



SARS-COV-2 outbreak and control in Kenya - Mathematical model analysis



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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic reached Kenya in March 2020 with the initial cases reported in the capital city Nairobi and in the coastal area Mombasa. As reported by the World Health Organization, the outbreak of COVID-19 has spread across the world, killed many, collapsed economies and changed the way people live since it was first reported in Wuhan, China, in the end of 2019. As at the end of December 2020, it had led to over 2.8 million confirmed cases in Africa with over 67 thousand deaths. The trend poses a huge threat to global public health. Understanding the early transmission dynamics of the infection and evaluating the effectiveness of control measures is crucial for assessing the potential for sustained transmission to occur in new areas.

We employed a SEIHCRD mathematical transmission model with reported Kenyan data on cases of COVID-19 to estimate how transmission varies over time. The model is concise in structure, and successfully captures the course of the COVID-19 outbreak, and thus sheds light on understanding the trends of the outbreak. The next generation matrix approach was adopted to calculate the basic reproduction number (R_0) from the model to assess the factors driving the infection. The model illustrates the effect of mass testing on COVID-19 as well as individual self initiated behavioral change. The results have significant impact on the management of COVID-19 and implementation of prevention policies. The results from the model analysis shows that aggressive and effective mass testing as well as individual self initiated behaviour change play a big role in getting rid of the COVID-19 epidemic otherwise the rate of infection will continue to increase despite the increased rate of recovery.

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1. Introduction

The current outbreak of COVID-19 pandemic has caused many fatalities, affected global economy and changed the way people live since it was first reported. COVID-19 had infected at least 4,801,202 people by May 20, 2020 with the total number of deaths standing at 318,935 and that of recoveries at 964,161 and had affected over 213 countries worldwide according world health organization (WHO, 2020a). In Africa, the virus has spread to dozens of countries within weeks. In Kenya the number of people tested of the virus by May 20, 2020 were 49,405 with 1029 cases, 366 recoveries and 50 deaths (WHO,

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2020a). In February 2020, WHO declared the disease COVID-19, a global pandemic (WHO, 2020b). The number of deaths associated with COVID-19 greatly exceed those due to the other two corona viruses (severe acute respiratory syndrome coronavirus; SARS-CoV, and Middle East respiratory syndrome coronavirus; MERS-CoV), and the outbreak is still ongoing, which poses a huge threat to the global public health and economics (Kuniya, 2020; Sookaromdee Wiwanitkit et al., 2019).

Coronaviruses are enveloped single-stranded RNA viruses that are zoonotic in nature (Adhikari et al., 2020; Salata et al., 2019; Ye et al., 2020). The virus spreads mainly from person-to-person and is transmitted between people who are in close contact with one another (within a distance of 1 m of each other). When an infected person coughs or sneezes, the droplets produced can land in the mouths or noses of people who are nearby or possibly be inhaled into the lungs (WHO. World health organization, 2020a). The most contagious people are those who have developed the symptoms (symptomatic). Some spread might be possible before people show symptoms; there have been reports of this occurring with this new coronavirus, but this is not thought to be the main way the virus spreads (WHO. World health organization, 2020b).

COVID-19 can also be transmitted through touching contaminated surfaces or objects. A person can be infected by touching a surface or object contaminated with the virus and then touching their own mouth, nose, or possibly their eyes, but this is not thought to be the main way the virus spreads (WHO. World health organization, 2020b). The speed at which a virus spreads from person-to-person varies. Some viruses are highly contagious (spread easily), like measles, while other viruses do not spread as easily. Another factor is whether the spread is sustained, spreading continually without stopping. The virus that causes COVID-19 has been spreading very fast in the community (*community spread*) where it is not sustained.

According to the WHO, the most common symptoms of COVID-19 are fever, tiredness, headache, chest pain and a dry cough. Some patients may also have a runny nose, sore throat, nasal congestion and aches and pains or diarrhoea (Verity et al., 2020). About 80% of people who get COVID-19 experience a mild case - about as serious as a regular cold - and recover without needing any special treatment (Zhao et al., 2020). Recovery depends on the strength of the immune system. About one in six people, the WHO says, become seriously ill. The elderly and people with underlying medical problems like high blood pressure, heart problems or diabetes, or chronic respiratory conditions, are at a greater risk of serious illness from Covid-19 (Huang et al., 2020).

Results in (Tang et al., 2020) revealed that interventions such as intensive contact tracing followed by quarantine and isolation can effectively reduce the transmission of COVID-19. The Kenyan government has adopted extreme measures to mitigate COVID-19 outbreak. On March 15, 2020, the government closed all the schools, banned public gatherings, and closed all inbound and outbound air transportation. The public panic in face of the ongoing COVID-19 outbreak reminds us the history of the 1918 influenza pandemic in London, United Kingdom (Linet et al., 2020).

In the early stages of a new infectious disease outbreak, it is crucial to understand the transmission dynamics of the infection. Estimation of changes in transmission over time can provide insights into the epidemiological situation and help identify whether outbreak control measures are having a measurable effect. Such analysis can inform predictions about potential future growth, help estimate risk to other counties, and guide the design of alternative interventions.

A simple mathematical model was used to trace the temporal course of the South Korea Middle East Respiratory Syndrome Coronavirus (MERS-CoV) outbreak (Hsieh, 2015). Further, a mathematical model for MERS-CoV transmission dynamics was used to estimate the transmission rates in two periods due to the implementation of intensive interventions (Chenet et al., 2020; Kimet et al., 2016). Other authors used clinical mathematical modeling technique for explaining the disease outbreak (Sookaromdee & Wiwanitkit, 2020). In (Tang et al., 2020), the likelihood-based estimates and the model-based estimates are applied to a deterministic model to estimate the control reproduction number of COVID-19 in Wuhan, China.

In this study, we extended the works of (Linet et al., 2020; Mbogo & Odhiambo, 2021). We note that the governmental action in Kenya, summarizes all measures including school closure, wearing of masks, social distancing, city lockdown, mass testing, hospitalization and quarantine of patients. The parameter values may be improved when more information is available. Nevertheless, our model is a preliminary conceptual model, intending to lay a foundation for further modelling studies, but we can easily tune our model so that the outcomes of our model are in line with previous studies (Chen Zhou et al., 2020; Chen et al., 2020; Hoseinpour Dehkordiet et al., 2020; Huet et al., 2020; Mbogo & Odhiambo, 2021).

The rest of the paper is organized as follows: in Section 2, we describe the formulated model. In Section 3, we carry-out model analysis including equilibrium analysis. The model is fitted to COVID-19 data in Section 4. The effects of social distancing and mass testing are also investigated in Section 4. In Section 5, we provide discussions and recommendations.

2. Model description and formulation

To describe the dynamics of COVID-19 in Kenya, we develop a seven disease state compartmental SEIHCARD-model describing the movement of individuals from one state to another starting from the susceptible class S , that is, individuals with no history of infection by the disease. Individuals get infected with the virus and move into compartment E , referred to as exposed, who are asymptomatic. Then the exposed can develop symptoms and move to compartment I , referred as infected individuals. The Infected individuals will take themselves to be hospitalized or quarantine themselves at home. Those who get hospitalized move to class H . The hospitalized can get worse and move to ICU class denoted as C or recover and move to compartment R . The last class is the Death, represented by compartment D containing those who succumb to COVID-19.

2.1. Model framework

Fig. 1 shows the structure of model.

The total population at any time t , is denoted by $N(t)$ and is given by

$$N(t) = S(t) + E(t) + I(t) + H(t) + C(t) + R(t). \tag{1}$$

The rate of generation of new COVID-19 cases is modelled by λS , where λ is the force of infection given by

$$\lambda(t) = \frac{(1 - \eta)(\beta_0 I(t) + \beta_1 H(t) + \beta_2 C(t))}{N(t)}. \tag{2}$$

2.2. Description of the variables and parameters used in the model

The variables and parameters description for the model are summarized in Tables 1 and 2:

Given the flow diagram in Fig. 1, the parameter description in Table 2, we have the following system of non-linear ordinary differential equations:

$$\begin{aligned} \frac{dS(t)}{dt} &= \rho\Lambda - \lambda(t)S(t), \\ \frac{dE(t)}{dt} &= \lambda(t)S(t) - \kappa E(t) - \gamma E(t), \\ \frac{dI(t)}{dt} &= (1 - \rho)\Lambda + (1 - \zeta)\gamma E(t) - \alpha I(t) - \mu_I I(t), \\ \frac{dH(t)}{dt} &= \alpha I(t) + \zeta\gamma E(t) + \sigma C(t) - (\omega + \delta + \mu_h)H(t), \\ \frac{dC(t)}{dt} &= \delta H(t) - (\sigma + \mu_c)C(t), \\ \frac{dR(t)}{dt} &= \kappa E(t) + \omega H(t), \\ \frac{dD(t)}{dt} &= \mu_c C(t) + \mu_h H(t) + \mu_I I(t), \end{aligned} \tag{3}$$

subject to the following initial conditions.

$$S(0) > 0, E(0) \geq 0, I(0) \geq 0, H(0) \geq 0, C(0) \geq 0, R(0) \geq 0, D(0) \geq 0.$$

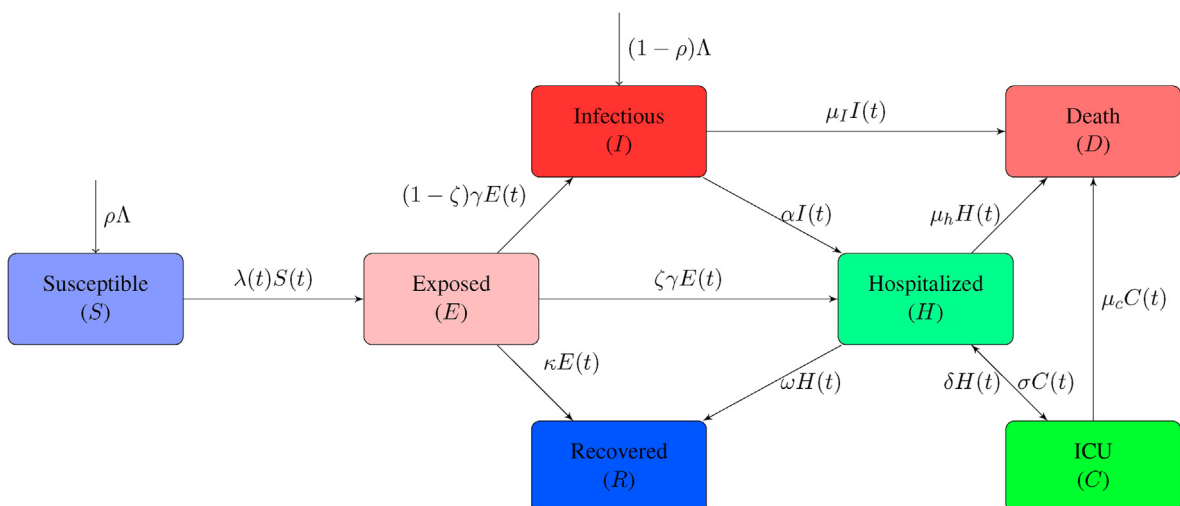


Fig. 1. The model Framework.

Table 1
Summary of variables in the concept model.

Variable	Description
S	Susceptible population
E	Exposed population
I	Infective population
H	Hospitalized population
C	Population in ICU
R	Recovered population
D	COVID-19 induced deaths

Table 2
Description of Parameters for the model.

Parameter	Description
Λ	Those entering a country from other countries
P	proportion of susceptible entering the country from other countries
K	rate of recovery after being exposed
β_0	Effective contact rate between susceptible and infected individuals.
β_1	Effective contact rate between susceptible and hospitalized individuals
β_2	Effective contact rate between susceptible and those in ICU
Γ	transition rate from exposed to infectious
A	hospitalization rate
Ω	recovery rate after treatment
Δ	transfer rate to ICU
Σ	recovery rate from ICU
H	effects of social distancing
Z	effects of mass testing
M	death rate due to COVID-19.

3. Basic properties of the model

3.1. Positivity of solutions

Positivity in the model is shown by proving the following theorem.

Theorem 1. *Let the parameters in model (3) be positive constants. A non-negative solution $(S(t), E(t), I(t), H(t), C(t), R(t), D(t))$ exists for all the state variables with non-negative initial conditions $\{S(0) = S_0 \geq 0, E(0) = E_0 \geq 0, I(0) = I_0 \geq 0, H(0) = H_0 \geq 0, C(0) = C_0 \geq 0, R(0) = R_0 \geq 0, D(0) = D_0 \geq 0\}$ for $\forall t \geq 0$. Proof. Considering the first equation in system (3), we have*

$$\begin{aligned} \frac{dS(t)}{dt} &= \rho\Lambda - \lambda(t)S(t), \\ \frac{dS}{dt} &\geq -\lambda(t)S(t). \end{aligned}$$

Upon integrating,

$$S(t) \geq S(0)\exp \int_0^t -\lambda(\tau)d\tau > 0.$$

Applying the above procedure to the rest of the equations in model system (3), we obtain:

$$\begin{aligned} E(t) &\geq E(0)\exp[-(\kappa + \gamma)t] > 0, \\ I(t) &\geq I(0)\exp[-(\alpha + \mu_1)t] > 0, \\ H(t) &\geq H(0)\exp[-(\omega + \delta + \mu_h)t] > 0, \\ C(t) &\geq C(0)\exp[-(\sigma + \mu_c)t] > 0, \\ R(t) &\geq R(0) > 0, \quad D(t) \geq D(0) > 0, \end{aligned}$$

Clearly, all the state variables, S, E, I, H, C, R, D of model system (3) are non-negative for all time $t > 0$.

3.2. Invariant region

Restating equation (1), we have

$$N(t) = S(t) + E(t) + I(t) + H(t) + C(t) + R(t).$$

Substituting the derivatives in system (3) and simplifying, we obtain

$$\begin{aligned} \frac{dN}{dt} &= \Lambda - \mu_I I(t) - \mu_H H(t) - \mu_C C(t) \\ \frac{dN}{dt} &\leq \Lambda - \mu N(t) \end{aligned}$$

Upon integration we get

$$N(t) \leq N_0 e^{-\mu t} + \frac{\Lambda}{\mu} (1 - e^{-\mu t}).$$

Clearly, there exists a bounded positive invariant region for model system (3), that is $N(t) \leq \frac{\Lambda}{\mu}$.

We shall study the dynamical nature of the COVID-19 model system (3) in the feasible closed region:

$$\Omega = \left\{ (S, E, I, H, C, R, D) \in \mathbb{R}_+^7 : N(t) = S + E + I + H + C + R + D \leq \frac{\Lambda}{\mu} \right\} \tag{4}$$

Therefore, any solution of our system (3) that commences in Ω , at any time $t \geq 0$ will always remain confined in that region. The region Ω is therefore positively invariant and attracting with respect to COVID-19 model system (3). The deterministic model in (3) is hence mathematically and biologically well-posed.

3.3. Equilibria analysis of the model

The basic reproduction number R_0 , is defined as the number of secondary infections produced by one infective that is introduced into an entirely susceptible population at the disease free equilibrium (Diekmann and HeesterbeekJohan, 1990). The next generation matrix approach is frequently used to compute R_0 , see (Van den DriesscheJames, 2002).

System (3) has a disease-free equilibrium (DFE) given by

$$E_0 = (S_0, 0, 0, 0, 0, 0, 0)$$

The matrix FV^{-1} is called the next generation matrix. The (i, k) entry of FV^{-1} indicates the expected number of new infections in compartment i produced by the infected individual originally introduced into compartment k .

$$FV^{-1} = \begin{pmatrix} \frac{(\eta-1) \left(\frac{\gamma(\zeta-1)(\delta\beta_2 + \beta_1(\sigma + \mu_c))}{\sigma\mu_h + \mu_c(\delta + \mu_h)} - \frac{\zeta\gamma\beta_0}{\alpha} \right)}{\gamma + \kappa} & \frac{(\eta-1)\beta_0}{\alpha} & \frac{(\eta-1)(\delta\beta_2 + \beta_1(\sigma + \mu_c))}{\sigma\mu_h + \mu_c(\delta + \mu_h)} & \frac{(\eta-1)(\sigma\beta_1 + \beta_2(\delta + \mu_h))}{\sigma\mu_h + \mu_c(\delta + \mu_h)} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

The (i, k) entry of FV^{-1} indicates the expected number of new infections in compartment i produced by the infected individuals originally introduced into compartment k . The disease reproduction number, R_0 , which is defined as the spectral radius of FV^{-1} , and denoted by $\rho(FV^{-1})$ is evaluated to:

$$R_0 = \frac{(1 - \eta) \left(\beta_0(1 - \zeta)\gamma + \frac{\gamma(\alpha + \zeta\mu_h)(\beta_2\delta + \beta_1(\mu_c + \sigma))}{\mu_c(\omega + \delta + \mu_h) + \sigma(\omega + \mu_h)} \right)}{(\gamma + \kappa)(\alpha + \mu_I)}. \tag{5}$$

Hence,

$$R_0 = R_I + R_H + R_C$$

where

$$\begin{aligned}
 R_I &= \frac{(1 - \eta)\beta_0(1 - \zeta)\gamma}{(\alpha + \mu_I)(\gamma + \kappa)}, \\
 R_H &= \frac{(1 - \eta)(\alpha + \zeta\mu_I)\beta_1\gamma(\mu_c + \sigma)}{(\mu_c(\omega + \delta + \mu_h) + \sigma(\omega + \mu_h))(\gamma + \kappa)(\alpha + \mu_I)}, \\
 R_C &= \frac{(1 - \eta)(\alpha + \zeta\mu_I)\beta_2\delta\gamma}{(\mu_c(\omega + \delta + \mu_h) + \sigma(\omega + \mu_h))(\gamma + \kappa)(\alpha + \mu_I)}.
 \end{aligned}$$

Here R_0 is the sum of three terms each representing the average new infections contributed by each of the three infectious classes. R_I represents the new cases generated by infected individuals in compartment I , R_H represents new cases generated by patients hospitalized, and R_C represents new cases from patients hospitalized and in ICU.

From R_0 in equation (5), each term is multiplied by $(1 - \eta)$ which represents the Government control measures, hence if the measures are followed, then the emergency of new corona cases is reduced. Therefore the government campaign of “social distancing” and “hygiene” is very important in preventing the development of new cases.

From Theorem 2 in (Van den DriesscheJames, 2002), we have the following result:

Theorem 2. The DFE, E_0 of the system of equation (3) is locally asymptotically stable when $R_0 < 1$ and unstable otherwise.

Question: What is likely disease burden (total infections, total hospital admissions, total ICU admissions, total deaths) if epidemic is not contained by a country?

- SEIHCRC model (incorporating social distancing, hygiene, quarantine and current curfew) will give insights on how soon Kenya is likely to reach 1,000 or 10,000 cases under current control measures.
- The model will give, at any time, the estimated number of new infections, the total infections, the total population hospitalized, the patients in ICU and the number recovered together with mortality estimates.
- The model to predict expected cases of COVID-19 in future (say two weeks time)

4. Numerical simulations

In this section, we present a series of numerical results of system (3) using COVID-19 reported cases data in Kenya to predict and estimate the incidence of the virus in the country.

4.1. Application of the model to COVID-19 data in Kenya

COVID-19 cases in Kenya were collected from March 13, 2020 to January 1, 2021 from the Ministry of Health (MoH) as shown in Figure (2).

Using least squares curve fitting method, the model system (3) was fitted to the COVID-19 reported cumulative cases in Figure (2) to estimate the model parameter. The parameter values which are calculated from the given data in Figure (2) are displayed in Table 3 and the initial conditions for the populations are as given in Table 4,

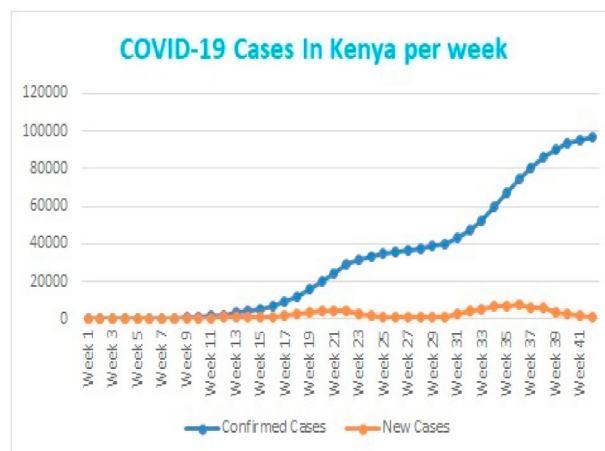


Fig. 2. Daily new confirmed and cumulative COVID-19 cases in Kenya.

Table 3
Model parameters values.

Parameter	Value
Λ	200
P	0.37
K	0.16
β_0	0.49
β_1	0.09
β_2	0.009
Γ	0.5
A	0.13
Q	0.027
Δ	0.00001
Σ	0.0001
H	0.09
Z	0.5
μ_l	0.001
μ_h	0.0008
μ_c	0.09

4.2. Effects of model parameters on R_0

Using parameter values in Table 3, we identified how different input parameters affect the reproduction number R_0 of our model as shown in Fig. 3. With the current intervention measures put in place in Kenya, our model shows the reproduction number has reduced to $R_0 = 1.68$.

From Fig. 3, it is evident that an increase in individual initiated behaviour and recovery rate are most likely to reduce the number of new cases and severity of COVID-19 infections. A lot more emphasis on individual change of behavior is therefore necessary. Such actions include compulsory face masks, regularly and proper washing of hands with soap and water or with alcohol-based hand sanitizers. To improve the rates of recovery, good care for COVID-19 patients is warranted. Infected individuals should be taken to isolation centres for proper treatment and care.

Results of parameter sensitivity, further indicate the need to reduce contacts between the susceptibles and the infected COVID-19 persons. This is achievable through compulsory social distancing and imposed night curfews in the country.

4.3. Data fitting and model predictions

Using the parameter values and initial values as given in Tables 3 and 4 respectively, and applying them on system (3), we have the fitted and projected curves as displayed in Fig. 4.

We observe that model system (3) fits well the COVID-19 data from Kenya (see Fig. 4a). Fig. 4b shows the projected COVID-19 cases in Kenya with current intervention measures. Moreover, with relaxed intervention measures, Kenya is likely to experience exponential growth in the number of COVID-19 cases (see Fig. 4b). The Kenyan government should therefore strictly deploy and implement existing control measures against COVID-19 in every county.

4.4. Impact of social distancing on the populations

Fig. 5a shows the impact of following government control measures and guidelines on the population at risk of contracting the virus (susceptible population). The simulation shows that ignoring safety guidelines such as social distancing and personal hygiene has devastating effect on the susceptible individuals denoted by the blue line in Fig. 5a.

Fig. 5b shows the impact of Government directive measures on COVID-19 new cases. If by October 1, 2020 (Week 29), all the government directive measures were adhered to, then we would not have significant new infections hence no deaths.

Fig. 6 shows the impact of social distancing and personal hygiene on the projections of the number of COVID-19 deaths. If individuals adhere to keeping social distance, wearing of face masks and keeping personal hygiene, then we will have minimal or no COVID 19 induced deaths as depicted by the pink line in Fig. 6.

4.5. Impact of mass testing on the populations

Fig. 7a presents the projections and the impact of mass testing on the non-hospitalized and hospitalized COVID-19 cases. From Fig. 7, it is shown that with aggressive mass testing, the asymptomatic and symptomatic patients who are not yet in hospital will be identified and either hospitalized or quarantined as shown by the green line in Fig. 7a hence preventing further transmission. This implies that correct information based on an adequate diagnosis system would be desired for the Kenyan government to act appropriately. Fig. 7b shows the impact of aggressive mass testing on patient recoveries, if the government embarks of aggressive and effective contact tracing, then infected individuals will be identified and given proper care hence increasing the number of recoveries as depicted by the green line in Fig. 7b. A combination of adherence to existing

Table 4
Initial conditions.

Variable	$S(0)$	$E(0)$	$I(0)$	$H(0)$	$C(0)$	$R(0)$	$D(0)$
Values	4.4×10^7	10	1	1	0	0	0

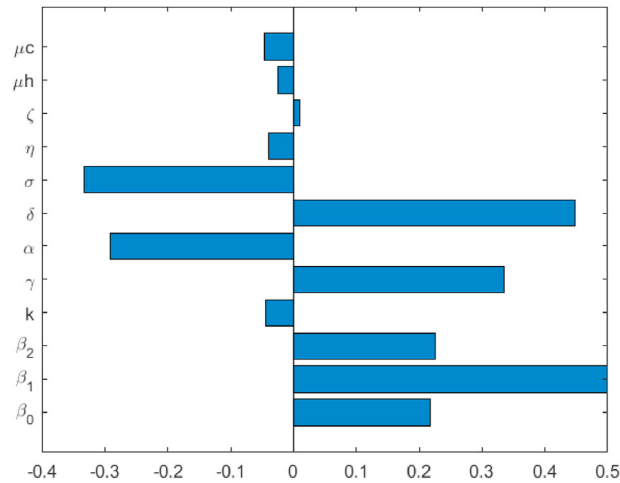


Fig. 3. Tornado plots of sensitivity indices of parameters that influence disease R_0 generated using parameter values in Table 3.

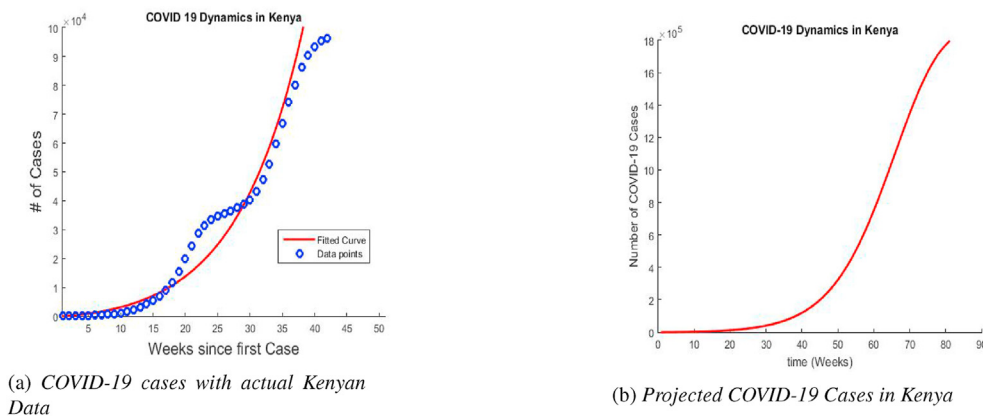


Fig. 4. Curve fitting and model prediction.

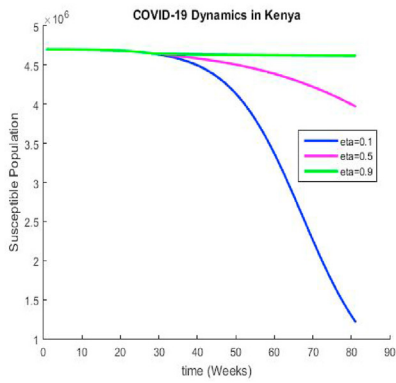
government control measures and improved medical environment is likely to yield most recoveries from COVID-19 infections as shown in Fig. 7b.

4.6. Implications of health care services on COVID 19 severity and deaths

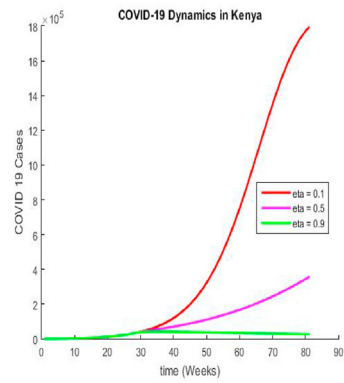
Fig. 8 shows the impact of hospital patient care on the number of COVID-19 hospitalized patients and in ICU and on the COVID 19 induced deaths. With proper medical care of patients, then there will less people developing severe complications hence very few will need ICU care as depicted by the blue and green lines in Fig. 8a. Similarly proper medical care of patients will lead to very few patients succumbing to death as depicted by the pink line in Fig. 8b.

5. Discussion and recommendation

In this study, we applied the SEIRHCRD compartmental model to the daily reported cases of COVID-19 to determine the transmission dynamics of COVID-19 in Kenyan population over time. The model simulation shows that ignoring safety guidelines such as social distancing, wearing of masks, frequent washing of hands with water and soap or using alcohol-based hand sanitizers and cutting down on travel has devastating effect on the disease dynamics. The model results also give



(a) Effects of social distancing on susceptible population



(b) Effects of social distancing on Exposed population

Fig. 5. Model prediction considering the impact of social distancing on the populations denoted by η in our model.

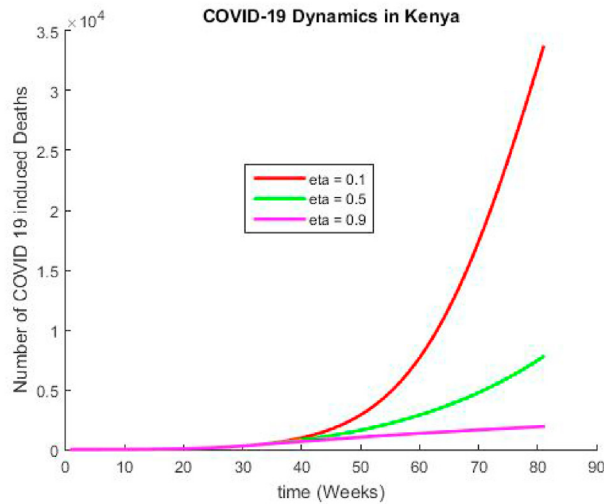
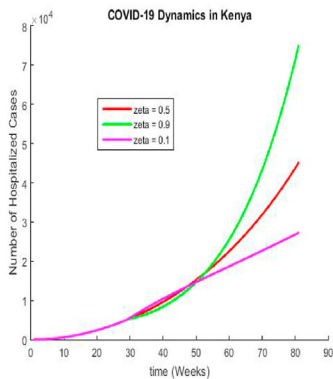
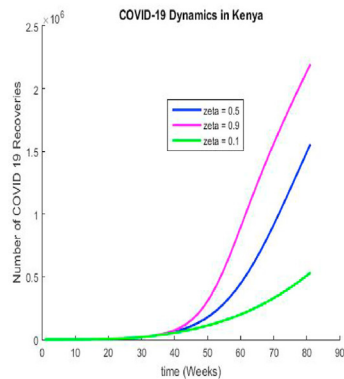


Fig. 6. Model prediction of COVID 19 induced deaths considering the impact of social distancing on the population denoted by η in our model.



(a) Prediction on asymptomatic and hospitalized populations



(b) Prediction on the recovery from COVID-19

Fig. 7. The impact of mass testing on the populations denoted by ζ in our model.

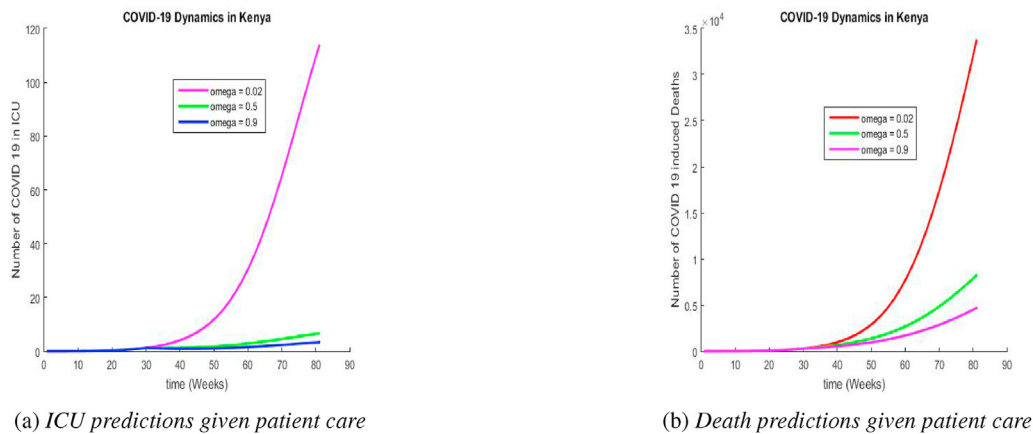


Fig. 8. Model prediction on the number in ICU and deaths from COVID-19 given hospital patient care.

insights to health policy-makers and Government on the effective approaches and implementable actions that can enhance the prevention, preparedness and readiness for future emergencies of COVID-19 and similar diseases.

The effort to evaluate the disease equilibrium shows that unless there is a dedicated effort from government, decision makers and individual Kenyans, the rate of COVID-19 infection will continue to increase despite the increased rate of recovery. Given the non availability of the vaccine in Kenya at the moment, individual initiated behavior change is needed to effectively reduce the final epidemic size. The most effective non-pharmaceutical interventions are the combination of keeping social distancing, mass-testing and hospital patient care.

Our study suggests that aggressive and effective mass testing is required to identify and isolate the asymptomatic patients in the community. Moreover, our analysis reveals that, individual initiated behavior change and improved hospital care will see Kenya free of COVID-19 new cases, deaths and improved recoveries from the disease.

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Availability of data and materials

All data used in this study are included in this manuscript.

Authors' contributions

All authors contributed to all sections of this manuscript.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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