Modelling the impact of vaccination on the COVID-19 pandemic in African countries

Dephney Mathebula[a,*], Abigail Amankwah[b], Kossi Amouzouvi[c], Kétévi A. Assamagan[d,*], Somiéalo Azote[e], Jesutofunmi Ayo Fajemisin[f], Jean Baptiste Fankam Fankam[g], Aluwani Guga[h], Moses Kamwela[i], Toivo S. Mabote[j], Mulape M Kanduza[k], Francisco Fenias Macucule[j], Azwinndini Muronga[h], Ann Njeri[l], Michael Oluwole[m], Cláudio Moisés Paulo[j]

[a] *University of South Africa, Department of Decision Sciences, South Africa*
[b] *African Institute for Mathematical Sciences(AIMS)–Ghana*
[c] *Kwame Nkrumah University of Science and Technology, Ghana*
[d] *Brookhaven National Laboratory, Physics Department, Upton, New York, USA*
[e] *Université de Lomé, Département de Physique, Lomé, Togo*
[f] *University of South Florida, Department of Applied Physics Tampa, Florida, USA*
[g] *University of Yaounde I, Department of Physics,Yaounde, Cameroon*
[h] *Nelson Mandela University, South Africa*
[i] *Lusaka Apex Medical University, Zambia*
[j] *Universidade Eduardo Mondlane, Grupo de Astrofísica, Ciências Espaciais e Inteligência Artificial, Maputo, Mozambique*
[k] *Cancer Diseases Hospital, Lusaka, Zambia*
[l] *University of Manchester, UK*
[m] *University of Ibadan, Nigeria*

Abstract

The rapid development of vaccines to combat COVID-19 is a great scientific achievement. In addition to non-pharmaceutical measures put in place to contain of the pandemic, pharmacological measures have been incorporated in the battle against the SARS-CoV-2, especially with the commencement of vaccination in early December 2020. This study used the SIDARTHE-V model, i.e. an extension of the SIDARTHE model with the impact of vaccination roll outs. We assessed the potential impact of vaccination in reducing the severity (deadly nature) of the virus in African countries. Model parameters were extracted by fitting simultaneously the COVID-19 cumulative data of active cases, recoveries, deaths and full vaccinations reported by the governments of Nigeria, South

*Corresponding Authors
Email addresses: mathed2@unisa.ac.za (Dephney Mathebula), ketevi@bnl.gov (Kétévi A. Assamagan)

Africa, Kenya, Ghana, Togo, Mozambique and Zambia. With countries having some degree of variation in their vaccination programs, we considered the impact of vaccination campaigns on the death rates in these countries. The study showed that the cumulative death rates declined drastically with the increased extent of vaccination in each country; while infection rates were sometimes increasing with the arrival of new waves, the death rates did not increase as we saw before vaccination.
Keywords: COVID-19, SIDARTHE-V, Basic reproduction number, SARS-CoV-2, Vaccination

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1. Introduction

Coronavirus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), continues to spread worldwide since 2019 [1]—in spite of the implementation of different control measures such as social distancing, wearing of face masks, sanitation, lock-downs, vaccinations, etc. We did a study on non-pharmaceutical interventions in Africa and linked them to early-stage outbreak dynamics [2].

In Ref. [3], the characterisation of omicron variant and the impact of vaccination, transmission rate, mortality, and reinfection in South Africa, Germany, and Brazil were studied. It was observed that the reinfection rate was as high as 40% in South Africa with only 29% of its population fully vaccinated, and as low as 13% in Brazil with over 70% and 80% of its population fully vaccinated and with at least one dose, respectively.

In Ref. [4], a model was developed and analysed to quantify early COVID-19 outbreak transmission in South Africa and explored vaccine efficacy scenarios. It was observed that a vaccine with 70% efficacy had the capacity to contain the COVID-19 outbreak at vaccination coverage of 94.44%; a vaccine with a 100% efficacy required a 66.10% coverage. Social distancing measures put in place have so far reduced the number of social contacts by 80.31%. Their results suggested that a highly efficacious vaccine would have been required to contain COVID-19 in South Africa. Therefore, social distancing measures to reduce contact remained key in controlling infections in the absence of vaccines and other therapeutics. The reduction in the number of contacts and transmission probability together with quarantining the infectious individuals were found to influence the basic reproduction number R_0. In addition, vaccination had contributed to the reduction of R_0 in South Africa [5].

In Ref. [6], a mathematical model of COVID-19 with vaccination and treatment was developed. The simulation results suggested that despite the effectiveness of COVID-19 vaccination and treatment to mitigate the spread of COVID-19, when $R_0 > 1$, additional efforts such as non-pharmaceutical public health interventions should continue to be implemented.

The rate at which the disease spread across Africa varied over time as individuals changed behavior in response to the pandemic evolution, changing government policies and vaccination programs. In this study, we investigated the impact of vaccination in the second year of COVID-19 pandemic in seven African countries (Ghana, Kenya, Mozambique, Nigeria, South Africa, Togo and Zambia). This is a continuation of our work reported in Ref. [2]. We modelled the outbreak in the seven African countries, noting that several model parameters varied over time. We analyzed data taken over a two-year period: the first (without vaccination) and second (with vaccination) years of the pandemic. We extracted and compared parameters to gauge the impact of vaccination as a pharmaceutical intervention.

A number of vaccines for COVID-19 have been developed by pharmaceutical and biotech companies. Each of these vaccines differs in the biotechnology used, efficacy, and geographic availability. In different African countries different vaccines were used, sometimes in combinations. For example, in South Africa, two commonly available vaccines are those developed by Pfizer and Johnson & Johnson.

Our study of vaccination impact was informed by details of the vaccination programs in the African countries considered. In the UK, the USA, and European Union, general vaccination roll outs started in earlier 2021, while African countries started vaccination campaigns later. Because of the unequal availability of vaccines around the world, the starting dates of the vaccination might have an impact in this study. However, given that we have analyzed vaccination data for one year in all countries considered, the starting dates of vaccination do not affect our conclusions.

The paper is organised as follows. In Section 2, we present the formulation of SIDARTHE-V model [7] considering the impact of vaccination campaigns. In Section 3, we present the analysis of COVID-19 data with vaccination campaigns in the seven African countries considered. We discuss the impact of vaccination in Section 4 and offer concluding remarks in Section 5.

2. SIDARTHE-V model with vaccination roll outs

In this study, we applied the SIDARTHE-V model [7] with vaccination campaigns in the second year of the pandemic. The original SIDARTHE-V of [7] assumes that all vaccinated are immunized. In this study, we considered the possibility that vaccinated individuals can still get infected, become infectious and threatened; these dynamics are captured by connecting the V and I compartments, as shown in Figure SM1, where the parameters and variables of the model are presented. Equations 1 describe the pandemic evolution, with vaccination roll outs:

$$\begin{cases} \dot{S} &= -\left(\alpha I + \beta D + \gamma A + \delta R\right) S - \phi S \\ \dot{V} &= -\alpha' IV + \phi S \\ \dot{I} &= \left(\alpha I + \beta D + \gamma A + \delta R\right) S + \alpha' IV - \left(\epsilon + \lambda + \zeta\right) I \\ \dot{D} &= \epsilon I - \left(\eta + \rho\right) D \\ \dot{A} &= \zeta I - \left(\theta + \mu + \kappa\right) A \\ \dot{R} &= \eta D + \theta A - \left(\tau_1 + \nu\right) R \\ \dot{T} &= \mu A + \nu R - \left(\tau_2 + \sigma\right) T \\ \dot{H} &= \lambda I + \kappa A + \sigma T + \xi R + \rho D \\ \dot{E} &= \tau_1 R + \tau_2 T \end{cases} \tag{1}$$

The basic reproduction number, R_0, is the average number of secondary cases produced by an infected individual in a population where everyone is susceptible [8]. Estimating R_0 helps in the implementation of appropriate responses to pandemic evolution, in particular the number of people vaccinate for herd immunity. In the SIDARTHE-V model, Equations (1), R_0 is given by:

$$R_0 = \frac{\alpha r_2 r_3 r_4 + \beta \epsilon r_3 r_4 + \delta \epsilon \eta r_3 + \delta r_2 \tau \zeta + \gamma r_2 r_4 \zeta}{r_1 r_2 r_3 r_4}, \tag{2}$$

where $r_1 = \epsilon + \zeta + \lambda$, $r_2 = \eta + \rho$, $r_3 = \theta + \mu + \kappa$, $r_4 = \nu + \xi$. For better understanding of the R_0 derivation, see [9]. From Equation (2), it can be seen that R_0 depends on the model parameters that affect pandemic evolution. Thus, it is very important to understand the model parameters and to make sure they are extracted correctly.

3. Analysis of COVID-19 data with vaccination

In our previous work [2], we studied the evolution of COVID-19 in African countries; however, vaccination was not considered and the Nigerian COVID-19 data was not included. For this reason, we start this section with the analysis of the data of Nigeria from the time when the first COVID-19 case was identified in that country—this includes the first year with no vaccination followed by another year with vaccination roll outs. For the other countries in this study, namely South Africa, Kenya, Ghana, Togo, Mozambique and Zambia, COVID-19 data of the first year without vaccination, were studied in Ref. [2]; in this section, we continue the analysis of COVID-19 data of these countries from the onsets of vaccination campaigns.

3.1. Analysis of COVID-19 data of Nigeria

In Nigeria, they confirmed the first case in the Infectious Disease Centre, Yaba, Lagos State, on February 27, 2020. An airplane from Milan, Italy, arrived at the International Airport, Lagos, on February 14, 2020 with an infected Italian citizen who went to his company's site in Ogun State the following day. The health authorities (Nigeria Centre for Disease Control) implemented containment measures by the contact tracing of 'Persons of Interest' which included all persons on the flight and those he had close contact with while in Lagos and Ogun States [10]. After a period of two weeks, cases were detected in Lagos and Abuja and this marked the emergence of the spread in the country. The Federal Government restricted international commercial flights into the country, effective from March 23, 2020 [11].

The Federal Government ordered the closure of schools and all the non-essential services (businesses and industries) and ordered cessation of all movements in Lagos State, Ogun State and the Federal Capital Territory, Abuja, on March 29, 2020 for an initial period of 14 days. Later, the restriction on movements was extended for another 14 days from April 12, 2020 [12].

Most State Governments restricted public gatherings and religious activities for over fifty (50) persons. The Federal Government lifted the travel ban on domestic flights on April 20, 2020, and ordered a Nationwide overnight curfew on movements from 8:00 pm to 6:00 am on May 2, 2020, and later eased the overnight curfew on movements on the September 3, 2020 to be from 12:00 am to 4:00 am.

On May 4, 2020, the Federal Government authorized the gradual easing of lockdown in the previously restricted states, and mandated the use of face masks in public.

On May 6, 2020, the Federal Government announced an extension of the travel ban on both International and local flights to, June 7, 2020 to curb the spread of coronavirus in the country.

The Federal Government reopened the international flight for operations on August 29, 2020 [13]. On January 27, 2021, the President signed six COVID-19 Health Protection Regulations 2021, with restrictions on gatherings, operations of public places, mandatory compliance with treatment protocols, offences and penalties, enforcement and application and lastly the interpretation and citations of the regulations [14].

After the first confirmed case on February 27, 2020, the number of confirmed cases increased drastically and the total number of confirmed cases as of March 27, 2022 was 255,341 with a total number of 249,566 discharged cases and 2,633 active cases. The first death case was on March 23, 2020 and have increased to a total number of 3,142 as of March 27, 2022. The health sector started COVID-19 sample test on April 8, 2020 and on March 27, 2022, they have recorded total tests of 4,589,725 [11, 12].

The first shipment of four million Oxford-AstraZeneca COVID-19 vaccines arrived in the country on March 2, 2021 and vaccination began on March 5, 2021. The country received subsequent shipments of Moderna, Johnson & Johnson and Pfizer COVID-19 vaccines on August 1, August 12 and October 14, 2021 respectively. Due to the single dose requirement of Johnson & Johnson COVID-19 vaccine, the Nigeria's National Primary Health Care Development Agency (NPHCDA) prioritised hard-to-reach and vulnerable areas for vaccination [15].

As of March 27, 2022, there were 21,049,754 persons who have received their first dose and 9,565,143 who have received their second dose [15].

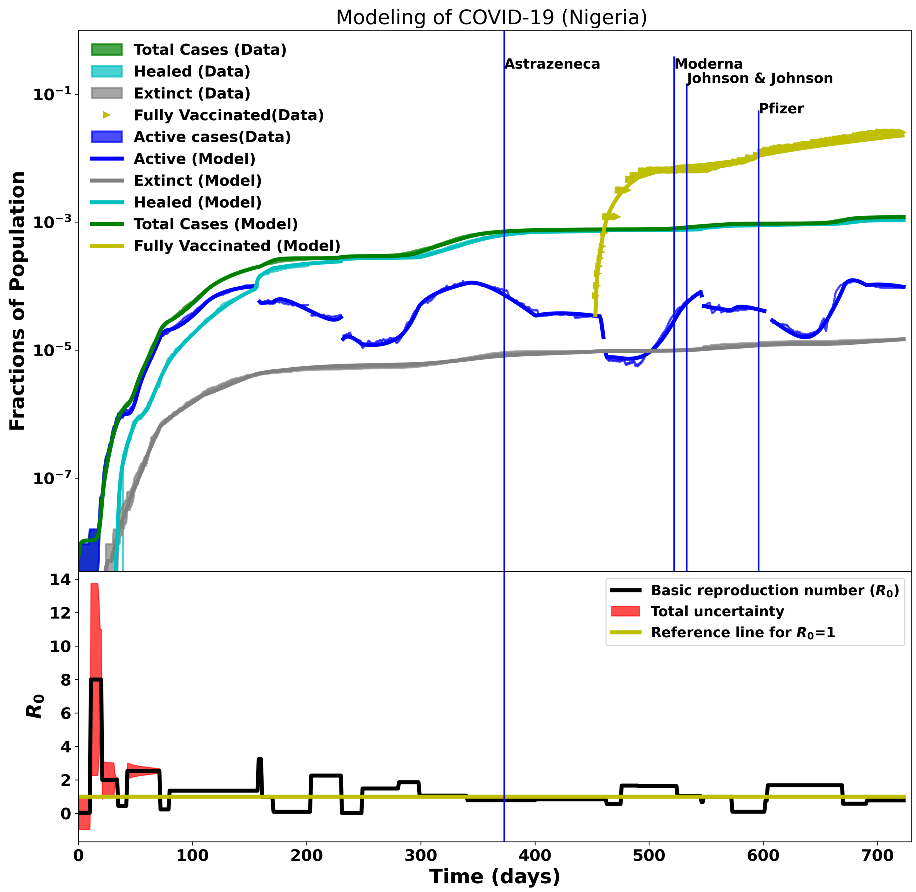

Figure 1: The modelling of 2 years of COVID-19 data of Nigeria. Day 0 corresponds to the onset of the pandemic, i.e. February 27, 2020. The top plot shows the data and model for active, recovered, death and total cases, and fully-vaccinated individuals. Vaccination drive started on March 5, 2021. The bottom plot shows the time-dependent basic reproduction number.

Figure 1 (top plot) shows the SIDARTHE-V modelling of the Nigerian COVID-19 data of active, recovered, extinct and fully-vaccinated cases. The time-dependent basic reproduction number R_0, obtained by fitting the model to the data, is shown in the bottom plot.

The R_0 increased significantly to eight after a week. This was largely due to learning period about the pandemic and lack of public control measures.

Around day 35, the R_0 dropped below one mainly because of introduction of public control measures by the government and awareness by the public. Another increase in R_0 to a point above two was observed around day 40 most likely because of the difficulties to comply with the control measures.

Around day 65, it also dropped below one. The R_0 later increased around day 75 above one and later rose to a point above three around day 150 due to ineffectiveness of the measures in some parts of the country and lack of enforcement strategies from the government.

Around day 165, the R_0 dropped well below one and increased above two around day 205. Another drop occurred around day 230 to point zero after some restrictions from the government. We see that around day 250, there was an increase in R_0 above one and was within the range of two around day 280 and even till after day 700, R_0 remained below two, these fluctuations were due to the negligence of the people to observe the control measures.

Figure SM2 shows the quality of the modelling as ratios of data over model predictions; the figure also shows the model prediction of the infected but unaffected population.

The vaccination has eased the anxiety caused by the pandemic and also enabled the government to relax lockdown protocols. Businesses and institutions such as the education sector have resumed their services.

3.2. COVID-19 vaccination analysis for South Africa

In South Africa, COVID-19 vaccination has been an ongoing immunisation campaign to vaccinate 40 million South Africans [16]. Four types of COVID-19 vaccines were approved by the South African Health Products Regulatory Authority (SAHPRA), namely, Johnson & Johnson, Pfizer, Sinovac and AstraZeneca [16]. For the South Africa COVID-19 case study, Johnson & Johnson's Janssen and Pfizer vaccines were considered [1]. As of June 9, 2022, $535,714$ COVID-19 hospital admissions were recorded in South Africa [17].

In our previous study [2], we covered the South African COVID-19 data up to adjusted alert level 3 that was effect from December 29, 2020, to February 28, 2021 [2]. Based on the changes of COVID-19 new cases in South Africa, the government introduced adjusted alert levels, defined in Ref. [2], as follows [18, 16]:

- Level 1: March 1–May 30, 2021;
- Level 2: May 31–June 15, 2021;
- Level 3: June 16–June 27, 2021;
- Level 4: June 28–July 25, 2021
- Level 3: July 26–September 12, 2021;
- Level 2: September 13–30, 2021; and
- Level 1: October 1, 2021–April 14, 2022.

On May 3, 2022, South Africa confirmed $3,661,635$ recovered individuals, $100,377$ death cases and ~ 17.7 million vaccinated individuals, $3,802,198$ positive cases [16]. The National State of Disaster in South Africa has been lifted since April 5, 2022 [18].

In South Africa, the health care workers were the first group to be vaccinated; it started on February 18, 2021 (day 350) until May 17, 2021 (day 439) under phase 1 of the Sisonke Protocol, which enabled the government to make the Johnson & Johnson vaccine quickly accessible through a research initiative [19, 20]. The death case remained constant during phase 1 while the number of active, healed and total cases slightly remained constant. During Phase 2 which started on May 18, 2021, everyone from age 16 and above was allowed to be vaccinated with the first dose of Johnson & Johnson and Pfizer.

Figure 2 (left plot) shows the modelling of the South African data; the first year of the pandemic was studied and discussed in Ref. [2]. The second year of the South African COVID-19 data, with vaccination roll outs, is extensively discussed in Section 4.

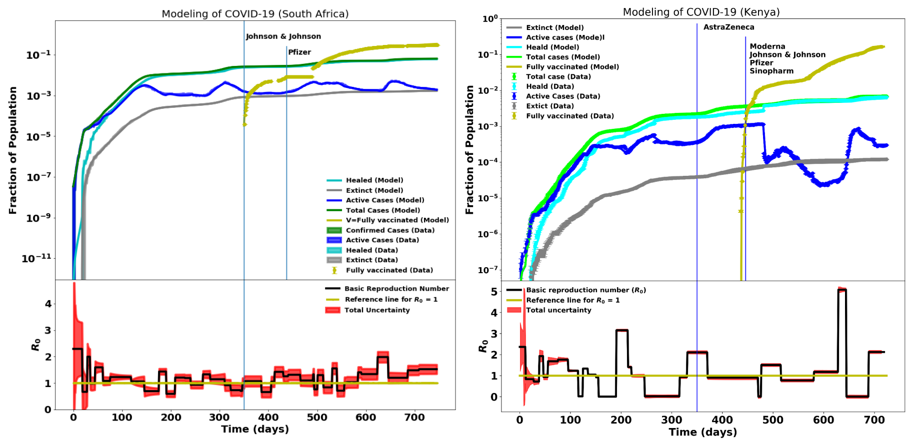

Figure 2: The modelling of about 2 years of COVID-19 data of South Africa (left plot) and Kenya (right plot). Day 0 corresponds to the onset of the pandemic, i.e. March 5, and March 12, 2020, for South Africa and Kenya respectively. The top plots show the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drives started on February 28, 2021 (South Africa) and March 5, 2021 (Kenya). The bottom plots show the time-dependent basic reproduction numbers.

3.3. COVID-19 vaccination analysis for Kenya

The data used in this analysis were taken from the daily press releases on the website of the Ministry of Health, Government of the Republic of Kenya [21]. Having received the first 1.12 million doses of the Oxford-AstraZeneca COVID-19 vaccine, the vaccination drive in Kenya kicked off on March 5, 2021. This was exactly one year after the first case of COVID-19 was reported in the country on March 12, 2020. Six hundred and sixty-seven doses of AstraZeneca were administered on the first day of vaccination to front-line healthcare workers only at the Kenyatta National Hospital, Nairobi. This was then followed by other essential workers such as security officers and teachers in the first few weeks of the vaccination programme, followed by targeted people with higher risks of severe disease and those aged 50 years and above. The administration of the second dose began on May 28, 2021 and 203 people received their second dose.

After 5 months of administering the AstraZeneca vaccine only, 880,460 doses of the Moderna vaccine were received on August 23, 2021 from the US government via COVAX, making Moderna the second COVID-19 vaccine to be offered in the country. Additional 141,600 doses of Johnson & Johnson vaccine were received soon afterwards on September 3, 2021. This was the third vaccine type to be offered and totaled to 4.2 million doses of vaccine received [21]. On September 17, 2021, the country received 795,600 doses of the Pfizer vaccine from the US government, making Pfizer the fourth vaccine offered. Shortly afterwards, on September 18 2021, the government received 200,000 doses of Sinopharm COVID-19 vaccine from the Chinese government. The government has authorised all five vaccines and they are currently being used across the country.

After a slow uptake of the vaccines among the population due vaccine hesitancy [22], a spike was observed on November 23, 2021, with the highest number of vaccination doses administered to 103,506 people in a single day. This followed a government directive on November 21, 2021 stating that anyone not vaccinated by December 21, 2021, would be refused in-person government services and access to public entertainment spots such as restaurants. By the end of 2021, 7% of the population was fully vaccinated and $\sim$ 10% of the population partly vaccinated. This figure slightly surpassed the government target of 10 million people by the end of the year 2021. Figure 2 (right plot) shows the modelling of two years of COVID-19 data in Kenya with the vaccination rolls commencing on day 358 (highlighted by the blue vertical line), almost a year after the first COVID-19 case was reported in the country—a detailed study of the data before vaccination campaigns was discussed in Ref. [2]. The issuance of the second dose began around day 450 as highlighted by the second blue vertical line. Around day 480 ($\sim$ 30 days after the second dose), there was a sharp decrease in the number of active cases. Into the second year of the pandemic, the basic reproduction number R_0 remained $\approx$1 or below 1 with slight variations during minor peaks. At day $\sim$ 650, R_0 increased sharply to $R \sim 5$. This was due to a slight but sharp increase in active cases, following a steady decrease in the number of active cases in the country.

Kenya is part of the WHO AFRO 20 priority African countries with a high risk of slow COVID-19 vaccination roll out [23]. Therefore, the WHO AFRO implemented phased COVID-19 vaccination campaigns in February 2022 in order to boost vaccination rates. This entailed community outreach efforts and increased number of vaccination sites from 800 to 6,000 sites. Over a period of two weeks (February 3–17), the daily vaccination average increased from 70,000 to 200,000 people. This also raised the percentage of the population that was fully vaccinated from 9.9% to 13.4%. As of March 11, 2022, two years after the first COVID-19 case was reported in the country and one year after the mass vaccination programme roll out, 8,054,405 vaccine doses had been administered and $\sim$ 14.8% (7,930,000) of the total population had been fully vaccinated. So far, a total of 323,140 COVID-19 cases have been reported and a total of 5,644 deaths recorded.

COVID-19 restrictions are no longer in place though the government is encouraging citizens to wear masks and maintain social distance where possible. Factors affecting the vaccination programme in Kenya include: i) funding, ii) the availability of vaccines, ii) storage requirements, iii) vaccine hesitancy among the population [22] and geographical inequalities in accessing vaccines in hard-to-reach areas [24]. The government aims to to vaccinate 15.91 million people by June 2023 in a 3-phased roll-out approach initially targeting 1.25 million people by June 2021 in phase one. This was followed by phase two, July 2021–June 2022, with a target of 9.76 million people, including the elderly and people with underlying health conditions. The third phase started in July 2022 and will run until June 2023, with a target of 4.9 million people above 18 years old, those with underlying health risks and essential workers.

3.4. COVID-19 vaccination analysis for Ghana

In Ghana, the government committed to acquiring COVID-19 vaccines on December 20, 2020 [25]. Ghana was the first country to receive COVID-19 vaccines from the COVAX initiative and began its first vaccine roll out on March 1, 2021 [26, 27, 28] with the AstraZeneca vaccine. Johnson & Johnson (J&J), Moderna, Pfizer, and Sputnik V were the COVID-19 vaccines also approved and administered in Ghana. Figure 3 (left plot) shows the modelling of the Ghanaian data over a two-year period: data from the first year of the pandemic—before vaccination started—were analyzed and discussed in Ref. [2]; in this study, we focused on the second year of data with vaccination drives.

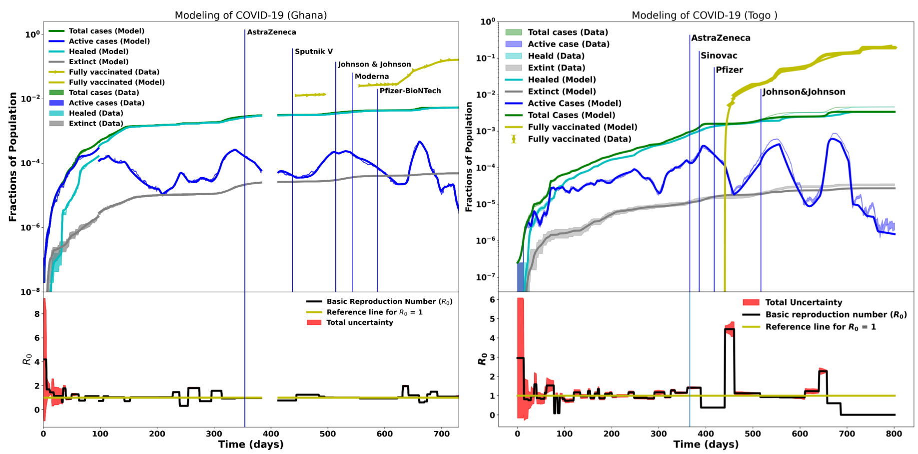

Figure 3: The modelling of about 2 years of COVID-19 data of Ghana (left plot) and Togo (right plot). Day 0 corresponds to the onset of the pandemic, i.e. March 12, and March 6, 2020, for Ghana and Togo respectively. The top plot show the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drives started on March 1, 2021 (Ghana) and March 9, 2021 (Togo). The bottom plots show the time-dependent basic reproduction numbers.

The second, third and fourth COVID-19 infection waves in Ghana were caused by the emergence of novel coronavirus variants namely Alpha, Delta and Omicron variants. A study conducted by [29] indicates that, the Delta, Alpha, Beta and Eta made up the top viral lineages within the sequenced SARS-CoV-2 genomes in Ghana. At the time of writing, the Beta variant was still being monitored in Ghana since it had the third highest frequency. During the second wave, regions further from Accra, such as the Northern and Upper East, had different variants. These locations lagged behind the rest of the country in the third wave and did not appear to experience one [30]. The Beta variety was prominent in Ghana when the airport reopened to foreign travelers in September 2020, and it remained the most dominant lineage throughout 2020. The Alpha variant superseded Beta in January 2021 and became the major cause of all reported illnesses until June 2021, when Delta lineages took over. The Delta lineages started in June 2021 until September 2021. Major variations such as Alpha, Beta, Delta, Eta, and Kappa were found in samples from tourists first, then in community instances, according to [29].

The president of Ghana and his vice were the first to receive the AstraZeneca vaccine on March 1, 2021 [31]. By March 2, 2021, vaccination was launched in the Ashanti region and over 10,000 people had been vaccination. The second doses of the AstraZeneca vaccine commenced on May 19, 2021.

By April 25, 2022, $14,268,269$ doses of these vaccines have been administered; 18.3% of Ghana's population has been fully vaccinated, 29.9% has received at least one dose of the vaccines and $360,201$ people have received the first booster dose. By April 30, 2022, there were $161,16$ -19 cases in Ghana. Out of were this, $159,737$ recovered and were discharged with $1,445$ deaths and 34 active cases. Greater Accra region recorded the highest number of COVID-19 cases at $90,826$ followed by the Ashanti region with $22,299$ cases [30].

3.5. COVID-19 vaccination analysis for Togo

On March 7, 2021, approximately one year after the detection of the first case, the country received 156000 doses of AstraZeneca through the COVAX facility [32, 33], and the vaccination campaign started the following day. 120000 additional doses of AstraZeneca were received on March 31, 2021. After these, additional 100620 Pfizer doses were obtained in May 2021, followed by 200000 doses of Sinovac on April 23, 2021. On August 7, 2021, Togo received additional 118000 doses of Johnson & Johnson vaccine out of 4 million doses that it had ordered. The World Health Organisation Coronavirus Dashboard indicates that, by August 14, 2022, Togo had received 3262548 COVID-19 vaccine doses, with 2152846 people vaccinated—corresponding to $\sim 25.4\%$ of the population qualified for vaccination—and 1425113 persons fully vaccinated [34]. The vaccination started with health workers on March 10, 2021, day 370 as showing Figure 3 (right plot), followed by clinically vulnerable individuals, then people over 50 years old [32, 33]. It took approximately 2 months to cover this targeted population. After priority groups had been vaccinated, there was a wider roll out among younger age groups. One month after vaccination campaign (from day 400) began, we started to see impact on infection rate, and this is reflected in R_0 as shown in Figure 3 (right plot). The data from the first year of the pandemic—before vaccination started—were analyzed and discussed in Ref. [2].

Active cases continued to decrease up to three months after the vaccination started while R_0 sharply increased in the third month. This increase in R_0 resulted from the relaxation of the control measures that where in place before the start of the vaccination. These measures were largely no longer respected, as people thought that the problem of COVID-19 would be solved immediately by the arrival of the vaccines. After day 470, the active cases started to increase again when the vaccine doses were finished and a new COVID-19 variant (delta) emerged. As the active cases started to increase, the government warned the population of the new variant and encouraged rigorous adherence to the control measures. More vaccines were received later and distributed across all the country. However, as the government accelerated the vaccination campaign, vaccine hesitancy set in. There was an increase in general vaccine hesitancy but especially towards COVID-19 vaccines [35, 36, 37]. Measures to encourage vaccination were therefore put in place, such as obligatory presentation of the COVID-19 vaccination card before entering any public institution. Despite these different strategies, as of 17 September 2021, the proportion of the population who had received two doses of the COVID-19 vaccine was only 5.6%. To reach the vaccination targets, the WHO Country Office in Togo provided technical and financial support to the Togolese government; through the Ministry of Health, Public Hygiene and Universal Access to Health Care (MSHPAUS), they initiated community dialogues and broad awareness-raising in the Grand-Lomé region, the epicentre of the epidemic in Togo. These reduced misinformation and removed barriers to vaccine acceptance. However, there has been rises and falls in the basic reproduction number; the rises may be related to the non-respect of the control measures. This overall observation allows to stress that both control measures and vaccination are necessary to overcome the COVID-19 pandemic.

3.6. COVID-19 vaccination analysis for Mozambique

The datasets used in this study for the particular case of Mozambique were taken from the daily press releases and daily bulletins on the website of the Government of the Republic of Mozambique [38, 39]. In Mozambique, the vaccination started on March 8, 2021, at the end of the first year of COVID-19. In this period, the country was coming out of the second wave that had its peak at the end of January 2021. In March 2021, when vaccination started, there was already a reduction of active cases due to non-pharmaceutical measures such as the implementation of Decree no 7/2021 of March 5 (see Ref. [40]) on March 7, 2021.

The first vaccination campaign targeted health professionals, older people, diabetic patients, defence and security forces as well as university teachers [41]. Between April 19 and May 10, 2021, we had the second stage of vaccination that covered final-year medical students, teachers who were not covered in the first stage, inmates, police and primary school teachers. The third stage of vaccination was between October 20 to November 3, 2021, which covered carriers, people that were not vaccinated in the first two stages, motorcycle taxis, students and all vulnerable people. At the end of the fourth wave, (January 23, 2022), booster doses were introduced [42]. Figure 4 (left) shows the modelling of COVID-19 in Mozambique with approximately one year of vaccination campaigns. Data from the first year of the pandemic—before vaccination started—were analyzed and discussed in Ref. [2]; Figure 4 (left) also shows the first year of data before vaccination.

Even with a very strong vaccination campaign in the country, wave number 5

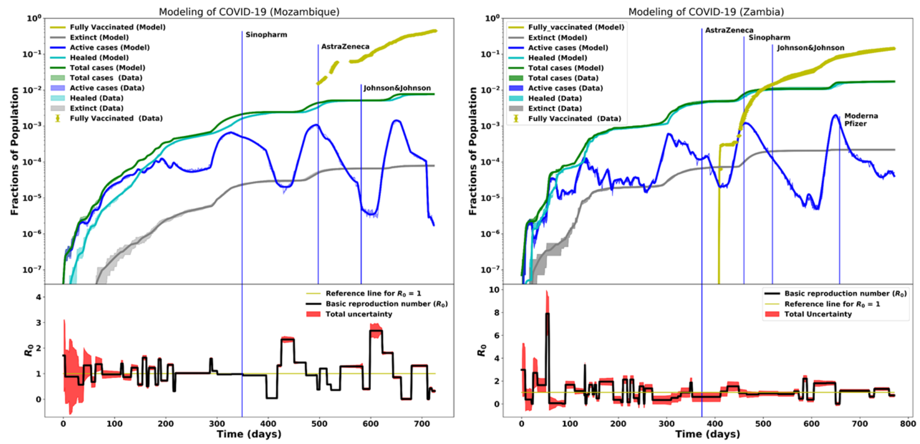

Figure 4: The modelling of ∼2 years of COVID-19 data of Mozambique (left plot) and Zambia (right plot). Day 0 corresponds to the onset of the pandemic, i.e. March 20, and March 18, 2020, for Mozambique and Zambia respectively. The top plots show the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drives started on March 8, 2021 (Mozambique) and April 14, 2021 (Zambia). The bottom plots show the time-dependent basic reproduction numbers.

of COVID-19 started in the last week of May 2022 (see Figure SM4). The onset of this wave coincided with the time when the winter brought unusually low temperatures in some regions and many people suffered from normal flu symptoms. This new wave was relatively small in terms of the number of people affected, duration and impact compared to the previous waves. The rate of deaths in the wave was very low, the rate of recovery was high with a small number of people needing hospitalization.

3.7. *COVID-19 vaccination analysis for Zambia*

Zambia launched its vaccination campaign on April 14, 2021, at the University Teaching Hospital, the country's largest hospital [43]. The COVID-19 vaccination Programme was an additional pillar to the COVID-19 response strategy for Zambia. Vaccines were distributed at the expected pace starting with the

AstraZenca brand, followed by several others (Pfizer, Moderna, Johnson and Johnson, Sinovac, and Sputinik). The first strategy was based on the COVAX mechanism which included AstraZeneca and Johnson & Johnson vaccines for, at least, 20% of the eligible population which was 3,676,791 adults of the 46%, which was 8,438,118 eligible population aged above eighteen years [34]. The campaign for the administration of AstraZeneca's second dose (fully vaccination) started on June 23, 2021, and resulted in 698-second doses administered by June 24, 2021 [43]. The second dose of the Sinopharm vaccine, with a total of 1,107 Sinopharm vaccines administered, commenced on May 21, 2021. Administration of the Johnson and Johnson vaccine started on July 24, 2021, with 3,333 doses given [43]. A total of 87,164 was cumulative of fully vaccinated persons from all mentioned vaccines. Fully vaccinated (second doses) with Pfizer and Moderna Vaccines were recorded on January 2, 2022. By April 30, 2022, 1237873 persons were fully vaccinated [43]. Figure 4 (right plot) shows the modelling of the COVID-19 of Zambia with approximately one year of vaccination campaigns. Data from the first year of the pandemic—before vaccination started—were analyzed and discussed in Ref. [2]; Figure 4 (right) also shows the first year of data without vaccination.

4. Impact of vaccination

In this study, we focused on the second year of the COVID-19 pandemic with vaccination roll outs. To discuss the impact of vaccination, we took the case of South Africa where the available data was statistically significant as described in Section 3.2. At the beginning of the vaccination campaign, around Day 349, as shown in Figure 5 (bottom plot), the number of active cases was declining and the R_0, estimated from the bottom plot of Figure 2, was 0.99 and the government relaxed the control measures to alert level one on March 1, 2021. The SIDARTHE-V model extrapolation into the period of vaccination is shown in Figure 5 and suggests that the active cases should dwindle and the death rate should plateau over time. The relaxation of the control measures without enough vaccinated individuals to reach herd immunity led to the third and fourth waves seen in Figure 5 (bottom plot), although vaccination was ramping up (Figure 2, top plot).

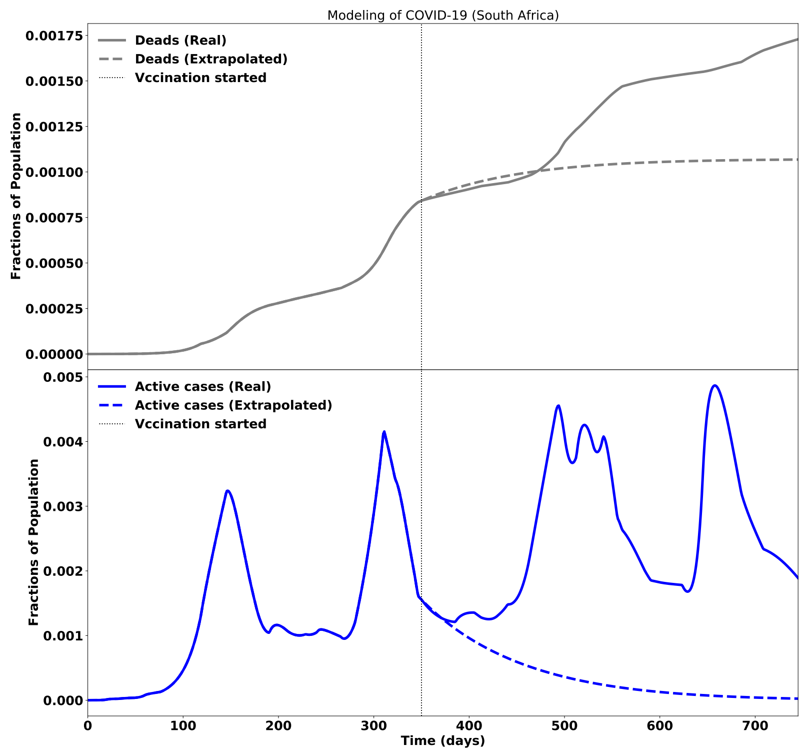

Figure 5: Death cases (top plot) and active case (bottom plot) with extrapolation into the period of the vaccination campaign, for South Africa. The plot is shown for a period of 2 years of the COVID-19. Day 0 is March 5, 2020. The vertical dotted-line indicates the start of vaccination campaign.

The number of people n to vaccinate to reach herd immunity is

$$n = N \times (1 - 1/R_0), \tag{3}$$

where N is the population. At the onsets of the third and fourth waves, R_0 was estimated at ~ 1.4 and ~ 2.0 respectively, as shown in Figure 6 (top plot). Assuming $N = 60$ million for South Africa, the number of the people to vaccinate at the beginning of the third and fourth waves were $n_1 = 17.1$ million and $n_2 = 30.0$ million respectively; however, the corresponding numbers of full-vaccinated persons were 318670 and 14031159. Although the vaccination was continuing as shown in Figure 2 (left plot), herd immunity was not reached.

The lack of herd immunity may be the cause of the fifth waves shown in the top plot of Figure 6. The impact of vaccination was beginning to be felt at the time of the fifth wave—this can be seen in:

- the fifth wave which was relative smaller than the previous ones;
- the cumulative deaths which was plateauing (top plot of Figure 6);
- the daily death counts which had fallen (bottom plot of Figure 6);
- and the relaxation of control measures to level one without resurgence any significant wave.

The impact of vaccination, inferred from Figure 6), appears consistent with an intuitive understanding of what vaccination would achieve. The vaccination program reduces COVID-19 hospitalizations and deaths; the more effective the vaccine, and delays to implementing a vaccination strategy can significantly increase the number of infections and subsequently the numbers of hospitalizations and deaths. The basic reproduction number, R_0, combines many effects——captured in the model parameters that appear in Equation 2—to provide an understanding of the pandemic evolution with control measures or vaccination impacts. These included the death rates (τ_1, τ_2) and worsening rates of infected population μ and ν. Comparing death rates before and after vaccination, we see that the parameters τ are reduced after vaccination campaigns; it means that we can have large infection rates without people dying in large numbers, see the bottom plot of Figure 6. Further, the reduction on the param-

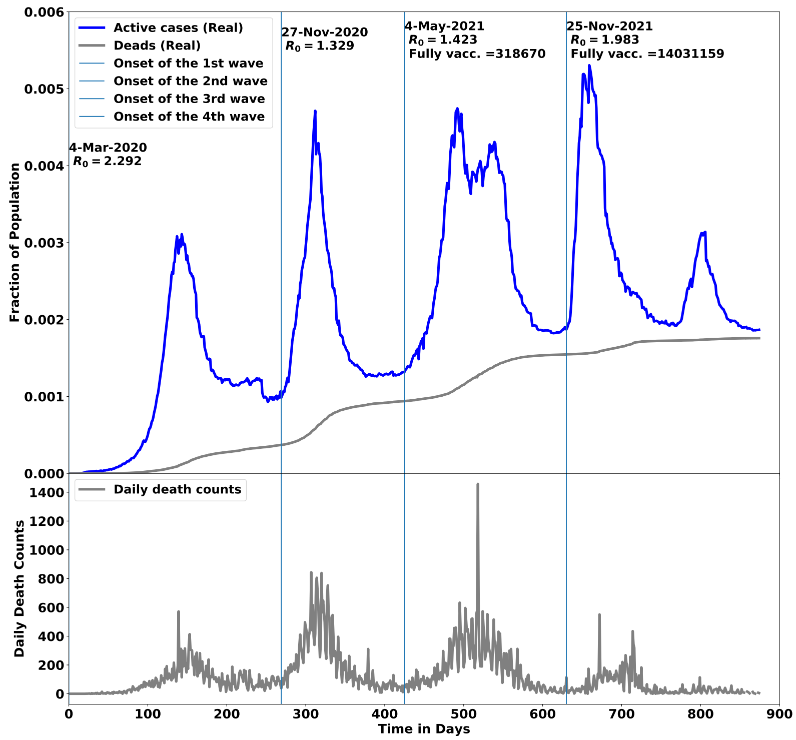

Figure 6: South African waves of COVID-19 and R_0 estimates at the beginning of each wave, numbers of fully-vaccinated persons at the onsets of the third and fourth waves, and the cumulative deaths as a function of time (top plot). Number of daily death counts is shown in the bottom plot. Day 0 is March 5, 2020. The vertical lines indicates the beginning of pandemic waves.

eters μ and ν would reduce severity of infections (see the fifth wave in the top plot of Figure 6 and help in reducing the number of deaths.

The number of death could have been drastically reduced had the non-pharmaceutical interventions been implemented for a while at the beginning of the vaccination program. This is on top of the observation that the death rates due to COVID-19 in Africa are relatively low.

From the data and model simulation, we conclude that vaccination provides an important element in the fight against COVID-19, and the delays in delivering vaccines has had a significant negative impact.

5. Conclusions

We studied the impact of vaccination in Nigeria, South Africa, Kenya, Ghana, Togo, Mozambique and Zambia. The SIDARTHE-V model was used in simultaneous fits to active, recovered, extinct and vaccinated cases in the countries considered. We observed that it is important to combine vaccination roll outs with control measures to contain the pandemic until herd immunity is achieved. To assess the impact of vaccination in Africa, we studied the South African case in more detail since it was the most impacted country in the continent, and also where we have statistically significant vaccination data. The impact of vaccination was observed after almost one year when $\sim$ a third of the population had been fully vaccinated. This was reflected in the significantly reduced daily death counts, the plateauing of the cumulative death rate and the relaxation of control measures without resurgence of COVID-19 peak waves. For the other countries studied, the impact of vaccination was not easy to gauge because of the relatively low number of COVID-19 cases and of fully vaccinated people. However, the conclusion reached in the South Africa case may be applicable to other countries, that is, vaccination roll outs need to be combined with control measures until enough population has been vaccinated such that the relaxation of control measures no longer lead to significant waves.

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Supplementary Material

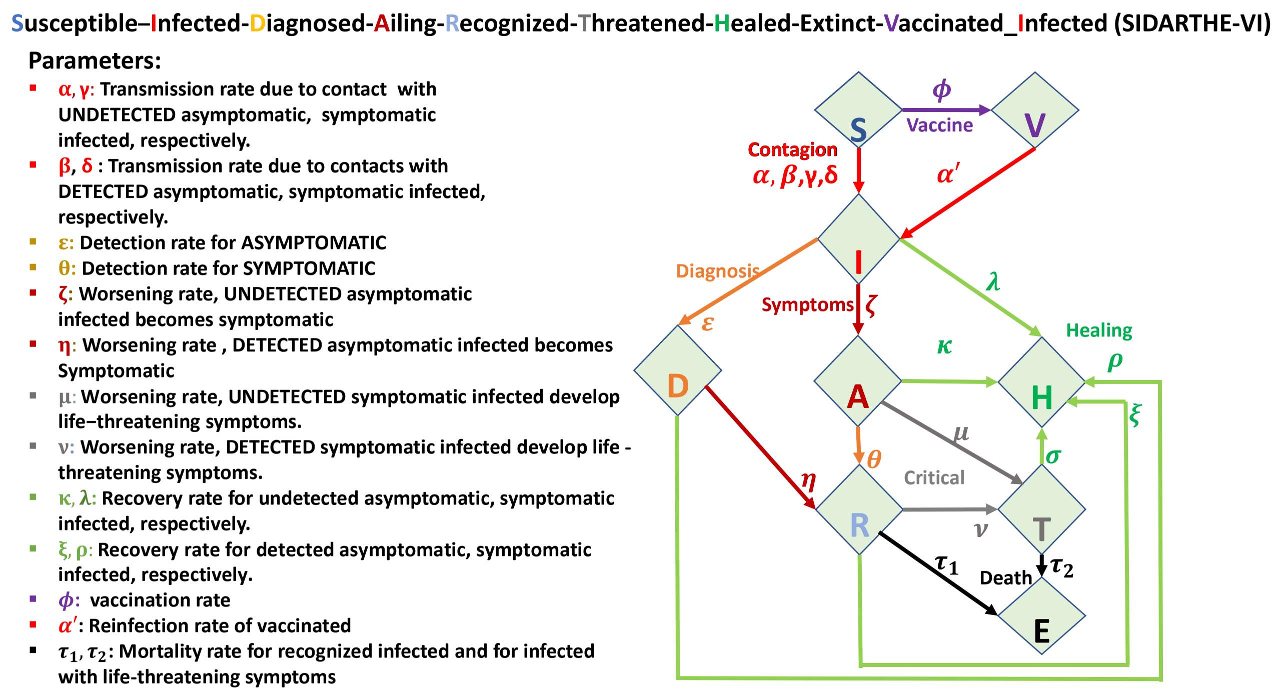

Figure SM1: Flow-chart representing the modified SIDARTHE-V model considering vaccination roll outs; we extended the original SIDARTHE-V of Ref. [7] with the possibility that vaccinated individuals may become infected.

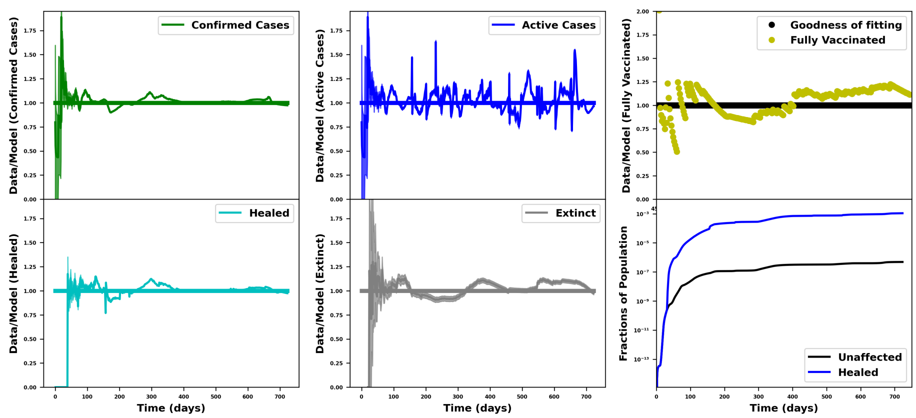

Figure SM2: The goodness-of-fit of the COVID-19 data modelling of Nigeria for confirmed, healed, active, extinct and fully-vaccinated cases. The bottom-right plot shows model prediction of the recovered population; also shown in bottom-right plot, is the non-diagnosed fraction of the people that were infected and recovered without symptoms—this fraction, called the unaffected cases, is not measured or included in the data.

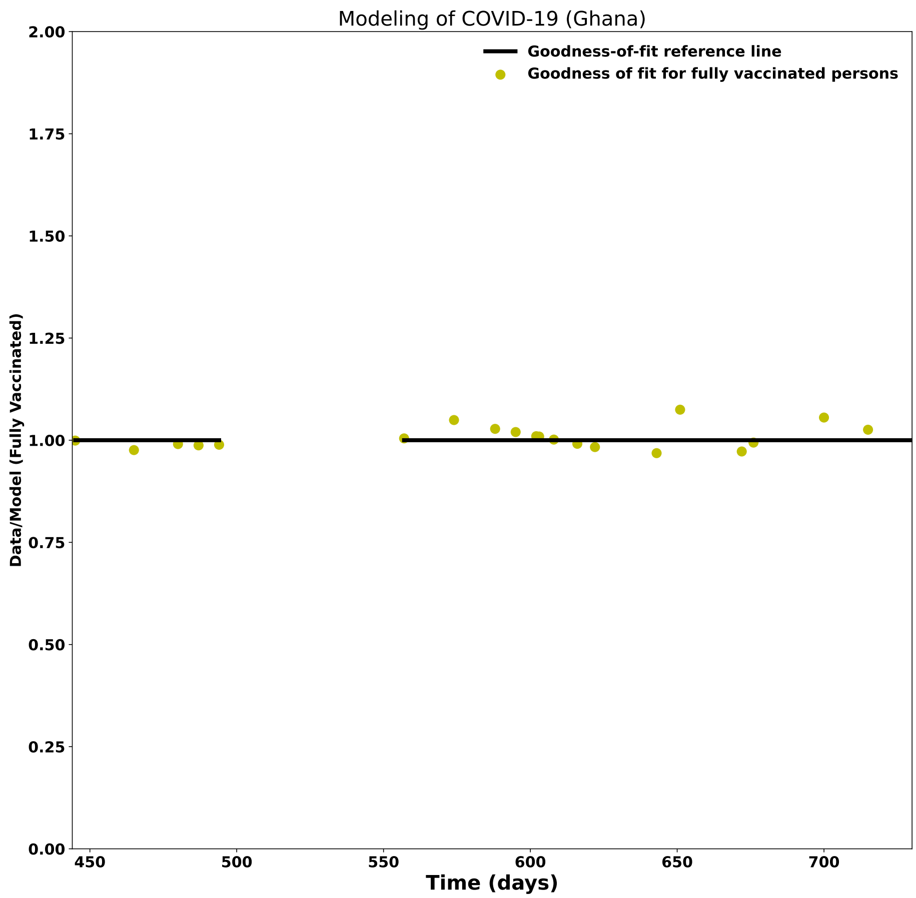

Figure SM3: The plot showing the goodness-of-fit of the COVID-19 data modelling of Ghana for fully-vaccinated individuals over time in days from March 1, 2021 to February 28, 2022.

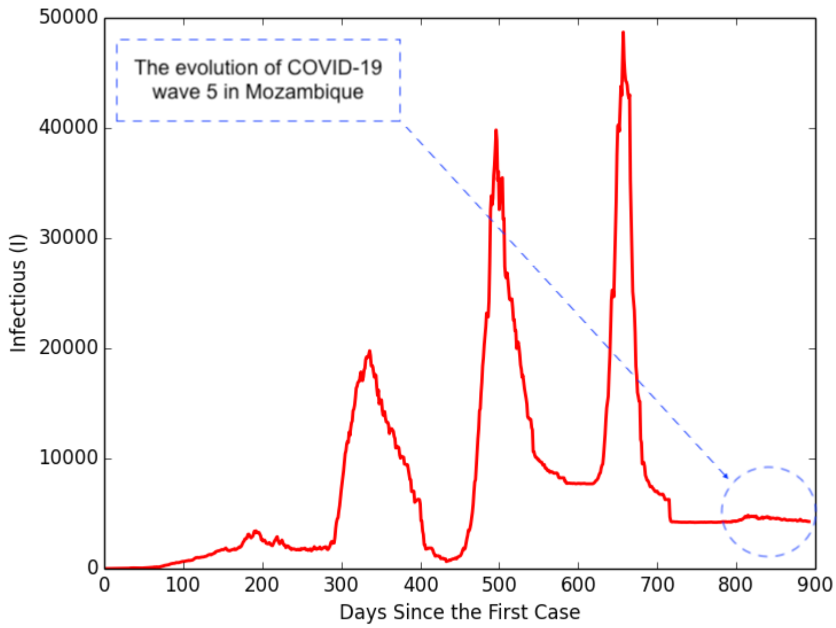

Figure SM4: COVID-19 pandemic waves in Mozambique. Day 0 corresponds to March 20, 2020. The fifth wave occurred during the vaccination campaigns and was relatively smaller than the previous ones.