



Mathematical Modeling of the Transmission Dynamics of Pediculosis Capitis

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ABSTRACT

This study presents a modified mathematical model to analyze the transmission dynamics of pediculosis capitis (head lice). By employing stability analysis on a modified model, we demonstrated that, when the basic reproduction number ($R_0 < 1$) is maintained below the critical threshold of one, complete eradication of head lice from a host population is achievable. Simulations based on our analytical results predict that this elimination can occur within a 30-day timeframe, providing a clear target for effective public health interventions.

Keywords: Modeling, transmission dynamics, stability analysis, pediculosis capitis, reproduction number.

1.0 INTRODUCTION

Pediculosis capitis (PC), the ectoparasitic disease resulting from the infestation of the human scalp by the head louse (*Pediculus humanus capitis*), stands as a remarkably persistent and widespread public health issue across the globe (Firoozfar et al., 2019). These small, hematophagous (blood-feeding), wingless insects are obligate human parasites, spreading primarily through direct head-to-head contact, a mode of transmission that makes community settings like schools and childcare centers potent epicenters for infestation. While less common, transmission via fomites such as shared combs, brushes, and hats also contributes to its propagation (Trüeb, Gavazzoni Dias & Dutra Rezende, 2023). It is a ubiquitous disease, particularly prevalent in the pediatric population aged 6–12 years, and is especially frequent within communities in developing countries (Jamani et al., 2019). The clinical impact of pediculosis capitis extends beyond simple annoyance.

The severity of an infestation can vary significantly depending on factors such as the density of the louse population, the individual's hypersensitivity to louse saliva, and the presence of secondary bacterial infections that arise from scratching (Alberfani & Mero, 2020). The hallmark symptom of intense pruritus (itching) can lead to sleep disruption, irritability, and a general decline in quality of life. Standard treatment protocols typically involve over-the-counter or prescription pediculicidal agents designed to eradicate both adult lice and their nits (Imboden, 2019). However, the efficacy of these chemical interventions is increasingly threatened by the global emergence of insecticide resistance, a significant challenge that necessitates a broader, more integrated approach to control (Burgess et al., 2023).

This reality underscores that prevention remains not only better but also cheaper than cure.

Beyond the physical manifestations, the psychosocial burden of head lice infestation is profound and often underestimated. The condition is frequently accompanied by intense social stigma, rooted in misconceptions that link it to poor personal hygiene (Hurst, Dotson, Butterfield, Corbett & Oneal, 2020). This stigma can lead to feelings of shame, anxiety, and social isolation for affected children and their families. Recent research has moved to quantify this burden, demonstrating a significant association between pediculosis capitis and lower health-related quality of life, including clinically relevant levels of anxiety, depression, and poor sleep quality among students (Gholamnia et al., 2022). The scale of the problem is often assessed by its prevalence, with rates exceeding 5% generally regarded as constituting an epidemic (Otti, Okorie & Bulus, 2023).

Contemporary studies consistently report high rates of infestation worldwide, affirming its status as an unabated challenge. For instance, Abah, Owens, and Maduiké (2023) documented a 17% prevalence rate within a Nigerian university community, with a pronounced gender disparity. Reinforcing this as a global issue, a recent study in Iran found a prevalence of 11.4% among elementary school girls (Kassiri et al., 2023). Given this persistently high prevalence, mathematical modeling has emerged as an invaluable tool for dissecting the complex transmission dynamics and evaluating potential control strategies. Foundational models, such as that proposed by Otti et al. (2023), have provided crucial insights into the roles of early detection and treatment. However, while these models are well-established, their

predictive power can be enhanced by addressing certain simplifying assumptions.

This study identifies a need for modification and improvement, motivated by two key limitations in the existing framework. First, many models assume a fixed population size, an idealization that does not hold true for head lice epidemics, which often last for several weeks or even months (Nolt et al., 2022). Over such extended periods, vital dynamics (births, deaths, and migration) can significantly alter population susceptibility. Second, and more critically, existing models often treat the susceptible population as a single, homogeneous group. This overlooks the crucial behavioral heterogeneity within a population; a significant number of individuals are aware of pediculosis capitis and its prevention, resulting in a reduced likelihood of transmission for them compared to an unaware cohort.

Therefore, we propose to improve the model by Otti et al. (2023) by incorporating vital dynamics for a varying population size and, most importantly, by

categorizing the susceptible population into two groups: "informed susceptible" and "simple susceptible." Through this enhanced framework, we aim to provide a more realistic and nuanced analysis of the transmission dynamics of pediculosis capitis.

2.0 MODEL FORMULATION

We adapt the deterministic (continuous-time) model proposed by Otti *et al.* (2023), which included detailed explanations about the formulation of the model. However, to guide the formulation of the modified model, we make the following additional assumptions:

- i. Since epidemics may last for some considerable length of time, we assume a varying population size throughout the epidemic period.
- ii. We believe that the rate at which an individual becomes infested depends on their susceptibility, with informed susceptible having a lower chance of contracting pediculosis capitis than simple susceptible.

The schematic compartmental flow diagram of the modified model is given in Figure 1.

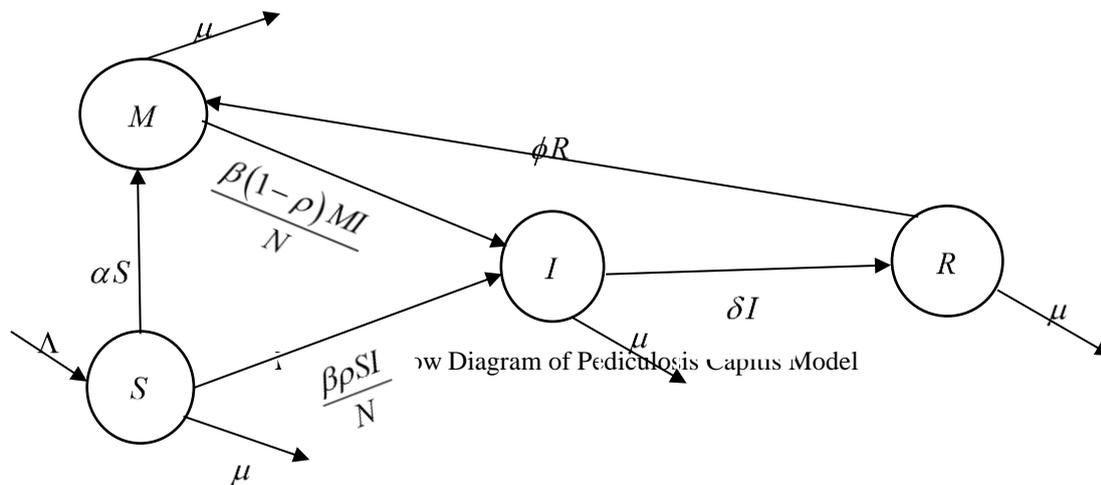


Figure 1: Schematic Representation of the Modified Model

2.1 Model State Variables and Parameters

We hereby present the state variables and parameters of the modified model on Table 1.

Table 1: State Variables and Parameters of the Modified Model

Variable/Parameter	Description
$M(t)$	The class of informed susceptible individuals at time t .
$S(t)$	The class of simple susceptible individuals at time t .
$I(t)$	The class of infested individuals at time t .
$R(t)$	The class of individuals who recovered at time t .
$N(t)$	The total population at time t .



Λ	Recruitment rate (immigration).
μ	Natural death rate
β	The transmission rate of pediculosis capitis.
δ	Recovery rate from pediculosis capitis.
ϕ	Rate at which recovered individuals transfer to informed susceptible class.
α	Rate at which simple susceptible individuals become informed.
$(1-\rho)$	Proportion of informed susceptible individuals.
ρ	Proportion of simple susceptible individuals.

1.3 Modified Model Equations

Based on the modification, the transmission dynamics of pediculosis capitis is govern by the following system of nonlinear ODEs:

$$\left. \begin{aligned} \frac{dM}{dt} &= \alpha S + \phi R - \frac{\beta(1-\rho)MI}{N} - \mu M \\ \frac{dS}{dt} &= \Lambda N - (\alpha + \mu)S - \frac{\beta\rho SI}{N} \\ \frac{dI}{dt} &= \frac{\beta(1-\rho)MI}{N} + \frac{\beta\rho SI}{N} - (\delta + \mu)I \\ \frac{dR}{dt} &= \delta I - (\phi + \mu)R \end{aligned} \right\} \quad (2.1)$$

2.4 Basic Model Equations

In a varying population of individuals, we suppose $M(t)$, $S(t)$, $I(t)$ and $R(t)$ denote the informed susceptible class, simple susceptible class, infested class and recovered/removed class of individuals involved in the pediculosis capitis epidemic at time t , so that

$$N(t) = M(t) + S(t) + I(t) + R(t) \quad (2.2)$$

Since $M(t)$, $S(t)$, $I(t)$ and $R(t)$ are fractions of $N(t)$, they must all reside within the interval $[0,1]$. In order to simplify the model analysis, we carry out dimensionless transformation by adopting the approach used by Barmparis and Tsironis (2020) of scaling the population of each class by the total population such that

$$m = \frac{M}{N}, s = \frac{S}{N}, i = \frac{I}{N} \text{ and } r = \frac{R}{N} \text{ then } m + s + i + r = 1, \text{ and the normalized model system becomes:}$$

$$\left. \begin{aligned} m'(t) &= \alpha s + \phi r - \beta(1-\rho)mi - \mu m \\ s'(t) &= \Lambda - (\alpha + \mu)s - \beta\rho si \\ i'(t) &= \beta(1-\rho)mi + \beta\rho si - (\delta + \mu)i \\ r'(t) &= \delta i - (\phi + \mu)r \end{aligned} \right\} \quad (2.3)$$

2.5 Analysis of the Modified Model

Head lice infestation caused by pediculosis capitis is incapable of becoming endemic. Just as Ismail, Kabakibi and Al-Kafri (2018) noted that this ectoparasitic condition can be eradicated entirely from the host.

Consequently, we focused our study on the disease free equilibrium state given by E^* where

$$\{m^*, s^*, i^*, r^*\} = \left\{ \frac{\alpha\Lambda}{\mu(\alpha + \mu)}, \frac{\Lambda}{\alpha + \mu}, 0, 0 \right\}.$$

3.5.1 Basic Reproduction Number

By definition, the basic reproduction number is the average number of secondary cases caused by a single infectious individual during the entire infectiousness period in a completely susceptible population (Delamater, Street, Leslie, Yang & Jacobsen, 2019). We shall use the Ngonghala, Iboi and Gumel (2020) technique of basic reproduction number.

Suppose $F = (f_1, f_2)^T$ and $V = (v_1, v_2)^T$, it follows therefore that

$$\left. \begin{aligned} f_1 &= \beta(1-\rho)mi + \beta\rho si \\ f_2 &= 0 \end{aligned} \right\} \tag{3.1}$$

$$\left. \begin{aligned} v_1 &= (\delta + \mu)i \\ v_2 &= (\phi + \mu)r - \delta i \end{aligned} \right\} \tag{3.2}$$

$$F = \begin{pmatrix} \beta m(1-\rho) + \beta \rho s & 0 \\ 0 & 0 \end{pmatrix} \tag{3.3}$$

$$V = \begin{pmatrix} \delta + \mu & 0 \\ -\delta & \mu + \phi \end{pmatrix} \tag{3.4}$$

By inverting (3.4), we obtain

$$V^{-1} = \begin{pmatrix} \frac{1}{\delta + \mu} & 0 \\ \frac{\delta}{(\delta + \mu)(\mu + \phi)} & \frac{1}{\mu + \phi} \end{pmatrix} \tag{3.5}$$

Therefore, $R_0 = \rho(F \times V^{-1})$ is obtained by multiplying (3.3) by (3.5), which is

$$\rho(F \times V^{-1}) = \begin{pmatrix} \frac{\beta m(1-\rho) + \beta \rho s}{\delta + \mu} & 0 \\ 0 & 0 \end{pmatrix} \tag{3.6}$$

Evaluating (3.6) at disease free equilibrium E^* , we get

$$\left(\begin{array}{cc} \frac{1}{\delta + \mu} \left(\frac{\beta \Lambda \rho}{\alpha + \mu} - \frac{\alpha \Lambda \beta (\rho - 1)(\alpha + \mu)}{\mu} \right) & 0 \\ 0 & 0 \end{array} \right) \tag{3.7}$$

The basic reproduction number is the spectral radius of (3.7), which yield

$$R_0 = \frac{1}{\delta + \mu} \left(\frac{\beta \Lambda \rho}{\alpha + \mu} - \frac{\alpha \Lambda \beta (\rho - 1)(\alpha + \mu)}{\mu} \right) \tag{3.8}$$

2.6 Stability Analysis of the Model

Studying the stability of equilibrium point E^* is crucial for understanding the transmission dynamics of pediculosis capitis. Through an analysis of equilibrium stability, we can ascertain whether pediculosis capitis will persist or eventually be eradicated within the host population (Van den Driessche & Watmough, 2002). A stable equilibrium suggests control of pediculosis capitis, whereas an unstable equilibrium E^* may result in epidemic that will become endemic.

2.6.1 Local Stability of the DFE

Theorem 2.1 *The disease free equilibrium state is locally asymptotically stable if $R_0 < 1$.*

Proof The jacobian matrix associated with the system of ODEs (2.3) is give below

$$J = \begin{pmatrix} -\beta i(1-\rho) - \mu & \alpha & \beta(-m)(1-\rho) & \phi \\ 0 & -\alpha - \beta i\rho - \mu & \beta\rho(-s) & 0 \\ \beta i(1-\rho) & \beta i\rho & -\delta - \mu + \beta m(1-\rho) + \beta\rho s & 0 \\ 0 & 0 & \delta & -\mu - \phi \end{pmatrix} \quad (3.9)$$

Evaluating (3.9) at the disease free equilibrium state E^* we obtain

$$J_{E^*} = \begin{pmatrix} -\mu & \alpha & -\frac{\alpha\beta\Lambda(1-\rho)}{\mu(\alpha + \mu)} & \phi \\ 0 & -\alpha - \mu & -\frac{\beta\Lambda\rho}{\alpha + \mu} & 0 \\ 0 & 0 & \frac{\alpha\beta\Lambda(1-\rho)}{\mu(\alpha + \mu)} + \frac{\beta\Lambda\rho}{\alpha + \mu} - \delta - \mu & 0 \\ 0 & 0 & \delta & -\mu - \phi \end{pmatrix} \quad (3.10)$$

Hence, the characteristic equation of (3.10) is given by

$$(\alpha\lambda + \alpha\mu + \lambda^2 + 2\lambda\mu + \mu^2)(-(\mu + \phi) - \lambda) \left(\frac{\alpha\beta\Lambda(1-\rho)}{\mu(\alpha + \mu)} + \frac{\beta\Lambda\rho}{\alpha + \mu} - (\delta + \mu) - \lambda \right) = 0 \quad (3.11)$$

By observation, the eigenvalues of the characteristic equation (3.11) are all negative provided $\beta\Lambda\{\alpha(-\rho) + \alpha + \mu\rho\} < \mu(\alpha + \mu)(\delta + \mu)$ since all the model parameters are positive, the roots are

$$\lambda_1 = -\mu, \lambda_2 = -(\alpha + \mu), \lambda_3 = -(\mu + \phi) \text{ and } \lambda_4 = \frac{\alpha\beta\Lambda(1-\rho)}{\mu(\alpha + \mu)} + \frac{\beta\Lambda\rho}{\alpha + \mu} - (\delta + \mu) \text{ respectively,}$$

implying local stability of the equilibrium point E^* which guarantees that pediculosis capitis could be eradicated completely. It follows therefore that the disease free equilibrium point E^* is locally asymptotically stable (LAS) whenever $R_0 < 1$.

2.6.2 Global Stability of the DFE

Theorem 2.2 *The disease free equilibrium state is globally asymptotically stable if $R_0 < 1$.*

Proof We construct a Lyapunov function $V(t)$ by adopting the idea in Shamaki (2023) in order to establish the global stability of the disease free equilibrium point E^* . It goes as follows, let

$$V(t) = (m - m^* \ln m) + (s - s^* \ln s) + (i - i^* \ln i) \quad (3.12)$$

By direct calculation of the derivative of $V(t)$ along the solutions curves, we get

$$\frac{dV}{dt}(E^*) = \left(1 - \frac{m^*}{m}\right) \frac{dm}{dt} + \left(1 - \frac{s^*}{s}\right) \frac{ds}{dt} + \left(1 - \frac{i^*}{i}\right) \frac{di}{dt} \quad (3.13)$$

Hence, it follows that

$$\frac{dV}{dt} = \left(\frac{m - m^*}{m}\right) \frac{dm}{dt} + \left(\frac{s - s^*}{s}\right) \frac{ds}{dt} + \left(\frac{i - i^*}{i}\right) \frac{di}{dt} \quad (3.14)$$

Substituting $m = (m - m^*)$, $s = (s - s^*)$ and $i = (i - i^*)$ into the modified model (2.3) we have

$$\left. \begin{aligned} m'(t) &= \alpha(s-s^*) + \phi r - \beta(1-\rho)(m-m^*)(i-i^*) - \mu(m-m^*) \\ s'(t) &= \Lambda - (\alpha + \mu)(s-s^*) - \beta\rho(s-s^*)(i-i^*) \\ i'(t) &= \beta(1-\rho)(m-m^*)(i-i^*) + \beta\rho(s-s^*)(i-i^*) - (\delta + \mu)(i-i^*) \end{aligned} \right\} \quad (3.15)$$

Obviously, the derivative of the Lyapunov function along the solution curve is now

$$\left. \begin{aligned} \frac{dV}{dt} &= \left(\frac{m-m^*}{m} \right) \left\{ \alpha(s-s^*) + \phi r - \beta(1-\rho)(m-m^*)(i-i^*) \right\} \\ &+ \left(\frac{s-s^*}{s} \right) \left\{ \Lambda - (\alpha + \mu)(s-s^*) - \beta\rho(s-s^*)(i-i^*) \right\} \\ &+ \left(\frac{i-i^*}{i} \right) \left\{ \beta(1-\rho)(m-m^*)(i-i^*) + \beta\rho(s-s^*)(i-i^*) - (\delta + \mu)(i-i^*) \right\} \end{aligned} \right\} \quad (3.16)$$

Simplifying further, we get

$$\begin{aligned} \frac{dV}{dt} &= \frac{(m-m^*)(\beta(i-i^*)(m-m^*)(\rho-1) + \mu(m^*-m) + r\phi + \alpha(s-s^*))}{m} \\ &+ \frac{(s-s^*)(-\beta(i-i^*)\rho(s-s^*) + \Lambda - (s-s^*)(\alpha + \mu))}{s} \\ &+ \frac{(i-i^*)(-((i-i^*)(\delta + \mu)) + \beta(i-i^*)\rho(s-s^*) - \beta(m-m^*)(\rho-1))}{i} \end{aligned} \quad (3.17)$$

By simple algebraic expansion of (3.17) we obtain

$$\begin{aligned} \frac{dV}{dt} &= \frac{\beta i^* (m^*)^2 \rho}{m} + \frac{\beta i^* (m^*)^2}{m} + \frac{\alpha m^* s^*}{m} + \frac{\beta i^* \rho (s^*)^2}{s} + \frac{\beta (i^*)^2 \rho s}{i} + \frac{\beta i^* m^*}{i} + \frac{\beta i^* m \rho}{i} \\ &- \frac{\beta i^* (m^*)^2 \rho}{m} - \frac{\beta i (m^*)^2}{m} - \frac{\mu (m^*)^2}{m} - \frac{m^* r \phi}{m} - \frac{\alpha m^* s}{m} - \frac{\beta i \rho (s^*)^2}{s} - \frac{\alpha (s^*)^2}{s} - \frac{\Lambda s^*}{s} \\ &- \frac{\mu (s^*)^2}{s} - \frac{\beta i^* m}{i} - \frac{\beta (i^*)^2 \rho s^*}{i} - \frac{\delta (i^*)^2}{i} - \frac{(i^*)^2 \mu}{i} - \frac{\beta i^* m^* \rho}{i} + \beta i^* m + 2\delta i^* + 2i^* \mu \\ &+ 2\beta i^* m^* \rho + 2\mu m^* + \Lambda + \beta m^* \rho + \beta i \rho s^* + \beta i m \rho + 2\beta i m^* + \beta m + r\phi + \alpha s^* + 2\mu s^* \\ &- 2\beta i^* m^* - \mu m - \beta i^* m \rho - \beta i^* \rho s - \delta i - \beta i m - i \mu - 2\beta i m^* \rho - \beta m \rho - \beta m^* - \mu s \end{aligned} \quad (3.18)$$

Clearly, collecting all the positive and all the negative terms together in (3.18) we have $\frac{dV}{dt} = f^+ - f^-$ where

f^+ and f^- refer to sum of all positive and all negative terms in (3.18) respectively. In line with Zhou, Hu, Zhu and Ma (2021), the time derivative of the Lyapunov function $\frac{dV}{dt}$ is negative definite provided $f^+ < f^-$

indicating that $\frac{dV}{dt} < 0$. Additionally, $\frac{dV}{dt} = 0$ if and only if $m = m^*$, $s = s^*$ and $i = i^*$. Therefore, the

largest compact invariant set in $(m^*, s^*, i^*, r^*) \in \Omega$ such that $\frac{dV}{dt} = 0$ is the singleton E^* . Hence, by

LaSalle’s invariant principle, all solutions approaches E^* as $t \rightarrow \infty$, then E^* is globally asymptotically stable (GAS) whenever $R_0 < 0$ as required.

3.0 NUMERICAL SIMULATION AND DISCUSSION

3.1 Numerical Simulation

To simulate the modified model that was presented in (2.3), we used MATLAB R2028a and the parameter values listed in Table 2. Some of these parameter values were unobtainable, so we had to get them from Otti *et al.* (2023), we estimated the state variables at the beginning of the epidemic, and made assumptions about other parameters.

Table 2: Model Variables and Parameters Values Used

Variable/Parameter	Value	Source
$m(t_0)$	0.25, 0.50, 0.65	Estimation
$s(t_0)$	0.70, 0.40, 0.20	Estimation
$i(t)$	0.05, 0.07, 0.10	Estimation
$r(t)$	0.00, 0.03, 0.05	Estimation
Λ	0.06	Assume
μ	0.05	Otti <i>et al.</i> (2023)
β	0.01	Otti <i>et al.</i> (2023)
δ	0.20	Otti <i>et al.</i> (2023)
ϕ	0.20	Otti <i>et al.</i> (2023)
α	0.01, 0.50, 0.90	Assume
$(1-\rho)$	0.15	Assume
ρ	0.85	Assume

Experiment 1: Impact of Changing the Initial Condition on the Dynamics of Pediculosis Capitis Transmission. In this experiment, we varied the initial conditions in order to demonstrate that the equilibrium point E^* is globally asymptotically stable. The calculated value of $R_0 = 0.034$ indicating that $R_0 < 1$ ascertaining that pediculosis capitis can be wiped out. In other words, pediculosis capitis will be eradicated within the host population. The simulation results are shown in Figure 2.

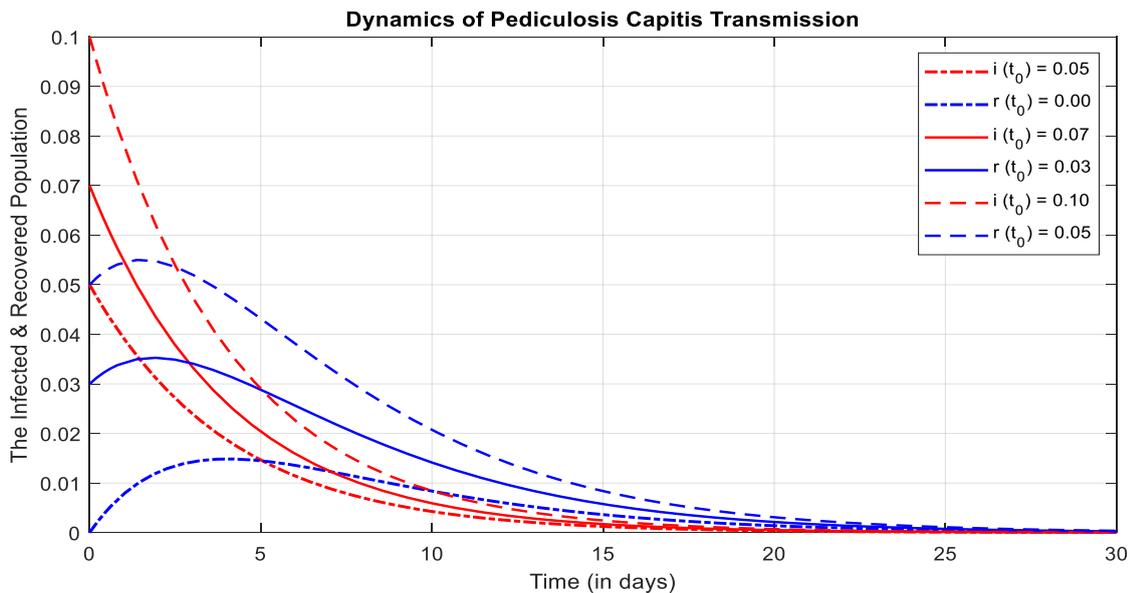


Figure 2: Effect of Varying $i(t_0)$ and $r(t_0)$ on the Dynamics of Pediculosis Capitis

Experiment 2: Effect of Public Health Campaigns on the Susceptible Individuals in the Transmission Dynamics of Pediculosis Capitis.

In this experiment, we examined the impact of positive response to public health campaigns, media coverage or/and improvement on individuals' hygiene against pediculosis capitis. Therefore, we varied rate α at which simple susceptible individuals become informed about pediculosis capitis from 0.20, 0.50 to 0.90 respectively, the simulation results are presented in Figure 3.

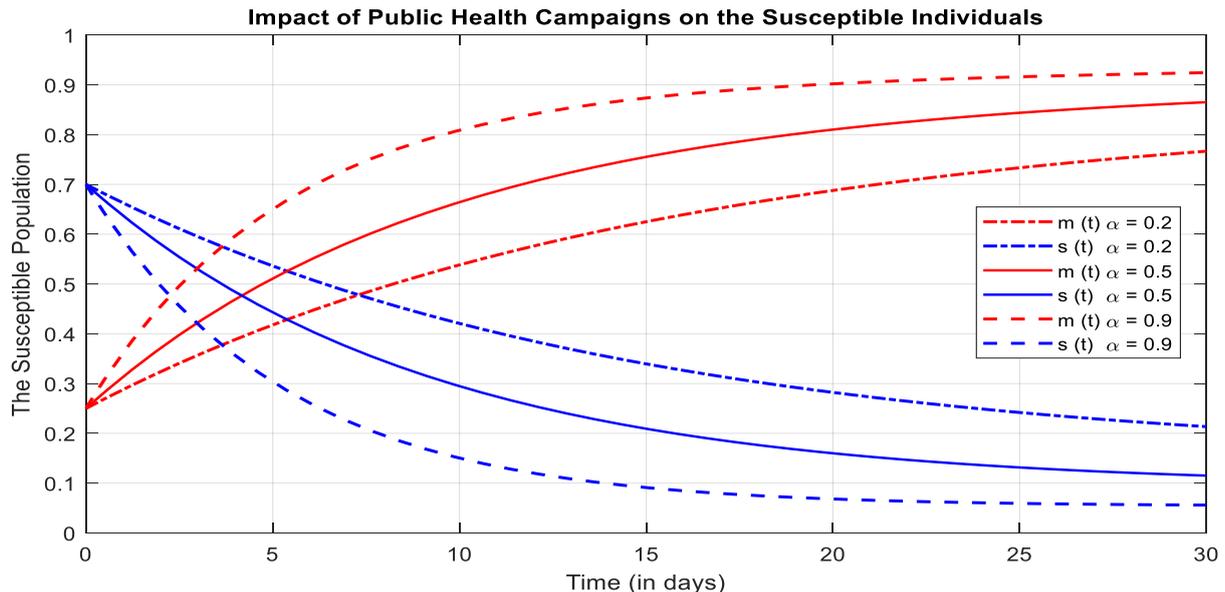


Figure 3: Impact of Public Health Campaigns on Susceptible Individuals

4.0 DISCUSSION

As seen in Figure 2, changes in the initial conditions have no effect on the eradication of pediculosis capitis, the only difference is in the time required for total elimination of the disease. This confirmed our analytical results and gave us the confidence that pediculosis capitis is controllable as long as the basic reproduction number is below one ($R_0 < 1$). Figure 2 has also demonstrated that the disease-free equilibrium point E^* is globally asymptotically stable (GAS). This means that any system small perturbation will have no effect on the long-term qualitative behavior of the transmission dynamic of pediculosis capitis.

Lastly, Figure 3 illustrates how the proportion of simple susceptible individuals decreases while the proportion of informed susceptible individuals is increasing in response to public health campaigns, media coverage, and/or improvements in personal hygiene against pediculosis capitis.

This proves that, in contrast to simple susceptible, where a large number of individuals get infested with pediculosis capitis, only a small proportion of

informed susceptible will become infested. Therefore, rapid dissemination of knowledge about pediculosis capitis is necessary as a control mechanism.

5.0 CONCLUSION

In conclusion, the role of mathematical model in informing effective strategies for controlling and preventing the spread of pediculosis capitis cannot be overemphasized. As such, modification due to Otti et al. (2023) model for the transmission dynamics of pediculosis capitis has been carried out. The modified mathematical model presented provides a framework for understand the dynamics of pediculosis capitis transmission, demonstrating the potential for complete eradication through stability analysis. The experiments of two different scenarios and simulation results show that controlling the disease is achievable as long as the basic reproduction number is below one, indicating that pediculosis capitis can be eliminated within the host population. Thus, the significance of public health campaigns, media coverage, and personal hygiene improvements is



highlighted in reducing the transmission of head lice infestations among susceptible populations.

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