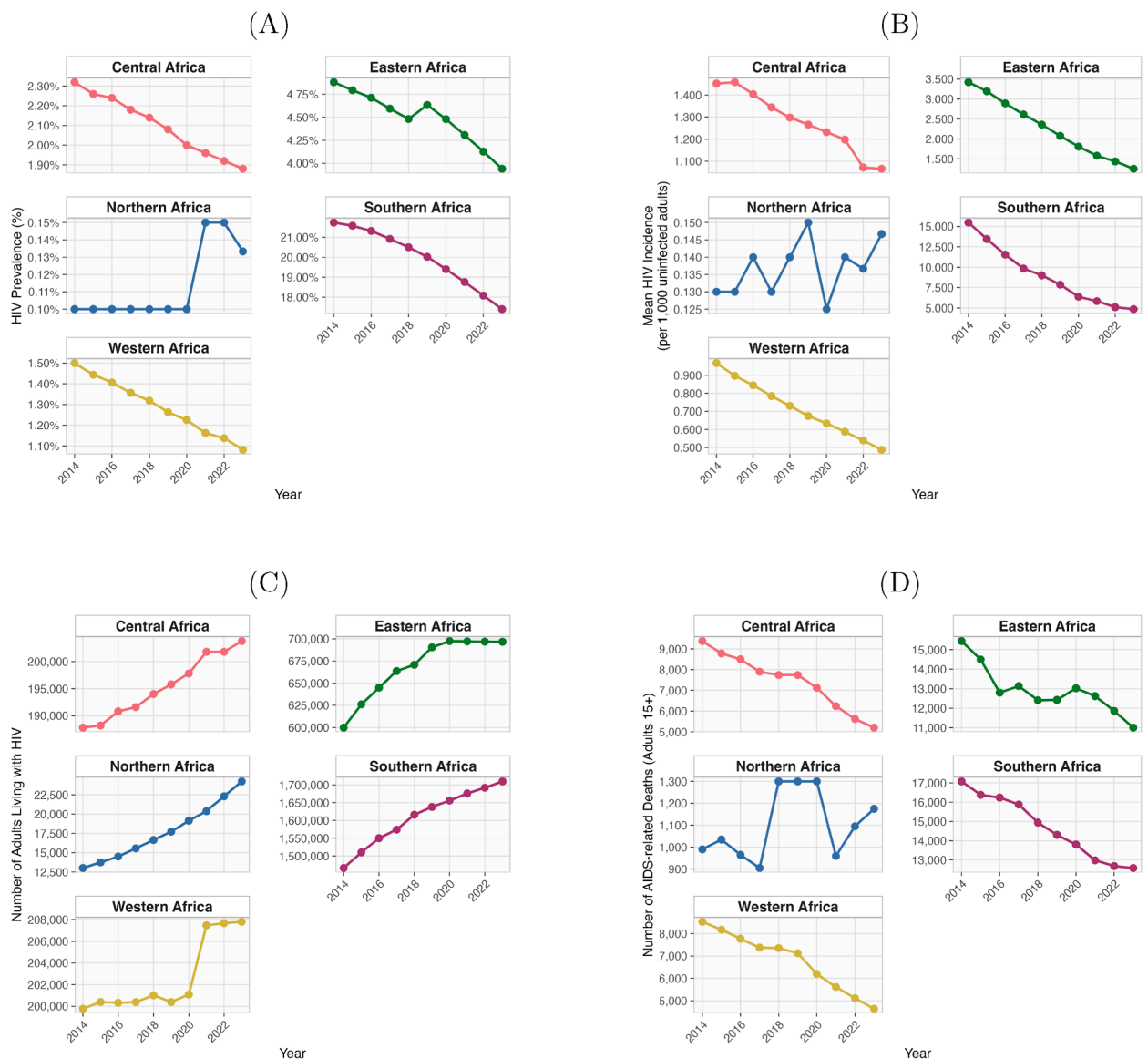


Fig. 2. Regional temporal trends in HIV indicators among adults in Africa over the period 2014–2023. Annual estimates are aggregated at the level of United Nations sub-regions. Panel (A) shows HIV prevalence (%), reported as population-weighted regional means. Panel (B) shows HIV incidence rate, defined as the number of new infections per 1000 uninfected adults (ages 15–49). Panel (C) reports the total number of adults (aged ≥ 15 years) living with HIV (ALHIV). Panel (D) shows the total number of HIV-related deaths among adults (aged ≥ 15 years).

and 2023, consistent with documented health system disruption, reduced access to HIV testing and treatment services, and political instability affecting continuity of care (van et al., 2024). By contrast, the increases observed in Egypt and Tunisia in terms of the absolute number of adults living with HIV are more plausibly attributable to improved case detection, expanded surveillance coverage, population growth, and enhanced survival under antiretroviral therapy, rather than to genuine increases in transmission rates. It should also be noted that the regional mean for North Africa is computed over a small number of countries (five to six, depending on data availability), which means that country-specific dynamics—particularly Sudan’s—exert a disproportionate influence on the regional aggregate. Changes in the set of countries contributing data across years further contribute to apparent discontinuities in the regional trend.

A similar pattern emerges for incidence (Fig. 2b). Southern Africa shows the most marked reduction, from 15.48 to 4.86 new infections per 1000 uninfected adults (−68.6%), followed by Eastern Africa (from 3.42 to 1.25, −63.4%). Central and Western Africa display more moderate declines (−26.6% and −49.7%, respectively). In North Africa, incidence shows a modest increase (from 0.130 to 0.147 per 1000, +12.8%), which should be interpreted cautiously in light of the evolving data

coverage and the disproportionate contribution of individual countries, particularly Sudan where health system disruption has likely contributed to increased transmission.

Despite declining prevalence, the absolute number of adults living with HIV is increasing in several regions, driven by demographic growth and improved survival due to antiretroviral therapy (Fig. 2c). Southern Africa increased from 1.47 to 1.71 million individuals (+16.6%), and Eastern Africa from approximately 600,000 to nearly 697,000 (+16.2%). More modest increases are observed in Central Africa (+8.5%) and Western Africa (+4.0%). North Africa shows a more pronounced relative increase (from approximately 13,000 to over 24,000, +86.2%), reflecting both improved detection and survival in Egypt and Tunisia, as well as the contribution of country-specific dynamics.

Regarding HIV-related deaths (Fig. 2d), North Africa shows an overall increase of approximately 18.7% over the study period, with notable year-to-year variability. This pattern is again primarily driven by Sudan, where mortality appears to have increased in association with health system fragility and interruptions in ART supply and delivery. In other North African countries, increases in recorded deaths may partly reflect improved death registration and cause-of-death attribution rather than true mortality escalation. Importantly, the absolute numbers involved remain very small compared to other regions (mean annual deaths of approximately 3595 for the entire subregion, Table 1), and therefore small absolute changes translate into disproportionately large relative variations that can appear misleading when plotted on the same scale as other regions. Reductions in HIV-related deaths were observed in Southern Africa (−26.3%), Eastern Africa (−28.7%), Central Africa (−44.6%), and Western Africa (−45.5%), consistent with the expansion of ART coverage across these subregions.

The North African patterns observed in Fig. 2a and d should be interpreted as a combination of a genuine but localized epidemiological signal in Sudan, improved surveillance and survival in Egypt and Tunisia, and methodological artefacts arising from a small regional sample, evolving data coverage, and high sensitivity of relative metrics to small absolute changes. These considerations caution against interpreting North African regional aggregates as reflecting a coherent or homogeneous subregional epidemic dynamic.

3.3. Cluster analysis and epidemic archetypes

Cluster analysis applied to HIV prevalence trajectories across African countries reveals the presence of two robust and clearly separated epidemic archetypes. The unsupervised K-means algorithm ($k = 2$) yields a silhouette score of 0.753, indicating strong internal coherence within clusters and substantial separation between them. This result suggests that, despite substantial heterogeneity at the national level, the long-term dynamics of HIV prevalence in Africa can be effectively summarized into two dominant epidemiological regimes, reflecting fundamentally different structural, behavioral, and programmatic contexts.

The first cluster (Cluster 1) corresponds to a small group of hyperendemic Southern and Eastern African countries, characterized by persistently high HIV prevalence levels and complex, partially divergent temporal trajectories. This cluster includes Botswana, Eswatini, Lesotho, Mozambique, Namibia, South Africa, Zambia, Malawi, Zimbabwe, and Uganda. As summarized in Table 3, these countries exhibit average prevalence levels ranging from approximately 7.8% to over 22%, substantially exceeding continental averages and confirming their classification as high-burden settings.

Fig. 3 illustrates the aggregate temporal trajectory of this cluster (green line) over the period 1990–2033, showing a sharp increase in prevalence from the early 1990s, peaking in the mid-2010s at approximately 20%, followed by a gradual but incomplete decline. Despite recent improvements, projections indicate that this group will remain in a hyperendemic state throughout the forecast horizon, with an estimated prevalence of 14.5% by 2033.

Despite their shared hyperendemic status, Cluster 1 countries display marked internal heterogeneity in temporal dynamics, as shown in Fig. 4, which plots country-specific historical series (1990–2023) alongside ensemble model forecasts (2024–2033) with 95% prediction intervals.

Disaggregated analysis reveals at least three distinct trajectory types within Cluster 1. First, Eswatini and Lesotho exhibit sustained upward trends, with Eswatini showing the highest prevalence (25.1% in 2023) and the most pronounced upward trend among all African countries (+0.74 percentage points/year; $R^2 = 1.000$, MAE = 0.134%), with projections indicating a further increase to 25.5% by 2033. Lesotho follows a similar pattern (prevalence 18.5% in 2023; +0.41 percentage points/year; $R^2 = 0.999$, MAE = 0.123%), with projections indicating stabilization around 19.1% by 2033. The persistence of these upward trajectories likely reflects structural vulnerabilities including extremely high community prevalence sustaining dense transmission networks, persistent gender inequality, high rates of circular male labor migration, geographic barriers to care access, and limited biomedical prevention coverage among key populations (Section 4). Second, Botswana and South Africa represent intermediate cases characterized by stabilization at hyperendemic plateau levels or incipient reversal. Botswana, despite its extremely high prevalence (16.6% in 2023), shows a relatively moderate trend (+0.05 percentage points/year; $R^2 = 0.998$, MAE = 0.105%), suggesting epidemic stabilization. South Africa, with a prevalence of 17.1% in 2023, shows a moderate historical upward trend (+0.46 percentage points/year) but projections indicate a reversal with an expected decline to 15.4% by 2033, likely reflecting the cumulative, albeit delayed, effect of the world's largest national antiretroviral therapy program. Third, Zimbabwe, Uganda, Malawi, and Zambia exhibit statistically significant long-term declines, reflecting the impact of earlier and more intensive scale-up of antiretroviral therapy, prevention programs, and behavioral interventions. Zimbabwe presents the most striking case: as the only country in Cluster 0 with a prevalence comparable to that of Cluster 1 (18.0%), it exhibits the most marked decline among all high-prevalence countries (−0.42

Table 3

Clustering and predictive summary of HIV prevalence across African countries (1990–2033). Average prevalence and trend slopes are computed over 1990–2023. Predictive performance metrics are reported only for Cluster 1 countries for which ensemble forecasting models were explicitly trained. Cluster 0 countries are included for completeness of the continental epidemiological stratification.

Country	Avg prev (%)	Slope	R ²	Adj. R ²	MAE	Forecast 2033 (%)
Cluster 1 (Top Burden)						
Eswatini	22.66	+0.736	1.000	0.999	0.134	25.5
Botswana	21.34	+0.053	0.998	0.998	0.105	16.7
Lesotho	19.71	+0.413	0.999	0.999	0.123	19.1
Zimbabwe	17.99	−0.420	0.999	0.999	0.090	10.3
South Africa	14.25	+0.463	0.999	0.999	0.089	15.4
Zambia	12.24	−0.058	0.982	0.978	0.118	9.0
Malawi	11.37	−0.188	0.997	0.996	0.087	6.8
Namibia	11.08	+0.149	0.998	0.998	0.091	8.0
Mozambique	9.42	+0.324	0.998	0.998	0.097	10.0
Uganda	7.84	−0.163	0.995	0.993	0.102	0.9
Cluster 0 (remaining African countries)						
Angola	1.55	0.02272	–	–	–	–
Eritrea	1.37	−0.05355	–	–	–	–
Ethiopia	1.86	−0.07675	–	–	–	–
Kenya	6.53	−0.19193	–	–	–	–
Madagascar	0.24	0.01631	–	–	–	–
Mauritius	0.99	0.04615	–	–	–	–
Rwanda	3.92	−0.07780	–	–	–	–
South Sudan	1.95	0.00673	–	–	–	–
Djibouti	2.07	−0.05042	–	–	–	–
Libya	0.10	0.00000	–	–	–	–
Somalia	0.32	−0.01458	–	–	–	–
Sudan	0.11	0.00219	–	–	–	–
Benin	1.12	−0.01184	–	–	–	–
Burkina Faso	1.54	−0.07132	–	–	–	–
Burundi	2.52	−0.13529	–	–	–	–
Chad	1.71	−0.02874	–	–	–	–
Congo	3.94	−0.06992	–	–	–	–
DR Congo	1.38	−0.04788	–	–	–	–
Gabon	3.79	0.01709	–	–	–	–
Gambia	1.47	0.03919	–	–	–	–
Ghana	2.02	−0.01977	–	–	–	–
Guinea	1.41	0.02481	–	–	–	–
Guinea-Bissau	2.97	0.05200	–	–	–	–
Liberia	1.98	−0.06608	–	–	–	–
Mali	1.35	−0.02112	–	–	–	–
Mauritania	0.42	−0.00791	–	–	–	–
Niger	0.45	−0.01476	–	–	–	–
Nigeria	1.72	−0.00073	–	–	–	–
Senegal	0.48	−0.00141	–	–	–	–
Sierra Leone	1.35	0.01547	–	–	–	–
Togo	2.63	−0.01618	–	–	–	–

percentage points/year; $R^2 = 0.999$, $MAE = 0.090\%$), justifying its classification in Cluster 0 and demonstrating that specific programmatic factors, notably early and massive expansion of antiretroviral therapy, voluntary medical male circumcision interventions, and mother-to-child transmission prevention programs—can produce measurable and sustained epidemiological reversal.

The analysis of predictive performance for all ten high-burden countries shows average in-sample $R^2 = 0.999$, average adjusted $R^2 = 0.999$, and average $MAE = 0.103\%$ (Table 3), indicating that the ensemble models reproduce historical epidemic dynamics with very high fidelity. These near-unity values reflect the structured, smooth nature of the underlying UNAIDS (UNAIDSa) series rather than overfitting: the adjusted R^2 , which penalizes model complexity, remains essentially identical, and the high fit is consistent with the biological regularity of long-term HIV trajectories well described by logistic growth dynamics. Critically, this high consistency implies that the dominant drivers of prevalence change have been stable throughout the observation period and that future trajectories are tightly coupled to the current intervention landscape. Consequently, any substantial deviation from the projected declines, whether due to funding disruptions, service interruptions, or the emergence of resistance, would represent a significant structural break, whereas the acceleration of declines in settings like Eswatini and Lesotho will require a discontinuous intensification of targeted prevention efforts beyond current coverage levels.

The second cluster (Cluster 0) encompasses the remaining 41 African countries (approximately 82% of the sample), representing a much larger and epidemiologically more heterogeneous group. These countries are characterized by substantially lower average prevalence levels (approximately 2.1%) and predominantly stable or slowly declining long-term

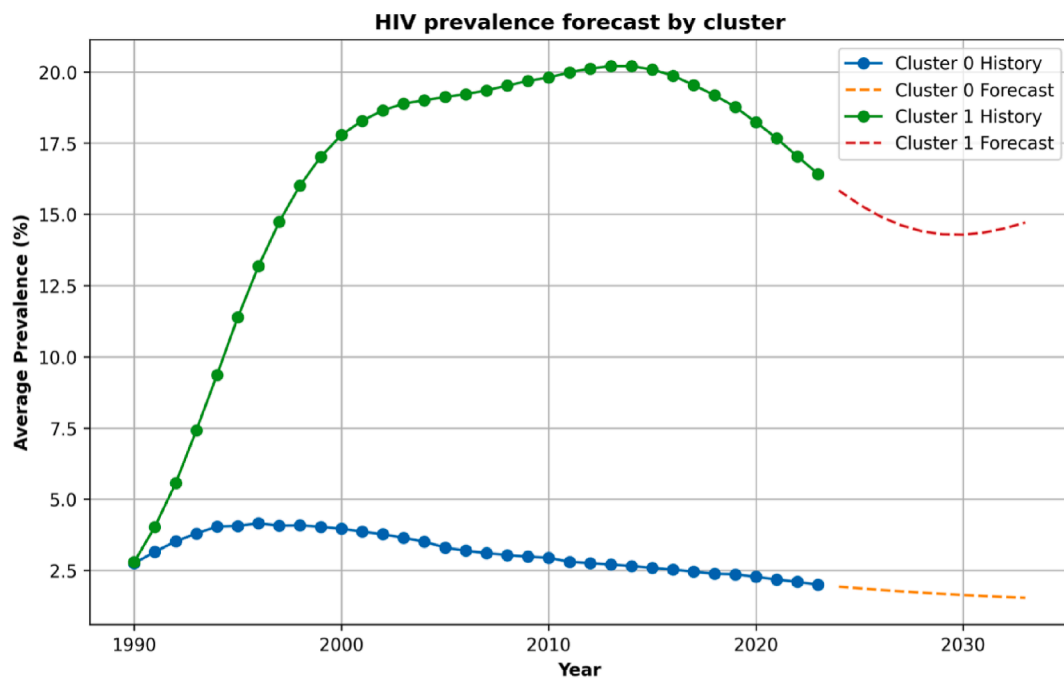


Fig. 3. Historical and projected HIV prevalence trajectories by epidemic cluster archetype in Africa. The solid lines represent the historical average prevalence patterns of the two epidemic clusters, highlighting the marked contrast between the hyperendemic Southern African group and the larger group of countries with lower overall prevalence. The dashed lines show the corresponding forecast trajectories, indicating the expected continuation of the long-term downward pattern in both clusters, although from substantially different baseline levels. Shaded bands denote the uncertainty around the forecasts and illustrate the range of plausible future trajectories generated by the model.

trends over the period 1990–2023. Unlike Cluster 1, HIV epidemics in this group are generally concentrated rather than generalized, with transmission dynamics often confined to specific risk groups or localized subpopulations. As shown in Fig. 3 (black line), this cluster has followed a radically different trajectory: moderate initial growth from 1990 (2.7%) to a peak in 1997 (4.0%), followed by a gradual but sustained decline to 2.0% in 2023. Projections for 2024–2033 (orange dotted line) indicate a continuation of the downward trend, with an estimated prevalence of 1.5% by 2033. However, this aggregate view masks substantial internal heterogeneity, and within Cluster 0 we can identify at least three distinct epidemiological subgroups, whose divergent linear trends are visualized in Fig. 5.

First, countries with moderate prevalence in sustained decline include Eastern and Southern African nations such as Zimbabwe, Zambia, Malawi, Kenya, and Uganda that have experienced significant generalized epidemics but are now in a phase of robust epidemiological decline. As shown in Fig. 5A, Zimbabwe has the most pronounced decline (−0.42 percentage points/year, prevalence 18.0%), followed by Kenya (−0.19 percentage points/year, prevalence 6.5%), Malawi (−0.19 percentage points/year, prevalence 11.4%), and Uganda (−0.16 percentage points/year, prevalence 7.8%). All of these countries show R^2 values greater than 0.95 for linear trends, indicating that the decline is statistically significant and sustained over time. These patterns suggest that these countries have passed the peak of the epidemic and are now benefiting from the cumulative effects of decades of prevention, testing, and treatment interventions, with projections suggesting achievement of prevalence rates below 10% by 2033.

Second, countries with stable or slightly increasing low prevalence include most nations in West and Central Africa (Nigeria, Ghana, Senegal, Ivory Coast, Cameroon, Democratic Republic of Congo) with prevalence rates ranging from 1 to 4%. As summarized in Table 3, these countries generally show stable or slightly declining trends, with slopes between −0.07 and +0.02 percentage points/year. A notable exception is Guinea-Bissau (prevalence 2.3%, trend +0.05 percentage points/year, Fig. 5B), which shows a statistically significant increase despite its relatively low prevalence, suggesting potential gaps in prevention services or the emergence of new risk factors.

Third, countries with very low prevalence include mainly North African and Sahel nations (Algeria, Morocco, Egypt, Libya, Tunisia, Sudan, Niger, Mauritania) with prevalence rates below 1%. These countries have avoided generalized epidemics, with HIV remaining concentrated in key populations. Trends are generally stable, reflecting low transmission epidemic equilibria, and represent “pre-epidemic” or “concentrated epidemic” scenarios where heterosexual transmission in the general population has never reached self-sustaining levels.

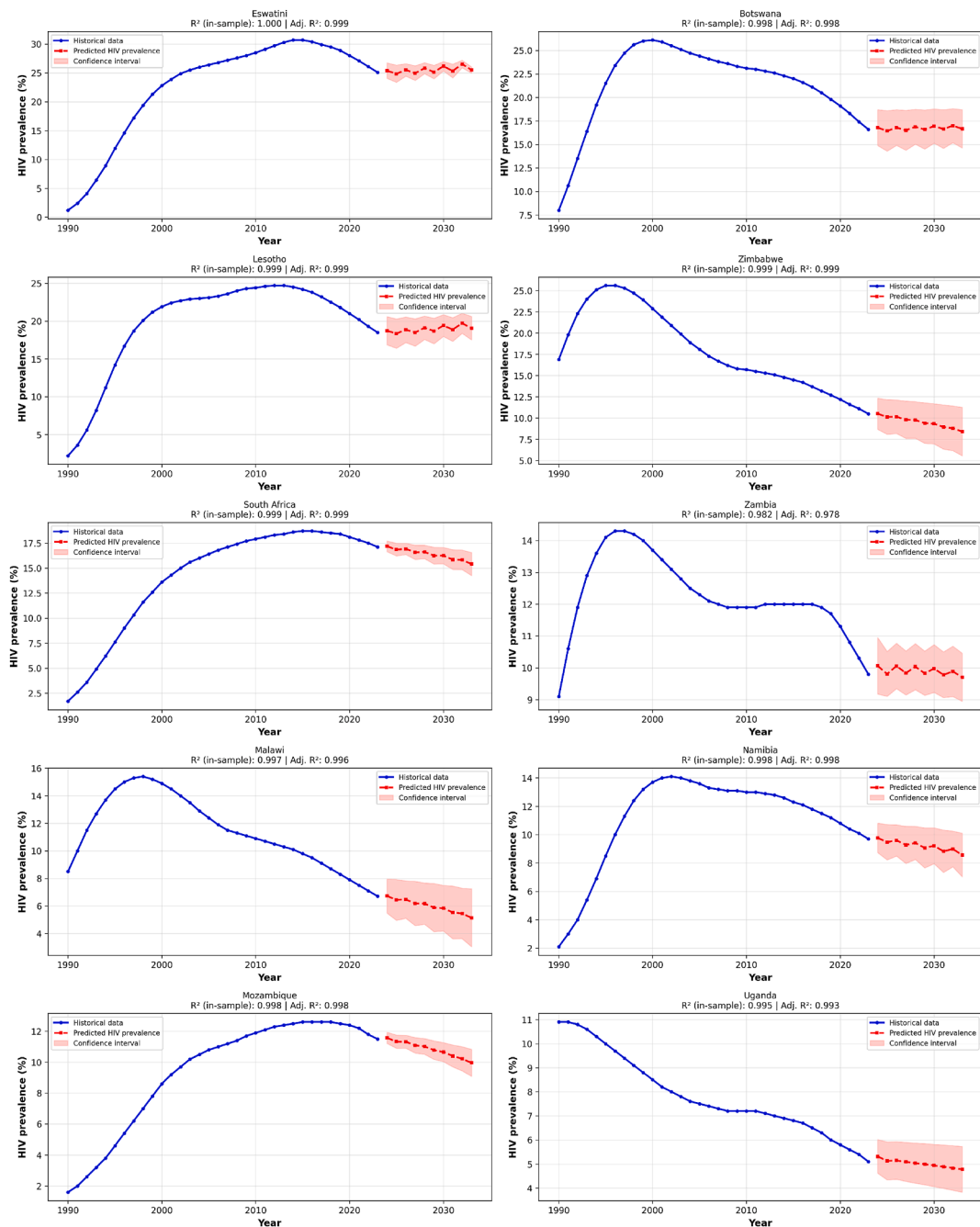


Fig. 4. Historical and projected trends in HIV prevalence in the ten African countries with the highest infection rates (adults aged 15–49, 1990–2033). Solid lines represent historical prevalence estimates from UNAIDS 2024 (UNAIDSa), while dashed lines indicate ensemble model projections for 2024–2033. Shaded areas denote 95% prediction intervals. Countries included in the analysis comprise both Cluster 1 (the six hyperendemic Southern African countries: Botswana, Eswatini, Lesotho, Mozambique, Namibia, and South Africa) and high-burden Cluster 0 countries (Zimbabwe, Malawi, Uganda, and Kenya).

4. Discussion

Our study provides continent-wide evidence of pronounced regional disparities and epidemiological heterogeneity of HIV across Africa, with important differences in levels and trends between regions and over time (Awad et al., 2018; Gedefie et al., 2025; Gökengin et al., 2016; Kumah et al., 2023; Ouyang et al., 2025; Stelzle et al., 2025). According to the epidemiological archetypes identified by our clustering analysis, these differences are not only geographic but also structural: Cluster 1 captures hyperendemic settings characterized by persistently high prevalence and slower epidemiological

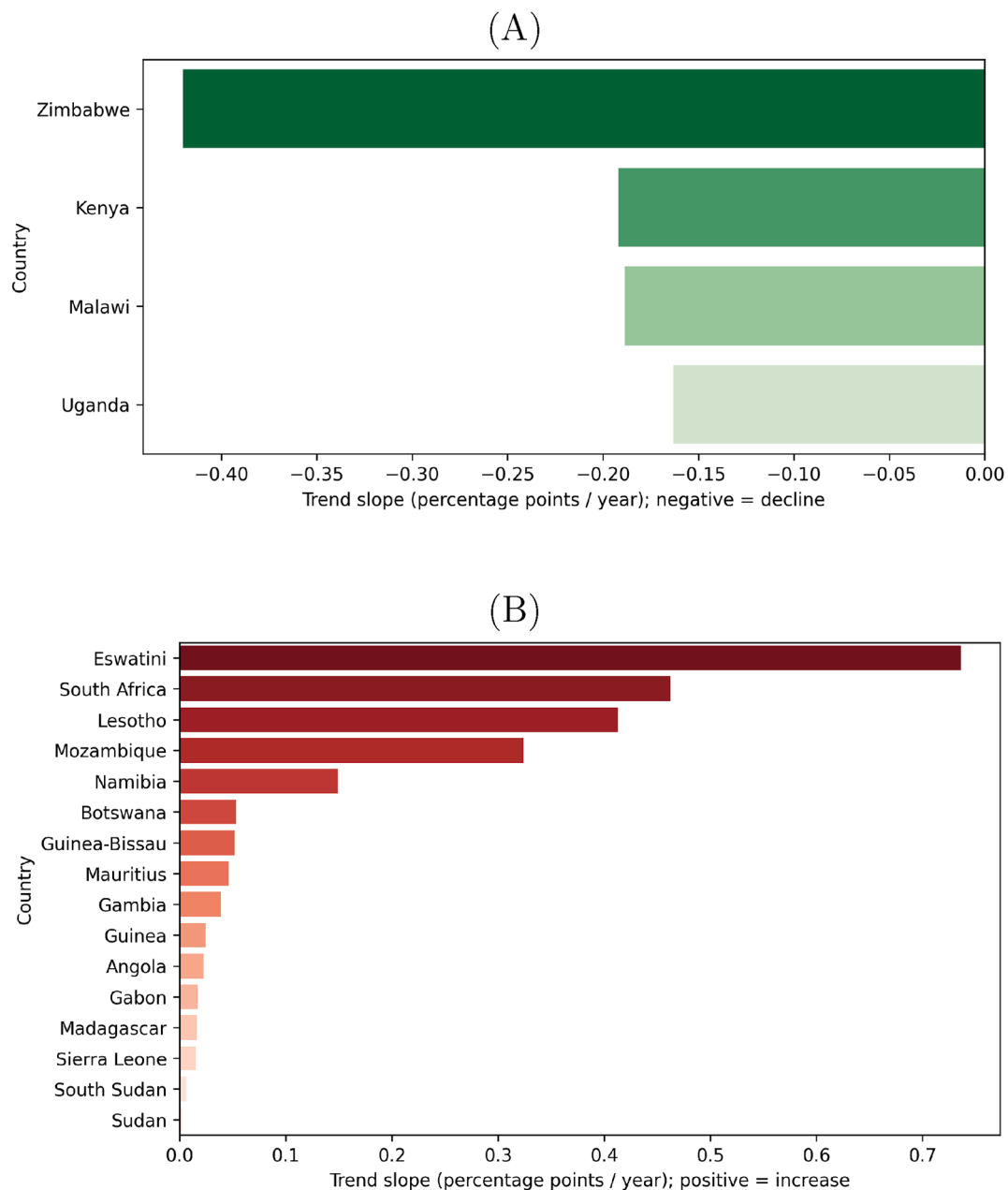


Fig. 5. Trends in HIV prevalence among adults aged 15–49 across selected African countries, estimated from annual UNAIDS 2024 estimates (UNAIDSa) over the period 1990–2023. Panel (A) displays countries with the most negative slope coefficients, representing sustained and statistically significant declines in HIV prevalence over the three-decade observation window. Panel (B) displays countries with non-negative slope coefficients, encompassing stable low-prevalence trajectories as well as settings exhibiting increasing trends. Slope values represent the average annual change in prevalence expressed in percentage points per year.

reversal, whereas Cluster 0 includes lower-burden settings with predominantly stable or declining trajectories. Among adults aged 15–49 years, mean prevalence declined between 2014 and 2023, reflecting slow but sustained progress across most regions. These patterns are consistent with long-term gains in prevention and treatment, while underscoring persistent differences in prevalence, incidence, and mortality that require differentiated, context-specific responses. This framework helps explain why Southern Africa remains concentrated within the highest-burden archetype, whereas Northern and Western Africa are more frequently associated with lower-prevalence trajectories, albeit with important within-region heterogeneity.

The heterogeneity documented across African regions does not occur in isolation but reflects broader global patterns in HIV epidemic evolution. Across world regions, substantial disparities in prevalence, incidence trajectories, and epidemic stage persist; however, the African context remains distinctive in both scale and structural complexity. In high-income regions such as Western Europe and North America, HIV epidemics are largely concentrated among key populations, including men who have sex with men, people who inject drugs, and migrant populations, with generalized heterosexual transmission remaining uncommon (UNAIDSa). In these settings, incidence has declined or stabilized over the past decade, supported by near-universal ART coverage, widespread PrEP uptake, and robust surveillance systems (van et al., 2024). By contrast, Eastern Europe and Central Asia represent a divergent trajectory, where incidence has continued to rise, driven by injecting drug use, limited harm reduction coverage, and restricted access to treatment (UNAIDSa). In Asia, epidemics remain predominantly concentrated but highly heterogeneous: substantial declines have been achieved in countries such as Thailand and Cambodia through targeted interventions, whereas other settings, including Pakistan and the Philippines, continue to experience increasing transmission among key populations (van et al., 2024). In Latin America and the Caribbean, trends are mixed, with declining mortality but persistent or rising incidence in several countries, particularly among MSM and transgender women (UNAIDSa).

Against this global backdrop, the African epidemic is distinguished by several features not observed elsewhere at comparable scale. First, sustained generalized heterosexual transmission leading to hyperendemic prevalence levels exceeding 15–25% in Southern Africa represents a unique global epidemiological configuration (Kharsany & Karim, 2016). Second, the coexistence of declining, stable, and increasing national trajectories within a single continent, as captured by the two-cluster structure identified in our analysis, reflects global epidemiological divergence but across a substantially wider burden spectrum. Third, although ART scale-up has reduced mortality globally and across Africa, the absolute number of adults living with HIV continues to increase in Africa, in contrast to most other regions, due to population growth and improved survival under treatment. This dynamic, often described as a ‘prevalence paradox’ (Jacob et al., 2013), highlights that declining rates do not necessarily translate into reduced population burden, with important implications for long-term health system planning. These comparisons indicate that while epidemiological heterogeneity is a global phenomenon, its expression in Africa is exceptional in magnitude, structural drivers, and programmatic demands.

The observed divergence from uniform epidemic control across African regions, and specifically the persistence of Cluster 1 hyperendemicity in Southern Africa, can be understood as the result of interacting socio-economic, biological, and programmatic mechanisms that vary substantially across settings. In hyperendemic Southern African countries (Cluster 1), multiple reinforcing factors sustain transmission despite high ART coverage. From a biological and network perspective, extremely high community prevalence generates dense and highly connected sexual networks, where even small gaps in viral suppression translate into disproportionately high transmission risk (Tanser et al., 2013). High levels of concurrent partnerships, well documented in this subregion, further amplify transmission dynamics by increasing exposure during the acute phase of infection, when infectiousness is highest. Recent evidence from Botswana confirms that concurrent partnerships remain strongly associated with HIV seroconversion (adjusted prevalence ratio = 1.28, 95% confidence interval: 1.05–1.56), underscoring the continued relevance of this structural driver in hyperendemic settings even in the ‘Treat All’ era (Moyo et al., 2025). This finding suggests that behavioral network characteristics continue to modulate transmission efficiency independently of treatment coverage, providing a partial explanation for the slower-than-expected declines observed in Cluster 1 countries.

At the socio-economic level, persistent gender inequalities, high rates of intimate partner violence (IPV), and the economic disempowerment of women and girls continue to shape structural vulnerability to HIV (Kuchukhidze et al., 2023). A recent meta-analysis specific to women living with HIV in Africa found a pooled IPV prevalence of 54.6% (95% confidence interval: 48.2–60.9%), with strong associations documented between IPV experience and low income (odds ratio [OR] = 2.96, 95% CI: 1.84–4.76) as well as controlling partner behavior (OR = 4.65, 95% CI: 2.53–8.55) (Fetene et al., 2025). This syndemic of violence and HIV complicates engagement across the entire care cascade, as women experiencing violence are more vulnerable to HIV acquisition and face significant barriers to accessing and remaining in HIV care, including fear of partner retaliation, restricted healthcare autonomy, and mental health comorbidities (Kuchukhidze et al., 2023). The challenge of reaching these groups is magnified in hyperendemic settings like Lesotho, where population-based HIV impact assessment data indicate that correlates of HIV infection among adolescent girls and young women (AGYW) include engagement in higher-risk sexual practices, having an HIV-positive partner, and cross-border mobility, underscoring the intersection of gendered power dynamics, economic marginalization, and mobility in shaping distinct vulnerability profiles that require tailored intervention packages beyond standard prevention programming (Low et al., 2019).

Sustained circular labor migration, particularly within mining and agricultural economies linking Lesotho, South Africa, Zimbabwe, and neighboring states, further compounds these vulnerabilities by disrupting family structures, creating sexual networks that bridge high-prevalence and lower-prevalence areas, and limiting the effectiveness of individual-level interventions (Nako et al., 2025). Recent cross-sectional evidence from South Africa demonstrates that internal migrants have significantly lower rates of HIV testing (87% vs. 92%, $p < 0.001$) and ART adherence among those on treatment (81% vs. 89%, $p = 0.003$) compared to permanent residents (Yorlets et al., 2025).

From a programmatic perspective, even well-resourced national HIV responses face diminishing returns in settings with extremely high baseline prevalence. Each incremental reduction in transmission requires reaching increasingly hard-to-engage populations who face complex, intersecting barriers to care. A 2025 systematic review on wealth, income, and HIV in sub-Saharan Africa confirms that income inequality, rather than absolute poverty alone, remains a consistent driver

of epidemic persistence, suggesting that structural economic interventions are required alongside biomedical prevention (Atkins et al., 2025). The review found that in settings with high income inequality, the protective effect of individual-level wealth is attenuated, and community-level socioeconomic gradients independently predict HIV risk. This finding is particularly salient for Cluster 1 countries such as South Africa and Namibia, which combine hyperendemic HIV prevalence with among the highest Gini coefficients globally.

These interacting mechanisms, i.e., dense sexual networks with persistent concurrency, gender-based violence as a syndemic amplifier, circular labor migration disrupting care continuity, and structural economic inequality limiting prevention effectiveness, provide a coherent explanatory framework for why Cluster 1 countries exhibit slower epidemiological reversal and why uniform epidemic control has not been achieved across the continent. This framework implies that achieving the 95–95–95 targets in hyperendemic settings will require multi-sectoral responses that address structural drivers alongside continued biomedical scale-up. Specifically, interventions must extend beyond the health sector to include economic empowerment programs for women and girls, workplace-based HIV services for mobile and migrant workers, legal and social protection against intimate partner violence, and social protection mechanisms that buffer against income shocks.

HIV-related mortality declined in most regions between 2014 and 2023. In South Africa, reductions were substantial, consistent with expanded ART coverage, earlier diagnosis, and strengthened community-based care (Elsbernd et al., 2022). Eastern Africa also experienced marked declines associated with large-scale treatment expansion and improved service integration, whereas progress has been slower in parts of Central and Western Africa, likely reflecting health system constraints, stigma, and instability. Evidence from cohort studies confirms improved survival but persistent inequities linked to late diagnosis, treatment initiation, and social determinants of health (Naghibifar et al., 2024). Mortality remained lowest in North Africa, although localized increases highlight the importance of sustained surveillance and equitable service delivery (Gona et al., 2020; GBD 2021 HIV, Collaborators, 2024). Collectively, these differences underscore the need for country-specific strategies to achieve global 95–95–95 targets (Cuadros et al., 2024; Wang et al., 2025).

Time series forecasting for the ten highest-burden countries indicates continued declines in most settings, with limited late-horizon increases in a few countries. Forecasts were derived from logistic and linear models that closely reproduced historical trajectories (average $R^2 = 0.998$), while ensuring epidemiologically plausible bounds between 0 and 100%. Although model diagnostics indicate strong fit, projections remain sensitive to future policy changes, funding fluctuations, and external shocks (Emmanuel et al., 2025; Mabaso et al., 2021). The recent withdrawal or reduction of international donor funding for HIV programs in several African countries, including the temporary freeze of United States President's Emergency Plan for AIDS Relief (PEPFAR) disbursements in early 2025, represents a substantial source of uncertainty that could alter these projected trajectories, particularly in countries with high donor dependency. Clustering based on historical prevalence and slope identified two main archetypes: Cluster 1, comprising high-burden epidemics with earlier peaks and heterogeneous trajectories, and Cluster 0, consisting of lower-burden settings with predominantly sustained downward trajectories. This distinction has direct programmatic implications. Cluster 1 countries, characterized by historical hyperendemic plateaus, require intensified interventions targeting persistent transmission drivers, improved retention in care, and focused prevention in high-risk populations and geographic hotspots, with particular urgency in settings still experiencing upward trends. In contrast, Cluster 0 countries require strategies aimed at sustaining declining trends, preserving treatment gains, and rapidly responding to early signals of stagnation or resurgence. Overall, these patterns suggest that the highest-burden epidemics are in a prolonged but gradual decline, while most other countries maintain steady reductions.

The two-cluster analytical framework derived in this study directly informs differentiated intervention priorities. Cluster 1 countries are characterized by historical hyperendemic plateaus with trajectories that either continue to rise or decline only slowly: for these settings, the critical challenge is not sustaining an existing downward trend but actively reinvigorating decline by addressing the structural drivers of persistent incidence, i.e., gender inequality (Fetene et al., 2025; Kuchukhidze et al., 2023), incomplete male circumcision coverage, low treatment uptake among men (UNAIDS; Stellenbosch University), and inadequate PrEP reach among adolescent girls and young women (UNFPA). Within this group, however, the heterogeneity documented in Fig. 4 necessitates further stratification: Eswatini and Lesotho require urgent intensification to reverse ongoing upward trends; South Africa, Botswana, Namibia, and Mozambique need sustained pressure to accelerate slow declines from hyperendemic plateaus; and Zimbabwe, Uganda, Malawi, and Zambia exemplify successful epidemic reversal and offer programmatic lessons for neighboring hyperendemic settings (CDC). The structural vulnerabilities underlying Lesotho's persistent transmission are particularly well documented, with circular male labor migration to South African mines creating sustained high-risk sexual networks that bridge geographic boundaries (Olowu, 2014), a dynamic further compounded by recent evidence from South Africa demonstrating that circular migrants exhibit significantly lower rates of HIV testing and treatment adherence compared to permanent residents (Yorlets et al., 2023). Concurrently, high levels of multiple concurrent partnerships remain strongly associated with HIV seroconversion in hyperendemic settings, as demonstrated in Botswana where concurrency independently predicts acquisition risk even in the era of universal treatment (Cui et al., 2025). In Lesotho, correlates of HIV infection among adolescent girls and young women specifically include engagement in higher-risk sexual practices, having an HIV-positive partner, and cross-border mobility (Low et al., 2019), underscoring the intersection of gendered power dynamics, economic marginalization, and mobility in shaping distinct vulnerability profiles. At the broader structural level, systematic review evidence confirms that income inequality, rather than absolute poverty alone, remains a consistent driver of epidemic persistence in sub-Saharan Africa (Atkins et al., 2025), suggesting that structural economic interventions are required alongside biomedical prevention in Cluster 1 settings.

In contrast, Cluster 0 countries face the distinct challenge of accelerating and sustaining already-existing downward trajectories: for those in robust decline (e.g., Kenya, Rwanda, Ethiopia), the priority is preventing programmatic complacency and protecting against funding disruptions; for those with stable low prevalence, the focus should be on concentrated epidemic dynamics and key populations (Silhol et al., 2024); and for the few with rising low-level trends (e.g., Guinea-Bissau), targeted investigation of local drivers is urgently needed (ISPUP). Across both clusters, the implementation of differentiated service delivery models that tailor care frequency, location, and intensity to patient needs and preferences has demonstrated substantial promise in improving retention and reducing health system burden in Malawi, South Africa, and Zambia (Huber et al., 2021). This direct mapping between epidemiological archetype and intervention strategy, rather than applying uniform continental approaches, represents the principal practical contribution of the cluster analysis presented here.

Emerging biomedical innovations, including mRNA-based HIV vaccine candidates currently under evaluation in phase I/II clinical trials, may further accelerate these trajectories if proven effective and equitably deployed.

Policy implications follow directly from these findings. In Southern Africa, where forecasts indicate a slow decline despite persistently high prevalence, priorities should focus on high-impact prevention strategies capable of reducing residual transmission, particularly among adolescent girls and young women, sex workers, transgender populations, and people who inject drugs, alongside continued expansion of testing and ART (Stevens et al., 2024). In Eastern Africa, where declines are more consolidated, efforts should prioritize sustaining progress by closing rural–urban service gaps, addressing stigma among mobile and migrant populations, and expanding digital health solutions and long-acting treatment options in settings at risk of plateauing. In Western and Central Africa, where populous countries contribute disproportionately to the burden despite lower average prevalence, strengthening surveillance and health information systems through real-time geospatial analytics and regional coordination mechanisms within ECOWAS is essential to detect emerging hotspots, service gaps, and supply-chain vulnerabilities earlier (Cuadros et al., 2023; Simela et al., 2025). Across all regions, integrating self-testing, PrEP (including long-acting formulations), long-acting ART, digital adherence tools, and differentiated service delivery models into nationally funded programmes will be essential to achieve the 2030 targets (Olasunkanmi et al., 2024; Pugh et al., 2022; Were et al., 2021). The sustainability of these gains will depend on continued domestic financing commitments, integration of HIV services within universal health coverage frameworks, and political will to address the structural drivers—gender inequality, economic marginalization, and mobility-related care disruptions—that continue to shape the African HIV epidemic.

4.1. Limitations and future research

Despite these strengths, several limitations should be considered. First, the analysis relies on UNAIDS national estimates, which may be affected by reporting gaps, surveillance heterogeneity, and modelling assumptions. Some countries lack complete time series, which may influence summary estimates. Second, standardized age definitions (15–49 years for prevalence and incidence, and ≥ 15 years for ALHIV and mortality) may introduce comparability constraints across indicators. Third, left-censored values were imputed using midpoint substitution, which may introduce minor bias, although sensitivity analyses indicate limited impact. Fourth, forecasts rely on extrapolation of historical patterns and remain sensitive to structural changes in policy, funding, and epidemiological dynamics. Fifth, the clustering approach is descriptive and based on two variables only (mean prevalence and slope), simplifying the multidimensional nature of HIV epidemics.

Future research should incorporate richer covariates, including ART coverage, viral suppression, demographic transitions, and behavioural indicators, to better explain cross-country heterogeneity. Subnational and spatially explicit analyses may reveal additional structure obscured at the national level. Methodologically, future work should compare mechanistic, Bayesian, and ensemble approaches to improve uncertainty quantification and robustness to structural breaks. As surveillance systems improve, real-time forecasting could increasingly support policy decision-making. Finally, assessing the impact of emerging prevention technologies and long-acting interventions will be critical for anticipating future epidemic trajectories.

5. Conclusion

This continent-wide analysis demonstrates a persistent and substantial heterogeneity in HIV trajectories across Africa, with hyperendemic Southern African countries showing slow declines, stabilization, or even rising prevalence, while most countries in the rest of the continent display sustained downward trends. The two-cluster segmentation derived from historical average prevalence and slope captures this divergence effectively and offers a practical lens for targeted action. Countries in Cluster 1, characterized by extremely high prevalence and heterogeneous or worsening trajectories, require intensive and long-term strategies including universal ART scale-up aligned with the 95–95–95 targets, expansion of biomedical prevention such as PrEP for high-risk and underserved populations, reinforcement of male circumcision programs where applicable, and structural interventions to address gender inequalities, socio-economic vulnerabilities, and barriers to care that continue to fuel transmission. Sustained political commitment and stable financing are indispensable to prevent reversals in countries such as Eswatini and Lesotho, where trends remain upward. In contrast, Cluster 0 countries face more diverse challenges: those with sustained declines (e.g., Zimbabwe, Kenya, Malawi, Uganda) must maintain programmatic momentum and prevent complacency; countries with stable low prevalence should prioritize services for

key populations to avoid escalation into generalized epidemics; and settings with increasing trends despite low baseline levels, such as Guinea-Bissau, require focused investigation of local drivers and targeted corrective action. Forecasts to 2033 indicate that, without strengthened and sustained interventions, the epidemiological divide between hyperendemic Southern Africa and the rest of the continent is likely to persist, with significant implications for resource allocation, geographic prioritization, and the feasibility of achieving the global HIV elimination goals by 2030. The consistently high goodness-of-fit values observed for the main forecasting models suggest that the structural drivers shaping these trajectories have remained relatively stable over time; consequently, meaningful departures from the projected paths will likely require equally meaningful changes in those drivers, particularly through stronger, broader, or more effectively sustained interventions. Ensuring robust surveillance, maintaining high ART and prevention coverage, addressing structural vulnerabilities, and tailoring interventions to country-specific epidemic patterns will be essential to convert current declines into durable and equitable progress toward long-term epidemic control.

CRedit authorship contribution statement

Francesco Branda: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Olalekan John Okesanya:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Mohamed Mustaf Ahmed:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Fabio Scarpa:** Writing – review & editing, Writing – original draft. **Antonello Maruotti:** Writing – review & editing, Writing – original draft. **Bonaventure Michael Ukoaka:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Tolutope Adebimpe Oso:** Writing – review & editing, Writing – original draft. **Precious Miracle Wagwula:** Writing – review & editing, Writing – original draft. **Zhinya Kawa Othman:** Writing – review & editing, Writing – original draft. **Jerico Bautista Ogaya:** Writing – review & editing, Writing – original draft. **Edgar G. Cue:** Writing – review & editing, Writing – original draft. **Victor C. Cañez:** Writing – review & editing, Writing – original draft. **Massimo Ciccozzi:** Writing – review & editing, Writing – original draft. **Don Eliseo Lucero Priso:** Writing – review & editing, Writing – original draft, Supervision. **Giancarlo Ceccarelli:** Writing – review & editing, Writing – original draft.

Informed consent

This study exclusively utilized secondary aggregate data freely accessible from the UNAIDS website. UNAIDS data are de-identified at the country level and aggregated annually, ensuring that no individual-level personal information is disclosed. According to the UNAIDS and WHO guidelines, research employing publicly available HIV epidemiological data does not require additional institutional review board (IRB) approval, provided that the analysis does not involve identifiable human subjects. All analyses adhered to international ethical standards for the secondary use of health data, including respect for confidentiality, data security, and responsible reporting.

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Conflict of interest

The authors declare no conflicts of interest.

Data availability

All data used in this study were derived from the UNAIDS global fact sheets and epidemiological databases, which are openly accessible via the UNAIDS website ([UNAIDSd](https://www.unaids.org/)). Researchers interested in reproducing or extending these analyses can download the same country-level HIV prevalence, incidence, and mortality figures directly from the UNAIDS Data Portal. The analysis scripts are stored in a private GitHub repository and can be accessed upon reasonable request.

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