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

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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,

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South 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 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, $SIDARTHEV$, Basic Reproduction Number, SARS-CoV-2, Vaccination

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1. Introduction

Coronavirus disease 2019 (COVID-19) that is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) continues to spread across the globe since 2019 [1]. COVID-19 continues to spread in spite of the implementation of different control measures such as social distancing, wearing of face masks, sanitation, lock-down, vaccination and many more. In Ref. [2], we studied first year of COVID-19 in ten African countries and reported time-dependent basic reproduction numbers. In this study, we investigated the impact of vaccination during the second of COVID-19 pandemic in seven African countries (Ghana, Kenya, Mozambique, Nigeria, South Africa, Togo and Zambia), as a continuation of the work reported in Ref. [2].

In [3], the characterisation of omicron variant during COVID-19 pandemic and the impact of vaccination, transmission rate, mortality, and reinfection in South Africa, Germany, and Brazil was studied. It was observed that the reinfection was as high as 40% in South Africa, which has only 29% of its population fully vaccinated, and as low as 13% in Brazil, which has over 70% and 80% of its population fully vaccinated and with at least one dose, respectively.

In [4], a model was developed and analysed to quantify early COVID-19 outbreak transmission in South Africa and explore vaccine efficacy scenarios. It was observed that a vaccine with 70% efficacy had the capacity to contain the COVID-19 outbreak but at a very higher vaccination coverage of 94.44% with a vaccine of 100% efficacy requiring 66.10% coverage. Social distancing measures put in place have so far reduced the number of social contacts by 80.31%. Their results suggest that a highly efficacious vaccine would have been required to contain COVID-19 in South Africa. Therefore, the current social distancing measures to reduce contact will remain key in controlling the infection in the absence of vaccines and other therapeutics.

The reduction in the number of contacts and transmission probability of the diseases together with quarantining the infectious individuals were found to influence the actual value of R_0. Apart from this, vaccination had attributed to

the reduction of R_0 in South Africa [5].

In [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.

To the best of our knowledge, vaccination must be implemented simultaneously with other control measures such as non-pharmaceutical control measures such as social distancing, avoiding crowded social gatherings, sanitizing, and the likes to reduce the spread of COVID-19 in South Africa.

The paper is organised as follows. In Section 2, we present the formulation of SIDARTHE-V model 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

The SIDARTHE-V model is an extension of the SIDARTHE model that we considered in the previous study [2]. With this model, we focus on the results during the vaccination process, but relying on the SIDARTHE model for those sections where vaccination data is lacking. Contrary to the SIDARTHE model which is based in the assumption that all vaccinated are immunized, SIDARTHE-V model assumes that vaccinated, in the V compartment, can still get infected and become infectious just like for non-vaccinated susceptible, in the S compartment. It is observed that a few portion of the vaccinated but infected, in the I_2 compartment, are threatened by the disease. The new model captures this dynamics by connecting the I_2 compartment to the T compartment, as shown in Figure SM1. The addition of these new connections in the SIDARTHE model have changed the partial differential equations of the SIDARTHE-V model to the following

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

In mathematical epidemiology, the basic reproduction number, R_0, plays an vital role. This R_0, which is commonly referred in the literature as the average number of secondary cases produced by an infected individual in a population where everyone is susceptible [7], is derived from the SIDARTHE-V model 1 and 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, Ref. [8] gives more details. From the Equation 2, can be seen that R_0 depends on the model parameters that affect pandemic evolution. The aim of this analysis was to estimate R_0 with model parameters that describe the real data [2]. Thus, it is very important to understand the model parameters and to make sure they are extracted correctly [2].

3. Analysis of COVID-19 data with vaccination

The study reported in Ref. [2] does not include Nigeria; for this reason, we start this section with the analysis of the data of Nigeria from 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. The first year of COVID-19 of the other countries, namely South Africa, Mozambique,

Zambia, Kenya, Togo and Ghana, were studied in Ref. [2]; in the 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, Nigeria on February 27, 2020. An airline 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 manifesto of the flight and those he had close contact with while in Lagos and Ogun State. 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.

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 and later extended it with another 14 days on April 12, 2020 [2, 3]. 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. The Federal Government ordered a Nationwide overnight curfew from 8:00 pm to 6:00 am on May 2, 2020 and later eased the overnight curfew to be from 12:00 am to 4:00 am. The Federal Government later authorized the gradual easing of lockdown in the previously restricted states on May 4, 2020 and mandated the use of face masks in public. On May 6, 2020, the Federal Government extended the travel ban on both International and local flights to June 7, 2020. The Federal Government reopened the international flight for operations on August 29, 2020 [1]. On January 27, 2021, the President signed six COVID-19 Health Pro-

tection 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 [5].

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 is 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 death cases 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.

The first shipment of four million Oxford-AstraZeneca COVID-19 vaccine arrived the country on March 2, 2021 and vaccination began on March 5, 2021 with a doctor at National Hospital Abuja and the President received his first dose on March 6, 2020 [4]. The country received subsequent shipment 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 executive director of Nigeria's National Primary Health Care Development Agency (NPHCDA) said had-to-reach riverine, desert and security compromised areas would initially be prioritised with the vaccine [6]. As of March 27, 2022, 21,049,754 persons have received their first dose and 9,565,143 have received their second dose.

From Figure 1, the Nigeria COVID-19 plot, we have the COVID-19 data at the top panel; we superimpose the modelling of the data and see good agreement in the infected, active, recovered, and dead cases. As a result, the fully vaccinations are also well modeled except the data of the total vaccinations. From the modeling, we derive R_0 for Nigeria as shown in the bottom panel of the plot. The initial R_0 is zero and increases significantly to eight after a week because of the negligence from the public on the measures. Around day 35, the R_0 dropped below one mainly because of the quick reaction from the government. Another increase in R_0 to a point above two was observed around day

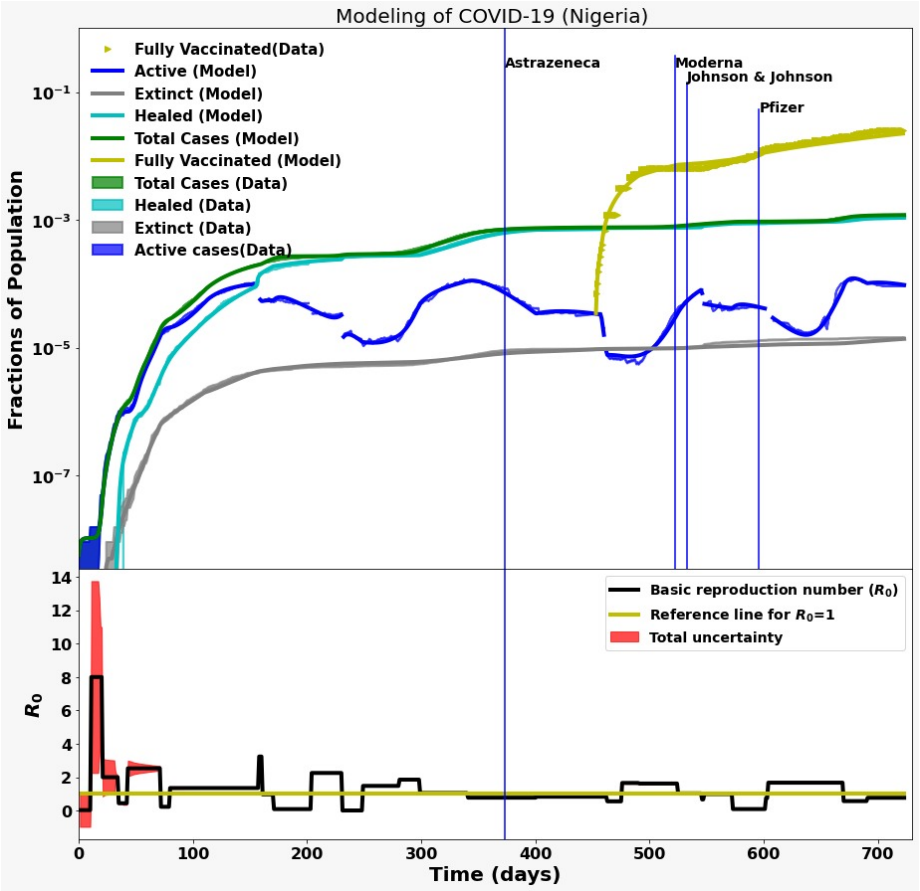

Figure 1: The modelling of COVID-19 data of Nigeria. Day 0 corresponds to the onset of the pandemic, i.e. February 27, 2020. The top shows the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drive started on March 5, 2021. The bottom plot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

40. Around day 65, it also dropped below one. The R_0 later increase 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.

Around day 165, the R_0 dropped to zero 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 about two around day 280 and even till after day 700, R_0 remains below two.

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.

3.2. COVID-19 vaccination analysis for South Africa

In South Africa, COVID-19 vaccination is an ongoing immunisation campaign against SARS-CoV-2 which aims to vaccinate 40 million South Africans [9]. There are four types of COVID-19 vaccines that have been approved for use in South Africa by the South African Health Products Regulatory Authority (SAHPRA), namely, Johnson & Johnson, Pfizer, Sinovac and AstraZeneca [9]. For South Africa COVID-19 case study, Johnson & Johnson's Janssen vaccine and Pfizer vaccine are considered. (i)Johnson & Johnson's Janssen vaccine: It is a viral vector vaccine based on a human adenovirus that has been modified to contain the gene for making the spike protein of the SARS-CoV-2 virus that causes COVID-19 [10]. The body's immune system responds to this spike protein to produce antibodies [11]. This vaccine does not need to be stored frozen and requires only one dose [11].

Only people of the age 18 and older can take this vaccine. A person is considered fully vaccinated two weeks after one shot [1]; (ii) Pfizer vaccine: Only people of the age 16 and older can take Pfizer vaccine. It is administered in two shots. A person is considered fully vaccinated two weeks after the second shot [1]. As of June 9, 2022, 535,714 COVID-19 hospital admissions were recorded in South Africa [12]. Figure 2 shows the modelling of the South African

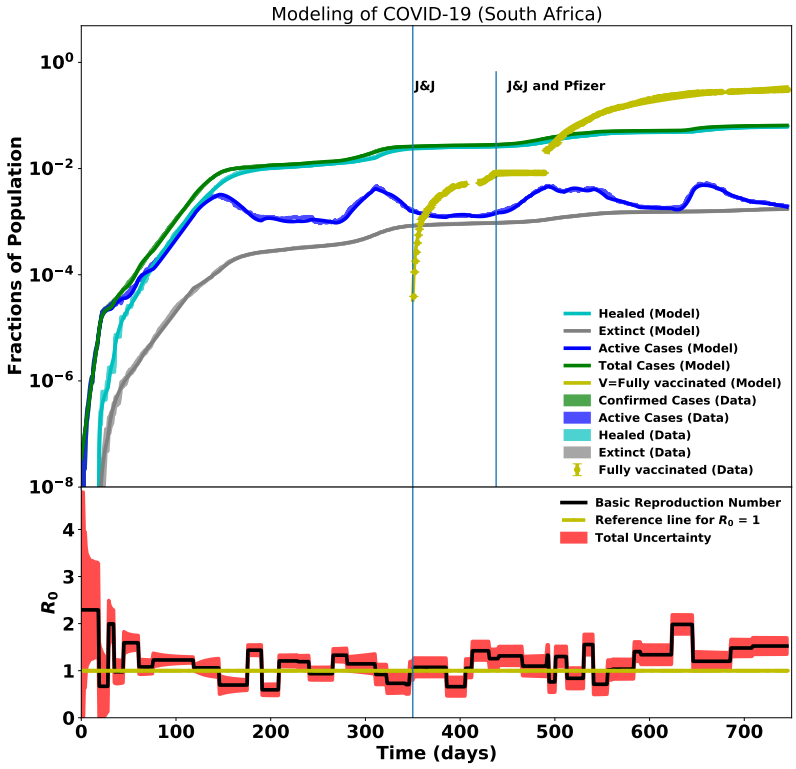

Figure 2: The modelling of COVID-19 data of South Africa. Day 0 corresponds to the onset of the pandemic, i.e. March 5, 2020. The top shows the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drive started on February 18, 2021. The bottom plot shows the time-dependent basic reproduction.

data with about one year of vaccination roll campaigns.

In our previous study we covered the South African COVID-19 data up to adjusted alert level 3 that was effect from 29 December 2020 to 28 February 2021 [2]. Based on the changes of COVID-19 new cases in South Africa, the government introduced adjusted alert levels as follows:(i) from October 1, 2021 to April 14, 2022 South Africa was at adjusted alert level 1, (ii) on September 13-30, 2021, South Africa was at adjusted alert level 2, (iii) from July 26 to September 26, 2021 South Africa was at adjusted alert level 3, and (iv) from June 28, 2021 until July 25, 2021, South Africa was at adjusted alert level 4 [9]. On May 3, 2022, South Africa confirmed $3,661,635$ recovered individuals, $100,377$ death cases and $34,941,461$ vaccinated individuals, $3,802,198$ positive cases [9]. The National State of Disaster in South Africa has been lifted since April 5, 2022 [13].

In South Africa, the health care workers were the first group to be vaccinated which started on February 18, 2021 (day 350) until May 17, 2021 (day 439) under phase 1 of the Sisonke Protocol. The death case remained constant during phase 1 while the number of active, healed and total cases slightly remained constant. Phase 2 which started on May 18, 2021, everyone from age 16 and above was allowed to be vaccinated with the first dose of J&J and Pfizer.

3.3. COVID-19 vaccination analysis for Kenya

Having received the first 1.12 M doses of Oxford-AstraZeneca COVID-19 vaccine, the vaccination drive in Kenya kicked off on March 05, 2021. This was exactly one year after the first case of COVID-19 was reported in the country on March 12 2020. 667 doses of AstraZeneca were administered on the first day of vaccination in the country 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, with 203 people receiving their second dose.

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

After a slow uptake of the vaccine among the population due vaccine hesitancy [14], a spike was witnessed on November 23, 2021, with the highest number of vaccination doses administered to 103,506 people in a single day since the vaccination roll out in March, corresponding to the peak observed around day 550 on the (ref Kenya plot). This followed a government directive on November 21, 2021 starting that anyone not vaccinated by December 21 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 M people by the end of the year 2021.

Kenya is part of the WHO AFRO 20 priority African countries with a high risk of slow COVID-19 vaccination roll out (cite Deph's document). 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 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%.

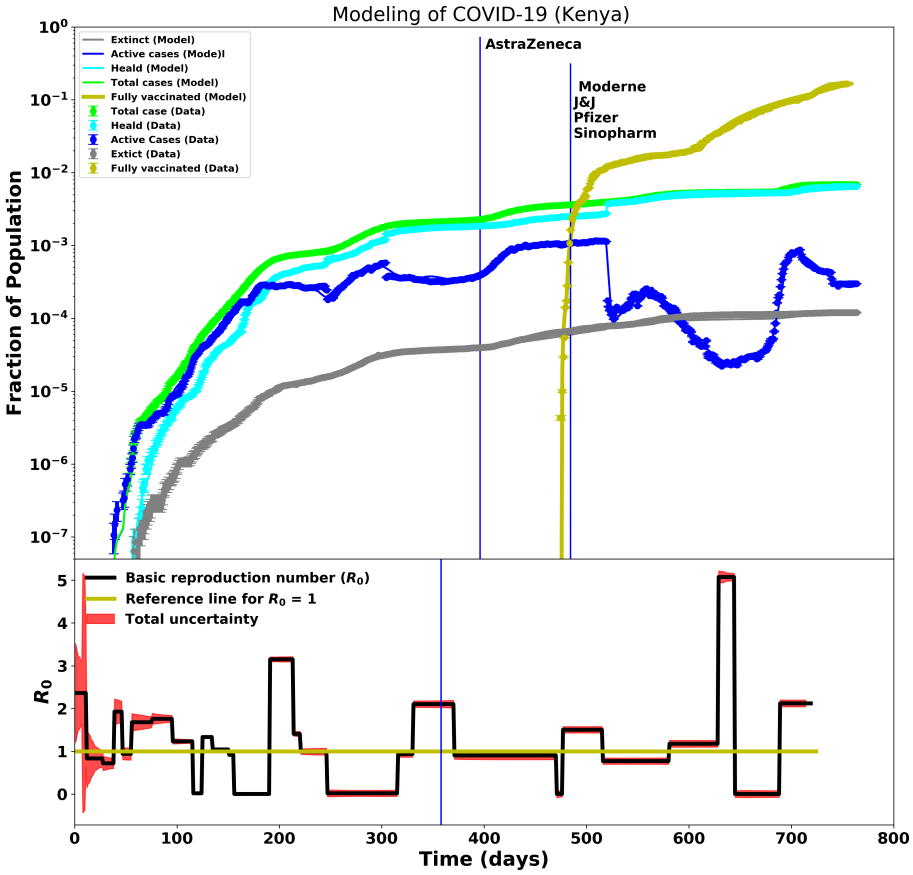

Figure 3: The modelling of COVID-19 data of Kenya. Day 0 corresponds to the onset of the pandemic, i.e. March 12, 2020. The top shows the data and model for active, recovered, death and total cases, and for fully-vaccinated individuals. Vaccination drive started on March 5, 2021. The bottom plot shows the time-dependent basic reproduction.

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 has been reported in the country and a total of 5,644 deaths. Figure 3 shows the modelling of the Kenyan data with about one year of vaccination roll outs.

COVID-19 restrictions are no longer in place though the government is encouraging citizens to wear masks and maintain social distancing 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 [14] and geographical inequalities in accessing vaccines in hard-to-reach areas [e.g., 15]. The government aims to to vaccinate 15.91 M people by June 2023 in a 3-phased roll-out approach initially targeting 1.25 M people by June 2021 in phase one. This was followed by the current phase two, July 2021 - June 2022, targeting 9.76 M people including mostly the elderly and the most vulnerable with underlying health conditions. The third phase will run from July 2022 - June 2023 and will target 4.9 M people above 18 years old, those with underlying health risks and essential workers The Conversation.

3.4. COVID-19 vaccination analysis for Ghana

In Ghana, the first official cases of COVID-19 were reported on March 12, 2020. As at then, 141 COVID-19 cases had been confirmed nationwide, with 5 fatalities [16]. The first two confirmed cases were identified as individuals having returned to the country from Norway and Turkey. by April 17, 2020, 10 out of 16 regions in Ghana had COVID-19 cases. Following this, the government took steps to prevent the virus from spreading. Thus, from March 15, Ghana government imposed restrictions on public gathering and air, sea and overland travels. These response protocols led to a significant reduction in the rate of infection till December 2020. As the number of COVID-19 cases in Ghana began to diminish, several flaws in the initial response accumulated and

consequently led to the country's second wave of infections around January 5, 2021. Among the country's response approaches for the second wave targeted to break the COVID-19 transmission chain are the adoption of a 14-day incubation period [17] and the acquisition of COVID-19 vaccines.

The government of Ghana committed to acquiring COVID-19 vaccines on December 20, 2020, guaranteeing that vaccinations deployed in the country are safe and effective [18]. Ghana is the first country to receive COVID-19 vaccines from the COVAX initiative and began its first vaccine roll out on March 1, 2021 [19, 20, 21] by administering AstraZeneca. Johnson & Johnson (J&J), Moderna, Pfizer, and Sputnik V are the COVID-19 vaccines also approved and administered in Ghana. Figure 4 (left plot) shows the modelling of the Ghanaian data with about one year of vaccination roll outs.

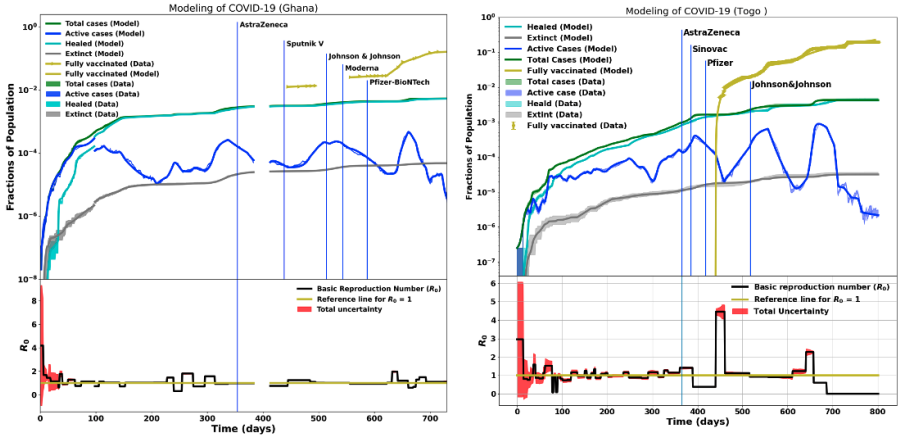

Figure 4: The modelling of COVID-19 data of Ghana (left plot) and Togo (right plot). Day 0 corresponds to the onset of the pandemic, i.e. March 12, and March 6, 2020, for Ghana and Togo respectively. The top shows the data and model for active, recovered, death and total cases, and for fully-vaccinated 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 [22] indicates that, the Delta lineages, Alpha, Beta and Eta made up the top viral lineages within the sequenced SARS-CoV-2 genomes in Ghana over the period. The Beta variant is being monitored in Ghana since it has the third highest frequency. During the second wave, regions further from Accra, such as the Northern and Upper East, tended to have different variants. These locations are still lagging behind the rest of the country in the third wave and do not appear to be experiencing one [23]. The Beta variety was prominent in Ghana when the airport reopened to foreign travelers in September 2020, and it remained the most dominant circulating 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 controlled Ghana starting in June 2021 and continued to do so until September 2021. Major variations such as Alpha, Beta, Delta, Eta, and Kappa were found in samples from arriving tourists before being seen in community instances, according to [22].

According to [24], the president of Ghana and his vice were the first to receive the AstraZeneca vaccine on the 1st of March 2021. By 2nd March 2022, vaccination was launched in the Ashanti region and and over 10,000 people had been vaccination. The second doses for the AstraZeneca vaccine commenced on 19 May 2021.

By April 25, 2022, $14,268,269$ doses of these vaccines have been administered. 18.3% of Ghana's population have been fully vaccinated, 29.9% have received at least one dose of the vaccines and $360,201$ persons have received the first booster dose. By April 30, 2022, there were $161,216$ COVID-19 cases in Ghana. Out of this, $159,737$ recovered and discharged with $1,445$ deaths and 34 active cases. Greater Accra region records the highest number of COVID-19 cases at $90,826$ followed by the Ashanti region with $22,299$ cases [23].

3.5. COVID-19 vaccination analysis for Togo

Like many countries around the world, Togo lives the long-running COVID-19 pandemic since March 6, 2020, when the first case was detected. Vari-

ous drastic measures including lockdown, social distancing, wear of face mask, have been immediately implemented by the Togolese government to counter the spread of the disease. However, all these efforts from the government and the communities remained insufficient to eradicate the disease as the country continues to experience the different waves with large number of daily infections until January 2021. The Government therefore decided to rely on national and international support to quickly get access to the COVID-19 vaccines with the aim to get 40% of the Togolese population immunized by December 2021. On March 8, 2021, exactly one year after the detection of the first case, the country received 196 000 doses of AstraZeneca through the COVAX facility [2,5], and the vaccination campaign started the following day. 120 000 additional doses of AstraZeneca were received on March 31. After these, further 100 620 Pfizer doses are obtained in May 2021 followed by 200 000 doses of Sinovac on 23 April. On August 7, 2021, Togo has received additional 118000 doses of Johnson Jansen vaccine out of 4 million doses that it had ordered. To date Togo has received 3290821 COVID-19 vaccine doses, with 2092750 people vaccinated, corresponding to approximately 20% of the of Togolese population who are qualified for vaccination and 1557538 fully vaccinated. The vaccination started with health workers people on March 10, 2021 (day 370), and next individuals who are clinically vulnerable followed by peoples the over-50s [2]. This took approximately 2 months to cover this target population of Togo. After priority groups have been vaccinated, there is a wider roll out among younger age groups. One month after the initiation of the vaccination campaign (from day 400), we start to see the impact of the vaccination on infection rate, and this is reflected in R_0. Figure 4 (right plot) shows the modelling of the COVID-19 of Togo with approximately one year of vaccination campaigns.

Active cases continue to decrease up to three months after the vaccination started while R0 sharply increases in the third month. This increase in R0 is the consequence of the relaxation in the application of the control measures that where in place before the start of the vaccination. These measures were almost no longer respected as people started thinking that the problem of COVID-19

is immediately solved by the arrival of the vaccines. After day 470, the active cases started increases again as the vaccine doses that were received run short and at the same time new COVID-19 variant (delta) emerges. As the active cases started increasing, the government warn the population of the existence of a new variant and encourage the people to rigorously apply the control measures in place. More vaccine was received later and distributed across all the country. However, as the government accelerate the deployment of COVID-19 vaccines, the issue of vaccine hesitancy arises. Globally, there has been a rise in general vaccine hesitancy but especially towards COVID-19 vaccines [4]. 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) gave support to the Togolese government by initiating community dialogues and broad awareness-raising in the Grand-Lomé region, the epicentre of the epidemic in Togo [1]. These enabled to reduce misinformation and break down the potential barriers to vaccine acceptance. This have considerably helped to decrease in the last six months. However, there are rises and falls in the basic reproduction number, and the rises may be related to the non-respect of the control measures in place. This overall observation allows us to stress that both control measures and vaccination are necessary to overcome the COVID-19 pandemic in Togo, that both control measures and vaccination are necessary in order to eradicate the COVID-19 disease.

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 [25, 26]. We have already conducted

two studies in which the results of the pandemic evolution in the first year using the SIDARTHE model are presented. In this study, we will focus on the results during the vaccination process using the SIDARTHE-V model, but relying on the SIDARTHE model for those sections where vaccination data is lacking.

In Mozambique, the vaccination started on March 8, 2021, at the end of the first year of COVID-19. In this period, we were coming out of the second wave that had its peak at the end of January 2021. In March 2021, when vaccination was implemented 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. [27]) on March 7, 2021.

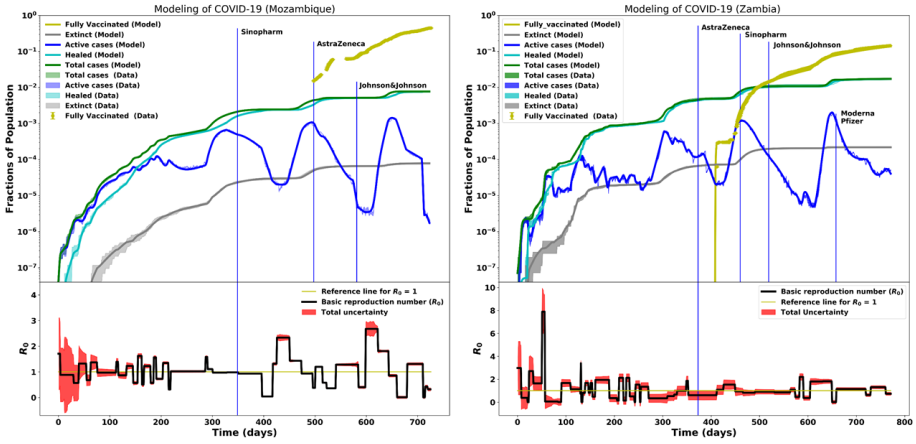

Figure 5: The modelling of COVID-19 data of Mozambique (left plot) and Zambia (right plot). Day 0 corresponds to the onset of the pandemic, i.e. March 20, and March 18, 2020, for Mozambique and Zambia respectively. The top shows the data and model for active, recovered, death and total cases, and for 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.

The first vaccination campaign targeted health professionals, older people, diabetic patients, defence and security forces as well as university teachers [28]. Between April 19 to 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 which covered carriers, people that were not vaccinated in the first two stages, motorcycle taxis, students and all vulnerable people. At the ending of the peak of the fourth wave (January 23, 2022), the booster dose was introduced to re-immunize people which was administered 6 months after the last immunization [29]. Figure 5 (right left) shows the modelling of COVID-19 in Mozambique with approximately one year of vaccination campaigns.

Even with a very strong vaccination campaign in the country, wave number 5 of COVID-19 started in the last week of May 2022 (see Figure SM4). The onset of this wave coincided with the time in which the winter was bringing very low temperatures in some regions of the country in an uncommon way and putting many people suffering from normal flu-like. 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 by the Minister of Health. Analysis of COVID-19 data of Zambia, the first three months of COVID-19 are described in Refs. [5,34] since the first two cases of COVID-19 on March 18, 2020. The goal of the COVID-19 vaccination campaign was to enhance the reduction of COVID-19 mortality and morbidity. 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). Variant-specific vaccine efficacy of 80% of those who have had two doses of vaccine (or one dose for Johnson & Johnson) receives a third dose six months after their second dose. The first strategy was based on

the COVAX mechanism which included AstraZeneca and Johnson and Johnson Vaccine for, at least, 20 percent of the eligible population which is 3,676,791 adults of the 46 percent, which is 8,438,118 eligible population aged above eighteen years. The campaign for the administration of AstraZeneca's second dose (fully vaccination) started on June 23, 2021, resulting in 698-second doses of AstraZeneca vaccines being administered by June 24, 2021. Administration of the second dose (fully vaccination) of Sinopharm vaccine in Zambia 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 of Johnson and Johnson being administered. A total of 87,164 was cumulative of fully vaccinated from all mentioned vaccines. Fully vaccinated (second doses) with Pfizer and Moderna Vaccines were recorded on January 2, 2022. Giving a cumulative (fully vaccinated) total of 1237873 of all mentioned vaccines as of April 30, 2022. Figure 5 (right plot) shows the modelling of the COVID-19 of Zambia with approximately one year of vaccination campaigns.

4. Discussion

5. Conclusion

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Supplementary Material

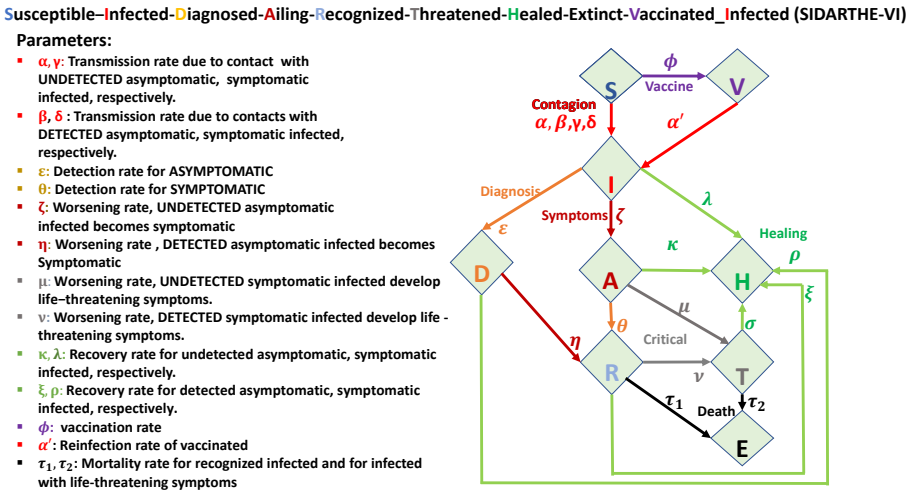

Figure SM1: Flow-chart representing the SIDARTHE-V model considering vaccination roll outs.

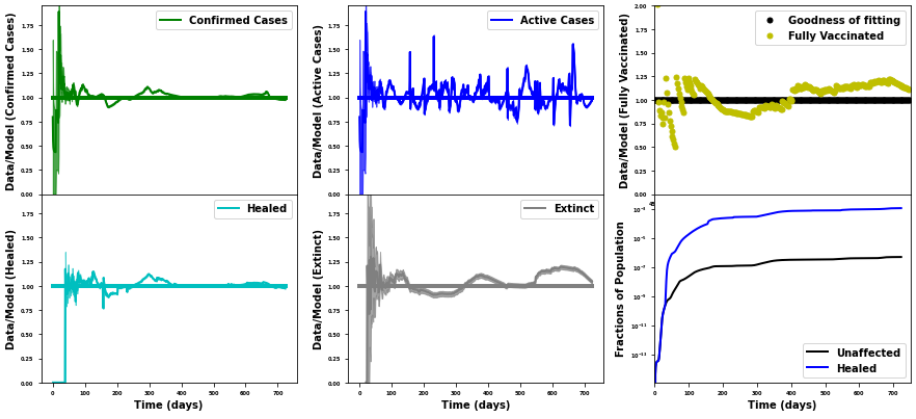

Figure SM2: The goodness-of-fit of the COVID-19 data modelling of Nigeria for confirmed, healed, active, extinct and fully-vaccinated cases. The bottom-right plot shows model prediction of the recovered population; also shown in bottom-right plot, is the undiagnosed fraction of the people that were infected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

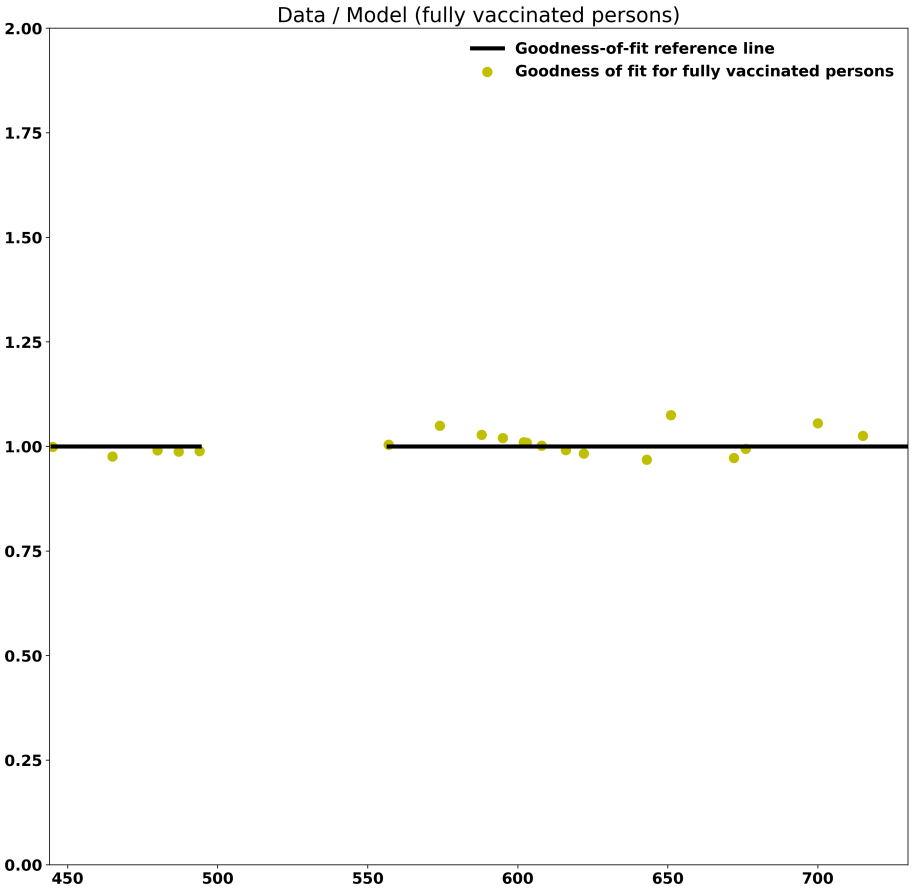

Figure SM3: The plot showing the goodness-of-fit of the COVID-19 data modelling of Ghana for fully-vaccinated individuals over time in days since the ...th of February, 2020 up to the of ...th of February, 2022.

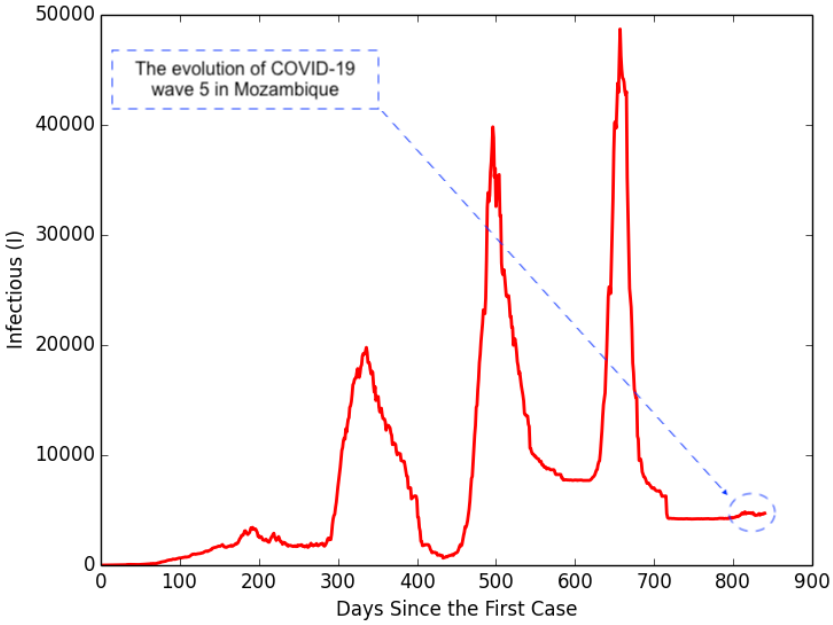

Figure SM4: The plot showing the Time Series for the Population in Compartment I(t) in Mozambique.

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