American Journal of Health Research
2025, Vol. 13, No. 5, pp. 281-293
https://doi.org/10.11648/j.ajhr.20251305.14

Research Article

Modelling the Spread of Zaire Ebola Virus Disease with Quarantine and Vaccination Interventions

Alex Emmanuel Nti*, Isaac Ampofi, Jehovah Baidoo

Department of Mathematical Sciences, University of Mines and Technology (UMaT), Tarkwa, Ghana

Abstract

One of the deadliest viral diseases in the world is Ebola virus disease. There are different types of Ebola virus with the Zaire Ebola Virus in DR Congo being very virulent resulting with a high disease induced rate. The resurgence of this disease makes it a necessity for a more robust modelling approach to understand its dynamics for proper policy implementation. In this work, a novel nonlinear mathematical model is developed using compartmental approach which is common in epidemiological modelling. The developed model strategically incorporated quarantine through contact tracing and mandatory vaccination of all quarantined individuals who are tested to be negative after the incubation period. In addition to this intervention strategy, a number of susceptible and recovered individuals with a waned immunity are also vaccinated. The developed model was assessed to be biologically feasible. The next generation matrix was used to determine the basic reproduction number while the Jacobian approach was used to linearise the system leading it into its stability analysis. Additionally, the 4^{th} Order Runge Kutta iterative scheme was extended on the model for simulations purposes. The results show that the model has two fixed points. These are the disease-free equilibrium point where the disease will fail to exist within the population, and the endemic point at which the disease will continue to persist within the population. The model was examined to be stable with all eigenvalues being negative. The numerical results showed that the appearance of the disease in the population will cause a rise in the number of exposed, quarantined, and infected compartments. This will lead to a decline in the number of susceptible persons. The basic reproduction number was attained to be 0.09779 indicating that the Zaire Ebola Virus disease will fail to exist over time. It is therefore realised that the developed model with the incorporated interventions is an effective approach to control Zaire Ebola Virus if the strategies are efficiently implemented.

Keywords

Vaccination, Quarantine, Runge Kutta, Basic Reproduction Number, Disease-Free Equilibrium

1. Introduction

Ebola Virus Disease (EVD) is a severe and often fatal illness that has caused significant outbreaks in West and Central Africa. Ebola virus which causes the deadly disease called Ebola Virus Disease was discovered in the late 70s in Sudan and Zaire, and has since spread throughout Africa [1]. There are five species of Ebola virus namely, Zaire Ebola Virus, Sudan Ebola Virus, Bundibugyo Ebola Virus, Reston Ebola Virus, and Tai Forest Ebola Virus. [2-4] underscored that a number of zoonotic viruses especially those belonging to the Pteropodidae family inhibits fruit bats that spread the Ebola

*Corresponding author: aenti@umat.edu.gh (Alex Emmanuel Nti)

Received: 19 September 2025; **Accepted:** 4 October 2025; **Published:** 30 October 2025

virus to people as they carry it asymptotically for an incubation period of 2 to 21 days. The illness spread once an individual is infected. The virus causes symptoms like fever, sore throat, etc. and spread through direct contact with contaminated surfaces, bodily fluids, infected blood, infected dead bodies of animals and humans, etc [1, 5-8].

There have been many strategic interventions to curb Zaire Ebola virus and its associated disease. In the area of vaccine development, the Recombinant Vesicular Stomatitis Virus-Zaire Ebola Virus (rVSV-ZEBOV) vaccine, which was authorized in 2019 has been a recent development in the management of Ebola virus disease [9]. Additionally, other monoclonal antibody therapies have been successful in reducing Ebola virus disease induced death.

The latest Zaire Ebola Virus outbreak occurred in DR Congo in 2022, following two outbreaks in 2021. These incidents underscore ongoing public health challenges in Central and West Africa [10]. Despite advancements in epidemiological and mathematical researches, Zaire Ebola virus outbreaks continue to cause considerable illness and death, particularly in settings with limited resources.

Among the Ebola viruses, the Zaire Ebola Virus is one of the most virulent Ebola strains with over 50% fatality rate. It poses a significant public health challenge due to its high fatality rate. An outbreak of the Zaire Ebola Virus disease in the years 2007-2008, 2012, and 2014 was fatal with over 28,000 cases and 11,000 deaths [11]. Also, an outbreak of the Zaire Ebola virus disease on 1st August, 2018 spread across almost twenty-four health zones of Ituri and North Kivu provinces in DR Congo [12, 13]. This outbreak recorded approximately 2,763 cases with a death rate of 66.63% by the 4th of August, 2019. Also, 3,458 and 145 cases were further reported in the same provinces, with 3,313 confirmed cases and a death rate of 64.35% by 16th April, 2022 [14-16].

Ebola virus disease leads to both liver and kidney failure coupled with internal and external bleeding. These dangers associated to the disease and experienced by the infected persons results into a faster progression of demise at an average of three days.

Due to the contagious nature of the disease, several interventions have been applied concurrently to control Ebola disease with vaccination of the human population as one of the most effective ways of containing the spread of the disease [16]. To this effect, many scholarly works like [17-21] have assessed the impact of vaccination intervention in controlling Ebola virus disease. Notwithstanding, epidemiological models with quarantine as an added intervention restrict the movement of the infected persons from interacting with the susceptible individuals thereby reducing the rate of spread of the disease [22]. Additionally, contact tracing the exposed individuals further yields an additional controlling strategy of the disease.

Mathematical modelling has proven to be a valuable tool for understanding the spread of infectious diseases. This helps to evaluate the effectiveness of interventions strategies. Nonlinear mathematical models are widely used to analyze disease dynamics. In the case of Ebola, interventions such as quarantine and vaccination are critical in reducing transmission and preventing the widespread of the disease [23].

Some studies examined the transmission dynamics of the Ebola virus using the basic Susceptible-Exposed-Infected-Recovered (SEIR) model [16]. Given the complexity of solving the model's equations analytically, the authors employed Euler and 4th Order Runge-Kutta (RK4) methods to numerically approximate the solution. Their work underscored that both Euler and RK4 methods provide useful approximations for modeling Ebola transmission. However, the RK4 method in particular was found to be more accurate than Euler's method. This was due to the RK4's ability to reduce numerical errors and also handle higher order ordinary differential equations.

This work focuses on developing a susceptible, exposed, infected, quarantined, recovered and vaccinated model of the Zaire Ebola Virus disease to understand its dynamics.

2. Model Formulation

This section develops a six-state human-to-human Zaire Ebola Virus disease dynamics model. The dynamics of the disease in this study is modelled based on the traditional SEIR epidemiological model, while incorporating quarantine and vaccination interventions.

The model is developed based on the following assumptions. The model has six (6) compartments. The compartments are, Susceptible (S), Exposed (E), Quarantined (Q), Infected (I), Removed (R), and Vaccinated (V). All individuals including newborns are susceptible to the disease, and all susceptible individuals can be vaccinated. All exposed individuals who have been identified and contact traced are quarantined. Also, quarantined individuals who are confirmed as not infected after the latent period are all vaccinated. Recovered individuals gain temporary immunity as their immunity wanes over time. Recovered individuals with temporal immunity can be vaccinated once their immunity begins to wane. All compartments experience the same natural death rate except the infected compartment which has both the natural death rate and the disease induced death rate. Both vaccination and recovered individuals have no permanent immunity, however, immunity due to vaccination has longer duration than autoimmunity.

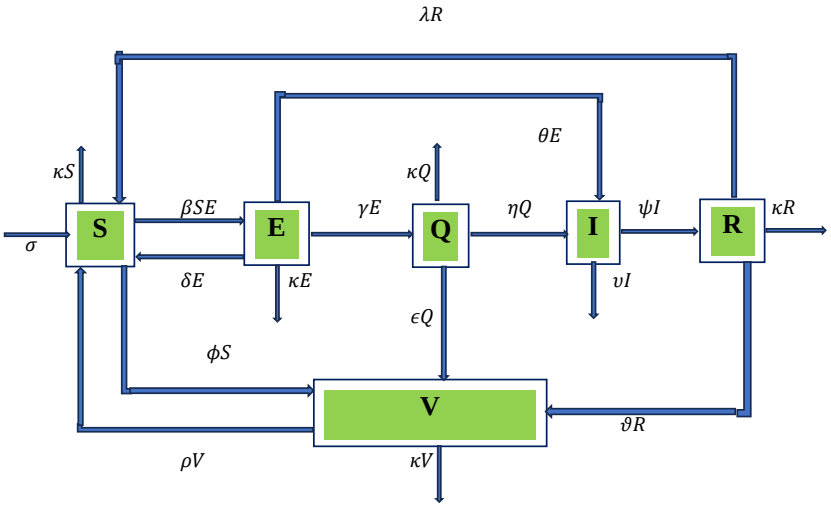

Figure 1. *Compartmental Scheme of Zaire Ebola Virus Disease.*

Figure 1 shows the flow chart of the novel Zaire Ebola Virus disease model, with the total population given as

$$T = S + E + Q + I + R + V \tag{1}$$

Table 1 is the definition of the model's parameters.

Table 1. *Description of Model's Parameters.*

Parameters	Description
β	Fraction of the susceptible individuals who are exposed
σ	Natural birth rate
γ	Progression rate of exposed individuals who are identified, contact traced and quarantined
η	Proportion of quarantined individuals who are tested to be infected
ψ	Recovery rate of infected individuals
λ	Rate of recovered individuals who lose immunity into the susceptible compartment
δ	Rate at which exposed non-contact traced persons revert into susceptible compartment
κ	Natural death rate.
θ	Rate at which non-contact traced exposed individuals move into infected compartment.
υ	Both disease induced and natural death rate
ϕ	Rate at which susceptible individuals receive vaccination.
ρ	Rate at which vaccinated individuals lose immunity to become susceptible.
ϑ	Fraction of recovered whose immunity wanes over time get vaccinated
ϵ	Proportion of the quarantined individuals who are tested to be negative and vaccinated.

From Figure 1, the nonlinear differential system yields

$$\left.\begin{aligned}
\frac{dS}{dt} &= \sigma + \lambda R + \rho V + \delta E - \beta SE - \phi S - \kappa S \\
\frac{dE}{dt} &= \beta SE - \theta E - \gamma E - \delta E - \kappa E \\
\frac{dQ}{dt} &= \gamma E - \eta Q - \varepsilon Q - \kappa Q \\
\frac{dI}{dt} &= \theta E + \eta Q - \psi I - \upsilon I \\
\frac{dR}{dt} &= \psi I - \vartheta R - \lambda R - \kappa R \\
\frac{dV}{dt} &= \phi S + \varepsilon Q + \vartheta R - \rho V - \kappa V
\end{aligned}\right\} \quad (2)$$

with the initial conditions for the Zaire Ebola Virus disease dynamics model variables given by:

$$S_0 = S(0), E_0 = E(0), Q_0 = Q(0), I_0 = I(0), R_0 = R(0), V_0 = V(0).$$

The model has a biological feasible region M_1 as:

$$M_1 = \left\{ (S,E,Q,I,R,V) \in \mathbb{R}^6 : 0 \le T \le \frac{\sigma}{\phi + \kappa} \right\} \quad (3)$$

3. Model Fixed Points

The model as indicated by Equation (2) has two fixed points. These are Zaire Ebola Virus disease-free equilibrium $\left(F^0\right)$ and its endemic equilibrium $\left(F^*\right)$. At the $\left(F^0\right)$, we set $E = Q = I = R = 0$ and solve for S and V. This yields:

$$F^0(S,E,Q,I,R,V) = \left(\frac{\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)}, 0, 0, 0, 0, \frac{\phi\sigma}{\kappa(\phi+\rho+\kappa)} \right) \quad (4)$$

At F^*, the Zaire Ebola Virus disease persist in the population over time. The endemic equilibriums deduced from Equation (2) yields:

$$\left.\begin{aligned}
S^* &= \frac{\sigma + \lambda R^* + \rho V^* + \delta E^*}{\beta E^* + \phi + \kappa} \\
Q^* &= \frac{\gamma E^*}{\eta + \varepsilon + \kappa} \\
I^* &= \frac{\theta E^* + \eta Q^*}{\psi + \upsilon} \\
R^* &= \frac{\psi I^*}{\vartheta + \lambda + \kappa} \\
V^* &= \frac{\phi S^* + \varepsilon Q^* + \vartheta R^*}{\rho + \kappa}
\end{aligned}\right\} \quad (5)$$

4. The Basic Reproduction Number

Basic reproduction number $\left(\Re_0\right)$ is the average number of secondary infections caused by a single infected individual in a fully susceptible population. In this Zaire Ebola Virus disease model in Equation (2), $\Re_0$ is derived from the exposed and infected compartments as:

$$\left.\begin{aligned}
\frac{dE}{dt} &= \beta SE - \theta E - \gamma E - \delta E - \kappa E \\
\frac{dI}{dt} &= \theta E + \eta Q - \psi I - \upsilon I
\end{aligned}\right\} \quad (6)$$

The Next Generation Matrix (NGM) is further applied on Equation (6).

The approach of the next generation matrix is employed to find the $\Re_0$ of the model. Here, we let $m = (S,E,Q,I,R,V)$. The NGM is such that Equation (6) is decomposed into two matrices. This gives

$$\frac{dm}{dx} = F - V \quad (7)$$

where, F is the transmission matrix and V is the transition matrix.

The $\Re_0$ is given by the spectral radius (φ) of the next generation matrix. This yields Equation (8) as:

$$\Re_0 = \varphi\left(FV^{-1}\right) \quad (8)$$

Applying Equation (7) on Equation (6) and solving for FV^{-1} yields:

$$FV^{-1} = \begin{bmatrix} \dfrac{\beta S^0}{\theta + \gamma + \delta + \kappa} & 0 \\ 0 & 0 \end{bmatrix} \quad (9)$$

Applying Equation (8) on Equation (9) gives the basic reproduction number as:

$$\Re_0 = \frac{\beta\sigma(\kappa+\rho)}{\kappa(\kappa+\phi+\rho)(\theta+\gamma+\delta+\kappa)} \quad (10)$$

From Equation (10), if $\beta\sigma(\kappa+\rho) < \kappa(\kappa+\phi+\rho)(\theta+\gamma+\delta+\kappa)$, then $\Re_0 < 1$, else $\Re_0 > 1$.

If $\Re_0 < 1$, the Zaire Ebola Virus disease will die out, else the disease will continue to persist since the number of infectious cases will continue to rise. This will cause the system to be unstable.

5. Stability Analysis of the Model

The stability of the Zaire Ebola Virus disease in Equation (1) is examined by computing its Jacobian matrix J at the F^0. We further compute the eigenvalues of JF^0 to enable us use the sign of the eigenvalues to evaluate the stability of the disease.

Theorem 1 A disease-free equilibrium of this Zaire Ebola Virus disease model is locally asymptotically stable (LAS) if the basic reproduction number $(\Re_0)$ of this model is less than one, else unstable.

The JF^0 is given by:

$$JF^0 = \begin{bmatrix} -b_0 & \delta - b_1 & 0 & 0 & \lambda & \rho \\ 0 & b_1 - b_2 & 0 & 0 & 0 & 0 \\ 0 & \gamma & -b_3 & 0 & 0 & 0 \\ 0 & \theta & \eta & -b_4 & 0 & 0 \\ 0 & 0 & 0 & \psi & -b_5 & 0 \\ \phi & 0 & \varepsilon & 0 & \vartheta & -b_6 \end{bmatrix} \quad (11)$$

where,

$$b_0 = \phi + \kappa,\ b_1 = \frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)},\ b_2 = \delta + \theta + \gamma + \kappa,$$

$$b_3 = \varepsilon + \eta + \kappa,\ b_4 = \psi + \upsilon,\ b_5 = \lambda + \vartheta + \kappa,\ \text{and}\ b_6 = \rho + \kappa.$$

From Equation (11), there are six eigenvalues. These are: $\mu_1 = -b_0 < 0,\ \mu_2 = -b_3 < 0,\ \mu_3 = -b_4 < 0,\ \mu_4 = -b_5 < 0,$ $\mu_5 = -b_6 < 0.$ It is seen than $b_0, b_3, b_4, b_5, b_6 > 0.$ Also, the sixth eigenvalue is $\mu_6 = (\theta + \phi + \delta + \kappa)(\Re_0 - 1).$

Thus,

$$\frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)} - (\delta+\theta+\gamma+\kappa) < 1$$

$$\frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)} < (\delta+\theta+\gamma+\kappa)$$

Dividing through by $\delta+\theta+\gamma+\kappa$ yields

$$\frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)(\delta+\theta+\gamma+\kappa)} < 1 \quad (12)$$

Comparing Equation (10) and Equation (12), $\Re_0 < 1$. This indicates that $\mu_6 < 0$ if and only if $\Re_0 < 1$.

The implication is that, at $\Re_0 < 1$ all the eigenvalues of JF^0 are negatives. Therefore, F^0 is LAS. At this LAS point, there will be no EBOV disease threat in the population.

Additionally, if $\Re_0 > 1$, thus

$$\frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)(\theta+\gamma+\delta+\kappa)} > 1$$

$$\Rightarrow \theta+\gamma+\delta+\kappa < \frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)}$$

$$\Rightarrow \frac{\beta\sigma(\rho+\kappa)}{\kappa(\phi+\rho+\kappa)} - (\theta+\gamma+\delta+\kappa) > 0$$

That is $\mu_6 > 0$. Hence, F^0 becomes unstable anytime $\Re_0 > 1$.

6. Numerical Scheme

In this section the 4th-order Runge-Kutta numerical method as applied in the work of [4, 16-17, 24-27] is extended to develop the scheme for the proposed Zaire Ebola Virus disease Model.

The following assumptions are made:

$$S(t) \approx S^r, E(t) \approx E^r, Q(t) \approx Q^r, I(t) \approx I^r, R(t) \approx R^r, \text{ and } V(t) \approx V^r.$$

The substitution of the assumptions into Equation (2) give rise to the 4th-order Runge Kutta scheme of the Ebola model below.

$$k_1 = h\left[\sigma + \lambda R^r + \rho V^r + \delta E^r - \beta S^r E^r - \phi S^r - \kappa S^r\right]$$

$$a_1 = h\left[\beta S^r E^r - \theta E^r - \gamma E^r - \delta E^r - \kappa E^r\right]$$

$$d_1 = h\left[\gamma E^r - \eta Q^r - \varepsilon Q^r - \kappa Q^r\right]$$

$$g_1 = h\left[\theta E^r + \eta Q^r - \psi I^r - \upsilon I^r\right]$$

$$l_1 = h\left[\psi I^r - \vartheta R^r - \lambda R^r - \kappa R^r\right]$$

$$m_1 = h\left[\phi S^r + \varepsilon Q^r + \vartheta R^r - \rho V^r - \kappa V^r\right]$$

$$k_2 = h\begin{bmatrix} \sigma + \lambda\left(R^r + \frac{l_1}{2}\right) + \rho\left(V^r + \frac{m_1}{2}\right) + \delta\left(E^r + \frac{a_1}{2}\right) \\ -\beta\left(S^r + \frac{k_1}{2}\right)\left(E^r + \frac{a_1}{2}\right) - \phi\left(S^r + \frac{k_1}{2}\right) - \kappa\left(S^r + \frac{k_1}{2}\right) \end{bmatrix}$$

$$a_2 = h\begin{bmatrix}\beta\left(S^r+\frac{k_1}{2}\right)\left(E^r+\frac{a_1}{2}\right)-\theta\left(E^r+\frac{a_1}{2}\right)\\-\gamma\left(E^r+\frac{a_1}{2}\right)-\delta\left(E^r+\frac{a_1}{2}\right)-\kappa\left(E^r+\frac{a_1}{2}\right)\end{bmatrix}$$

$$d_2 = h\begin{bmatrix}\gamma\left(E^r+\frac{a_1}{2}\right)-\eta\left(Q^r+\frac{d_1}{2}\right)-\varepsilon\left(Q^r+\frac{d_1}{2}\right)\\-\kappa\left(Q^r+\frac{d_1}{2}\right)\end{bmatrix}$$

$$g_2 = h\begin{bmatrix}\theta\left(E^r+\frac{a_1}{2}\right)+\eta\left(Q^r+\frac{d_1}{2}\right)-\psi\left(I^r+\frac{g_1}{2}\right)\\-\upsilon\left(I^r+\frac{g_1}{2}\right)\end{bmatrix}$$

$$l_2 = h\begin{bmatrix}\psi\left(I^r+\frac{g_1}{2}\right)-\vartheta\left(R^r+\frac{l_1}{2}\right)-\lambda\left(R^r+\frac{l_1}{2}\right)\\-\kappa\left(R^r+\frac{l_1}{2}\right)\end{bmatrix}$$

$$m_2 = h\begin{bmatrix}\phi\left(S^r+\frac{k_1}{2}\right)+\varepsilon\left(Q^r+\frac{d_1}{2}\right)+\vartheta\left(R^r+\frac{l_1}{2}\right)\\-\rho\left(V^r+\frac{m_1}{2}\right)-\kappa\left(V^r+\frac{m_1}{2}\right)\end{bmatrix}$$

$$k_3 = h\begin{bmatrix}\sigma+\lambda\left(R^r+\frac{l_2}{2}\right)+\rho\left(V^r+\frac{m_2}{2}\right)+\delta\left(E^r+\frac{a_2}{2}\right)\\-\beta\left(S^r+\frac{k_2}{2}\right)\left(E^r+\frac{a_2}{2}\right)-\phi\left(S^r+\frac{k_2}{2}\right)-\kappa\left(S^r+\frac{k_2}{2}\right)\end{bmatrix}$$

$$a_3 = h\begin{bmatrix}\beta\left(S^r+\frac{k_2}{2}\right)\left(E^r+\frac{a_2}{2}\right)-\theta\left(E^r+\frac{a_2}{2}\right)\\-\gamma\left(E^r+\frac{a_2}{2}\right)-\delta\left(E^r+\frac{a_2}{2}\right)-\kappa\left(E^r+\frac{a_2}{2}\right)\end{bmatrix}$$

$$d_3 = h\begin{bmatrix}\gamma\left(E^r+\frac{a_2}{2}\right)-\eta\left(Q^r+\frac{d_2}{2}\right)-\varepsilon\left(Q^r+\frac{d_2}{2}\right)\\-\kappa\left(Q^r+\frac{d_2}{2}\right)\end{bmatrix}$$

$$g_3 = h\begin{bmatrix}\theta\left(E^r+\frac{a_2}{2}\right)+\eta\left(Q^r+\frac{d_2}{2}\right)-\psi\left(I^r+\frac{g_2}{2}\right)\\-\upsilon\left(I^r+\frac{g_2}{2}\right)\end{bmatrix}$$

$$l_3 = h\begin{bmatrix}\psi\left(I^r+\frac{g_2}{2}\right)-\vartheta\left(R^r+\frac{l_2}{2}\right)-\lambda\left(R^r+\frac{l_2}{2}\right)\\-\kappa\left(R^r+\frac{l_2}{2}\right)\end{bmatrix}$$

$$m_3 = h\begin{bmatrix}\phi\left(S^r+\frac{k_2}{2}\right)+\varepsilon\left(Q^r+\frac{d_2}{2}\right)+\vartheta\left(R^r+\frac{l_2}{2}\right)\\-\rho\left(V^r+\frac{m_2}{2}\right)-\kappa\left(V^r+\frac{m_2}{2}\right)\end{bmatrix}$$

$$k_4 = h\begin{bmatrix}\sigma+\lambda\left(R^r+l_3\right)+\rho\left(V^r+m_3\right)+\delta\left(E^r+a_3\right)\\-\beta\left(S^r+k_3\right)\left(E^r+a_3\right)-\phi\left(S^r+k_3\right)-\kappa\left(S^r+k_3\right)\end{bmatrix}$$

$$a_4 = h\begin{bmatrix}\beta\left(S^r+k_3\right)\left(E^r+a_3\right)-\theta\left(E^r+a_3\right)\\-\gamma\left(E^r+a_3\right)-\delta\left(E^r+a_3\right)-\kappa\left(E^r+a_3\right)\end{bmatrix}$$

$$d_4 = h\begin{bmatrix}\gamma\left(E^r+a_3\right)-\eta\left(Q^r+d_3\right)-\varepsilon\left(Q^r+d_3\right)\\-\kappa\left(Q^r+a_3\right)\end{bmatrix}$$

$$g_4 = h\begin{bmatrix}\theta\left(E^r+a_3\right)+\eta\left(Q^r+d_3\right)-\psi\left(I^r+g_3\right)\\-\upsilon\left(I^r+g_3\right)\end{bmatrix}$$

$$l_4 = h\begin{bmatrix}\psi\left(I^r+g_3\right)-\vartheta\left(R^r+l_3\right)-\lambda\left(R^r+l_3\right)\\-\kappa\left(R^r+l_3\right)\end{bmatrix}$$

$$m_4 = h\begin{bmatrix}\phi\left(S^r+k_3\right)+\varepsilon\left(Q^r+d_3\right)+\vartheta\left(R^r+l_3\right)\\-\rho\left(V^r+m_3\right)-\kappa\left(V^r+m_3\right)\end{bmatrix}$$

Hence, the RK4 scheme for the proposed Ebola model is given by:

$$S^{r+1} = S^r + \frac{1}{6}\left[k_1+2k_2+2k_3+k_4\right] \quad (13)$$

$$E^{r+1} = E^r + \frac{1}{6}\left[a_1+2a_2+2a_3+a_4\right] \quad (14)$$

$$Q^{r+1} = Q^r + \frac{1}{6}\left[d_1+2d_2+2d_3+d_4\right] \quad (15)$$

$$I^{r+1} = I^r + \frac{1}{6}\left[g_1+2g_2+2g_3+g_4\right] \quad (16)$$

$$R^{r+1} = R^r + \frac{1}{6}\left[l_1 + 2l_2 + 2l_3 + l_4\right] \quad (17)$$

$$V^{r+1} = V^r + \frac{1}{6}\left[m_1 + 2m_2 + 2m_3 + m_4\right] \quad (18)$$

7. Numerical Results and Discussions

At this point, the model's numerical simulations were run with various initial and parameter values where accessible, some of these parameters were taken from the body of existing research, and where not, they were calculated or assumed to match the model analysis. The compartments values cover the Zaire Ebola Virus in three provinces in DR Congo; Kivu, North Kivu, and South Kivu where the outbreak of Ebola was deemed very fatal. Table 2 is the initial values of the compartments and the parameters.

Table 2. *Parameter Values of the Model.*

Compartment	Value/millions	Source
$S(0)$	18.8	[28, 4]
$E(0)$	0.25	[28, 4]
$Q(0)$	0.0001	[28, 29]
$I(0)$	0.003481	[28, 29]
$R(0)$	0.001162	[28, 29]
$V(0)$	0.303	[28, 29]
Parameter		
β	0.28770	[17, 24, 4]
σ	0.02020	Assumed
γ	0.09410	Assumed
η	0.09000	Assumed
ψ	0.33380	Computed
λ	0.02000	Assumed
δ	0.09500	Assumed
κ	0.00500	Assumed
θ	0.76130	[17, 24, 4]
υ	0.53000	[30, 31]
ϕ	0.08000	Assumed
ρ	0.00200	Assumed
ϑ	0.07000	Assumed
ϵ	0.02000	Assumed

7.1. Dynamics of All Compartments

Figure 2 shows the dynamics of all the six compartments of Ebola disease dynamics in DR Congo provinces. Thus, Susceptible (S), Exposed (E), Quarantined (Q), Infected (I), Recovered (R), and Vaccinated (V) of the Ebola disease outbreak.

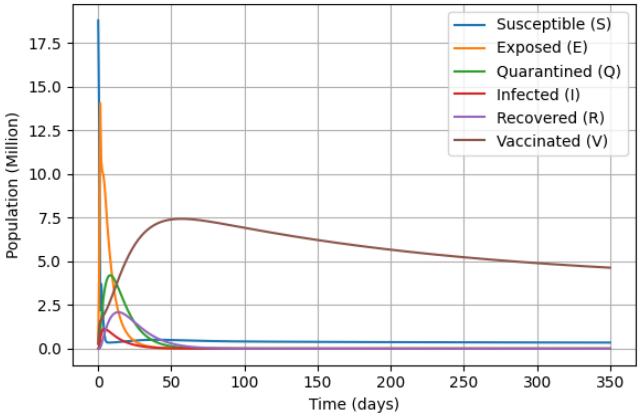

Figure 2. *Dynamics of All Compartments.*

Figure 2 illustrates how the susceptible population declines precipitously at first, perhaps as a result of vaccination, and then stabilizes over time, whereas the number of exposed, quarantined, and infected individuals peak and then abruptly declines before the end of the first 2 months of the outbreak of the Ebola disease in DR Congo provinces. It is also evident that when the number of infected people decreases over time, the number of recovered people peaks and then falls. However, the number of people who have had vaccinations also rises quickly in the early stages of the EBOV illness and stays high throughout time, suggesting that many people are vaccinated. This means that, As the number of people exposed, infected, and quarantined declines, the outbreak appears to be under control, and most of the population is either vaccinated or recovering. Also, the susceptible population levels off as a result of immunity from vaccination or recuperation.

7.2. Dynamics of the Implementation of the Interventions

In this section, we explore the impact of the interventions implemented in this model to control the EBOV disease. The interventions considered in this work are, quarantine and vaccination. For the quarantine, we assume to contact trace more exposed individuals represented as a variation in γ. Also, the vaccination strategy was applied in three compartments as seen in Figure 1. We considered a variation in $\phi, \varepsilon, \vartheta$ respectively as all other values remain unchanged over time.

Figure 3(a) to Figure 3(f) show the dynamics of Zaire

Ebola Virus disease outbreak in the various compartments when more exposed individuals are contact traced and quarantined.

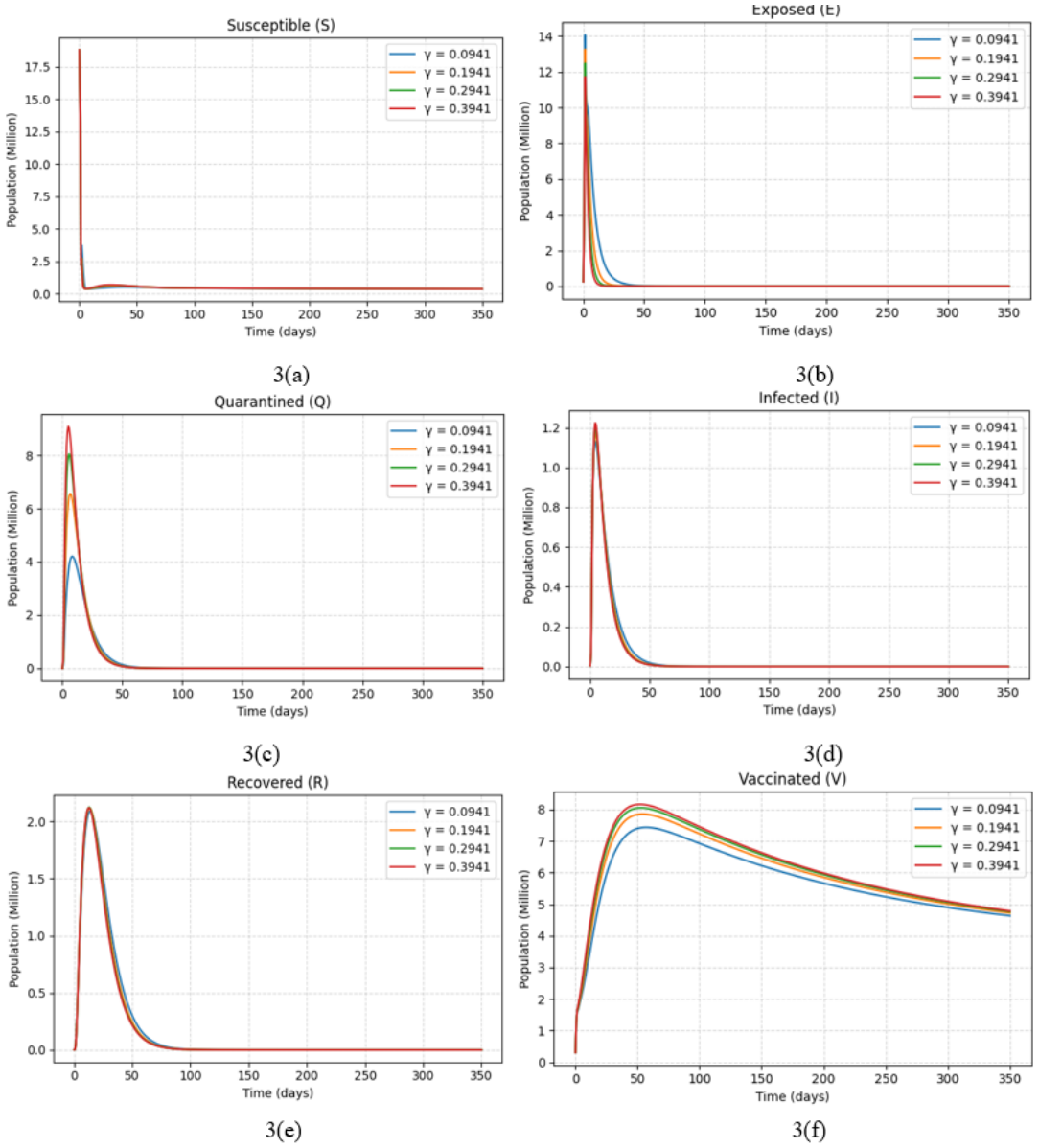

Figure 3. *Zaire Ebola Virus disease dynamics with variation in* γ .

Figure 3 shows that as γ increases, the number of quarantiened individuals increase in Figure 3(c). The impact of this is that, the number of susceptibility declines in Figure 3(a). Also, the immediate peak of the exposed compartments in Figure 3(b) declines, while the infected compartment in Figure 3(d) which experienced an earlier rise in the number of cases also declined to zero in less than two months. Additionally, the recovered persons shot up in the early stages of the disease, but declined as the numbers in the infected conpartment declined. Finally, the number of people vaccinated peaked but gradually decreased over time. It is seen from Figure 3 that a variation in γ actually causes a change in each state or compartments. Implicitely, a proper implementation of the quarantine intervention through contact tracing has a positive effect in controlling the spread of the Ebola disease in DR congo.

Again, Figure 4(a) to Figure 4(f) is the strategy to vaccinate all quarantined individuals who were proven not to be infected with the disease after the mutation stage. These persons are medically tested and found to be negative after the mutation stage.

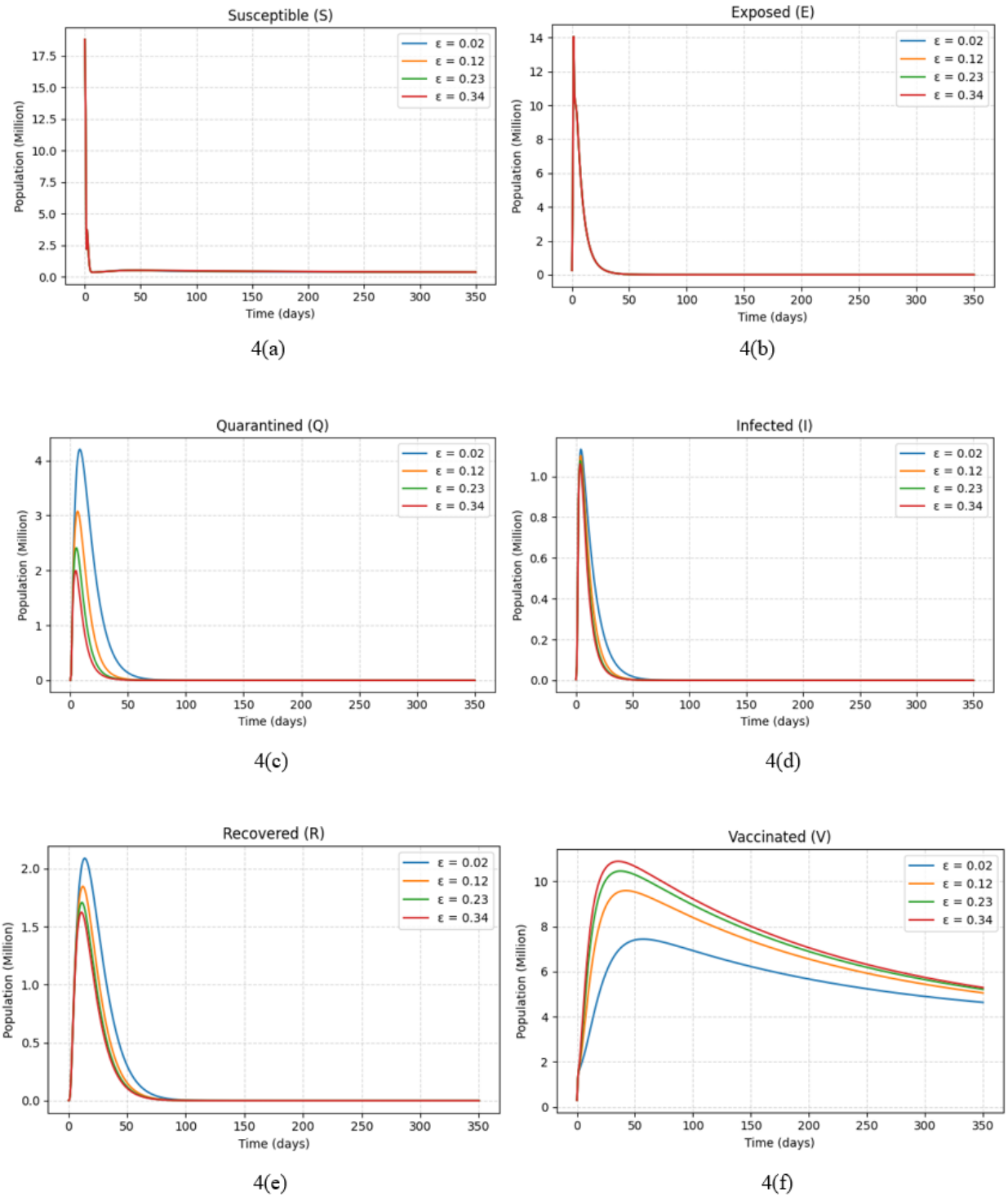

Figure 4. *Zaire Ebola Virus disease dynamics with variation in* ε .

It is seen from Figure 4(a) and Figure 4(b) that a change in ε causes a rapid decline in the number of susceptible persons, and a sharp peak in the exposed persons. However, the number of exposed persons reduces to near zero within the first month and finally extinguishes in less than two months (60 days). Figure 4(c) to Figure 4(e) show that an increase in ε causes a change in decline in the number of persons who are quarantined, infected and recovered. This means that a change in ε has its proportional change in the quarantined, infected and the recovered compartments. Additionally, Figure 4(f) shows that an increase in ε increases the number of persons who are vaccinated over time. Generally, the intervention strategy to increase the rate of ε has a positive ripple effect in extinguishing the disease within the shortest possible time whiles increasing the number of vaccinated persons, and further reducing the number of individuals in the susceptible chamber.

Figure 5(a) to Figure 5(f) also show the impact of varying

ϕ during the outbreak of Zaire Ebola disease in DR Congo.

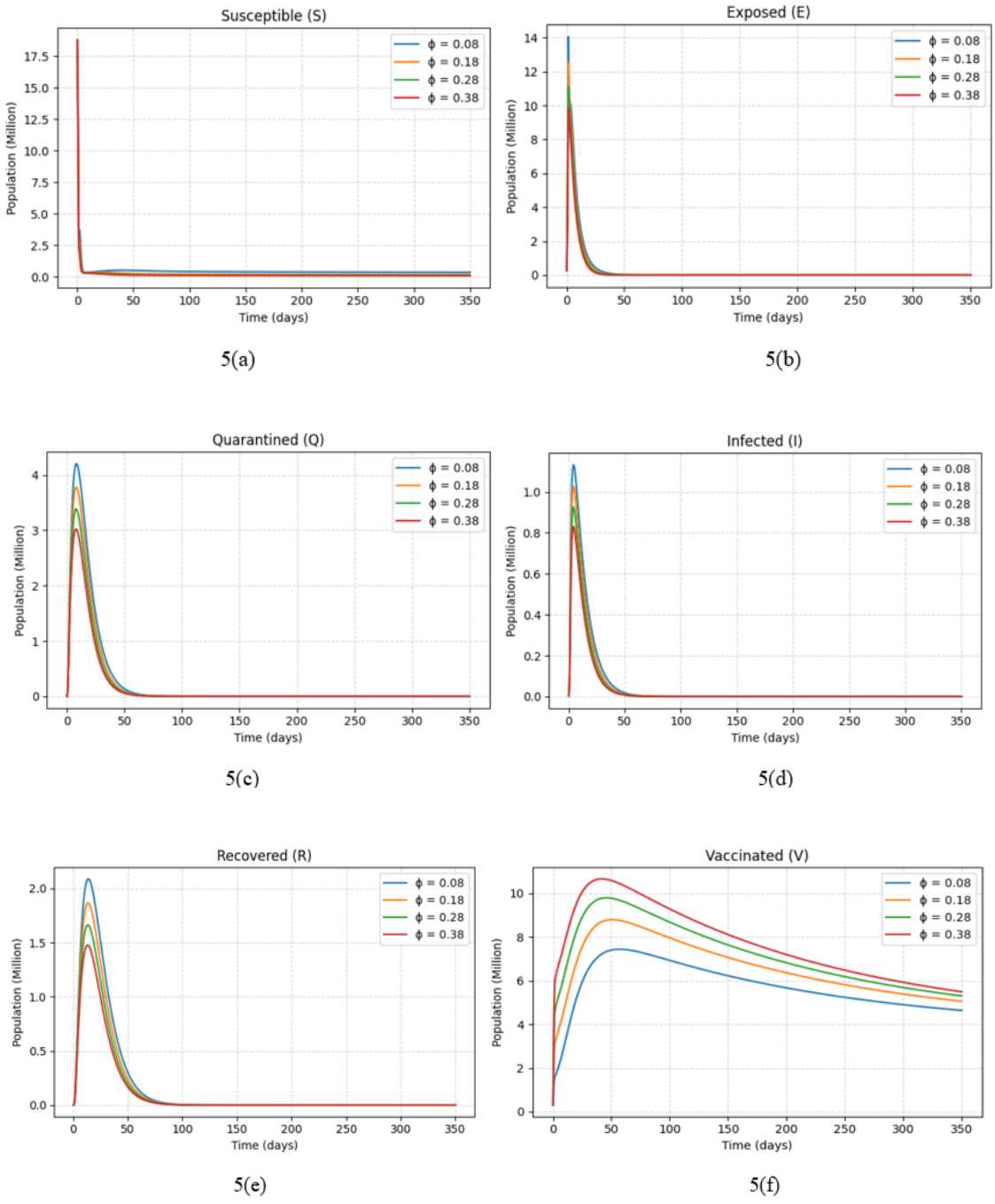

Figure 5. *Zaire Ebola Virus disease dynamics with variation in* ϕ.

From Figure 5, it is seen from Figure 5(a) that a change in ϕ causes a sharp decline in the susceptible compartment to near zero in less than a month, but finally goes to zero as ϕ increases. Again, Figure 5(b) to Figure 5(e) show that, a variation in ϕ causes a sharp rise in the number of individuals who are exposed, quarantined, infected and recovered in the first 50 days, but decline to zero by the 100th day. Additionally, an increase in ϕ causes a proportional change in the number of exposed, quarantined, infected and recovered persons. Also, a variation in ϕ causes a proportional variation in the number of vaccinated persons. It is further seen in Figure 5(f) that an increase in ϕ increase the number of vaccinated individuals. Finally, the strategy to increase ϕ has a positive impact by leaving no person to be susceptible within the population as a result of the vaccination of the total populace as seen in Figure 5(a) and Figure 5(f).

Finally, Figure 6(a) to Figure 6(d) also shows the impact of varying ϑ in the developed model.

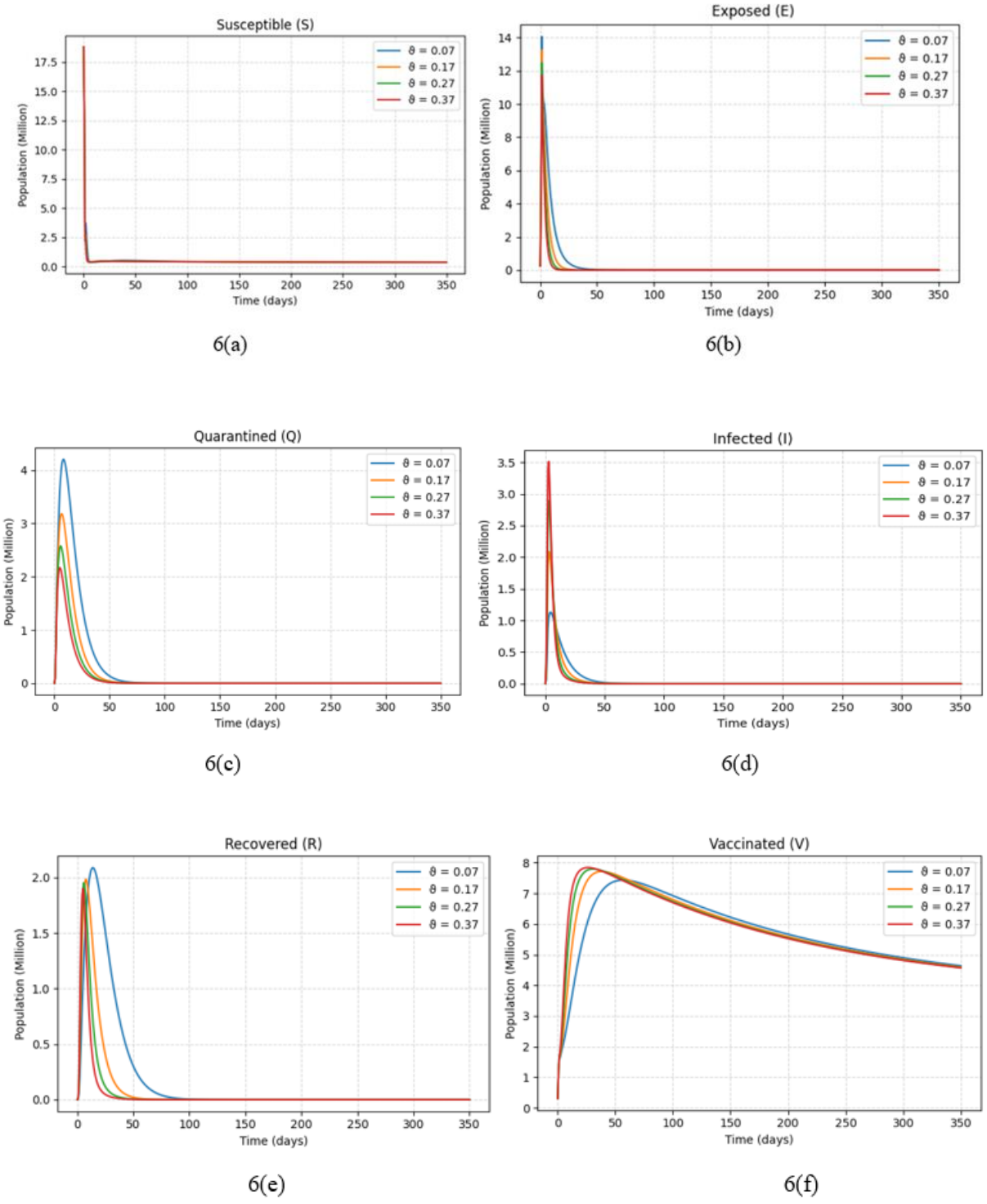

Figure 6. *Zaire Ebola Virus disease dynamics with variation in* ϑ *.*

Also, from Figure 6, Figure 6(a) show that a change in ϑ causes an immediate reduction in the number of susceptible persons. Again, 6(a) to 6(f) show that a change in ϑ causes a proportional change in the exposed, quarantined, infected, recovered and the vaccinated compartments. Additionally, a decrease in the value of ϑ causes a variation in the number of individuals in the exposed, quarantined, infected, recovered and vaccinated chambers. As ϑ increases, Figure 6(b) to Figure 6(e) rise and fall to zero in less than 100 days. It is finally seen in Figure 6(f) that an increase in ϑ increases

the number of persons vaccinated over time.

8. Summary of Results

The developed Ebola model for Zaire Ebolavirus disease in the DR Congo shows that the inception of the disease will cause an immediate peak in the number of persons who are exposed, quarantined, and infected. However, as the number of recovered people increase with an additional introduction of vaccination intervention, the number of vaccinated people will also increase. This will cause a shrink in the number of susceptible people leading to a reduction in the number of people who are exposed, quarantined and infected. This will control the disease from escalating in the short-run.

The analysis of the impact of the intervention strategies show that as we increase or improve the contact trace strategies to help quarantine more exposed persons, the number of exposed persons who might be interacting with the susceptible individuals will also decline. This will cause few persons to be re-exposed to the disease to help reduce the number of infected cases in few days to enable the disease die out of the population. Additionally, a combined intervention strategy of quarantine and vaccination has helped to lower the number of susceptible persons, reduce the number of persons contracting the disease thereby causing the disease to extinguish in less than three months.

9. Conclusion

The paper developed a novel compartmental model for the Zaire Ebola virus disease dynamics in DR Congo. The formulation of the model was based on existing literature and realistic assumptions that really explains the dynamics of Ebola virus disease in DR Congo. The model had two fixed point being the disease-free equilibrium and the endemic equilibrium. The model produced a basic reproduction number of 0.09779 indicating that the disease will fail to exist over time. The numerical simulations through the extension of the 4^{th} Order Runge Kutta iterative scheme unraveled that the presence of the Ebola virus in the population will cause an immediate increase in the number of exposed, quarantined, infected, and vaccinated persons, but will all be under control in less than three months by efficiently executing the interventions strategies.

Abbreviations

DR	Democratic Republic
EVD	Ebola Virus Disease
NGM	Next Generation Matrix
RK4	Runge-Kutta Order 4
rVsV - ZEBOV	recombinant Vesicular stomatitis Virus-Zaire Ebola Virus

Author Contributions

Alex Emmanuel Nti: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Software, Visualization, Validation, Writing – original draft, Supervision

Isaac Ampofi: Conceptualization, Resources, Formal Analysis, Writing – review & editing

Jehovah Baidoo: Data curation, Methodology

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Bibby, K., Casson, L. W., Stachler, E., Haas, C. N. Ebola virus persistence in the environment: state of the knowledge and research needs. Environmental Science & Technology Letters. 2015, 2(1), 2-6. https://doi.org/10.1021/ez5003715

[2] World Health Organization. Ebola disease: Key facts. Available from: https://www.who.int/news-room/fact-sheets/detail/ebola-virus-disease (accessed 4 September 2025).

[3] Centres Disease Control. CDC: Signs and symptoms. Available from: https://www.cdc.gov/ebola/signs-symptoms/?CDC_AAref_Val=https://www.cdc.gov/vhf/ebola/symptoms/index.html (accessed 7 September 2025).

[4] Tahir, M., Inayat Ali Shah, S., Zaman, G., and Muhammad, S. Ebola virus epidemic disease its modeling and stability analysis required abstain strategies, Cogent Biology. 2018, 4(1), 1488511. https://doi.org/10.1080/23312025.2018.1488511

[5] Ivorra, B., Ngom, D., Ramos, Á. M. Be-codis: A mathematical model to predict the risk of human diseases spread between countries-validation and application to the 2014–2015 ebola virus disease epidemic. Bulletin of Mathematical Biology. 2015, 77(9), 1668-1704.

[6] Legrand, J., Grais, R. F., Boelle, P. Y., Valleron, A. J., Flahault, A. Understanding the dynamics of Ebola epidemics. Epidemiology & Infection. 2007, 135(4), 610-621. https://doi.org/10.1017/S0950268806007217

[7] Leroy, E. M., Kumulungui, B., Pourrut, X., Rouquet, P., Hassanin, A., Yaba, P., Dđicat, A., Paweska, J. T., Gonzalez, J. P., Swanepoel, R. Fruit bats as reservoirs of Ebola virus. Nature. 2005, 438(7068), 575-576. https://doi.org/10.1038/438575a

[8] Centers for Disease Control and Prevention. CDC: Outbreak History: Available from: https://www.cdc.gov/ebola/outbreaks/ (accessed 11 September 2025).

[9] Henao-Restrepo, A. M., Camacho, A., Longini, I. M., Watson, C. H., Edmunds, W. J., Egger, M., Carroll, M. W., Dean, N. E., Diatta, I., Doumbia, M., Draguez, B. Efficacy and effectiveness of an rVSV-vectored vaccine in preventing Ebola virus disease: final results from the Guinea ring vaccination, open-label, cluster-randomised trial (Ebola Ça Suffit!). The Lancet. 2017, 389(10068), 505-518. https://doi.org/10.1016/S0140-6736(16)32621-6

[10] Dembek, Z., Hadeed, S., Tigabu, B., Schwartz-Watjen, K., Glass, M., Dressner, M., Frankel, D., Blaney, D., Eccles III, T. G., Chekol, T., Owens, A. Ebola virus disease outbreaks: lessons learned from past and facing future challenges. Military Medicine. 2024, 189(7-8), e1470-e1478. https://doi.org/10.1093/milmed/usae204

[11] Daniel, D. F. N. R. Epidemiological and Clinical Characteristics, Diagnosis and Prevention of Ebola Virus Disease. Master's thesis. Lithuanian University of Health Sciences. University of Alberta. 2025, 1-65.

[12] Forgie, E. M. E. "The West Knows Best": Unintended Consequences of Western Aid During the West African and Democratic Republic of the Congo Ebola Epidemics. https://doi.org/10.7939/r3-xy5b-dq07

[13] Banadyga, L., Zhu, W., Kailasan, S., Howell, K. A., Franaszek, K., He, S., Siragam, V., Cheng, K., Yan, F., Moffat, E., Cao, W. Atypical Ebola virus disease in a nonhuman primate following monoclonal antibody treatment Is associated with glycoprotein mutations within the fusion loop. MBio. 2021, 12(1), 10-1128. https://doi.org/10.1128/mbio.01438-20

[14] World Health Organization. WHO: Ebola Virus Disease Democratic Republic of the Congo: External Situation Report 45 / 2019. Available from: https://tdr.who.int/home/our-work/global-engagement/ebola-virus-disease-democratic-republic-of-congo-external-situation-report-45-2018 (accessed 2 September 2025).

[15] World Health Organization. WHO: Ebola virus disease-Democratic Republic of the Congo Disease outbreak news. https://www.who.int/emergencies/disease-outbreak-news/item/2025-DON580 (accessed 7 September 2025).

[16] Ahmad, W., Abbas, M. Effect of quarantine on transmission dynamics of Ebola virus epidemic: a mathematical analysis. The European Physical Journal Plus. 2021, 136(4), pp. 1-33. https://doi.org/10.1140/epjp/s13360-021-01360-9

[17] Ahmad, W., Rafiq, M., Abbas, M. Mathematical analysis to control the spread of Ebola virus epidemic through voluntary vaccination. The European Physical Journal Plus. 2020, 135(10), p. 775. https://doi.org/10.1140/epjp/s13360-020-00683-3

[18] Brettin, A., Rossi-Goldthorpe, R., Weishaar, K., Erovenko, I. V. Ebola could be eradicated through voluntary vaccination. Royal Society Open Science. 2021, 5(1), p. 171591. https://doi.org/10.1098/rsos.171591

[19] Chowell, G., Tariq, A., Kiskowski, M. Vaccination strategies to control Ebola epidemics in the context of variable household inaccessibility levels. PLOS Neglected Tropical Diseases. 2019, 13(11), p. e0007814. https://doi.org/10.1371/journal.pntd.0007814

[20] Potluri, R., Kumar, A., Maheshwari, V., Smith, C., Oriol Mathieu, V., Luhn, K., Callendret, B., Bhandari, H. Impact of prophylactic vaccination strategies on Ebola virus transmission: a modeling analysis. Plos one. 2020, 15(4), p. e0230406. https://doi.org/10.1371/journal.pone.0230406

[21] Area, I., Ndairou, F., Nieto, J. J., Silva, C. J., Torres, D. F. Ebola model and optimal control with vaccination constraints. arXiv preprint arXiv: 1703.01368. 2017. https://doi.org/10.48550/arXiv.1703.01368

[22] Madubueze, C. E., Kimbir, A. R., Onah, E. S., Aboiyar, T. Analysis of a Mathematical Model of Ebola Virus Disease with Contact Tracing and Quarantine Measures. Transaction of the Nigerian Association of Mathematical Physics. 2017, 3, 75-82.

[23] Mhlanga, A. Dynamical analysis and control strategies in modelling Ebola virus disease. Advances in Difference Equations. 2019, 2019(1), p. 458. https://doi.org/10.1186/s13662-019-2392-x

[24] Rafiq, M., Ahmad, W., Abbas, M., Baleanu, D. A reliable and competitive mathematical analysis of Ebola epidemic model. Advances in Difference Equations. 2020, 2020(1), p. 540. https://doi.org/10.1186/s13662-020-02994-2

[25] Villanueva, R. J., Arenas, A. J., Gonz âlez-Parra, G. A nonstandard dynamically consistent numerical scheme applied to obesity dynamics. Journal of Applied Mathematics. 2008, 2008(1), p. 640154. https://doi.org/10.1155/2008/640154

[26] Tahir, M., Anwar, N., Shah, S. I. A., Khan, T. Modeling and stability analysis of epidemic expansion disease Ebola virus with implications prevention in population. Cogent Biology. 2019, 5(1), p. 1619219. https://doi.org/10.1080/23312025.2019.1619219

[27] Ali, M. A., Rafiq, M., Ozair Ahmad, M. Numerical analysis of a modified SIR epidemic model with the effect of time delay. Punjab University Journal of Mathematics. 2020, 51(1).

[28] City population Menu: CONGO (DEM. REP.): Provinces. Available from: https://www.citypopulation.de/en/drcongo/cities/ (Accessed 11 September 2025).

[29] International Federation of Red Cross. IFRC: Emergency Plan of Action Final Report: Democratic Republic of Congo (DRC), AFRICA, Ebola Virus Disease Epidemic, 2024, pp. 1-61.

[30] Rachah, A., Torres, D. F. Predicting and controlling the Ebola infection. Mathematical methods in the Applied Sciences. 2017, 40(17), 6155-6164. https://doi.org/10.1002/mma.3841

[31] Agbata, C. A. Mathematical Model for the Control of Ebola Virus Disease with Vaccination Effect. Journal of Mathematical Epidemiology. 2025, 1(1), 26-48. https://doi.org/10.64891/jome.6