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MATHEMATICAL ANALYSIS OF THE ENDEMIC EQUILIBRIUM OF MALARIA-HYGIENE MODEL

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***Abstract* - In this study, we analyzed the endemic equilibrium point of a malaria-hygiene mathematical model. We prove that the mathematical model is biological and meaningfully well-posed. We also compute the basic reproduction number using the next generation method. Stability analysis of the endemic equilibrium point show that the point is locally stable if reproduction number is greater that unity and globally stable by the Lasalle's invariant principle. Numerical simulation to show the dynamics of the compartment at various hygiene rate was carried out.**

Keywords- **Malaria, Hygiene, Endemic Equilibrium, Mathematical Model.**

I. INTRODUCTION

One of the serious public health problem affecting the wealth and health of individuals and nations in Africa is Malaria [1, 2]. From 2015-2017, no progress in reducing the global case of malaria has been made [3]. Preventive and symptomatic treatment of malaria, use of long-lasting insecticidal mosquito nets (LLINs) and spraying are efforts employed in malaria prevention, these have reduced the incidence and mortality of malaria [4, 5].

Poor Sanitation system- stagnant water and streams, Socio-economic factors are the ideal location for the development of malaria transmission vector (Anopheles mosquitoes) [6]. The link of the water, sanitation and hygiene (WASH) efforts with malaria transmission has been neglected. Regular cleaning of the surrounding has been associated with malaria infection prevalence [7].

Mathematical modelling has been an essential tool for understanding disease transmission dynamics [8]. [9] proposed a mathematical model of typhoid fever assuming budget allocation for protection against the disease as a variable. The model analysis revealed that sanitation and awareness program has capacity to control the spread of the infection. [10] Formulated a mathematical model of cholera using hygiene consciousness as a control strategy. Using the next generation, the basic reproduction was computed and they showed that the disease free equilibrium is locally stable. The numerical simulation revealed that hygiene consciousness is effective in controlling cholera. [11] model the transmission dynamics of cholera establishing the effects of hygiene, famine, climate and environment. Numerical simulations was carried out to show the evolution of cholera spread. [12] proposed a system of non-linear ordinary differential equation of TB to study the effects of hygiene as a control strategy. The equilibrium points was analyzed and established. The local and global stability of the DFE is stable when unity is less than one. The result of the simulation shows that hygiene consciousness can help control TB disease. Many mathematical models have been formulated to study malaria transmission but to the knowledge of the author none has studied transmission of malaria and hygiene model.

II. MODEL FORMULATION

In this model, the total human population denoted by $N_H$is subdivided into Unhygienic susceptible human population S_u, Hygienic Susceptible Human population S_h, Unhygienic infected human population I_u, hygienic infected human population $I_h$and the Recovered Human population R_h. The mosquito population denoted by N_v is subdivided into Non-disease carrier mosquitoes S_v and disease carrier mosquitoes I_v. Therefore, we have the following sub populations:

$$N_H = S_u + S_h + I_u + I_h + R. \qquad (1)$$

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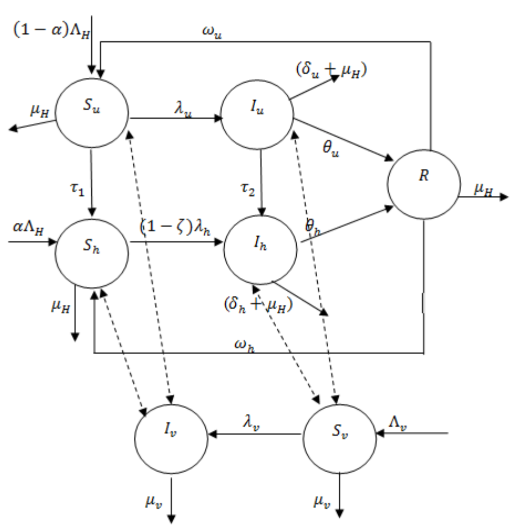
$$N_v = S_v + I_v. \tag{2}$$

Let Λ_H be the recruitment rate of the human population. A fraction $(1-\alpha)\Lambda_H$enters unhygienic susceptible human class while the remaining fraction $\alpha\Lambda_H$ enters the hygienic susceptible human class. The unhygienic susceptible class is increased by the rate at which unhygienic human class lose immunity after recovery given as ω, and reduced by the rate of progression to hygienic classτ_1, the force of infection for the unhygienic classλ_u and natural human death rate μ_H. The hygienic susceptible human compartment is increased by the τ_1, while the compartment is reduced by natural human death rate μ_H and the force of infection for the hygienic class $(1-\zeta)\lambda_h$. The unhygienic infected human class I_u is increased by λ_u and reduced by natural human death rate μ_H, rate of progression from $I_u$to I_h given as τ_2, malaria induced death for unhygienic human class δ_u and recovery for unhygienic human θ_u. The hygienic infected class I_h is increased by $(1-\zeta)\lambda_h$ and $\tau_2$then reduced by the recovery rate for a hygienic human class given as θ_h, malaria induced death for hygienic human class $\delta_h$and natural death rate μ_H. The Human recovery class R is increased by θ_h and θ_u, then reduced by μ_H, ω_h and ω_u. The susceptible mosquito class S_v is increased by the Mosquito recruitment rate given as Λ_v, reduced by the mosquitoes death rate μ_v, and force of infection for mosquito g



iven as λ_v. The infected mosquito class I_v is increased by λ_v and μ_v.

Figure 1. Model Schematic Diagram

Given the above description and definitions of variables and parameters in Table 1 and 2, the following are the model equations:

$$\frac{dS_u}{dt} = (1-\alpha)\Lambda_H - (\tau_1 + \lambda_u + \mu_H)S_u + \omega R \tag{3}$$

$$\frac{dS_h}{dt} = \alpha\Lambda_H + \omega R + \tau_1 S_u - ((1-\zeta)\lambda_h + \mu_H)S_h, \tag{4}$$

$$\frac{dI_u}{dt} = \lambda_u S_u - (\tau_2 + \delta_u + \theta_u + \mu_H)I_u, \tag{5}$$

$$\frac{dI_h}{dt} = (1-\zeta)\lambda_h S_h + \tau_2 I_u - (\delta_h + \theta_h + \mu_H)I_h, \tag{6}$$

$$\frac{dR}{dt} = \theta_u I_u + \theta_h I_h - (\omega + \mu_H)R, \tag{7}$$

$$\frac{dS_v}{dt} = \Lambda_v - \lambda_v S_v - \mu_v S_v, \tag{8}$$

$$\frac{dI_v}{dt} = \lambda_v S_v - \mu_v I_v \tag{9}$$

where

$$\lambda_u = \frac{b_1\beta_{vh}I_v}{N_H},\ \lambda_h = \frac{b_2\beta_{vh}I_v}{N_H},\ b_1 > b_2, \lambda_v = \frac{b_3\beta_{hv}(I_u+\rho I_h)}{N_H}, \delta_u > \delta_h,\ \theta_h > \theta_u. \tag{10}$$

Table 1. Variables

Symbols	Description
S_u	Unhygienic Susceptible Human
S_h	Hygienic Susceptible Human
I_u	Unhygienic Infected Human
I_h	Hygienic Infected Human
R	Recovered Human
S_v	Non-disease carrier Mosquitoes
I_v	Disease carrier Mosquitoes

Table 2. Model Parameters

Parameters	Definitions
Λ_H	Recruitment rate of Human Population
Λ_v	Recruitment rate of Mosquitoes
τ_1	Progression from $S_u\ to\ S_h$
τ_2	Progression from $I_u\ to\ I_h$
δ_u	Disease-Induced death for the unhygienic human class

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δ_h	Disease-Induced death for the hygienic human class
b_1	Biting rate of mosquito for unhygienic human class
b_2	Biting rate of mosquito for hygienic human class
β_{vh}	Transmission probability of infection from mosquito to human
β_{hv}	Transmission probability of infection from human to mosquitoes
λ_u	The force of infection for unhygienic human class
λ_h	The force of infection for hygienic human class
λ_v	Force of infection for mosquitoes
b_3	Biting rate of mosquitoes
ζ	Rate of reduction of infection for hygienic class
ρ	Modification Parameter
θ_u	Rate of recovery for unhygienic human class
θ_h	Rate of recovery for hygienic human class
ω	Rate at which recovered human become susceptible
α	Hygienic rate
μ_H	Natural human death rate
μ_v	Natural death rate of mosquitoes
N_H	Total Human Population

III. MODEL ANALYSIS

3.1 Invariant Region

The invariant region can be obtained by the following theorem.

Theorem 3.1

The solutions of the model are feasible for all $t > 0$ if they enter the invariant region

$$\Omega = \Omega_H \times \Omega_v. \tag{12}$$

Proof:

Let

$$\Omega = (S_u, S_h, I_u, I_h, R, S_v, I_v) \in \mathbb{R}_+^7, \tag{13}$$

be any solution of the system with non-negative initial conditions.

Hence, all feasible solution set of the human population of the malaria model enters the region

$$\Omega_H = \left\{(S_u, S_h, I_u, I_h, R) \in \mathbb{R}_+^5 : S_u \geq 0, S_h \geq 0, I_u \geq 0, I_h \geq 0, R \geq 0, N_H \leq \frac{\Lambda_H}{\mu_H}\right\}. \tag{14}$$

Similarly, the feasible solution set of the vector population enter the region

$$\Omega_v = \left\{(S_v, I_v) \in \mathbb{R}_+^2 : S_v \geq 0, I_v \geq 0, N_v \leq \frac{\Lambda_v}{\mu_v}\right\}. \tag{15}$$

Therefore, the region Ω is positively invariant i.e. the solution remains positive for all initial values.

Thus, the model is biologically meaningful and mathematically well-posed in the domain Ω.

3.2 Disease Free Equilibrium (DFE)

The DFE of the model equations (3 - 9) is given as

$$E_0 = (S_u^0, S_h^0, I_u^0, I_h^0, R^0, S_v^0, I_v^0) = \left(\frac{(1-\alpha)\Lambda_H}{(\tau_1+\mu_H)}, \frac{\Lambda_H(\tau_1+\alpha\mu_H)}{\mu_H(\tau_1+\mu_H)}, 0,0,0, \frac{\Lambda_v}{\mu_v}, 0\right) \tag{16}$$

3.3 Reproduction Number (R_0)

The basic reproduction number (R_0) is defined as the number of secondary malaria infections produced by one infected individual in a completely susceptible community. The next-generation method will be employed to compute R_0. $F(x)$ is the rate of new infection appearance while $V(x)$ is the rate of transfer of individuals into compartments. So we have

$$FV^{-1} = R_0 = \sqrt{\frac{b_3\beta_{vh}\beta_{hv}\Lambda_v\mu_H(b_1\mu_H(1-\alpha)(k_2+\tau_2\rho)+b_2k_1\rho(\alpha\mu_H+\tau_1)(1-\zeta))}{\Lambda_H\mu_v^2k_1k_2(\tau_1+\mu_H)}} \tag{17}$$

3.4 Endemic Equilibrium (EE)

The EE is when the disease continues in the community. It is computed by equating all the model equations to zero. It is denoted by

$$E_* = (S_u^*, S_h^*, I_u^*, I_h^*, R^*, S_v^*, I_v^*) \tag{18}$$

So,

$$S_u^* = \frac{\Lambda_H((1-\alpha)\Lambda_H+\omega R^*)}{\Lambda_H(\tau_1+\mu_H)+b_1\mu_H\beta_{vh}I_v^*}, \tag{19}$$

$$S_h^* = \frac{\Lambda_H(\alpha\Lambda_H + \omega R^* + \tau_1 S_u^*)}{((1-\zeta)b_2\mu_H\beta_{vh}I_v^*) + \Lambda_H\mu_H}, \quad (20)$$

$$I_u^* = \frac{b_1\mu_H\beta_{vh}I_v^* S_u^*}{\Lambda_H k_1}, \quad (21)$$

$$I_h^* = \frac{\mu_H\beta_{vh}I_v^*\left((1-\zeta)k_1b_2S_h^* + b_1\tau_2S_u^*\right)}{\Lambda_H k_1 k_2}, \quad (22)$$

$$R^* = \frac{\theta_u I_u^* + \theta_h I_h^*}{k_3}, \quad (23)$$

$$S_v^* = \frac{\Lambda_v\Lambda_H}{b_3\beta_{hv}\mu_H(I_u^* + \rho I_h^*) + \Lambda_H\mu_v}, \quad (24)$$

$$I_v^* = \frac{\lambda_v^* S_v^*}{\mu_v}, \quad (25)$$

Where

$$k_1 = (\tau_2 + \delta_u + \theta_u + \mu_H); k_2 = (\delta_h + \theta_h + \mu_H); k_3 = (\omega + \mu_H)$$

Substituting (24) for S_v^* (21) and (22) for I_u^* and I_h^* respectively, (25) becomes

$$Z_1 I_v^{*2} - Z_2 I_v^* = 0 \quad (26)$$

This gives solutions of

$I_v^* = 0$ which is the DFE point,

or $I_v^* = \frac{Z_2}{Z_1}$ (27)

Where

$$Z_1 = \frac{b_3\beta_{vh}\beta_{hv}\mu_H\mu_v(b_1\mu_H(1-\alpha)(k_2+\tau_2\rho) + b_2k_1\rho(\alpha\mu_H + \tau_1)(1-\zeta))}{k_1k_2(\tau_1+\mu_H)} \quad (28)$$

$$Z_2 = R_0 - 1 \quad (29)$$

It therefore shows that there exist a unique Endemic Equilibrium point at $R_0 > 1$.

3.5 Local Stability of EEP

Theorem 3.2: The EE of the model is locally asymptotically stable whenever $R_0 > 1$.

Proof:

At the Endemic Equilibrium point, we have a Jacobian Matrix given as:

$$J(E_*) = \begin{bmatrix} -A & 0 & 0 & 0 & \omega & 0 & -A_1 \\ \tau_1 & -A_2 & 0 & 0 & \omega & 0 & -A_3 \\ A_4 & 0 & -P_1 & 0 & 0 & 0 & A_1 \\ 0 & A_5 & \tau_2 & -P_2 & 0 & 0 & A_3 \\ 0 & 0 & \theta_u & \theta_h & -P_3 & 0 & 0 \\ 0 & 0 & -A_6 & -A_7 & 0 & -(\lambda_v^* + \mu_v) & 0 \\ 0 & 0 & A_6 & A_7 & 0 & 0 & -\mu_v \end{bmatrix} \quad (30)$$

Where

$$\left.\begin{array}{c} A = \tau_1 + \lambda_u^* + \mu_H; A_1 = \frac{b_1\beta_{vh}\mu_H S_u^*}{\Lambda_H};\ A_2 = (1-\zeta)\lambda_h^* + \mu_H; \\ A_3 = \frac{(1-\zeta)b_2\beta_{vh}\mu_H S_h^*}{\Lambda_H};\ A_4 = \frac{b_1\beta_{vh}\mu_H I_v^*}{\Lambda_H}; \\ A_5 = \frac{(1-\zeta)b_2\beta_{vh}\mu_H I_v^*}{\Lambda_H}; A_6 = \frac{b_3\beta_{hv}\mu_H S_v^*}{\Lambda_H}; \\ A_7 = \frac{\rho b_3\beta_{hv}\mu_H S_v^*}{\Lambda_H}; \\ P_1 = \tau_2 + \delta_u + \theta_u + \mu_H; \\ P_2 = \delta_h + \theta_h + \mu_H; \\ P_3 = \omega + \mu_H \end{array}\right\} \quad (31)$$

Applying elementary row operation to (30) we have

$$J(E_*) = \begin{bmatrix} -A & 0 & 0 & 0 & \omega & 0 & -A_1 \\ 0 & -AA_2 & 0 & 0 & A\omega & 0 & -A_8 \\ 0 & 0 & -AP_1 & 0 & A_4\omega & 0 & A_9 \\ 0 & 0 & 0 & -A_{12} & A_{12} & 0 & -A_{14} \\ 0 & 0 & 0 & 0 & -A_{17} & 0 & A_{18} \\ 0 & 0 & 0 & 0 & 0 & -(\lambda_v^* + \mu_v) & -\mu_v \\ 0 & 0 & 0 & 0 & 0 & 0 & -A_{19} \end{bmatrix} \quad (32)$$

Where

$A_8 = AA_3 + \tau_1 A_1; A_9 = A_4A_1 + AA_3; A_{10} = A_8 - AA_2A_3; A_{11} = A_6\theta_h + \theta_u A_7; A_{12} = Ak_1(AA_2k_2 + AA_5\omega); A_{13} = AA_2A_4\tau_2\omega; A_{14} = AA_{10}k_1 + AA_2A_9\tau_2; A_{15} = A_{11}A_{13} - A_3A_6A_{12}; A_{16} = A_{11}A_{14} - A_{12}\theta_u\mu_v; A_{17} = AA_{13}k_1\theta_h - A_{12}(Ak_1k_3 - \theta_u A_4\omega); A_{18} = Ak_1(\theta_h A_{14} - A_9A_{12}); A_{19} = A_{15}A_{18} + A_{16}A_{17}\}$ (33)

$$|J - \lambda I| = 0$$

$$\begin{bmatrix} -(A+\lambda) & 0 & 0 & 0 & \omega & 0 & -A_1 \\ 0 & -(AA_2+\lambda) & 0 & 0 & A\omega & 0 & -A_8 \\ 0 & 0 & -(AP_1+\lambda) & 0 & A_4\omega & 0 & A_9 \\ 0 & 0 & 0 & -(A_{12}+\lambda) & A_{12} & 0 & -A_{14} \\ 0 & 0 & 0 & 0 & -(A_{17}+\lambda) & 0 & A_{18} \\ 0 & 0 & 0 & 0 & 0 & -((\lambda_v^*+\mu_v)+\lambda) & -\mu_v \\ 0 & 0 & 0 & 0 & 0 & 0 & -(A_{19}+\lambda) \end{bmatrix} = 0 \quad (34)$$

It is observed that all the eigenvalues of $J(E_*)$ are negative. Hence, it is concluded that the endemic equilibrium E^* of the model is locally asymptotically stable if $R_0 > 1$.

3.6 Global stability of EEP.

Theorem 3.3: The Endemic Equilibrium E_* is globally asymptotically stable if $R_0 > 1$.

Proof:

We define the Lyapunov function U as:

$$U = \left(S_u - S_u^* - S_u^* \log\frac{S_u}{S_u^*}\right) + \left(S_h - S_h^* - S_h^* \log\frac{S_h}{S_h^*}\right) + \left(I_u - I_u^* - I_u^* \log\frac{I_u}{I_u^*}\right) + \left(I_h - I_h^* - I_h^* \log\frac{I_h}{I_h^*}\right) + \left(R - R^* - R^* \log\frac{R}{R^*}\right) + \left(S_v - S_v^* - S_v^* \log\frac{S_v}{S_v^*}\right) + \left(I_v - I_v^* - I_v^* \log\frac{I_v}{I_v^*}\right) \quad (35)$$

$$\frac{dU}{dt} = \left(1 - \frac{S_u^*}{S_u}\right)\frac{dS_u}{dt} + \left(1 - \frac{S_h^*}{S_h}\right)\frac{dS_h}{dt} + \left(1 - \frac{I_u^*}{I_u}\right)\frac{dI_u}{dt} + \left(1 - \frac{I_h^*}{I_h}\right)\frac{dI_h}{dt} + \left(1 - \frac{R^*}{R}\right)\frac{dR}{dt} + \left(1 - \frac{S_v^*}{S_v}\right)\frac{dS_v}{dt} + \left(1 - \frac{I_v^*}{I_v}\right)\frac{dI_v}{dt} \quad (36)$$

$$\frac{dU}{dt} = G_1 - G_2 \quad (37)$$

Substituting the expression for the derivatives and separating positive and negative terms as G_1 and G_2, we have

$$G_1 = \Lambda_H + 2\omega R + (\tau_1 + \lambda_u)S_u + (1-\zeta)\lambda_h S_h + (\tau_2 + \theta_u)I_u + \theta_h I_h + \Lambda_v + \lambda_v S_v + \frac{\omega R^* S_u^*}{S_u} + \frac{\omega R^* S_h^*}{S_h} + \frac{\tau_1 S_u^* S_h^*}{S_h} + \frac{(1-\zeta)\lambda_h S_h^* I_h^*}{I_h} + \frac{\tau_2 I_u^* I_h^*}{I_h} + \frac{\theta_u I_u^* R^*}{R} + \frac{\theta_h I_h^* R^*}{R} + \frac{\lambda_v S_v^* I_v^*}{I_v} \quad (38)$$

$$G_2 = \tau_1 S_u^* + (1-\zeta)\lambda_h S_h^* + (\tau_2 + \theta_u)I_u^* + \theta_h I_h^* + 2\omega R^* + \lambda_v S_v^* + \frac{(1-\alpha)\Lambda_H S_u^*}{S_u} + \frac{\omega R S_u^*}{S_u} + \frac{(\tau_1 + \lambda_u + \mu_H)(S_u - S_u^*)^2}{S_u} + \frac{\alpha \Lambda_H S_h^*}{S_h} + \frac{\omega R S_h^*}{S_h} + \frac{\tau_1 S_u S_h^*}{S_h} + \frac{((1-\zeta)\lambda_h + \mu_H)(S_h - S_h^*)^2}{S_h} + \frac{\lambda_u S_u I_u^*}{I_u} + \frac{k_1(I_u - I_u^*)^2}{I_u} + \frac{(1-\zeta)\lambda_h S_h I_h^*}{I_h} + \frac{\tau_2 I_u I_h^*}{I_h} + \frac{k_2(I_h - I_h^*)^2}{I_h} + \frac{\theta_u I_u R^*}{R} + \frac{\theta_h I_h R^*}{R} + \frac{k_3(R-R^*)^2}{R} + \frac{\Lambda_v S_v^*}{S_v} + \frac{(\lambda_v + \mu_v)(S_v - S_v^*)^2}{S_v} + \frac{\lambda_v S_v I_v^*}{I_v} + \frac{\mu_v (I_v - I_v^*)^2}{I_v} \quad (39)$$

If $G_1 < G_2$, then $\frac{dU}{dt} \le 0$, $\frac{dU}{dt} = 0$ if and if $S_u = S_u^*, S_h = S_h^*, I_u = I_u^*, I_h = I_h^*, R = R^*, S_v = S_v^*, I_v = I_v^*$. The largest invariant set in $\left\{(S_u^*, S_h^*, I_u^*, I_h^*, R^*, S_v^*, I_v^*) \in \Omega; \frac{dU}{dt} = 0\right\}$ is a singleton of E_* with E_* as the endemic equilibrium.

Therefore by the Lasalle's invariant principle, E_* is globally asymptotically stable in Ω if $G_1 < G_2$.

3.7 Numerical Simulation

In this section, we carry out numerical simulations for the model equations using the parameter values in table 3 and initial conditions $S_u(0) = 55, S_h = 45, I_u(0) = 45, I_h(0) = 30, R(0) = 50, S_v(0) = 1000, I_v(0) = 50$.

Table 3: Parameter values of Model

Symbols	Values	Source
Λ_H	100	[13]
Λ_v	1000	[14]
τ_1	0.25	(Assumed)
τ_2	0.5	(Assumed)
δ_u	0.13	(Assumed)
δ_h	0.06	(Assumed)
b_1	0.17	(Assumed)
b_2	0.1	(Assumed)
β_{vh}	0.03	[15]
β_{hv}	0.09	[15]
b_3	0.12	[16]
ζ	0.08	(Assumed)
ρ	0.5	(Assumed)
θ_u	0.05	(Assumed)
θ_h	0.15	(Assumed)
ω	0.7902	[14]
α	0.46	(Assumed)
μ_H	0.00004	[13]
μ_v	0.0000569	[14]

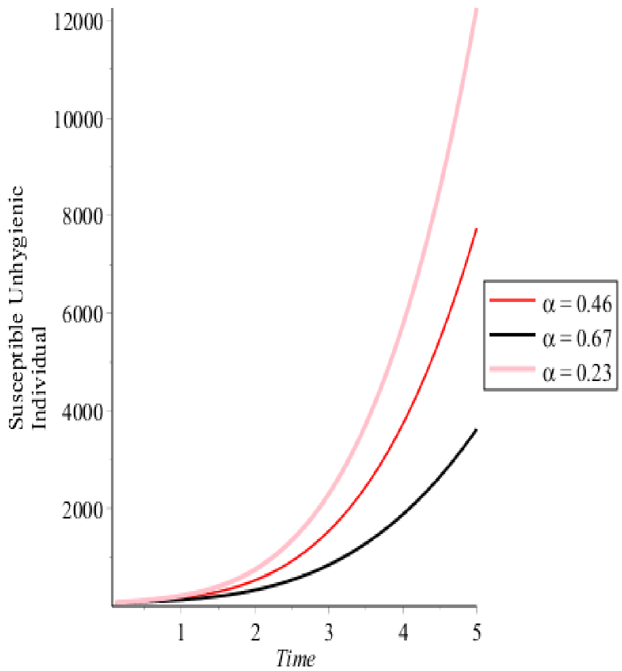

Figure 2: Plots of Susceptible Unhygienic Individuals for various values of α

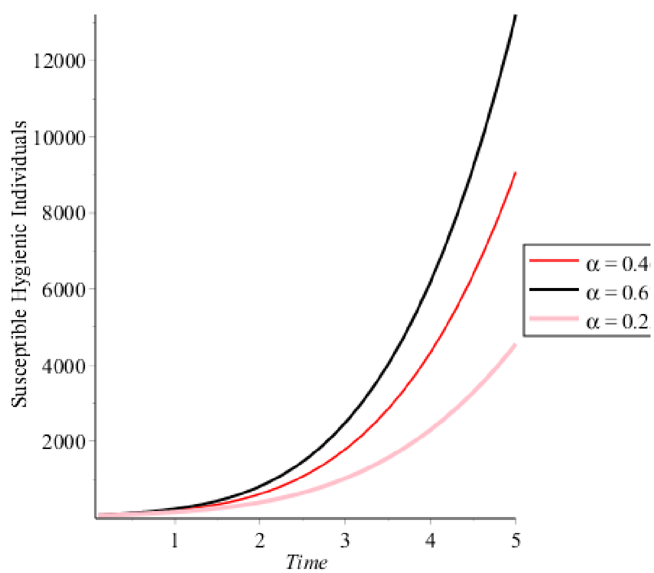

Figure 3: Plots of Susceptible Hygienic Individuals for various values of α

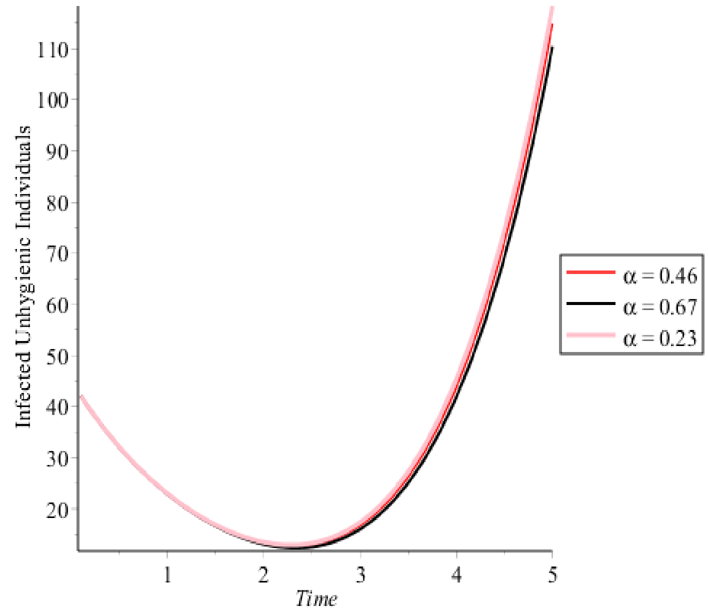

Figure 4: Plots of Infected Unhygienic Individuals for various values of α

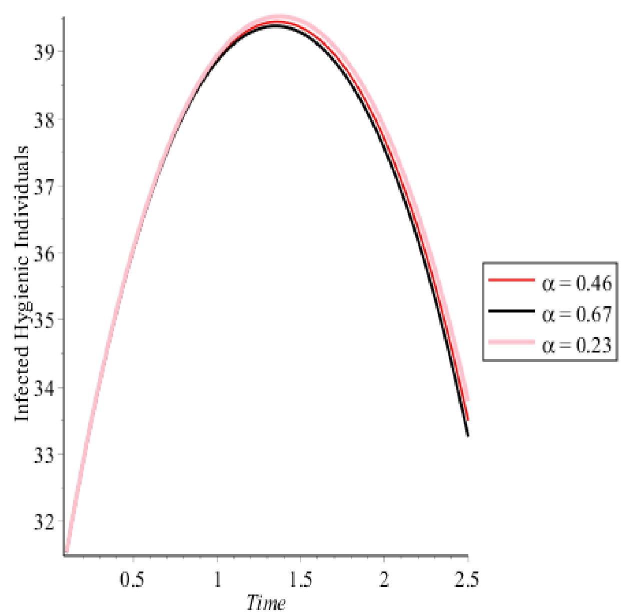

Figure 5: Plots of Infected Hygienic Individuals for various values of α

IV. CONCLUSION

In this study, we proposed and analyzed the endemic equilibrium point of a malaria hygiene mathematical model. We solve the mathematical model showing the endemic equilibrium points. The analysis show that the endemic equilibrium point is locally stable if $R_0 > 1$ given that the eigenvalues of the Jacobian matrices are negative, also by the Lasalle's invariant principle defining a Lyapunov function we show that the endemic equilibrium is globally in the set Ω.

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