

Infectious Disease Modelling

COVID-19 outbreak and control in Kenya- Insights from a mathematical model

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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 of May 25,2020 It had led to over 100,000 confirmed cases in Africa with over 3000 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 results from the model analysis shows that non-pharmaceutical interventions over a relatively long period is needed to effectively get 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 (17). 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 (17). In February 2020, WHO declared the disease COVID-19, a global

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pandemic (18). 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 (10; 13)

Coronaviruses are enveloped single-stranded RNA viruses that are zoonotic in nature (1; 12; 21). 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 one meter 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 (19). 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 (20).

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 (20). 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 (16). 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 (22). 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 (8).

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 (11).

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 (6). 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(3; 9). Other authors used clinical mathematical modeling technique for explaining the disease outbreak (14). In this study, we extended the work of (11). We note that the governmental action in Kenya, summarizes all mea-

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sures 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 (2–4; 7).

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 dicussions and recommendations.

2 Model Description and Formulation

To describe the dynamics of COVID-19 in Kenya, we develop a seven disease state compartmental SEIHCRD-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

Figure 1 shows the structure of model

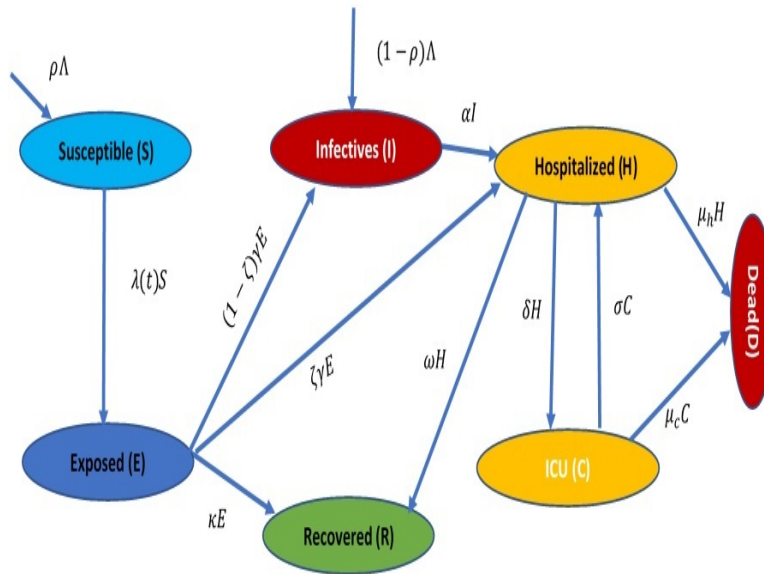


Figure 1: *The Model Framework*

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

$$N(t) = S(t) + E(t) + I(t) + H(t) + C(t) + R(t) + D(t). \quad (1)$$

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

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

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 :

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
ρ	proportion of susceptible entering the country from other countries
κ	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
α	hospitalization rate
ω	recovery rate after treatment
δ	transfer rate to ICU
σ	recovery rate from ICU
η	effects of social distancing
ζ	effects of mass testing
μ	death rate due to COVID-19.

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

$$\begin{aligned}
\frac{dS(t)}{dt} &= \rho\Lambda - (1 - \eta)(\beta_0 I(t) + \beta_1 H(t) + \beta_2 C(t))S(t), \\
\frac{dE(t)}{dt} &= (1 - \eta)(\beta_0 I(t) + \beta_1 H(t) + \beta_2 C(t))S(t) - \kappa E(t) - \gamma E(t), \\
\frac{dI(t)}{dt} &= (1 - \rho)\Lambda + (1 - \zeta)\gamma E(t) - \alpha I(t), \\
\frac{dH(t)}{dt} &= \alpha I(t) + \zeta\gamma E(t) + \sigma C(t) - (\omega + \delta + \mu_h)H(t), \\
\frac{dC(t)}{dt} &= \delta H(t) - (\sigma + \mu_c)C(t), \\
\frac{dR(t)}{dt} &= \kappa E(t) + \omega H(t), \\
\frac{dD(t)}{dt} &= \mu_c C(t) + \mu_h H(t),
\end{aligned} \tag{3}$$

subject to the following initial conditions

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

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 $\{S(0) = S_0 \leq 0, E(0) = E_0 \geq 0, I(0) = I_0 \geq 0, H(0) = H_0 \geq 0, C(0) = C_0 \geq 0, R(0) = R_0 \geq 0, D(0) = D_0 \geq 0\}$ for $\forall t \geq 0$.*

Proof. Considering the first equation in system (3), we have

$$\begin{aligned}
\frac{dS(t)}{dt} &= \rho\Lambda - (1 - \eta)(\beta_0 I(t) + \beta_1 H(t) + \beta_2 C(t))S(t), \\
\frac{dS}{dt} &\geq \rho\Lambda.
\end{aligned}$$

Upon integrating,

$$S(t) \geq S(0) \exp(\rho\Lambda) > 0.$$

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

$$\begin{aligned}
E(t) &\geq E(0) \exp\{-(\kappa + \gamma)\} > 0, \\
I(t) &\geq \frac{1 - \rho}{\alpha} + \left\{ I_0 - \frac{1 - \rho}{\alpha} \right\} \exp\{-\alpha t\} > 0, \\
H(t) &\geq H(0) \exp\{-(\omega + \delta + \mu_h)\} > 0, \\
C(t) &\geq C(0) \exp\{-(\sigma + \mu_c)\} > 0, \\
R(t) &\geq R(0) > 0, \quad D(t) \geq D(0) > 0,
\end{aligned}$$

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

3.2 Invariant Region

Restating equation (1), we have

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

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

$$\frac{dN}{dt} \leq \Lambda \tag{4}$$

Integrating equation 4, we get

$$N(t) \leq N_0 e^{\Lambda t} \tag{5}$$

where $N_0 = S_0 + E_0 + I_0 + H_0 + C_0 + R_0 + D_0$.

Clearly, there exists a bounded positive invariant region for model system (3). Let us denote this region as $\Omega \in \mathbb{R}_+^7$, where,

$$\Omega = \left\{ (S, E, I, H, C, R, D) \in \mathbb{R}_+^7 : N(t) = S + E + I + H + C + R + D \right\}. \tag{6}$$

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 (5). The next generation matrix approach is frequently used to compute R_0 , see (15).

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

$$E_0 = (1, 0, 0, 0, 0, 0, 0).$$

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 .

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

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 model reproduction number, R_0 , which is defined as the spectral radius of FV^{-1} , and denoted by $\rho(FV^{-1})$ is evaluated to:

$$R_0 = \frac{(1-\eta)\left(\frac{\beta_0(1-\zeta)\gamma}{\alpha} + \frac{\gamma\zeta(\beta_2\delta+\beta_1(\mu_c+\sigma))}{\mu_c(\omega+\delta+\mu_h)+\sigma(\omega+\mu_h)}\right)}{\gamma+\kappa}. \quad (7)$$

Hence,

$$R_0 = R_I + R_H + R_C$$

where

$$R_I = \frac{(1-\eta)\beta_0(1-\zeta)\gamma}{\alpha(\gamma+\kappa)},$$

$$R_H = \frac{(1-\eta)\beta_1\gamma\zeta(\mu_c+\sigma)}{(\mu_c(\omega+\delta+\mu_h)+\sigma(\omega+\mu_h))(\gamma+\kappa)},$$

$$R_C = \frac{(1-\eta)\beta_2\gamma\delta\zeta}{(\mu_c(\omega+\delta+\mu_h)+\sigma(\omega+\mu_h))(\gamma+\kappa)}.$$

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 (7), 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 (15), we have the following result:

Theorem 2. *The DFE, E_0 of the system of equations (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?

- SEIHCRD 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 May 15, 2020 from the Ministry of Health (MoH) as shown in Table (3).

Table 3: *COVID-19 Cases in Kenya*

Day (March)	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Cases	1	1	3	3	7	7	7	7	7	16	16	25	28	31	31	38	42	50	59
Day (April)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15				
Cases	81	110	122	126	142	158	172	179	184	189	191	197	208	216	225				
Day(April)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30				
Cases	234	246	262	270	281	296	303	320	336	343	355	363	374	384	396				
Day(May)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Cases	411	435	465	490	535	582	607	621	649	672	700	715	737	758	781				

The parameter values which are calculated from the given data in Table 3 are displayed in Table 4 and the initial conditions for the populations are as given in Table 5,

Table 4: Model parameters values

Parameter	Value
Λ	100
ρ	0.839
κ	0.00001
β_0	0.5
β_1	0.09
β_2	0.005
γ	0.09
α	0.001
ω	0.0027
δ	0.00002
σ	0.0009
η	0.0000013
ζ	0.005
μ_h	0.009
μ_c	0.03

Table 5: *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

4.2 Effects of model parameters on R_0

Using parameter values in Table 4, we identified how different input parameters affect the reproduction number R_0 of our model as shown in Figure 2.

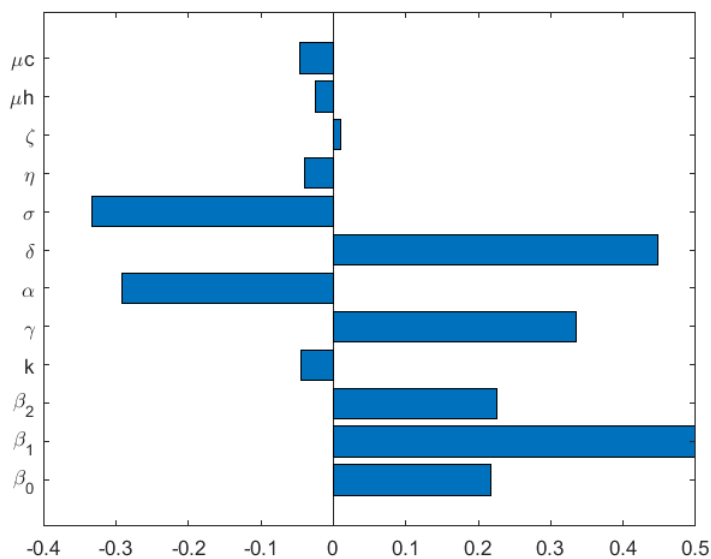


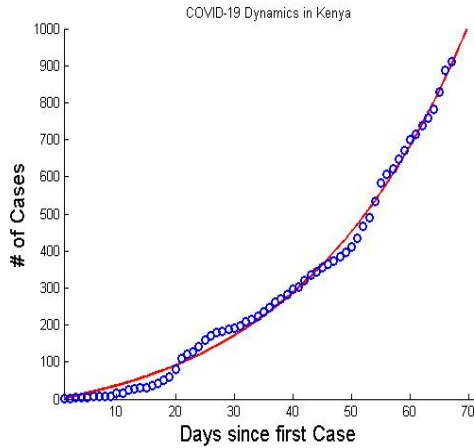
Figure 2: Tornado plots of sensitivity indices of parameters that influence disease R_0 generated using parameter values in Table 4

From Figure 2, it is evident that an increase in government action and recovery rate are most likely to reduce the number of new cases and severity of COVID-19 infections. A lot more emphasis on government action 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, cessation of movement and patrolled night curfews. 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.

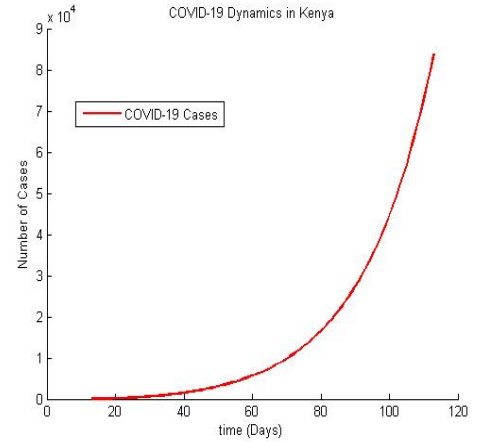
Results of parameter sensitivity, further indicate the need to reduce contacts between the susceptibles and the infected COVID-19 persons. This is achievable through compulsory social distancing and imposed night curfews in the country.

4.3 Data fitting and model predictions

Using the parameter values and initial values as given in Tables 4 and 5 respectively, and applying them on system (3), we have the fitted and projected curves as displayed in Figure 3.



(a) *COVID-19 cases with actual Kenyan Data*

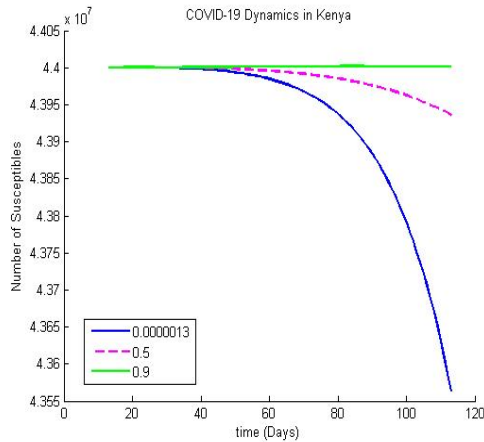


(b) *Projected COVID-19 Cases in Kenya*

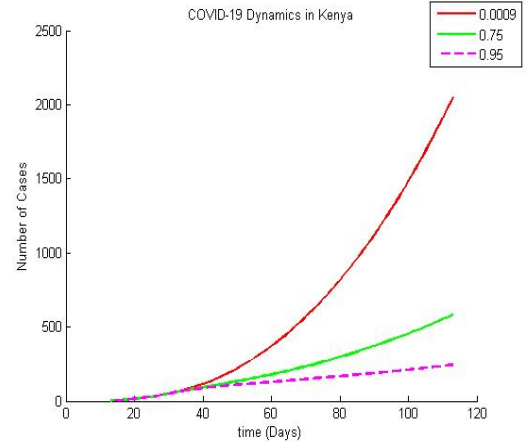
Figure 3: *Curve fitting and model prediction*

Figure 3b shows the projected COVID-19 cases in Kenya if no intervention is applied. We observe that model system (3) fits well the COVID-19 data from Kenya (see Figure 3a). Moreover, in the absence of interventions, Kenya is likely to experience exponential growth in the number of COVID-19 cases (see Figure 3b). 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



(a) *Effects of social distancing on susceptible population*



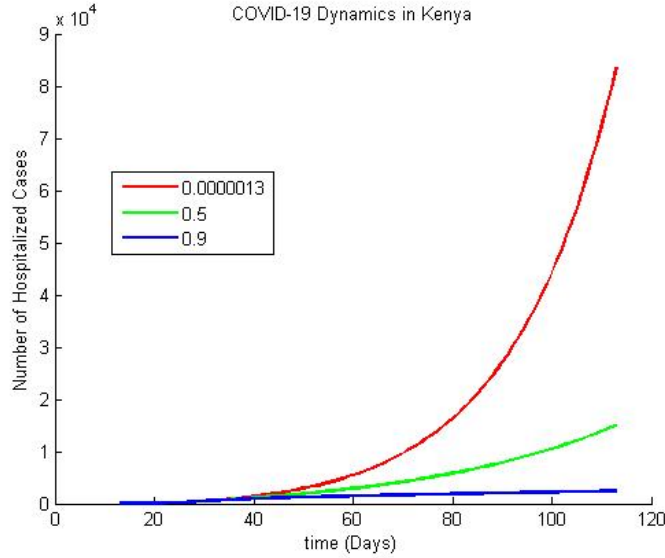
(b) *Effects of social distancing on Exposed population*

Figure 4: *Model prediction considering the impact of social distancing on the populations denoted by η in our model*

Figure 4a 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, wearing of masks, frequent wash of hands and cutting down on travel has devastating effect on the susceptible individuals denoted by the

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5 blue line in Figure 4a.
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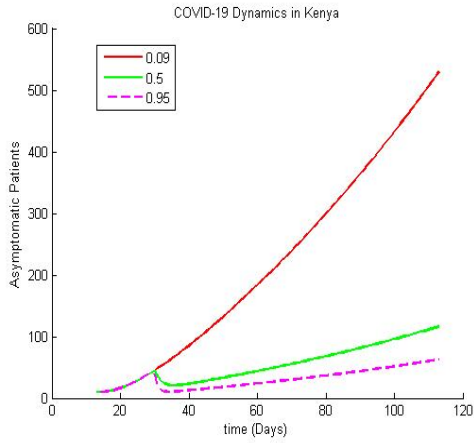
8 Figure 4b shows the impact of Government directive measures on COVID-19 new cases. If by
9 May 10, 2020, all the government directive measures were adhered to, then we would not have
10 significant new infections hence no deaths.
11



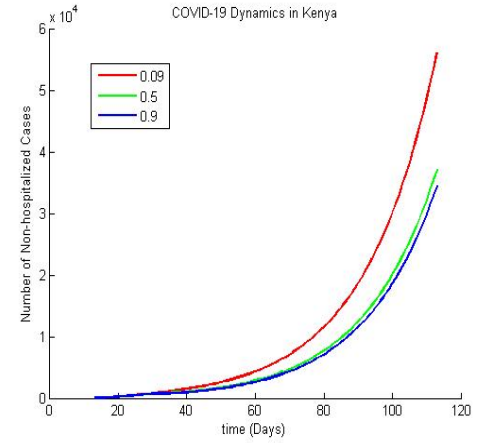
32 Figure 5: Model prediction of the number hospitalized considering the impact of social distancing
33 on the population denoted by η in our model.
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36 Figure 5 shows the projections of the number of COVID-19 cases hospitalized and the impact of
37 the government and personal intervention measures. With no interventions at all, depicted by
38 the red line in Figure 5, the model suggests we would rapidly run out of available hospital beds,
39 but with full implementation of intervention measures, the hospitals will be free of COVID-19
40 patients.
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4.5 Impact of mass testing on the populations



(a) Effects of mass testing on asymptomatic population

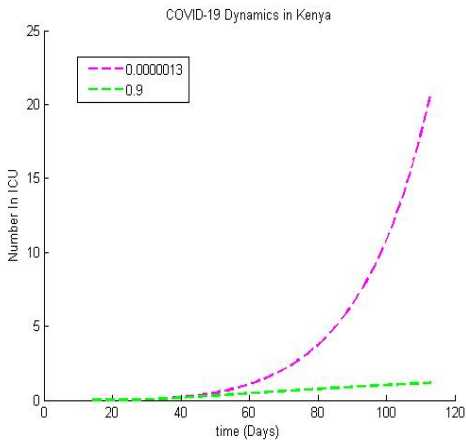


(b) Effects of mass testing on symptomatic population

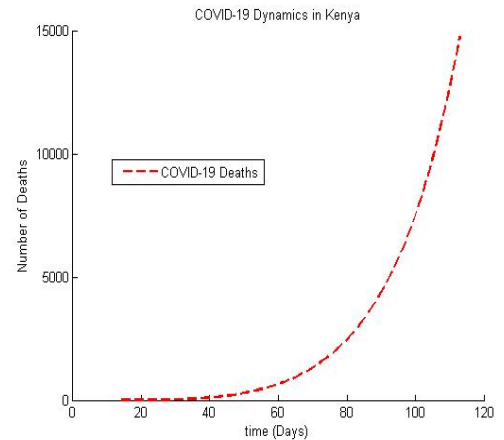
Figure 6: The impact of mass testing on the populations denoted by γ and α in our model

Figure 6 presents the projections and the impact of mass testing on the non-hospitalized COVID-19 cases. From Figure 6, it is shown that with mass testing, the asymptomatic and symptomatic patients who are not yet in hospital will be identified and either hospitalized or quarantined 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.

4.6 Other predictions



(a) ICU predictions



(b) Death predictions

Figure 7: Model prediction on the number in ICU and deaths from COVID-19

Figure 7 shows the number of COVID-19 hospitalized patients and in ICU and the death projections and the impact of non-pharmaceutical interventions.

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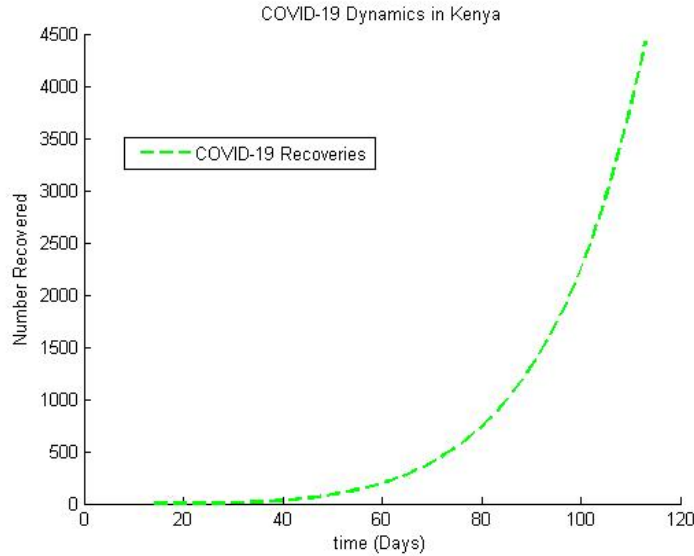


Figure 8: *Model prediction on the recovery from COVID-19*

A combination of adherence to existing government control measures and improved medical environment is likely to yield most recoveries from COVID-19 infections as shown in Figure 5.

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 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 absence of vaccine at the moment, non-pharmaceutical intervention over a relatively long period 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.

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5 **Availability of data and materials**
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7 All data used in this study are included in this manuscript.
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10 **Authors' contributions**
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12 All authors contributed to all sections of this manuscript.
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15 **Ethical approval and consent to participate**
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17 Not applicable.
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20 **Consent for publication**
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22 Not applicable.
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26 **Conflicts of Interest**
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28 The authors declare that there is no conflict of interest regarding the publication of this article
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COVID-19 outbreak and control in Kenya- Insights from a mathematical model

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Conflicts of Interest

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

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