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Effects of Religious Leaders on Non-Pharmaceutical and Pharmaceutical Intervention Measures in Covid-19 Spread In Kenya

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Abstract: **This research addresses the numerical modelling of religious leaders' effect on adherence to pharmaceutical and non-pharmaceutical intervention measures to reduce COVID-19 spread in Kenya. Disease-free equilibrium was determined. A SEIR compartmental model that considers the significance of religious leaders was developed. The basic reproduction number (R_0) was determined using the next-generation matrix method. The model was solved numerically to determine the effect of religious leaders in COVID-19 prevention campaigns and control of spread. These results are presented in graphs and tables. Therefore, stakeholders and policy makers of should use religious leaders in fighting the pandemic from the population.**

Keywords: **COVID-19; Disease-free equilibrium; Mathematical modeling; Non-pharmaceutical; Numerical simulation; Pharmaceutical; Reproduction number.**

I. INTRODUCTION

On 31st December, 2019, COVID-19 which is highly contagious was reported in Wuhan City, Hubei Province of China Wang et al. (2020). The origin and cause have still not been discovered though much research is being done. COVID-19 disease is creating a lot of public health challenges worldwide. As of 28th September, 2021, over 249,434 cases and 5,116 deaths in 188 countries had been recorded Bazzani et al. (2020). The disease incubation period ranges from 2 to 14 days Hethcote (2000). During this time, the individuals who are infected may be asymptomatic though, they may be unaware of the infection, but they have the ability of infecting other people Li et al, (2020). The symptoms and physical characteristics of Wuhan's first 425 laboratory tested and confirmed cases shows that the primary R_0 is 2.2 and the incubation period of these early cases to be 7.5 ± 3.4 days.

The symptoms which are common for COVID-19 are; increase in temperatures, dry cough, and fatigue. The first COVID-19 case was reported in Wuhan, Hubei, China and the first COVID-19 case was reported on 12th March 2020 in Kenya. Mild symptoms include sores in the throat, severe headache, aches, joint pains, loose stool, and pimples on the skin or decreased melanin on the figures or toes and itchy watery eyes. Severe symptoms include straining when breathing, loss of speech or balance, confusion, and pain in the respiratory surface. The ministry of health has adopted strict measures to curb the spread of COVID-19. On 15th March 2020, the government of Kenya closed down all public and private learning institutions, banned all public gatherings, and suspended international and local flights. Treatment mainly looks at managing all the signs and symptoms as the virus progresses. To curb down and prevent the spread of COVID-19, mass gatherings and close contact with the sick should be avoided. People should stay at home as much as possible, especially those with pre-existing illnesses, considering that some people could be asymptomatic Organization (2020). People should wear face masks, especially in public places where it is challenging to avoid close contact. COVID-19 models have been developed to describe the dynamics of COVID-19 in Kenya. Osei-Tutu et al. (2021), studied the effect of COVID 19 and religious leaders' restrictions on the health of Ghana Christians. They used thematic analysis to propose psych spiritual impacts, spirituality life, financial difficulties, challenges of child care, and fear of infection. Aleta et al. (2020), carried out a research on the effect of carrying out tests, contact tracing, and quarantining people at home on the wave two of COVID-19. They used the SLIR model with some additional compartments. They proposed that a response system based on enhancing carrying out tests and contact tracing may have a significant effect in reducing social-distance interventions in the absence of immunity against SARS-Cov-2. Kimathi et al. (2021), studied on effects of social distancing and contact reduction in Kenya. They developed an age-structured compartmental model to assess the impact of the strategies on COVID-19 severity and burden. They proposed that the dependency of COVID-19 transmission severity and deaths on age is crucial to the design of social distancing measures and projection on the expected disease burden in the country. Mumbu and Hugo (2020), studied on COVID-19 transmission impacts with prevention measures in Tanzania. They used the trace determinant approach in the local stability disease-free equilibrium points. They proposed that wearing face masks and hospitalization services can contain the disease from spreading. Haruna et al. (2021), studied the effects of quarantine and treatment in COVID-19 in Kenya. They used the SEAIR model with eight compartments and proposed quarantine and treatment as solution to compact COVID-19 in the community. Many intervention measures have been taken on to stop the spread of this disease. However, people are pretty ignorant of the pharmaceutical and non-pharmaceutical interventions instituted since there is a lot of misinformation on these measures. Religious leaders and faith communities are the largest and most organized civil institutions that claim billions of believers' allegiance. Therefore, implementers of the various interventions can utilize them and their experience of working with people to boost the adherence to COVID-19 intervention in the communities. This study is designed to determine the effect of religious leaders on adherence to pharmaceutical and non-pharmaceutical interventions on the COVID-19 spread in Kenya.

II. MATHEMATICAL FORMULATION

In this research the total population $N(t)$, at time (t), is divided into eight subpopulations; Susceptible $S(t)$, Stay-at-home susceptible, $S_h(t)$, Exposed, $E(t)$,Infected and symptomatic, $I_S(t)$,infected and Asymptomatic, $I_A(t)$,Treatment at home, $T(t)$, Hospitalized, $H(t)$ and Recovered, $R(t)$. The Susceptible individuals are recruited into the population at a constant rate of, $\prod$. β_1 and β_2 is the contact rate of susceptible individuals with asymptomatic and infected individuals respectively. The susceptible individuals stay at home at the rate of $\upsilon+\theta_1$ and move from stay at home due to different reasons at the rate of $\tau-\theta_1$ .It is also assumed that θ_1 is the rate of adherence to covid-19 protocols due to religious leader's influence to the non-pharmaceutical intervention measures and θ_2 is the rate of adherence to covid-19 protocols due to religious leader's influence to pharmaceutical intervention measures (vaccination). After completing the period of incubation, the individuals now become infected at a rate of γ. From this $\alpha\gamma$ proportion now show the COVID-19 symptoms and the others $(1-\alpha)\gamma$ start infecting the uninfected individuals. $\sigma\delta$ Proportion of asymptomatic individuals become positive and joined treatment at home after tests. The other $(1-\sigma)\delta$ proportion of asymptomatic individuals recover from the disease. Now from individuals who are infected, $C\varepsilon\theta_2$ fraction of individuals go to the hospitalized compartment. The rest receive treatment at their home at a constant rate $(1-C)\varepsilon\theta_2$. Individuals who get treatment can fail to recover hence, $\phi\rho$ fraction move to the hospitalized compartment. Individuals who recover can get into contact with the disease again at a rate of ω individuals who are hospitalized recover from the pandemic a rate κ. The asymptomatic, symptomatic, treated and hospitalized individuals die due to the disease at a rate ρ_1 , ρ_2, ρ_3, ρ_4 respectively. The whole population have an average death rate of μ.

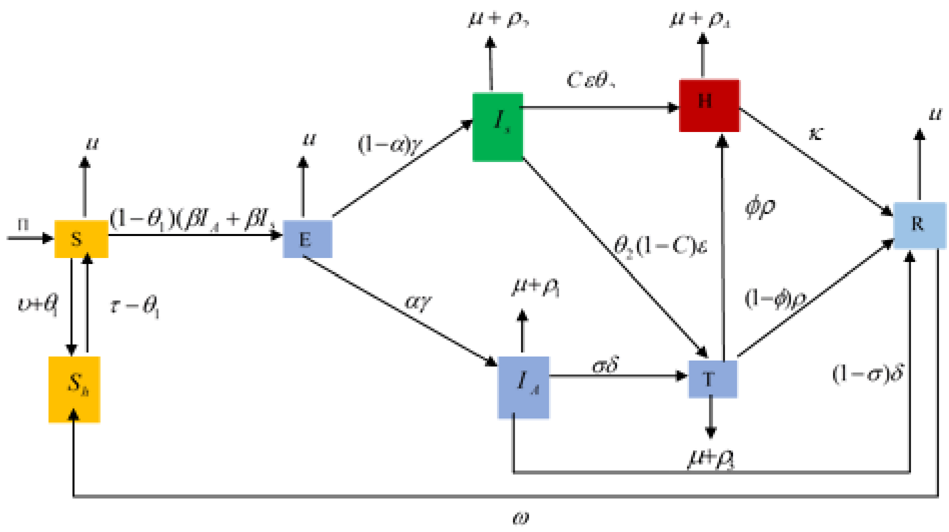

Fig. 1. Compartmental flow diagram of the COVID-19 pandemic transmission

MODEL EQUATIONS

Given the dynamics in Fig. 1. The following system of non-linear ordinary differential equations, with non-negative initial conditions, describe the dynamics of covid-19 infections.

$$\left.\begin{aligned}
\frac{dS}{dt} &= \prod + (\tau-\theta_1)S_h - (1-\theta_2)(\beta_1 I_A + \beta_2 I_S)S - (\mu+\upsilon+\theta_1)S \\
\frac{dS_h}{dt} &= (\upsilon+\theta_1)S + \omega R - \mu S_h - (\tau-\theta_1)S_h \\
\frac{dE}{dt} &= (1-\theta_2)(\beta_1 I_A + \beta_2 I_S)S - (\mu+\gamma)E \\
\frac{dI_A}{dt} &= \alpha\gamma E - (\rho_1+\delta+\mu)I_A \\
\frac{dI_S}{dt} &= (1-\alpha)\gamma E - (\varepsilon\theta_2+\mu+\rho_2)I_S \\
\frac{dT}{dt} &= \theta_2(1-C)\varepsilon I_S + \sigma\delta - (\mu+\rho+\rho_3)T \\
\frac{dH}{dt} &= C\varepsilon\theta_2 I_S + \phi\rho T - (\kappa+\mu+\rho_4)H \\
\frac{dR}{dt} &= (1-\sigma)\delta I_A + \kappa H + (1-\phi)\rho T - (\omega+\mu)R
\end{aligned}\right\}$$

(1)

Assuming that all the model parameters are positive, the initial conditions for model (1) are given by;

$$\begin{aligned}
&S(0)=S_0\ge 0, S_h(0)=S_h\ge 0, E(0)=E_0\ge 0, I_A(0)=I_A\ge 0, I_S(0)=I_S\ge 0,\\
&T(0)=T_0\ge 0, H(0)=H_0\ge 0, R(0)=R_0\ \ge 0
\end{aligned}$$

(2)

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i. Positivity of the model solutions

The model (1) describes human populations and hence it is important to prove that the solutions to model (1) with positive initial conditions will remain positive for all $t \geq 0$.

Theorem 2.1: *If the initial conditions of the model (1) are non-negative, in the feasible set* Ω *,then the solution set is positive for future time* $t \geq 0$.

Proof*:* So as to prove the existence of positivity of solution to model (1) given that all the model parameters are non-negative we proceed as below;

From the model (1) the first equation can be written as;

$$\frac{dS}{dt} = \prod + (\tau - \theta_1)S_h - \{(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + (\mu + \upsilon + \theta_1)\}S \tag{3}$$

From (3); we obtain the inequality;

$$\frac{dS}{dt} \geq -\{(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + (\mu + \upsilon + \theta_1)\}S \tag{4}$$

When we separate the variable we obtain;

$$\frac{dS}{S} \geq -\{(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + \mu + \upsilon + \theta_1\}d\bar{t} \tag{5}$$

Upon integrating (5) w.r.t $\bar{t}$ from 0 to t and solving we obtain;

$$\ln S(t) - \ln S(0) \geq -\{(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + \mu + \upsilon + \theta_1\}t$$

(6)

Introducing the exponent on both sides of (6) we get;

$$S(t) \geq S(0)\exp\{-(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + \mu + \upsilon + \theta_2\}t$$

Which shows that,

$S(t) \geq 0$ for $t \geq 0$ since $S(0) \geq 0$ and $\exp\{-(1-\theta_2)(\beta_1 I_A + \beta_2 I_S) + \mu + \upsilon + \theta_1\}t \geq 0$ for $t \geq 0.$

Similarly, we have the following;

$$S_h(t) \geq S_h(0)\exp\{-[\mu + \tau - \theta_1)S_h]t\} > 0,$$
$$E(t) \geq E(0)\exp\{-(\gamma + \mu)t\} > 0,$$
$$I_A(t) \geq I_A(0)\exp\{-(\rho_1 + \delta + \mu)t\} > 0,$$
$$I_S(t) \geq I_S(0)\exp\{-(\mu + \varepsilon\theta_2 + \rho_2)t\} > 0,$$
$$T(t) \geq T(0)\exp\{-(\rho_3 + \mu + \rho)t\} > 0,$$
$$H(t) \geq H(0)\exp\{-(\kappa + \mu + \rho_4)t\} > 0,$$
$$R(t) \geq R(0)\exp\{-(\mu + \omega)t\} > 0.$$

Therefore, all the solutions of the model (1) with non-negative initial conditions will remain non-negative for all time $t \geq 0$
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ii. Invariant region

The analysis of the model (1) will be performed in a region Ω of biological interest. The following theorem is on the region that model (1) is restricted to.

Theorem 2.2. *The feasible region* Ω *defined by;*

$$\Omega = \left\{ S(t), S_h(t), E(t), I_A(t), I_S(t), T(t), H(t), R(t) \in N \le N \le \max\{N(0), \frac{\prod}{\mu}\} \right\}$$

All the initial conditions in (2) are positively invariant and attracting with respect to model (1) for all $t \ge 0$.

Proof. Upon Summing up the differential equations in model (1), we obtain that the total population satisfies the differential equation;

$$\frac{dN(t)}{dt} = \prod - \mu N - \rho_1 I_A - \rho_2 I_S - \rho_3 T - \rho_4 H,$$

(7)

In the absence of mortality due to covid-19 infection, it becomes,

$$\frac{dN(t)}{dt} \le \prod - \mu N$$

(8)

The differential inequality (8) can be written as,

$$\frac{dN(t)}{dt} + \mu N \le \prod \tag{9}$$

Integrating (9) yields

$$N(t) \le \frac{\prod}{\mu} + \left(N(0) - \frac{\prod}{\mu} \right) e^{-\mu t} \tag{10}$$

Where $N(0)$ is the initial population size. From (10), we observe that as $t \to \infty, N(t) \to \frac{\prod}{\mu}$. So if $N(0) \le \frac{\prod}{\mu}$, then $Lim_{t\to\infty} N(t) = \frac{\prod}{\mu}$. On the other hand, if $N(0) \ge \frac{\prod}{\mu}$, then N will decrease to $\frac{\prod}{\mu}$ as $t \to \infty$. This means that $N(t) \le \max\left\{ N(0), \frac{\prod}{\mu} \right\}$. Therefore $N(t)$ is bounded above. Subsequently,

$\{S(t), S_h(t), E(t), I_A(t), I_S(t), T(t), H(t) \text{ and } R(t)\}$ are bounded above.

iii. Disease Free Equilibrium (DFE)

A disease-free equilibrium is a state in which the number of infected individuals in a population remains constant over time, and no new cases of the disease are introduced. To obtain this equilibrium point of model (1), the derivatives with respect to time in model (1) are set to zero, all the infected and recovered classes are also set to zero.

This yields,

$$E = 0, I_A = 0, I_S = 0, T = 0, H = 0, R = 0,$$

$$\prod + (\tau - \theta_1) S_h - (\mu + \upsilon + \theta_1) S = 0$$

(11)

$$(\upsilon+\theta_1)S-\mu S_h-(\tau-\theta_1)S_h=0$$

(12)

Solving (11) and (12) simultaneously yields;

$$S=\frac{\prod(\upsilon+\tau-\theta_1)}{\mu(\upsilon+\tau-\theta_1)+\upsilon(\upsilon+\theta_1)}$$

$$S_h=\frac{\prod(\upsilon+\theta_1)}{u(\upsilon+\tau-\theta_1)+\upsilon(\upsilon+\theta_1)}$$

Therefore, the equilibrium point is given as;

$$E_0=\left(\frac{\prod\{\upsilon+\tau-\theta_1)\}}{\mu\{\upsilon+\tau-\theta_1)+\upsilon(\upsilon+\theta_1\}},\frac{\prod(\upsilon+\theta_1)}{\mu\{\upsilon+\tau-\theta_1)+\upsilon(\upsilon+\theta_1\}},0,0,0,0,0,0\right)$$

iv. Basic reproduction number

The basic reproduction number is a measure of average number of secondary infections caused by a single infected individual in a population where everyone is susceptible to the disease. The next generation matrix method Hethcote (2000), will be used to compute the basic reproduction number of the model (1). Using the notation F for the new infections and V for the transition terms, the following is obtained,

$$F=\begin{pmatrix}(1-\theta_2)(\beta_1 I_A+\beta_2 I_S)S(t)\\0\\0\\0\\0\end{pmatrix} and \ V=\begin{pmatrix}-(\mu+\gamma)E\\ \alpha\gamma E-(\rho_1+\delta+\mu)A\\ (1-\alpha)\gamma E-(\varepsilon\theta_2+\mu+\rho_2)T\\ \theta_2(1-C)\varepsilon I_S+\sigma\delta I_A-(\mu+\rho+\rho_3)T\\ \phi\rho I_A+C\theta_2\varepsilon I_S-(\kappa+\mu+\rho_4)H\end{pmatrix}$$

(13)

The partial derivatives of F and V with respect to the infected classes evaluated at the disease free equilibrium are denoted by F and V respectively and obtained as follows:

$$\mathrm{F}=\begin{pmatrix}0&\beta_1(1-\theta_2)S^0&\beta_2(1-\theta_2)S^0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\end{pmatrix}$$

$$\mathrm{V}=\begin{pmatrix}-(\gamma+\mu)&0&0&0&0\\-\alpha\gamma&-\psi_1&0&0&0\\-(1-\alpha)\gamma&0&-\psi_2&0&0\\0&0&-(1-C)\varepsilon\theta_2&-\psi_3&0\\0&0&-C\varepsilon\theta_2&-\phi\rho&-\psi_4\end{pmatrix}$$

Where;

$$\psi_1 = \rho_1 + \delta + \mu,\ \psi_2 = \rho_2 + \theta_2\varepsilon + \mu,\ \ \psi_3 = \rho_3 + \rho + \mu,\ \psi_4 = \rho_4 + \kappa + \mu,$$

The dominant eigenvalue corresponding to the spectral radius FV^{-1} of the matrix FV^{-1} is the basic reproduction number given by;

$$R_0 = \frac{\left((1-\alpha)(\delta+\rho_1+\mu)\beta_2 + (\varepsilon\theta_2+\rho_2+\mu)\alpha\beta_1\right)\gamma\prod(1-\theta_2)}{\mu(\upsilon+\tau-\theta_1)+\upsilon(\upsilon+\theta_1)(\delta+\rho_1+\mu)(\varepsilon\theta_2+\rho_1+\mu)}$$

III. RESULTS AND DISCUTION

The qualitative analysis of the system of differential equations of the model was performed using Runge-Kutta-fehlberg method. The Time from June 2021 to December 2021 was considered for model curve fitting to the daily cases of SARS-Cov-2 Corona virus in Kenya https://ourworldindata.org/coronavirus. This study utilizes the model parameters given in Table. 1. The model initial values are assumed and estimated based on the literature that exist as shown below.

$$S_0 = 418{,}170, S_h = 41{,}817, E = 0, I_A = 297, I_S = 52, T = 0, H = 0, R = 0$$

Table (1): Parameters values used in simulation.

Parameter	Description	Value	Source
$\prod$	Rate of recruitment of individuals	2000	Assumed
β_1	Rate of contact of susceptible individuals with asymptomatic.	0.0000217	Kiarie et al. (2022)
β_2	Rate of contact of susceptible individuals with symptomatic.	0.00000217	Kimathi et al. (2021)
ρ	Rate of progression from (Home-based)Treatment	0.0714	$\frac{1}{14}$
δ	Rate of progression from asymptomatic	0.0714	$\frac{1}{14}$
ε	Rate of progression from Symptomatic/Infected class	0.57	$\frac{1}{10}$
τ	Rate at which people are getting exposed.	0.53	Haruna et al. (2021)
υ	Susceptible individuals that stay at home	0.46	Assumed
μ	Population natural death rate	0.0001	Kiarie et al. (2022)
κ	Rate of recovery of Quarantine/Hospitalized	0.85	Yang et al. (2021b)
ρ_1	Disease induced death rate of asymptomatic individuals.	0.00002	Assumed
ρ_2	Disease induced rate of death of symptomatic individuals.	0.00004	Assumed
ρ_3	Disease induced rate of death of individuals under treatment.	0.00003	Yang et al. (2021b)
ρ_4	Disease induced rate of death of individuals under quarantine/hospitalized.	0.00003	Haruna et al. (2021)
γ	Rate of progression from exposed to infectious.	0.143	$\frac{1}{7}$
ϕ	Proportion of (home-based) Treatment class that need hospitalization.	0.55	Yavuz et al. (2021b)
C	Proportion of symptomatic/infected that need hospitalization	0.5	Assumed
σ	Proportion of asymptomatic that test positive and treated.	0.35	Yousefpour et al. (2020a)
α	Proportion of exposed individuals that become asymptomatic	0.75	Alawadhi et al. (2020)
ω	Rate of becoming susceptible after recovery.	0.00001	Yavuz et al. (2021b)

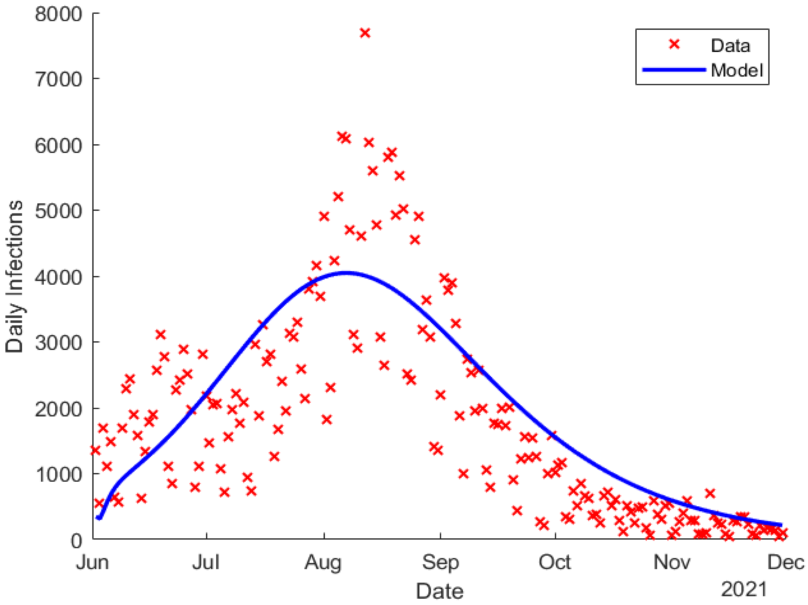

Fig. 1. Curve fitting with reported daily infections in Kenya

From Fig. 2. We can see that model (1) fits reasonably well to the COVID-19 data in Kenya. The red star symbol represents the reported daily infections and the blue curve is the model fitting. There was exponential growth of daily infections from the period of June 2021 to September 2021 with peak between August 2021 and September 2021. This was caused by: Lift of the movement ban by the GoK into and out of Nairobi metropolitan area and Mombasa counties which are Major cities in Kenya; resumption of domestic commercial and passenger flights as well as international flights on August 2021. This led to increase in the rate of interaction with the infected population. After September 2021 there was a decline trend of daily infection cases due to the infected people taking medication, many people also got vaccinated after the development of the infrastructure for a widespread vaccination campaign in densely populated areas country wide and also increase in the number of vaccination posts from initial 200 to 3000 on October 2021 This was after Kenya received adequate supply of vaccines from countries like United State.

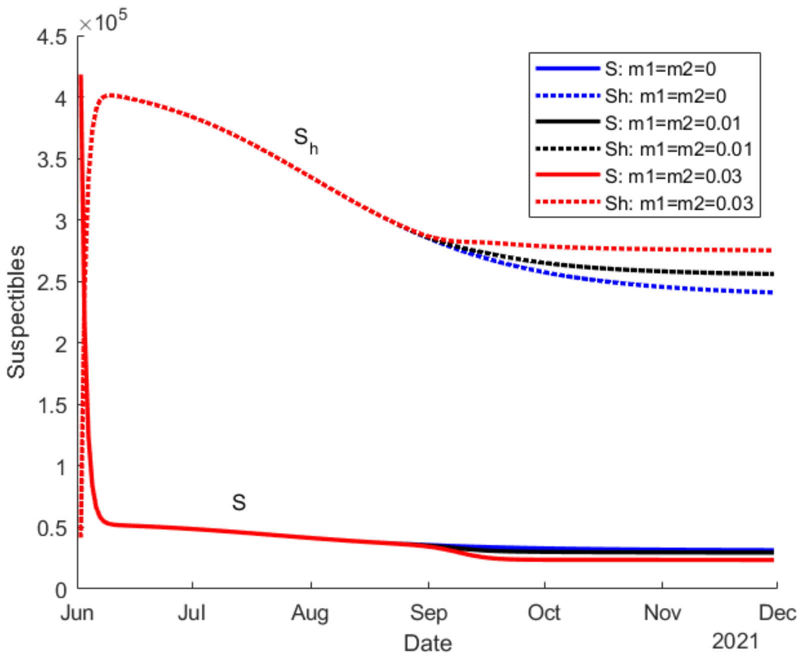

Fig. 3. Susceptible

(θ_1 (m1) and θ_2 (m2))

Fig. 3. Shows that from June to Mid-August 2021 the susceptible population was decreasing due to the lockdown measures which were imposed by the GoK. There was no movement into and out of major towns like Nairobi and also Mombasa, social gatherings were also suspended and also many organizations allowed people to work from home especially those with 58 years and above and this reduced the rate of contact with the asymptomatic and symptomatic. From September to December 2021, as the intensity of religious leaders (θ_1 (m1) and θ_2 (m2)) increased, the susceptible population decreased as a result of taking up the mitigation measures due to the religious leader's influence; since the number of congregants was increased up from 30 to 100 per hour in the churches.

From June to July 2021 stay at home population increased because most organizations allowed there workers to work from home, most university classes were held online, social gatherings were also suspended leading to most meetings to be held online. From July to September 2021 the number started decreasing due to the opening up of the learning institutions, domestic commercial passenger flights and also international flights resumed on August 12 2021, people started going back to work after the ban for movement into and out of Nairobi metropolitan area, and Mombasa county was lifted on July 12 2021 by the Kenyan government. From September to December as the intensity of religious

(θ_1 (m1) and θ_2 (m2)) increased the population of stay-at-home due to most people heeding to the religious leader's advice on the non-pharmaceutical mitigation measures also increased. Therefore, the government should use every mechanism to educate the religious leaders who will in turn educate the people on the importance of taking up the pharmaceutical θ_2 and non-pharmaceutical θ_1 measures so as to curb the spread of the pandemic.

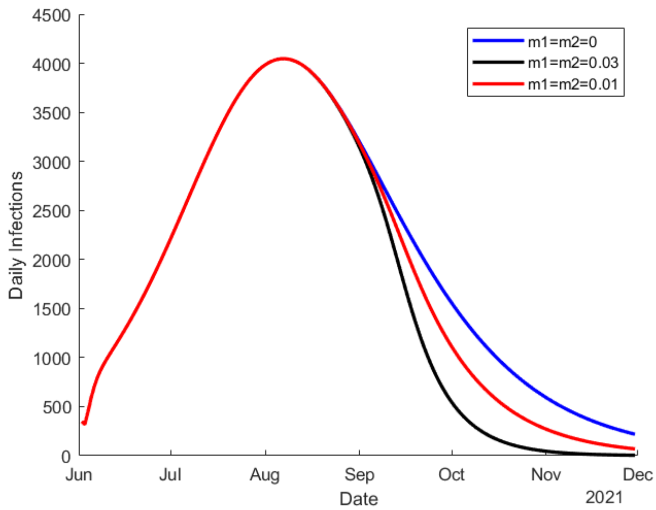

Fig. 4. Daily infections

Fig. 4. Shows that the daily infection were increasing from June 2021 to mid-August 2021. We can see that by intensifying the role of religious leaders (θ_1 (m1) and θ_2 (m2)) then the number of daily infections are decreasing since the religious leaders encourages the congregant's to get vaccinated, wear masks, wash hands and also keep social distances. Therefore, the government should work with the religious leaders to educate people on the importance of taking up pharmaceutical (θ_2) and non-pharmaceutical (θ_1) mitigation measures to fight the pandemic.

IV. CONCLUSION

The results were determined and computed using MATLAB. The basic reproduction number R_0 was calculated using next generation matrix method, the disease-free equilibrium was also calculated. We presented the data using graphs depicting the effect of using religious leaders on informing the congregant's about the use of pharmaceutical and non-pharmaceutical intervention to reduce spread of COVID-19. We therefore that recommend the government stakeholders and policy makers to educate the religious leaders who will in turn educate the people on the importance of strictly adhering to the pharmaceutical and non-pharmaceutical intervention measures in combating the pandemic.

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