BMC Research Notes

RESEARCH NOTE

Open Access

Machine learning approach and geospatial analysis to determine HIV infection, awareness status, and transmission knowledge among adults in Sub-Saharan Africa

Abel Endawkie[1*], Birhan Asmame Miheretu[2], Anteneh Yalew[3], Peter S. Nyasulu[4], Getahun Worku[5], Ashebir Asaminew[6] and Bayuh Asmamaw Hailu[7]

Abstract

Background HIV/AIDS remains a major public health challenge, in Sub-Saharan Africa (SSA). In 2020, 16% of people living with HIV did not know their HIV status in SSA. Understanding the geospatial distribution of HIV infection, awareness status, and transmission knowledge is crucial for designing effective prevention and control strategies to end the HIV/AIDS pandemic by 2030. However, to the best of our literature searching the evidence of geospatial analysis and a machine learning algorithm, specifically a decision tree to decide on a Sustainability Development Goal (SDG), and to establish a clear pathway of HIV awareness status and HIV infection rates in each region of SSA is limited. Therefore, this study aims to determine HIV Infection, awareness status, and transmission knowledge among Adults in SSA using a machine learning approach and geospatial analysis.

Methods The study used demographic and health survey data from 2009 to 2019. Machine learning algorithms and geospatial analysis techniques were employed to determine HIV infection, awareness of HIV status, and HIV transmission knowledge.

Results The overall prevalence of HIV infection among adults in SSA from 2009 to 2019 is 4.96%. The machine learning algorithm (decision tree) indicates that infected individuals are unaware of their HIV infection, about half of them do not have HIV transmission knowledge, and more of them were found in Southern SSA. The spatial hotspots show that high HIV prevalence, low levels of HIV status awareness, and adequate transmission knowledge are specifically located in the Southern and some Eastern SSA.

Conclusion The machine learning algorithm (decision tree) revealed that the risk of HIV infection is high among individuals who are unaware of their HIV status and lack knowledge about HIV transmission in Southern and eastern parts of Sub-Saharan Africa. The spatial analysis revealed the high-risk areas of HIV infection with low HIV status awareness and HIV transmission knowledge were located in Southern and some Eastern SSA countries. Therefore public health strategies should focus on educating individuals about the importance of knowing their HIV status,

*Correspondence:
Abel Endawkie
abelendawkie@gmail.com

Full list of author information is available at the end of the article

transmission knowledge, and ensuring accessible testing options in these affected regions to address the observed spatial disparities in HIV infection, HIV status awareness, and HIV transmission knowledge to achieve the 2030 Sustainable Development Goal of ending the HIV/AIDS epidemic in Africa.

Keywords Machine learning approach, Geospatial analysis, HIV infection awareness status, HIV transmission knowledge, Sub-Saharan Africa

Introduction

HIV stands for human immunodeficiency virus. It harms the human immune system by destroying a type of white blood cell that helps the human body fight infection. This puts infected humans at risk for serious infections and certain cancers. HIV is spread by contact with certain body fluids infected person. HIV can also be transmitted from a mother to her child during pregnancy and delivery [1].

AIDS is killing in the absence of effective treatment and has become a pandemic. The global roll-out of HIV treatment has saved millions of lives; about 16.6 million AIDS-related deaths have been averted over the last two decades [1, 2]. However, HIV continues to be a major global public health issue, having claimed 40.1 million lives so far. In 2021; globally 0.65 million people died from HIV-related causes and 1.5 million people are now infected. An estimated 38.4 million people were living with HIV at the end of 2021, and 25.6 million of them are in the African region [1, 3].

Now the day is the action strategy of global health sector strategies (GHSSs) guiding the health sector in implementing strategically focusing responses to achieving the goals of ending AIDS by 2030 [4]. The 2022–2030 strategies recommend shared and disease-specific country actions supported by actions by WHO and partners [5].

The international community has committed to ending the AIDS epidemic as a public health threat by 2030 [4, 6]. Interim targets have been established for the global target in 2025 (95–95–95), and fast track for achieving 2030 targets [5]. In 2020, 16% of people living with HIV did not know their HIV status, including 10.2 million who were not on treatment in SSA countries [7].

Previous spatial analyses of the HIV pandemic across SSA have mainly focused on the prevalence of infection in administration units in a few countries [8–12]. However, to the best of our literature searching the evidence of geospatial analysis and a machine learning algorithm, specifically a decision tree to decide on a Sustainability Development Goal (SDG), and to establish a clear pathway that integrates the first 95–95–95 targets with HIV awareness status and HIV infection rates in each region of Sub-Saharan Africa (SSA) is limited. So this study is the first to show the different aspects of HIV prevention-based analysis in SSA countries by focusing on geospatial analysis and establishing a clear pathway that integrates the first 95–95–95 targets with HIV awareness status and HIV infection rates using a machine learning approach. This work includes more countries and the corresponding estimates of the transmission knowledge and awareness of their status among adults which estimate HIV infection prevalence and density. This study is useful for measuring the need for community or specific area prevention of HIV infection rather than medication using the evidence related to HIV transmission knowledge and awareness status. This research considers the epidemiological distribution, transmission knowledge, and the status of the first 95-95-95 among adults and HIV-infected people to help to effective HIV response towards 2030 SDG. To implement a prevention strategy, first, identify the individual living with HIV who knows their infection, and about HIV transmission knowledge of infected people using a machine learning approach specifically a decision tree. Therefore, this study investigated using a machine learning approach and geospatial analysis to determine HIV Infection, awareness status, and transmission knowledge among Adults in Sub-Saharan Africa.

Methods

Study design

The research used a cross-sectional study design based on secondary data from the recent demographic and health survey (DHS) in Sub-Saharan Africa.

Study settings

The study was done in Sub-Saharan Africa, which is located in Continent Africa, with a diverse population. SSA or Non-Mediterranean Africa is the area and regions of the continent of Africa that lie south of the Sahara.

Source and study population

The source population was all individuals who were at home during one of the visits and were between 15 and 49 years of age (women) or up to 59 years of age (men) were eligible for the survey before the survey in Sub-Saharan Africa, whereas those in the selected Enumeration Areas (EAs) were the study population.

Data source

We extracted the demography and health survey (DHS) program available from 2009 to 2019 in 31 Sub-Saharan African countries. In most countries, DHS includes voluntary HIV testing in adults. GPS coordinates of sample locations randomly displaced up to 2 km for urban and up to 5 km for rural sample locations, to ensure the confidentiality of participants (DHS data).

Variable measurement

The outcomes of interest included individual HIV status (either Negative or Positive), awareness of HIV status as determined by responses to the question regarding whether the individual has ever been tested for HIV (Yes or No), and HIV knowledge, which is assessed through a combination of various variables.

HIV transmission Knowledge: The comprehensive knowledge of HIV/AIDS, was categorized as "Yes" or "No." An individual was deemed to possess comprehensive knowledge of HIV/AIDS if they understood that consistently using condoms during sexual intercourse and having one uninfected, faithful partner can lower the risk of contracting HIV. Additionally, they needed to recognize that a person who appears healthy can still be HIV-positive and reject two prevalent misconceptions: that mosquitoes can transmit HIV/AIDS and that sharing food with an infected person can spread the virus [13].

Young adult According to the World Health Organization (WHO), young adults are typically defined as individuals aged 15 to 24 years. So the young adults in this study analysis are those in the aged "15–24"based on the WHO definition [14].

Caseload A caseload in this study refers to the number of cases or clients that had HIV, or had poor awareness status, or poor HIV knowledge in the area based on the specific report interest. It's a way to quantify the number of case.

Data management, processing, and analysis

Data used were extracted, cleaned, coded, and analyzed using STATA version 17 Statistical software. Sample weights were done before further analysis, and descriptive statistics were described using frequencies, percentages, mean, and standard deviation, and presented using tables, figures, and narratives.

Machine learning approach for diction tree

To decide on a Sustainability Development Goal (SDG), we aim to establish a clear pathway that integrates the first 95–95–95 targets with HIV awareness status and HIV infection rates in each region of Sub-Saharan Africa (SSA). To achieve this objective, we employed a machine learning algorithm, specifically a decision tree. The decision tree is analyzed using R software.

Spatial analysis

A geospatial analysis of HIV infection, HIV awareness status, and transmission knowledge was conducted. To know the status of the unmeasured area forecast based on other neighbor-measured areas kriging method is used using QGIS version 3.24. The Kriging predictor is an "optimal linear predictor" and an exact interpolator, meaning that each interpolated value is calculated to minimize the prediction error for that point.

To identify the concentration of cases in a specific area or caseload density (case density) analysis using DHS data integrated with World Pop data (World Pop) was conducted. WorldPop takes a global database of the administrative unit-based census and projection counts for each year and utilizes a set of detailed spatial data sets to disaggregate them to counts for each 100×100 m grid cell on the planet. These data are typically available as counts in these grid cells. The count data is the number of population in each five-year age range by sex each year. Using centered enumeration areas of DHS data, World Pop data was buffered by a radius of two kilometers of an urban area and five kilometers of rural areas to count the population in these circular buffered areas. Based on the enumeration areas' prevalence, the number of the population with cases in each buffered area is estimated. Estimates of the number of adults and adults living with HIV who have no HIV test and HIV transmission knowledge for each enumeration area were derived by multiplying the estimated prevalence in each grid cell by the corresponding population estimate from World Pop. The density map shows the estimated number of cases per km^2 and their geographical distribution over the area of interest. Kernel density estimation (KDE) is also considered the most accurate of these case-load mapping techniques [15]. Kernel density estimate (KDE) is a process of inferring the probability density at every location [16]. The spatial analysis was computed using QGIS version 3.24 and SAGA GIS version 7.8.2 was implemented.

Ethical approval No ethical approval was needed because we had used the demographic and health survey which identifies all data before making it public, and the used DHS data sets are openly accessible. An authorization letter was requested to download the DHS data set and this was obtained from the Central Statistical Agency (CSA) after being requested at https://dhsprogram.com/. The dataset and all methods of this study were conducted according to the guidelines laid down in the Declaration of Helsinki and based on DHS research guidelines.

Results

Socio-demographic characteristics of respondent

This research involved 384,076 individuals who underwent HIV testing and were evaluated for their awareness status and knowledge of HIV transmission. Of these respondents, 175,557 were young adults. Additionally, 232,649 participants, representing 60.6% of the total, were from rural areas.

Prevalence of HIV infection among adults in SSA

The overall prevalence of HIV infection in SSA is 4.96%. About one in twenty (18,988) of adults are HIV positive and HIV prevalence among young adults (2.3%) in SSA is generally lower compared to all adults (Supplementary file 1).

The spatial distribution of HIV infection in SSA

In SSA countries, there is spatial variation in HIV prevalence within and between the national/sub-national levels. About one in twenty or 494 per 10,000 individuals are HIV infected in SSA. The lowest risk of HIV per 10,000 adults is in Niger which accounts for 36 and the highest finds in Lesotho which accounts for 2,485 individuals. Among young adults at the SSA level HIV prevalence are generally lower compared to all adults, 210, and ranges from 8 (Niger) to 1074 (Lesotho) per 10,000 young adults.

In both adults and young adults, Southern SSA countries were at high risk of HIV compared to other regions. The next high-risk region is found in Eastern SSA. In almost all regions in Southern SSA countries, at least one out of 10 and above 350 out of 10,000 individuals were infected by HIV both adults and young adults, respectively. In most Eastern and a few other regions, at least 750 adults and 170 young adults out of 10,000 individuals were infected by HIV (Fig. 1).

Spatial distribution of inadequate HIV transmission knowledge and awareness status

Nearly 60% of adults and 53% of People Living with HIV (PLHIV) do not have HIV transmission knowledge. Nearly half (50%) of adults are aware of their HIV status and 19% of PLHIV don't know they have the virus (Fig. 2).

Two in five (40%) SSA adults have HIV transmission knowledge. About one in five adults in Chad (17%) and Niger (21%) have HIV transmission knowledge; which indicates the lowest coverage of HIV transmission knowledge compared to other countries. About half of PLHIV (47%) have HIV transmission knowledge (Fig. 2).

Machine learning approaches of decision tree for predicting HIV Seropositivity from adults who have inadequate HIV transmission knowledge and awareness status

The risk of HIV is based on Seropositivity, infected people knowing they are infected, and HIV transmission knowledge in each SSA region is high.

In Fig. 3 node 6 indicates infected individuals are unaware of their HIV infection, about half of them do not have HIV transmission knowledge, and more of the samples were found in Southern SSA. Node 11 indicates infected individuals are aware of their HIV infection, but they do not have HIV transmission knowledge. The decision tree reveals a significant relationship ($p<0.001$) between awareness of HIV status and testing behavior, indicating that individuals who know their status

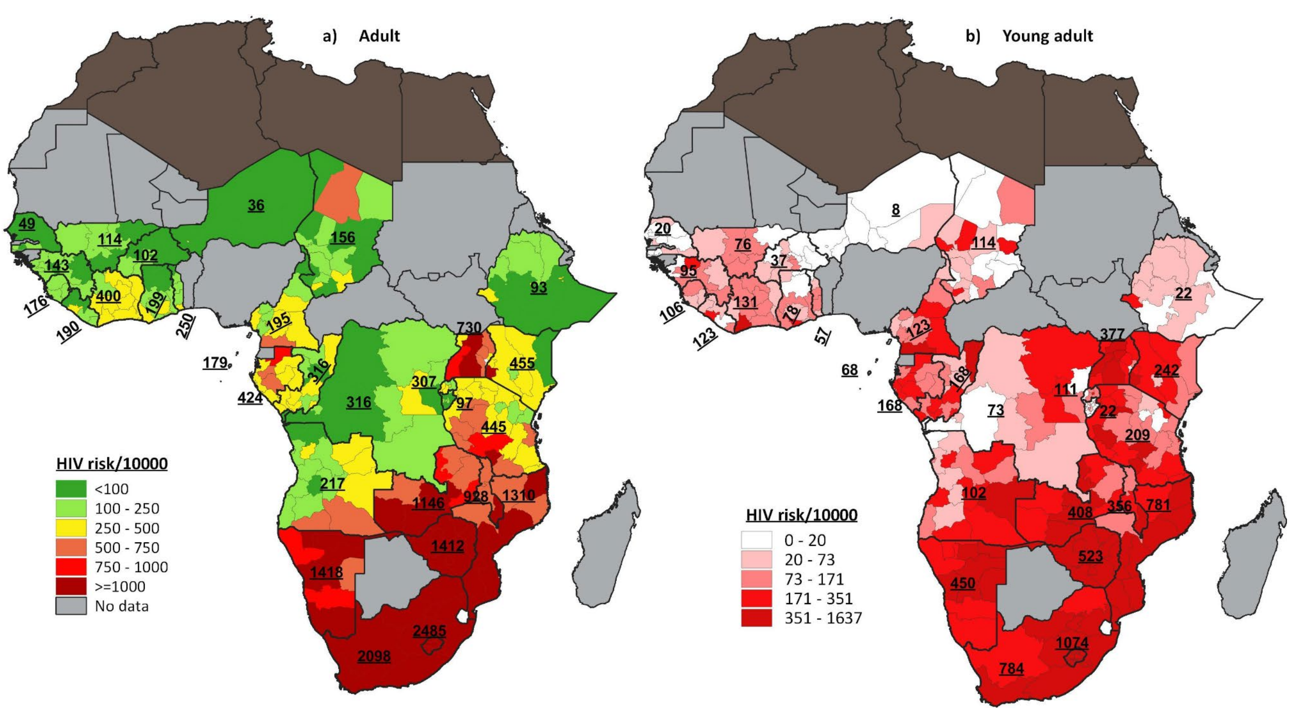

Fig. 1 The spatial distribution of HIV per 10,000 populations in each region of SSA. Legend: The left panel (**a**) indicates the risk of HIV among adults and the right panel (**b**) indicates among young adults per 10,000 populations

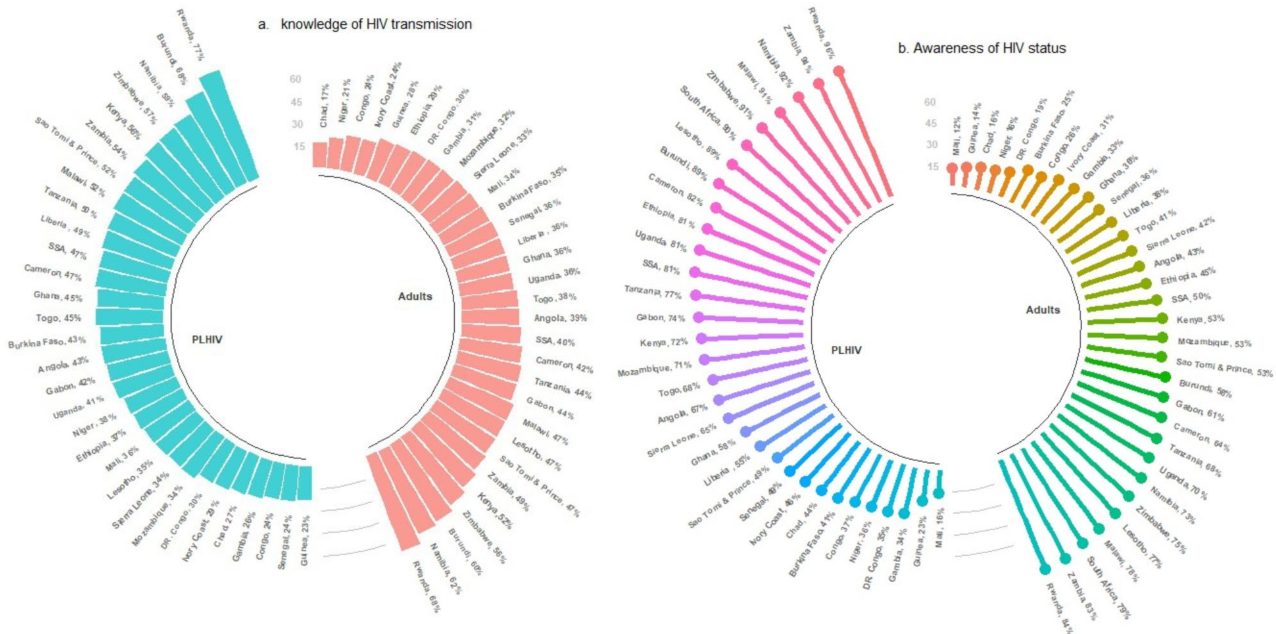

Fig. 2 The percentage of HIV transmission knowledge and HIV status awareness in SSA. Legend: The left panel (Fig. 2a) the HIV transmission knowledge and the right panel (Fig. 2b) The HIV status awareness. In each panel, the right side indicates PLHIV and the left side indicates all adults

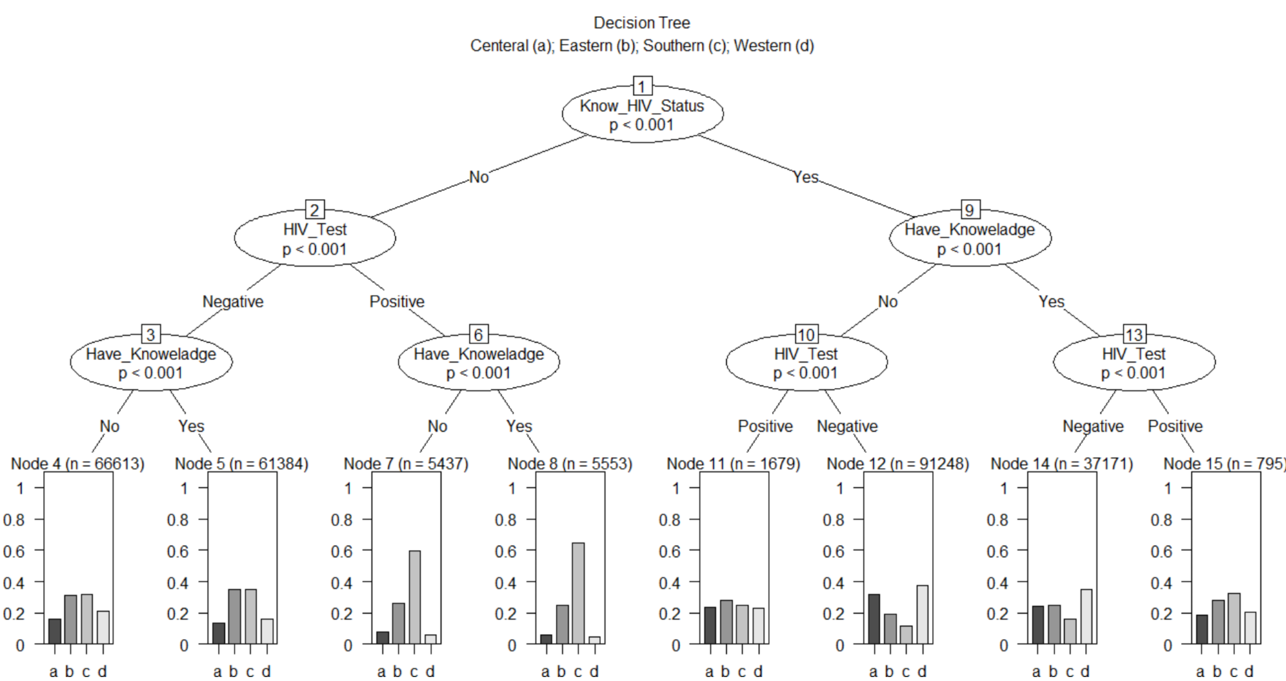

Fig. 3 Decision tree for predicting HIV Seropositivity

are more likely to engage in HIV testing. Additionally, the tree examines how test outcomes (positive or negative) influence knowledge of HIV status, showing that individuals with negative results are generally aware of their status, while those with positive results exhibit varying levels of awareness, highlighting potential gaps in knowledge for some individuals. All regions contribute an almost equal number of infections and individual contributions except Eastern SSA, which is a few more contribute (Fig. 3).

Spatial interpolation of HIV transmission knowledge and awareness status

Figure 4a, b presents the predicted do not have HIV transmission knowledge of adults. Interesting findings, characterized by a higher density of HIV transmission

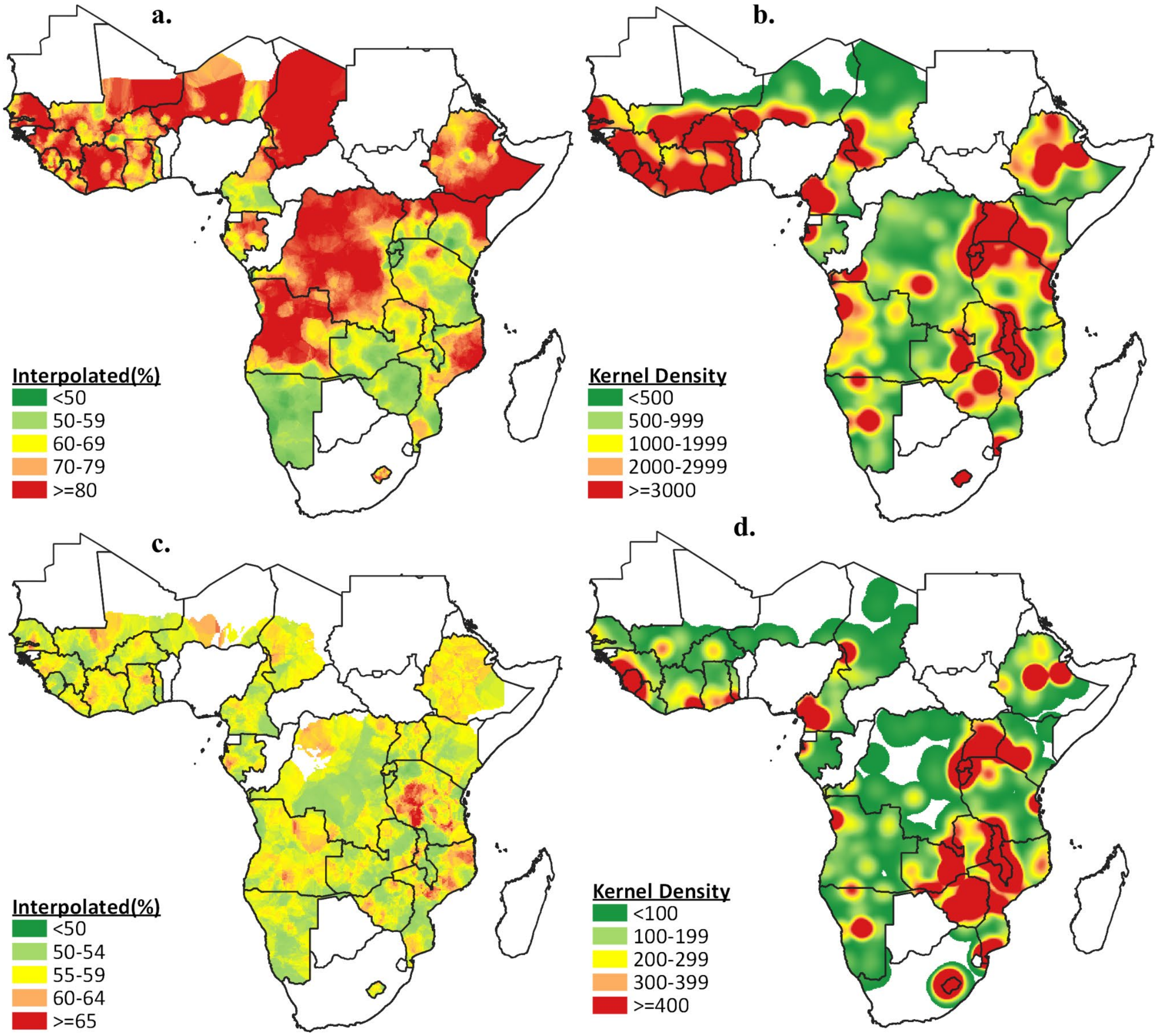

Fig. 4 Inverse distance weighting prediction and kernel density estimation don't have HIV transmission knowledge

knowledge in low prevalence areas among adults were obtained. Most areas of Western SSA are more suffering in both prevalence and caseload. Figure 4c and d HIV transmission knowledge among adults living with HIV are low in almost throughout all SSA countries; in almost all areas of SSA above 50% of HIV-infected people do not have HIV transmission knowledge (Fig. 4c). In the density of the knowledge of HIV infected people some countries have higher number of HIV infected peoples do not have HIV transmission knowledge (Fig. 4d).

Prevalence of don't have HIV transmission knowledge among adults (a), the density of don't have HIV transmission knowledge among adults (b), Prevalence of don't have HIV transmission knowledge among PLHIV (c), the density of don't have HIV transmission knowledge among PLHIV (d).

Figure 5a, b presents interpolated or predicted unaware of their HIV status among adults. Contrasting findings, characterized by the higher density of HIV testing in low prevalence areas among adults were obtained except Western SSA. Most areas of Western SSA are more suffering in both prevalence and caseload compared to other regions. Figure 5c, d presents the predicted/interpolated adults living with HIV who do not know their infections among people living with HIV. Adults living with HIV know their infections are low in almost throughout all SSA countries except most areas of Southern SSA; almost all areas of Western; most areas of Central and some areas of Eastern SSA (Fig. 5).

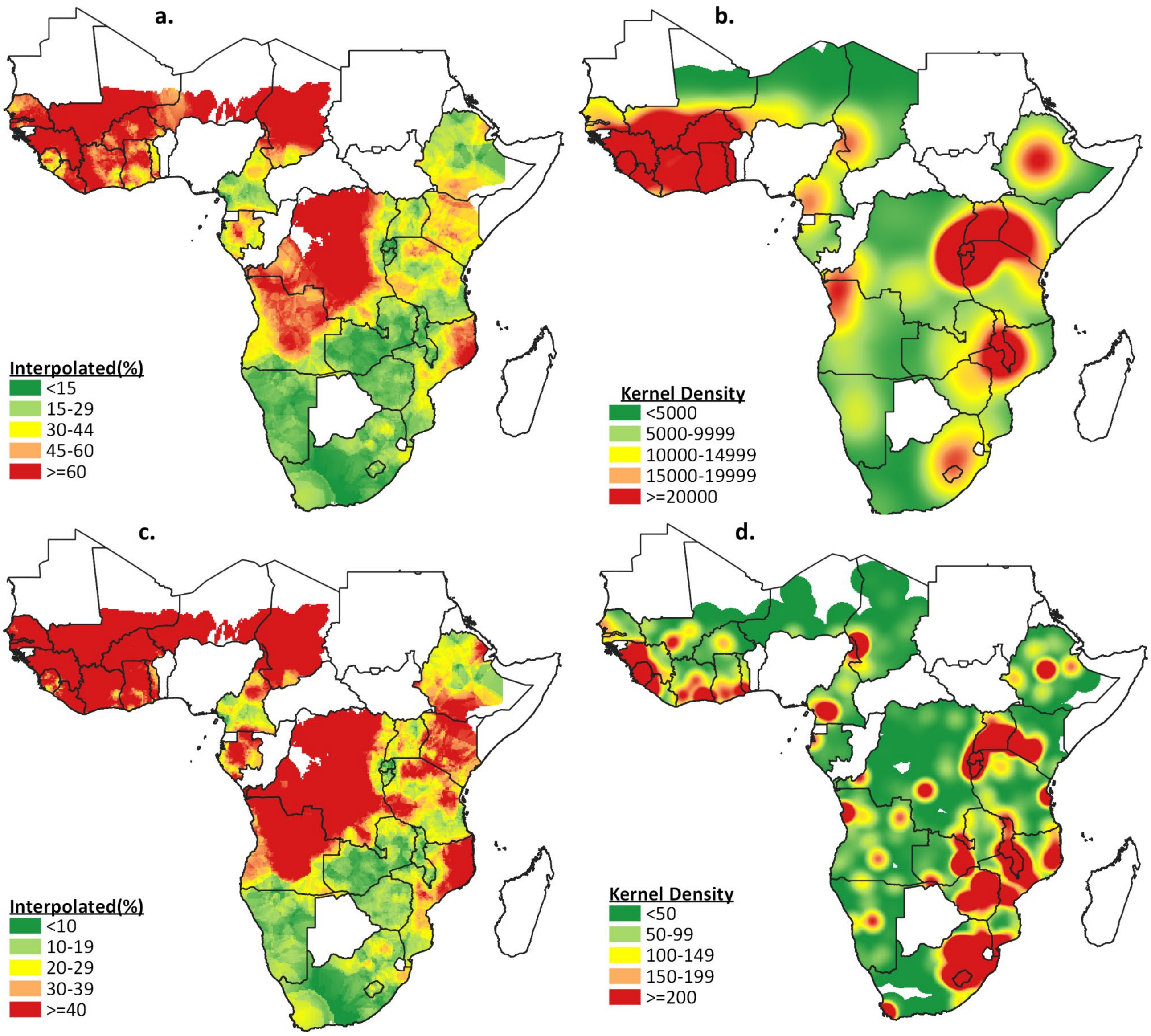

Fig. 5 IDW prediction and kernel density estimation of unaware of their HIV status. Legend: Prevalence of unaware of HIV status among adults (**a**), density of unaware of their HIV status among adults (**b**), Prevalence of PLHIV who don't know they have the virus (**c**), density of PLHIV who don't know they have the virus (**d**). Countries that don't have color were not included in the analysis

Discussion

The study finding showed that about one in twenty or 494 per 10,000 individuals were HIV infected in SSA from 2009 to 2019 which ranged from 0.4 to 24.9%. The HIV prevalence rates among adults show significant disparities: Angola, Tanzania, and Zimbabwe, highlighting significant variations in HIV prevalence rates, with Lesotho showing the highest adult prevalence at 24.9% and Niger has the lowest at 0.4%. Other countries with notable prevalence rates include Malawi (9.3%), Mozambique (13.1%), and Namibia (14.2%), indicating substantial public health challenges. The finding of this study is lower than the study findings of previous studies in SSA countries [17, 18].

From 2009 to 2019 in Sub-Saharan Africa (SSA), nearly half of people living with HIV (PLHIV) lack knowledge about HIV transmission. Additionally, some countries with low HIV infection prevalence show significant gaps in transmission knowledge. This is study is supported by other study findings in Kenya [19], previous study finding in SSA [20, 21] in Mozambique, 48% of people living with HIV infection were aware of their status, and 21% were unaware [22, 23].

Community disease control recommends that everyone between the ages of 13 to 64 get tested for HIV at least once as part of routine health care and that those with risk factors get tested more frequently. Patients who may be at high risk for HIV should be screened at least annually [24]. Therefore, to achieve further reductions in new HIV infections, it is essential for individuals with HIV to know their status, receive a quick diagnosis, and be linked to treatment immediately. Awareness of one's status is crucial to maximizing the benefits of antiretroviral therapy (ART).

Low prevalence of HIV infection countries have a higher prevalence of unawareness of HIV status in adults and PLHIV. The study is supported by other study findings in Africa [25, 26]. This indicates that PLHIV who are unaware of their infection cannot get such type of benefit and will harm their partners and themselves and will be challenging to achieve SDG 2030.

The decision tree reveals a significant relationship between awareness of HIV status and testing behavior, indicating that individuals who know their status are more likely to engage in HIV testing. This connection underscores that those aware of their status are likely to have undergone testing, as supported by the statistically robust p-value. Additionally, the tree examines how test outcomes (positive or negative) influence knowledge of HIV status, showing that individuals with negative results are generally aware of their status, while those with positive results may exhibit varying levels of awareness, highlighting potential gaps in knowledge for some individuals.

The findings from the spatial interpolation of HIV infection, HIV transmission knowledge and awareness highlight significant disparities across Sub-Saharan Africa (SSA). Adults in high-prevalence of HIV infection areas tend to have lower levels of HIV transmission knowledge, and low awareness levels in regions of Southern and some Eastern SSA countries. This study finding is supported by other study finding [27]. This suggests a critical gap in education and awareness in high-burden areas, where knowledge is essential for prevention and management. These findings underscore the importance of system strengthen to improve HIV transmission knowledge and awareness, particularly in high-prevalence areas where the lack of information may exacerbate the epidemic. Enhanced educational campaigns and access to testing are crucial for reducing transmission rates and improving health outcomes across the region.

Practical and policy implication: The study identified specific regions and subnational areas within Sub-Saharan Africa that have a high prevalence of HIV infection, low HIV status awareness, and poor HIV transmission knowledge. Tailoring interventions to local contexts: by guiding the development of location-specific strategies and interventions to improve HIV testing and awareness of transmission modes. The Southern SSA countries were at high risk of HIV and the Eastern SSA region must increase overall government spending on HIV and prioritize provinces with low HIV transmission knowledge and awareness of their HIV status especially among adults and improve programs that will reduce the numbers of new infections based on this finding.

Strength and limitation Comprehensive geospatial analysis techniques, including spatial hotspot analysis and interpolation, to examine the within-country and between-country variations in HIV infection, awareness, and transmission knowledge across Sub-Saharan Africa could be the strength of the study. The study focused on the adult population but did not examine potential differences in the spatial patterns across subgroups, such as by age, gender, or socioeconomic status limitation of the study. This study used data collected almost 10 years ago from 2009 to 2019 and therefore some of the findings may not be reflective of what is happening at the present countries which produced DHS data after 2020 is the limitation of this study.

Conclusion

The machine learning algorithm (decision tree) revealed that the risk of HIV infection is high among individuals who are unaware of their HIV status and lack knowledge about HIV transmission in southern and eastern part of Sub-Sharan Africa. The findings suggest that enhancing awareness of HIV status can lead to increased testing, which is vital for early detection and treatment. The spatial analysis revealed the high-risk areas of HIV infection with low HIV status awareness and HIV transmission knowledge were located in Southern and some Eastern SSA countries. Therefore public health strategies should focus on educating individuals about the importance of knowing their HIV status, transmission knowledge and ensuring accessible testing options in these affected regions to address the observed spatial disparities in HIV infection, HIV status awareness and HIV transmission knowledge to achieve the 2030 Sustainable Development Goal of ending the HIV/AIDS epidemic in Africa.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13104-024-07053-7.

Supplementary Material 1

Acknowledgements

The author is sincerely grateful to the DHS and World Pop program for allowing me to use the 31 SSA countries dataset. Disclosure statement: Not applicable.

Author contributions

Author contributors: AE and BAH made a role in data curation, formal analysis, investigation methodology, software. AE, BAM, AY, PN, GW, AA and BAH contributed for writing of the draft and reviewing and editing.

Funding

No funding source.

Data availability

Data availability statement: The data was obtained from The DHS Program (https://dhsprogram.com/data) by requesting from The DHS Program after creating an account and submitting a concept note with project title. More access information can be found on The DHS Program website(https://dhsprogram.com/data/Access-Instructions.cfm). We confirmed that interested researchers would be able to access these data in the same manner as the authors. We also confirm that we had no special access privileges that others would not have.

Declarations

Ethical approval

The utilized DHS data sets are publicly available, and the DHS program de-identifies all data before making them available to the public. The geospatial data (WorldPop) do not contain variables at the level of human subjects. Therefore, this work did not require ethical approval.

Consent for publication

No consent to publish was needed for this study as we did not use any details, images, or videos related to individual participants. In addition, the data used are available in the public domain.

Conflict of interest

The author declares no conflict of interest.

Author details

[1]Department of Epidemiology and Biostatistics, School of Public Health, College of Medicine and Health Sciences, Wollo University, Dessie, Ethiopia
[2]Department of Geography and Environmental Studies, Wollo University, Dessie, Ethiopia
[3]Health Sciences Research Office, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa
[4]Division of Epidemiology and Biostatistics, Department of Global Health, Faculty of Medicine and Health Sciences, Stellenbosch University, Cape Town, South Africa
[5]Department of Statistics, College of Natural Science, Wollo University, Dessie, Ethiopia
[6]Development Bank, Addis Ababa, Ethiopia
[7]Division of Epidemiology and Biostatistics, Monitoring and Evaluation, Wollo University, Dessie, Ethiopia

Received: 29 June 2024 / Accepted: 19 December 2024
Published online: 23 December 2024

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