A model of COVID-19 pandemic evolution in African countries taking into account the impact of vaccination

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Abstract

A study on the COVID-19 pandemic evolution in selected African countries was carried out in this paper. For each of the considered countries, the data of the active, recovered, and death cases were modelled simultaneously taking into account the impact of vaccination. In this study, which is a continuation of previous work reported in [9] we are using two years of data since the announcement of the first case in each country.

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.

To Be Continued

The rest of the paper is organised as follows. In Section 2, we present the formulation of $SIDARTHEV$ model taking into account infectious vaccinated individuals. In Subsection 2.1, we present the analysis of COVID-19 data taking into account the transmission dynamics of COVID-19 since the vaccination program started in each country of the following countries: Nigeria, South Africa, Mozambique, Cameroon, Ghana and Zambia considered in this study. In Section 3, we present the discussion of the analysis of COVID-19 data results followed by discussion and conclusion, respectively.

2. Formulation of SIDARTHE model taking into account infectious vaccinated individuals

The $SIDARTHEV$ model is an extension of the SIDARTHE model that we considered in the previous study [9]. 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, $SIDARTHEV$ 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. This results into the diagram below

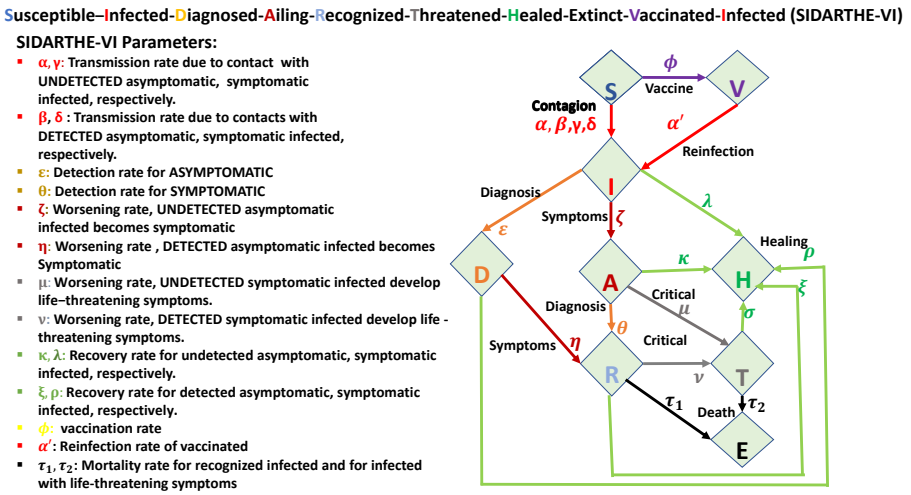

Figure 1: Flow-chart representing the $SIDARTHEV$ model taking into account infectious vaccinated individuals.

The addition of these new connections in the SIDARTHE model have changed the partial differential equations of the $SIDARTHEV$ model to the following

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

2.1. The basic reproduction number

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 [8], is derived from the $SIDARTHEV$ model 1 and is given by

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

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, [2] 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 [9]. Thus, it is very important to understand the model parameters and to make sure they are extracted correctly [9].

3. Analysis of COVID-19 data

3.1. ***Analysis of COVID-19 data of Nigeria from the emergence of the disease***

In Nigeria, they confirmed the first case in the Infectious Disease Centre, Yaba, Lagos State, Nigeria on the 27^{th} of February, 2020. An airline from Milan, Italy arrived at the International Airport, Lagos on the 24^{th} of February, 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 23^{rd} March, 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 29^{th} March, 2020 for an initial period of 14 days and later extended it with another 14 days on 12^{th} April, 2020 [18, 19]. 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 the 20^{th} of April, 2020. The Federal Government ordered a Nationwide overnight curfew from 8:00 pm to 6:00 am on the 2^{nd} May, 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 the 4^{th} of May, 2020 and mandated the use of face masks in public. On the 6^{th} of May, 2020, the Federal Government extended the travel ban on both International and local flights to 7^{th} June, 2020. The Federal Government reopened the international flight for operations on 29^{th} August, 2020 [17]. On the 27^{th} of January, 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 [21]. After the first confirmed case on 27^{th} February, 2020, the number of confirmed cases increased drastically and the total number of confirmed cases as of 27^{th} March, 2022 is 255,341 with a total number of 249,566 discharged cases and 2,633 active cases. The first death case was on the 23^{rd} March, 2020 and have increased to a total number of 3,142 death cases as of 27^{th} March, 2022. The health sector started covid-19 sample test on the 8^{th} April, 2020 and on the 27^{th} March, 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 2^{nd} March and vaccination began on 5^{th} March, 2021 with a doctor at National Hospital Abuja and the President received his first dose on 6^{th} March, 2020 [20]. The country received subsequent shipment of Moderna, Johnson Johnson and Pfizer Covid-19 vaccines on the 1^{th} August, 2021, 12^{th} August, 2021 and on the 14^{th} October, 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), Dr. Shuaib said had-to-reach riverine, desert and security compromised areas would initially be prioritised with the vaccine [22]. As of 27^{th} March, 2022, 21,049,754 persons have received their first dose and 9,565,143 have received their second dose.

From Figure 9, the Nigeria COVID-19 plot, we have the COVID-19 data at the top panel; we superimpose the modeling 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 40. Around day 65, it also dropped below one. The R_0 later increase around day 75 above one

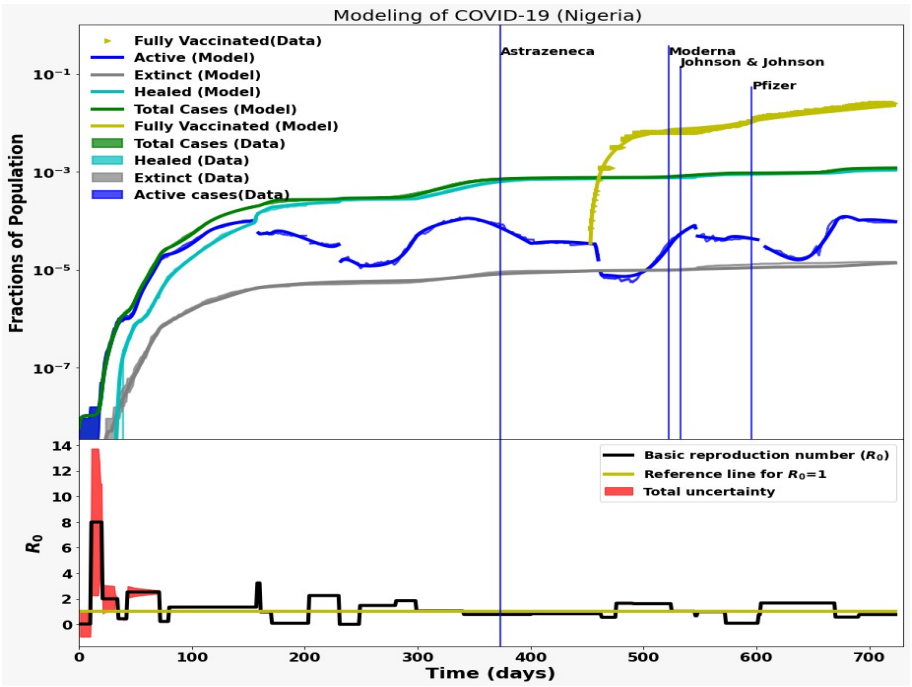

Figure 2: Graphs showing COVID-19 data and SIDARTHEV model of Nigeria taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the 27^{th} of February, 2020 up to the of 27^{th} of February, 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot.

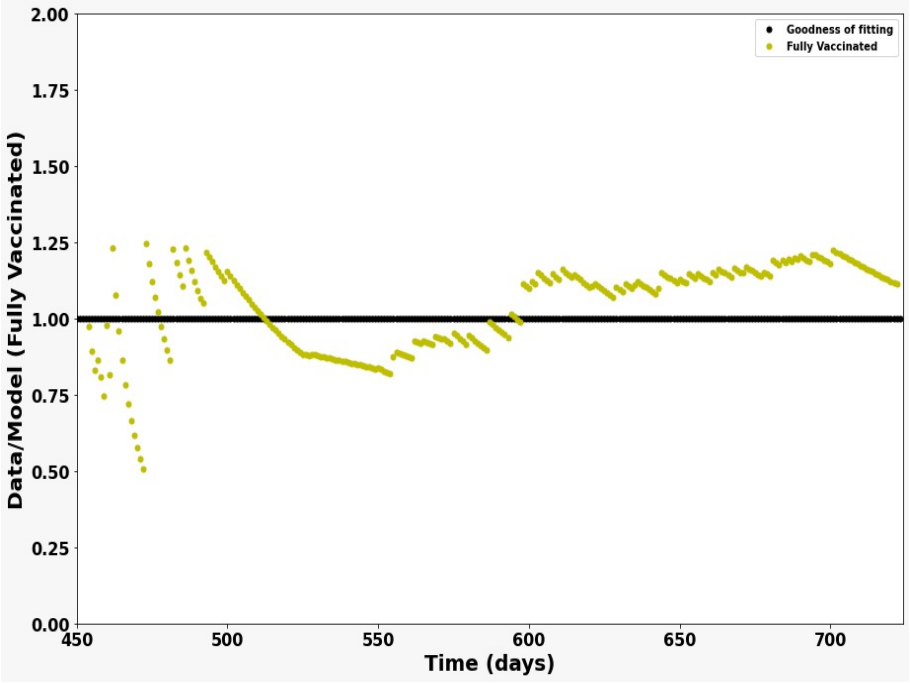

Figure 3: The plot showing the goodness-of-fit of the COVID-19 data modelling of Nigeria for fully-vaccinated individuals over time in days since the 27^{th} of February, 2020 up to the of 27^{th} of February, 2022.

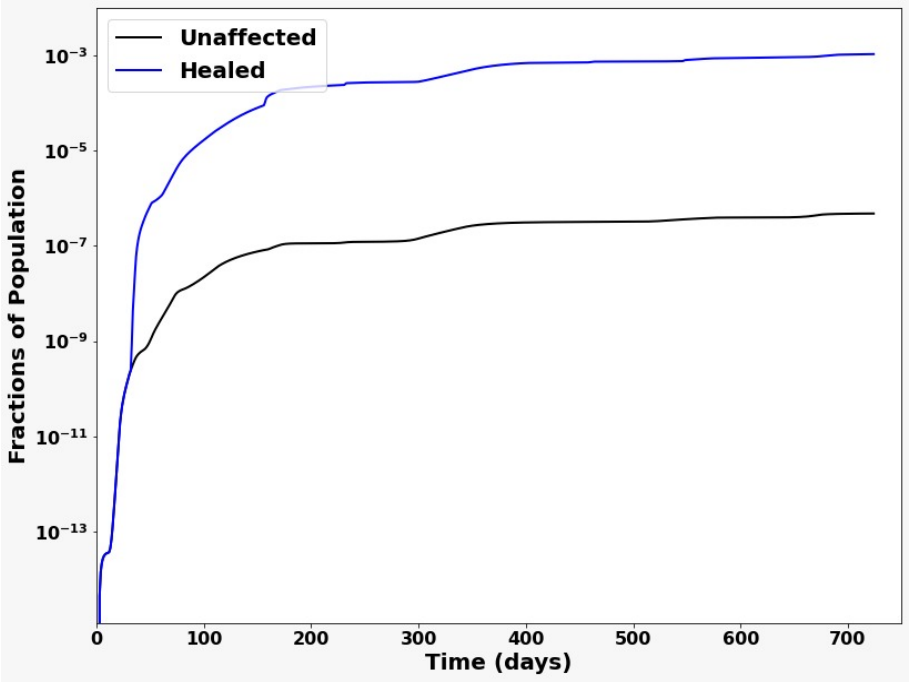

Figure 4: The model prediction of the recovered population is shown in the bottom-right plot; also shown, is the undiagnosed fraction of the people that were infected and recovered without symptoms. This fraction, called the unaffected cases, is not measured or included in the data

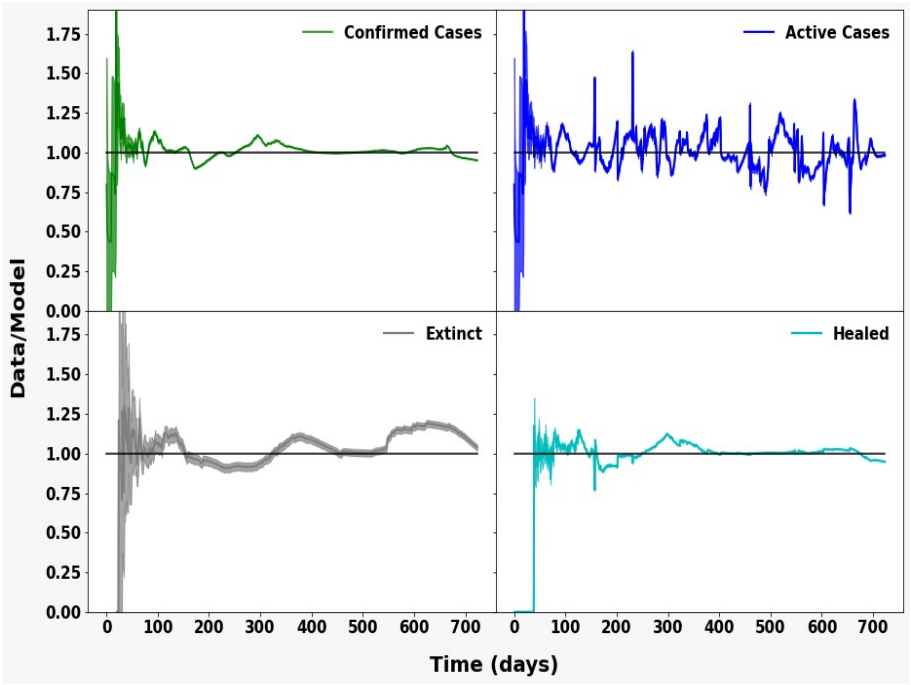

Figure 5: The plot showing the goodness-of-fit of the COVID-19 data modelling of Nigeria for confirmed cases, active cases, extinct and healed individuals over time in days since the 27th of February, 2020 up to the of 27th of February, 2022

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.

3.2. ***Analysis of COVID-19 data of 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 [3]. 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 [3]. 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 [4]. The body's immune system responds to this spike protein to produce antibodies [5]. This vaccine does not need to be stored frozen and requires only one dose [6], [7]. 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 the 9^{th} of June, 2022, $535,714$ COVID-19 hospital admissions were recorded in South Africa [11].

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 [9]. Based on the changes of COVID-19 new cases in South Africa, the government introduced adjusted alert levels as follows:(i) from the 1st of October 2021 to the 4^{th} of April 2022 South Africa was at adjusted alert level 1, (ii) from the 13^{th} to the 30 September 2021 South Africa was at adjusted alert level 2,

(iii) from the 26^{th} of July to the 26^{th} of September 2021 South Africa was at adjusted alert level 3, and (iv)from the 28^{th} of June 2021 until 25^{th} of July 2021, South Africa was at adjusted alert level 4 [3]. As of 3^{rd} of May 2022, South Africa has confirmed $3,661,635$ recovered individuals, $100,377$ death cases and $34,941,461$ vaccinated individuals, $3,802,198$ positive cases [3]. The National State of Disaster in South Africa has been lifted since 5 April 2022 [10].

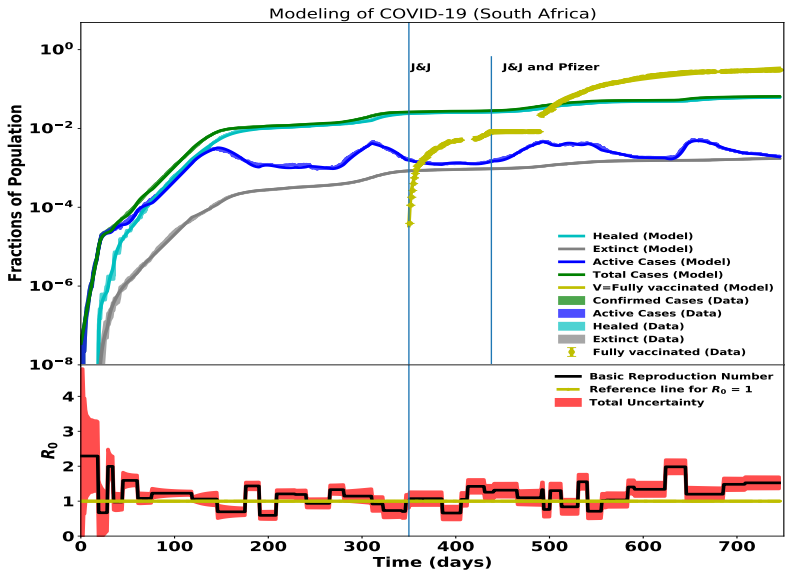

Figure 6: Graphs showing COVID-19 data and $SIDARTHEV$ model of South Africa taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the 18^{th} of February 2021 up to the 20^{th} of March of 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot. The analysis for the period when vaccination was not yet implemented which from the 5^{th} of March 2020 up to the 26^{th} of March 2021 is documented on previous study [**?**].

PLOTS' INTERPRETATIONS

In South Africa, the health care workers were the first group to be vaccinated which started on the 18^{th} of February 2021 (day 350) until 17^{th} of May 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 the 18^{th} of May 2021, everyone from age 16 and above was allowed to be vaccinated with the first dose of JJ and Pfizer.

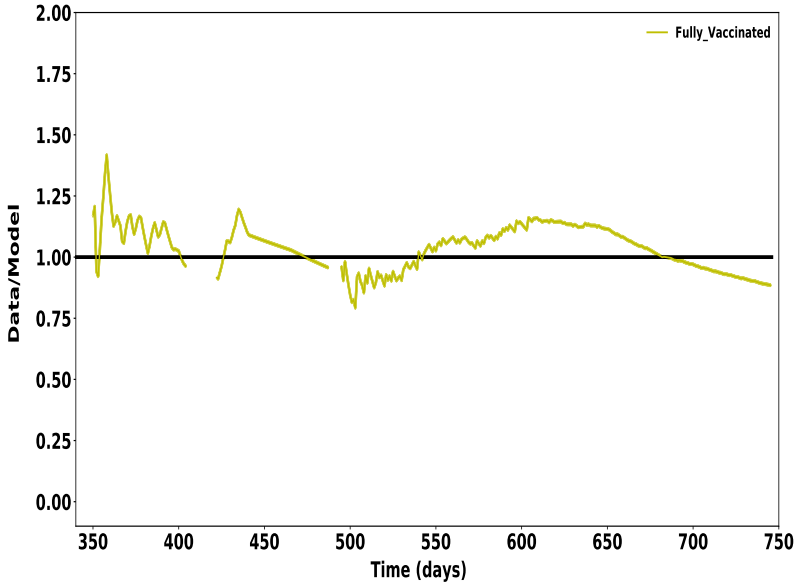

Figure 7: The plot showing the goodness-of-fit of the COVID-19 data modelling of South Africa for fully-vaccinated individuals over time in days since the 28^{th} of February 2021 up to the 20^{th} of March of 2022.

3.3. ***Analysis of COVID-19 data of Mozambique***

In Mozambique, the vaccination campaign started on March 8, 2021, at the end of the first year of COVID-19 occurrence and in the period when the country was coming out of the second wave that had its peak at the end of January 2021. During the time when this vaccination campaign was implemented in the country, there was already a reduction of COVID-19 active cases which is believed that might be due to the non-pharmaceutical measures and implementation strategies from the Government [14].

Taking in consideration the actions plan of the Government, the first round of the vaccination campaign targeted health professionals with the aim of protecting this most important group where in the process of controlling the virus in the country are a very important pillar [13].

The continuity of vaccination data after the first gap (between days 350 and 500) of vaccination data is seen at the peak of the third wave where we can see a reduction in active cases and an increase in recovered cases without much variation in the dead data.

The fourth wave (omicron wave) was the most infectious wave, having an initial growth close to 90 percent but which did not take long period of time compared to other waves, and return to stability compared to the other waves, where the concept of booster dose was introduced which has the function of re-immunising people and should be administered 6 months after the last immunization [14].

Figure **??** represents the following data sets: total data infected (green), active (blue), recovered (light blue), dead (gray), fully vaccinated (yellow) which are people who received two doses or one dose of Johnson Johnson-that already guarantees immunity, vaccinated with one dose that does not guarantee immunity yet (red), vaccinated with the booster dose (pink) and we also have the fitted model curves in the first 5 data sets described here. The first vertical bar between days 300-400 (day 349) demarcates the day of vaccination initiation, where the Sinopharm vaccine was administered; the second bar (day 500) demarcates the introduction of the Astrazeneca vaccine and the third bar near day 600 (day 583) describes the day of implementation of Johnson Johnson single

dose vaccination.

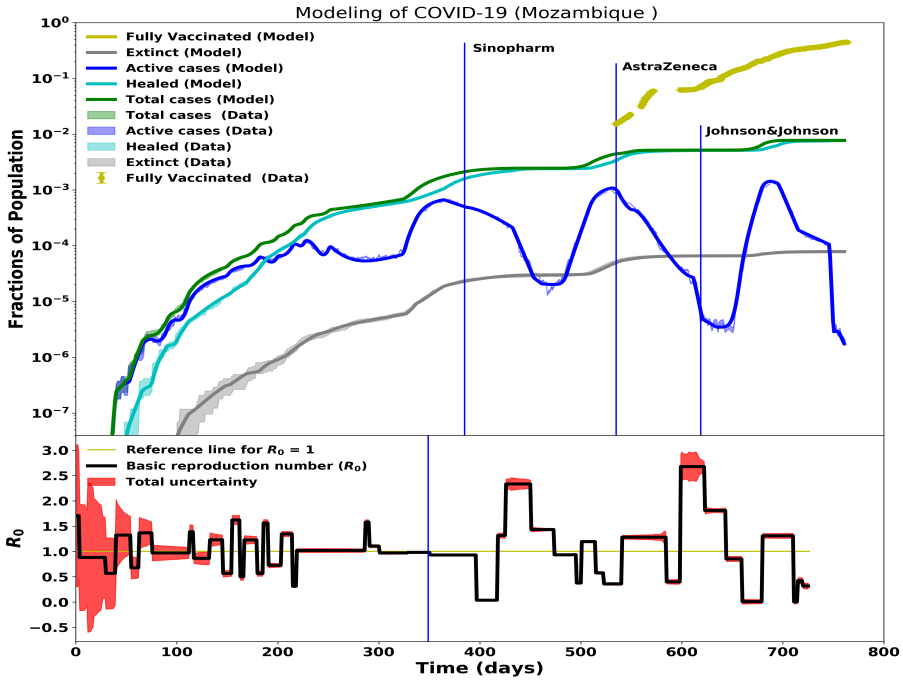

Figure 8: Graphs showing COVID-19 data and SIDARTHEV model of Mozambique taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the 22^{nd} of March 2020 up to the 22^{nd} of March of 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot.

3.3.1. ***Current Situation in Mozambique***

Even with a very strong vaccination campaign in the country, wave number 5 for COVID-19 started to show up from the last week of may of 2022 (see Figure 10).

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 itself showed to be very small in terms of height, duration and impact in the country compared with others (1 to 4). The rate of deaths in the

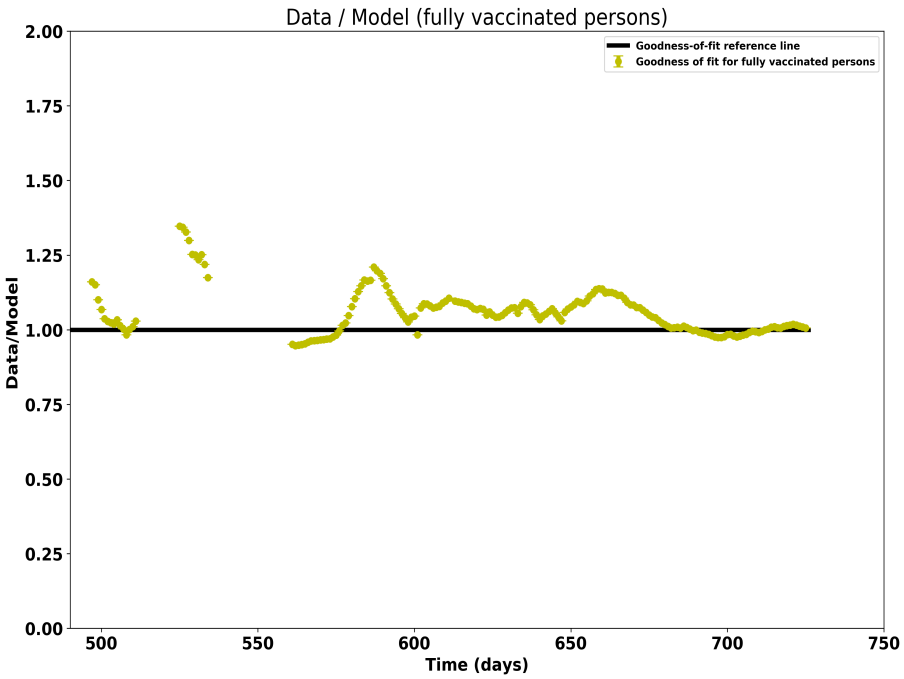

Figure 9: The plot showing the goodness-of-fit of the COVID-19 data modelling of Mozambique for fully-vaccinated individuals over time in days since the 22^{nd} of March 2020 up to the 22^{nd} of March of 2022.

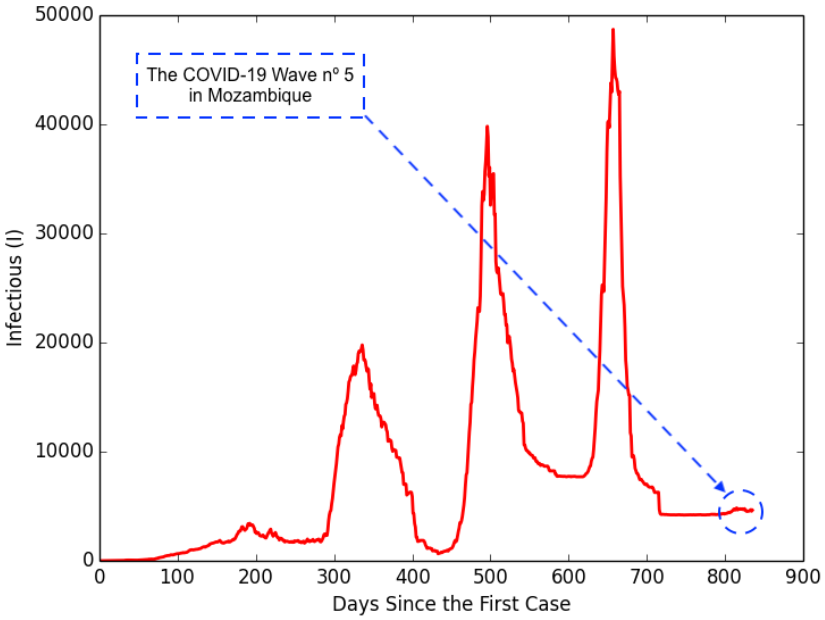

Figure 10: The plot showing the Time Series for the Population in Compartment I(t) in Mozambique.

wave is very small, the recovered people are too high in a small period of time, and the number of people entering the hospital system is too small.

3.4. ***Analysis of COVID-19 data of Zambia***

Zambia launched its vaccination campaign on 14th April 2021 at the University Teaching Hospital, the country's largest hospital by the then 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 23rd June 2021, resulting in 698-second doses of AstraZeneca vaccines being administered by 24th June 2021. Administration of the second dose (fully vaccination) of Sinopharm vaccine in Zambia with a total of 1,107 Sinopharm vaccines administered, commenced on 21st May 2021. Administration of the Johnson and Johnson vaccine started on 24th July 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 2nd January 2022. Giving a cumulative (fully vaccinated) total of 1237873 of all mentioned vaccines as of 30th April 2022. The vertical bars in the graphs indicate the introduction of a particular vaccine and the number of persons vaccinated is a reflection of the combination of vaccines given on that day. Cumulative totals were reported for the different variables modeled.

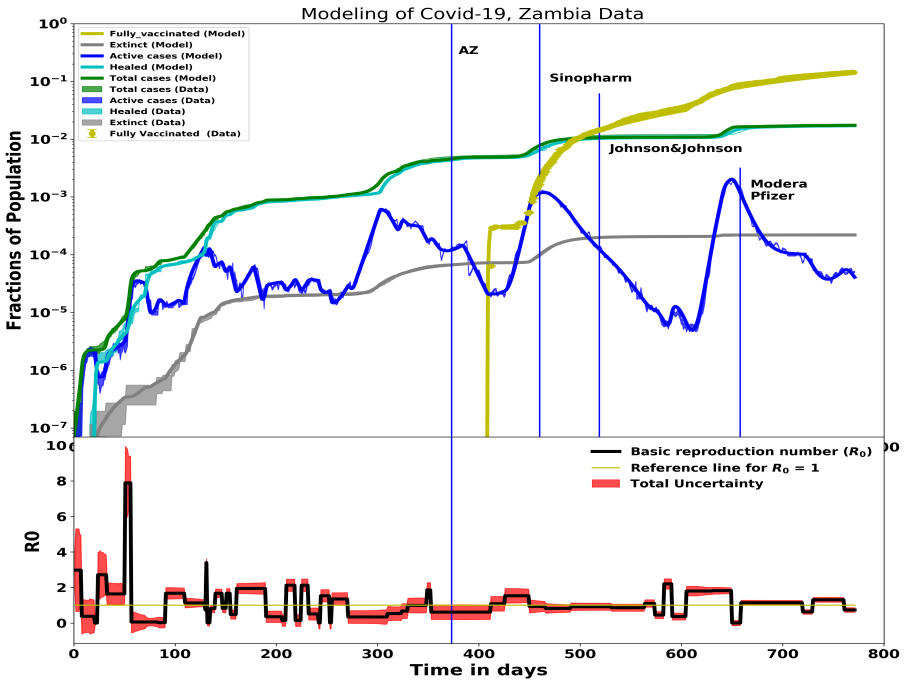

Figure 11: The model prediction of the recovered population is shown in the bottom-right plot; also shown, is the undiagnosed fraction of the people that were infected and recovered without symptoms. This fraction, called the unaffected cases, is not measured or included in the data

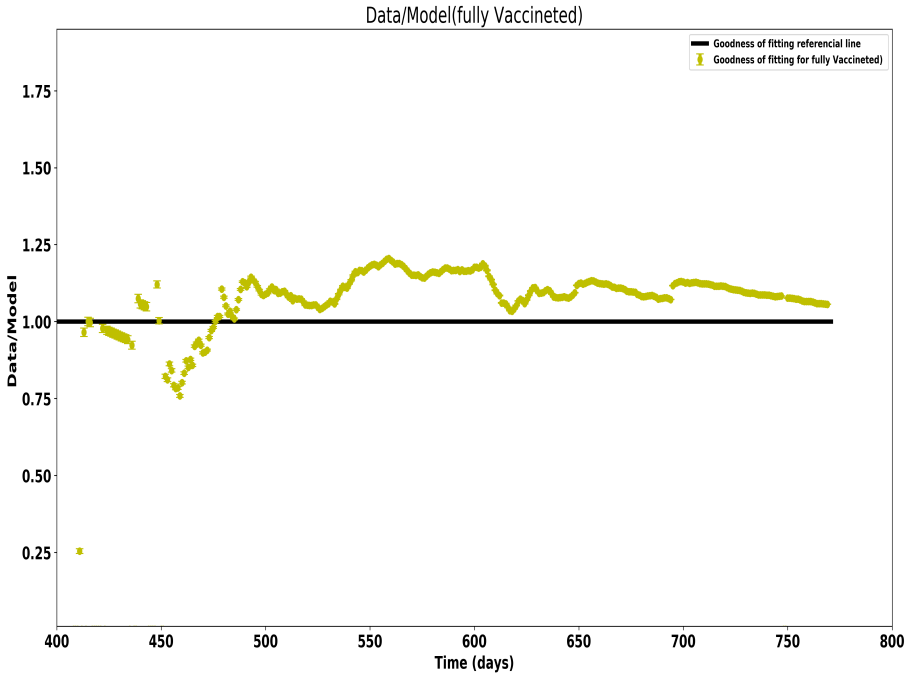

Figure 12: The plot showing the goodness-of-fit of the COVID-19 data modelling of Zambia for fully-vaccinated individuals over time in days since the ...th of February, 2020 up to the of ...th of February, 2022.

4. 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 frontline 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 03 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 [**?**], 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 (3-17 Febrauary), 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%.

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. 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 [**?**] and geographical inequalities in accessing vaccines in hard-to-reach areas [e.g., **?**]. 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.

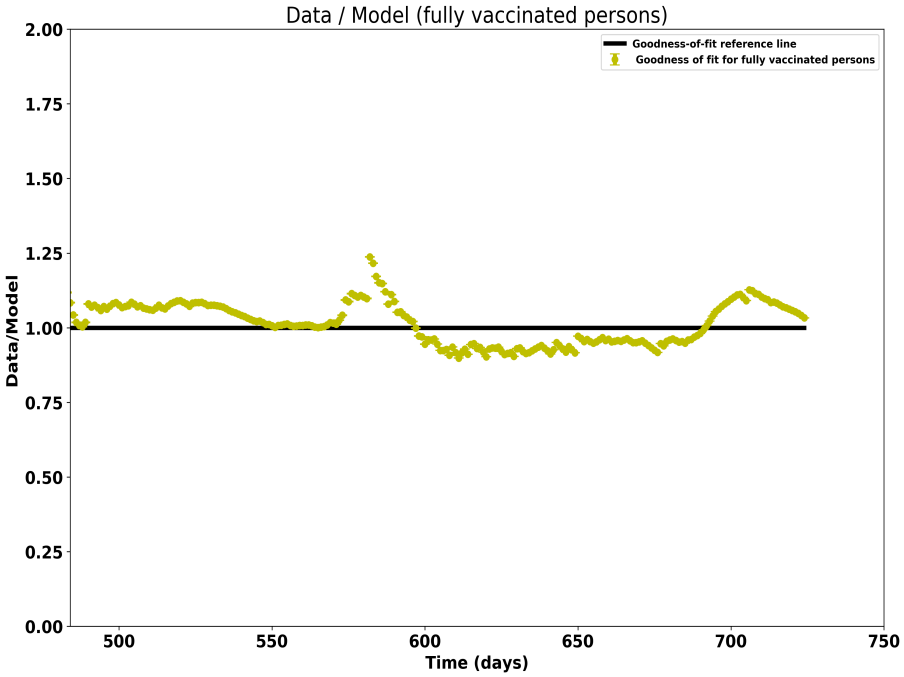

Figure 13: The plot showing the goodness-of-fit of the COVID-19 data modelling of Kenya for fully-vaccinated individuals over time in days since the ...th of February, 2020 up to the of ...th of February, 2022.

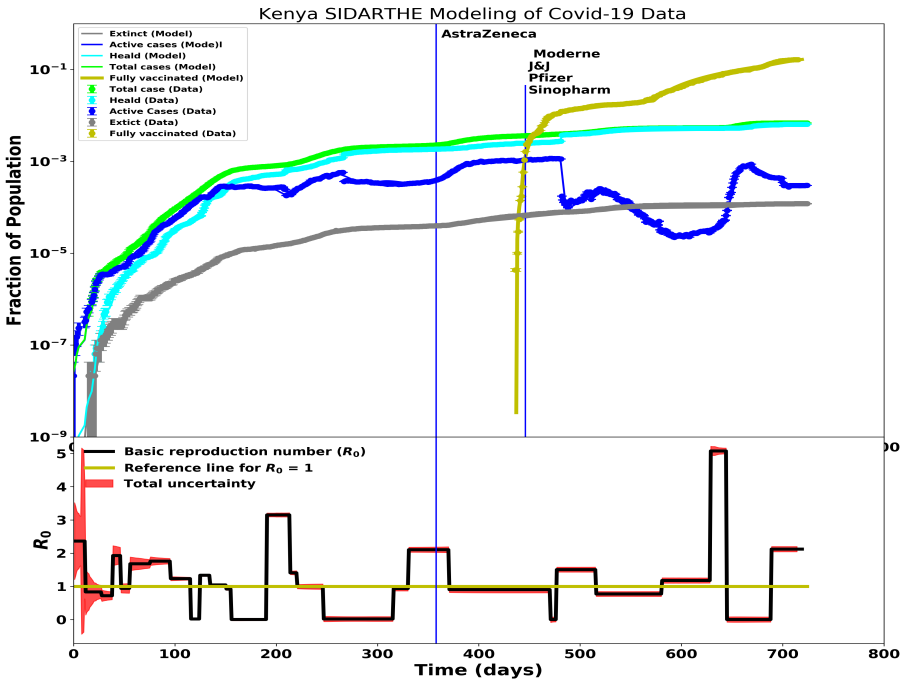

Figure 14: The model prediction of the recovered population is shown in the bottom-right plot; also shown, is the undiagnosed fraction of the people that were infected and recovered without symptoms. This fraction, called the unaffected cases, is not measured or included in the data

272 *4.1. Analysis of COVID-19 data of Togo*

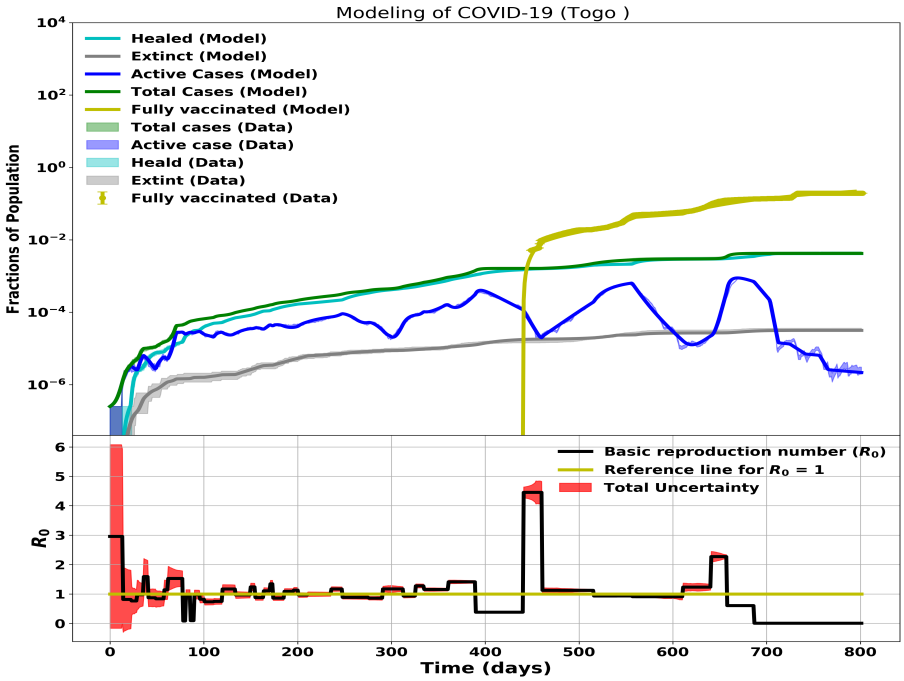

Figure 15: The model prediction of the recovered population is shown in the bottom-right plot; also shown, is the undiagnosed fraction of the people that were infected and recovered without symptoms. This fraction, called the unaffected cases, is not measured or included in the data

5. COVID-19 Vaccination Analysis for Ghana

In Ghana, the first official cases of COVID-19 were reported on 12 March 2020. As at then, 141 COVID-19 cases had been confirmed nationwide, with 5 fatalities [**?**]. The first two confirmed cases were identified as individuals having returned to the country from Norway and Turkey. As at 17 April 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 5th, 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 [**?**] 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 [**?**]. Ghana is the first country ro recieve COVID-19 vaccines from the COVAX initiative and begsn its first vaccine rollout on March 1st, 2021 [**?** **?** **?**] by administering AstraZeneca. Johnson & Johnson (J&J), Moderna, Pfizer, and Sputnik V are the COVID-19 vaccines also approved and administered in Ghana.

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 [**?**] 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 [**?**]. 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 [**?**].

According to [**?**], 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. As at 25th April 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. Currently, there are $161,216$ COVID-19 cases in Ghana. Out of this, $159,737$ have recovered and discharged with $1,445$ deaths and 34 active cases as at 30th April 2022 . Greater Accra region records the highest number of COVID-19 cases at $90,826$ followed by the Ashanti region with $22,299$ cases [**?**].

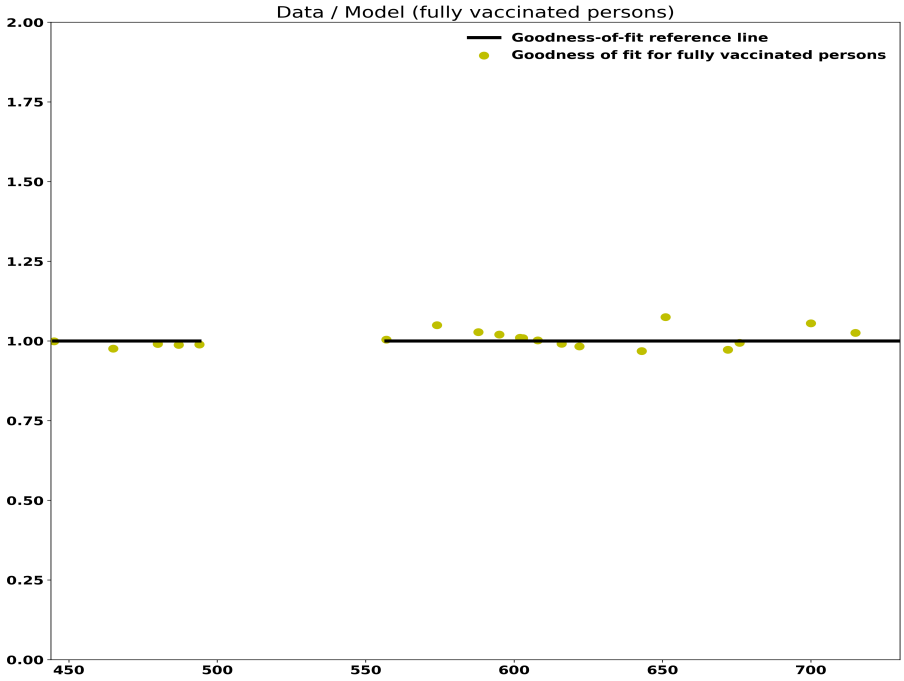

Figure 16: The plot showing the goodness-of-fit of the COVID-19 data modelling of Kenya for fully-vaccinated individuals over time in days since the ...th of February, 2020 up to the of ...th of February, 2022.

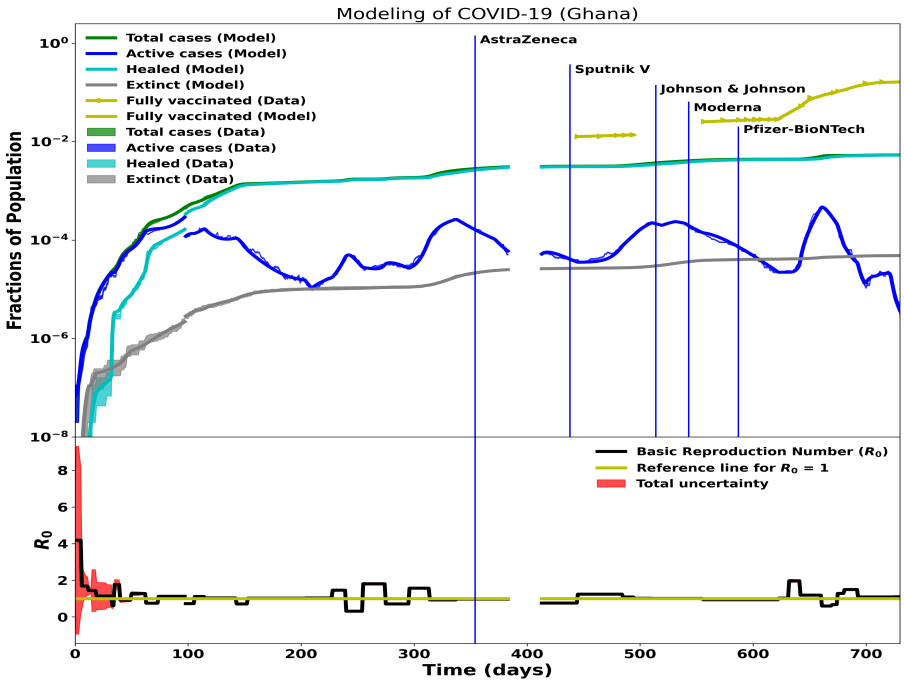

Figure 17: The model prediction of the recovered population is shown in the bottom-right plot; also shown, is the undiagnosed fraction of the people that were infected and recovered without symptoms. This fraction, called the unaffected cases, is not measured or included in the data

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