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Mathematical analysis of unreported gender based sexual violence cases in Indonesia

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Abstract

Sexual violence remains a pervasive public health and social issue, with the World Health Organization reporting that one in three women globally experiences such violence in their lifetime. Moreover, more than half of the victims do not report their experiences, underscoring the need for analytical tools that account for both reported and unreported cases. This study presents a nonlinear compartmental model (SUVPR: Susceptible–Unreported Violence–Reported Violence–Punishment–Recovered) to analyze the underlying mechanisms and contributing factors that shape the dynamics of gender based sexual violence in Indonesia. The model incorporates key behavioural and reporting dynamics to reflect real-world conditions accurately. Using the next-generation matrix method, we derive the basic reproduction numbers R_0=0.0117309 for the sexual violence-free equilibrium point and R_0=1.10671391 for the sexual violence endemic equilibrium point. The analysis with the Routh-Hurwitz criterion indicates that both equilibrium points are locally asymptotically stable under certain parameter conditions. The identification of the effective contact rate and the reporting rate as key determinants of R_0 indicates that enhancing reporting mechanisms and reducing societal tolerance toward violence may substantially mitigate the transmission dynamics of sexual violence.

Subject Classification (2020): *97M10.*

Keywords: *Mathematical modelling, Ordinary differential equation, Nonlinear dynamical system, Basic reproduction number, Next generation matrix method, Sexual violence, Stability of equilibria.*

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1. Introduction

According to the interpretation provided by the World Health Organization (WHO), sexual violence encompasses all forms of sexual acts or interventions—whether carried out directly or as attempts—that are imposed upon an individual through coercion, regardless of the relationship between the perpetrator and the victim or the circumstances under which the act occurs [1]. Sexual violence experienced by one in three women worldwide during their lifetime includes coerced sexual acts or attempts, non-consensual acts, or those carried out through force [2]. In Indonesia, the increase in gender-based sexual violence (GBV) directed at women, as reported by the National Commission on Violence Directed at Women (Komnas Perempuan Indonesia), has been occurring since 2014, peaking in 2022 with 339,782 cases, decreasing by 15% to 289,111 in 2023, and rising again in 2024 to 330,097 cases [3, 4].

Stephanie et al. investigated the characteristics of sexual violence against women by employing data mining techniques to examine the relationship between such violence and online news content. In this study, which utilized both TF-IDF and chi-squared (χ^2) methods, the researcher found that the chi-squared method yielded better results in revealing the relationship [5]. Carillo et al. examined women as victims of sexual violence by utilizing a combination of Global and Local Moran's spatial autocorrelation, and analyzed the prevention of sexual violence against women in Mexico using Geographically Weighted Regression (GWR). Findings from the study indicate that variations in poverty, age categories of victims, and levels of education substantially impact the occurrence of sexual violence [6].

Subsequently, Bahri constructed the SVPR model to investigate the dynamics of sexual assault in Indonesia using reported cases of violence collected by Komnas Perempuan Indonesia [7]. The 2022 Gender Equality Barometer study revealed that over 50% of victims did not report their experiences [8]. To address this gap, unlike the previous researchers and to improve upon earlier studies, it is necessary to construct a mathematical model that considers both reported and unreported perpetrators so that the real conditions of the dynamics of sexual violence in Indonesia can be accurately understood.

2. Methods

This model of gender based sexual violence against women uses data from several official sources, including the number of reported cases from the annual report of Komnas Perempuan Indonesia, as well as the number of unreported and convicted perpetrators from the Quantitative Study Report on the Gender Equality Barometer by INFID.

Assuming that there are no changes within each subpopulation, both equilibrium points, that are gender based sexual violence-free and endemic, are identified. Thereafter, the basic reproduction number is determined through the application of the **Next Generation Matrix** method. The stability type of the violence-free equilibrium is analyzed by evaluating the eigenvalues derived from the **Jacobian Matrix**, in accordance with the **Eigenvalue Theorem**. Meanwhile, the analysis of the endemic equilibrium's stability is conducted utilizing the **Stability Theorem** alongside the **Routh-Hurwitz Condition**. Finally, numerical simulations are conducted using **MAPLE software** to analyze the dynamics of each subpopulation.

3. Result and Discussion

3.1 *Sexual Violence Model Formulation*

Within the framework of gender based sexual violence perpetrator modelling, the entire population, represented by N, is systematically split into five mutually exclusive and collectively exhaustive groups: the susceptible group (S), the unreported violence group (U), the reported violence group (V), the punished group (P), and the recovered group (R). Individuals categorized as susceptible may transition into the unreported violence compartment upon engaging in acts of sexual violence, whereas those who do not commit such acts proceed directly to the recovered category. Cases initially unreported may subsequently be reclassified as reported violence following disclosure. Upon completion of judicial processes, perpetrators adjudicated as guilty are assigned to the punishment category; conversely, those acquitted or who have served their sentences transition to the recovered category. Individuals classified as "recovered" may relapse into the susceptible class due to external environmental factors, highlighting the ongoing risk factors associated with sexual violence and indicating that those acquitted or having served their sentences remain vulnerable to returning susceptibility. The following compartmental Figure 1 illustrates this real-world phenomenon.

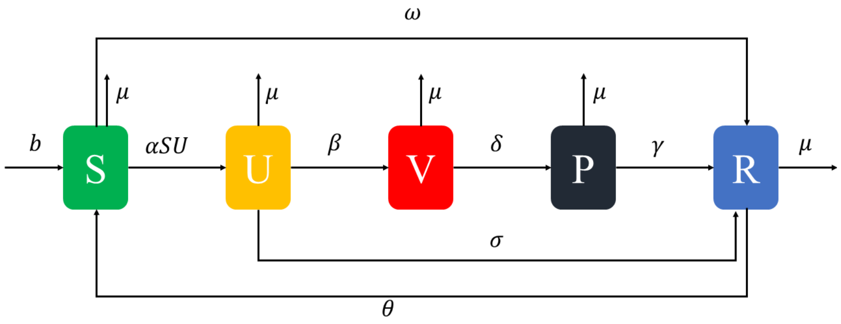

Figure 1
Gender based sexual violence SUVPR model compartmental diagram

Mathematically, the diagram can be represented by the ensuing set of nonlinear equations,

$$\begin{aligned}\frac{dS}{dt} &= b - \alpha SU + \theta R - (\omega+\mu)S,\\ \frac{dU}{dt} &= \alpha SU - (\beta+\mu+\sigma)U,\\ \frac{dV}{dt} &= \beta U - (\delta+\mu)V,\\ \frac{dP}{dt} &= \delta V - (\gamma+\mu)P,\\ \frac{dR}{dt} &= \sigma U + \gamma P + \omega S - (\theta+\mu)R\end{aligned} \tag{1}$$

with

$$S(0) > 0, U(0) \geq 0, V(0) \geq 0, P(0) \geq 0, R(0) \geq 0.$$

where the parameters used are described in Table 1.

Table 1

Parameter Description for SUVPR Model

Parameters	Description
b	Natality rate
α	The rate of effective interpersonal interactions contributing to the transmission dynamics of sexual violence.
β	The rate at which unreported violence becomes reported
δ	The transition rate from reported violence to punishment
σ	The rate at which unreported violence becomes recovered
γ	The rate when punished individuals become recovered
ω	Transition rate from susceptible to recovered
θ	Transition rate from recovered becomes susceptible
μ	Natural death rate

3.2 *The Free and Endemic Sexual Violence Equilibria*

To determine the two equilibria, each equation in the system (1) is set equal to zero [9]. By assuming that $S = S^0, U = U^0, V = V^0, P = P^0$, and $R = R^0$. The sexual violence-free equilibrium point represents a stable state in which there is no unreported violence and no reported violence in the population, resulting in $(U^0 = V^0 = 0)$ [10, 11, 12]. Consequently, no individuals are being punished for committing sexual violence, which means $(P^0 = 0)$. Thus, we obtain that the equilibrium point for gender based sexual violence-free

$$E_0 = (S^0, U^0, V^0, P^0, R^0) = \left(\frac{b(\theta+\mu)}{\mu(\omega+\mu+\theta)}, 0,0,0, \frac{b\omega}{\mu(\omega+\mu+\theta)}\right). \tag{2}$$

The reproduction number $(\Re_0)$ is derived at the sexual violence-free equilibrium. It quantifies the potential spread of sexual violence within a fully susceptible population, denoting the average number of secondary perpetrators induced by a single primary perpetrator [13, 14]. This is computed through applying the method of Next-Generation Matrix [15, 16], accounting for the dynamics of subpopulations U, V, and P,

$$\frac{dU}{dt} = \alpha SU - (\beta + \mu + \sigma)U,$$
$$\frac{dV}{dt} = \beta U - (\delta + \mu)V,$$
$$\frac{dP}{dt} = \delta V - (\gamma + \mu)P,$$

The matrix F^* and V^* for the model are

$$F^* = \begin{bmatrix} \alpha SU \\ 0 \\ 0 \end{bmatrix}, \text{ and } V^* = \begin{bmatrix} (\beta + \mu + \sigma)U \\ -\beta U + (\delta + \mu)V \\ -\delta V + (\gamma + \mu)P \end{bmatrix}$$

Next, matrix F and V are calculated based on partial derivatives of F^* and V^* with respect to variables $U, V,$ and P [17]. Then, substitute the values of the sexual violence-free equilibrium in Eq. (2) into F and V to obtain:

$$F = \begin{bmatrix} \frac{\alpha b(\theta + \mu)}{\mu(\omega + \mu + \theta)} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \text{ and } V = \begin{bmatrix} \beta + \mu + \sigma & 0 & 0 \\ -\beta & \delta + \mu & 0 \\ 0 & -\delta & \gamma + \mu \end{bmatrix}$$

We can calculate

$$K = FV^{-1} = \begin{bmatrix} \frac{\alpha b(\theta + \mu)}{\mu(\omega + \mu + \theta)(\beta + \mu + \sigma)} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The largest eigenvalue of the matrix K determines $\Re_0$, namely:

$$\Re_0 = \frac{\alpha b(\theta + \mu)}{\mu(\omega + \mu + \theta)(\beta + \mu + \sigma)}. \tag{3}$$

The endemic equilibrium point for gender based sexual violence is reached when individuals who perpetrate sexual violence continue to exist within the community, implying that $U > 0$ and $V > 0$. From Eq. (1), let $S = S^*, U = U^*, V = V^*, P = P^*$, and $R = R^*$, we can derive the equilibrium point for sexual violence

$$E_* = (S^*, U^*, V^*, P^*, R^*) \tag{4}$$

where

$$S^* = \frac{\beta + \mu + \sigma}{\alpha},$$
$$U^* = \frac{(\delta + \mu)}{\beta} V^*,$$
$$P^* = \frac{\delta}{\gamma + \mu} V^*,$$
$$R^* = \frac{(\alpha\sigma(\delta + \mu)(\gamma + \mu) + \alpha\beta\delta\gamma)V^* + \omega\beta(\gamma + \mu)(\beta + \mu + \sigma)}{\alpha\beta(\gamma + \mu)(\theta + \mu)},$$
$$V^* = \frac{\beta\left(\alpha b\,\mu + \alpha b\,\theta - \beta\mu^2 - \beta\mu\omega - \beta\mu\theta - \mu^3 - \mu^2\omega - \mu^2\sigma - \mu^2\theta - \mu\omega\sigma - \mu\sigma\theta\right)(\mu + \gamma)}{\alpha\mu\,\Delta},$$

$$\begin{aligned}\Delta = {} & \beta\delta\gamma + \beta\delta\mu + \beta\delta\theta + \beta\gamma\mu + \beta\gamma\theta + \beta\mu^2 + \beta\mu\,\theta + \delta\gamma\mu + \delta\gamma\sigma \\ & + \delta\gamma\theta + \delta\mu^2 + \delta\mu\,\sigma + \delta\mu\,\theta + \gamma\mu^2 + \gamma\mu\,\sigma + \gamma\mu\,\theta + \mu^3 \\ & + \mu^2\sigma + \mu^2\theta.\end{aligned}$$

3.3 *Stability Analysis*

Lemma 3.1: (Routh-Hurwitz Condition). [18] *Let $r_1, r_2, \dots, r_n$ be real numbers and define $a_j = 0$ if $j > n$. Consider polynomial $p(z) = r_n + r_{n-1}z + r_{n-2}z^2 + \cdots + r_1 z^{n-1} + z^n$. All roots of $p(z)$ have negative real part if and only if for each $k = 1, \dots, n$, the determinant of the matrix $M_{k\times k}$ is positive*

$$M_{k\times k} = \begin{bmatrix} r_1 & r_3 & r_5 & \cdots & r_{2k-1} \\ 1 & r_2 & r_4 & \cdots & r_{2k-2} \\ 0 & r_1 & r_3 & \cdots & r_{2k-3} \\ 0 & 1 & r_2 & \cdots & r_{2k-4} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & r_k \end{bmatrix}.$$

Theorem 3.2: *If the basic reproduction number satisfies $\mathfrak{R}_0 < 1$, then the gender based sexual violence-free equilibrium point is locally asymptotically stable.*

Proof: The stability of the system's equilibrium points in model (1) is assessed through linearization with the Jacobian matrix [19, 20].

$$\mathcal{J} = \begin{bmatrix} -\alpha U - (\omega+\mu) & -\alpha S & 0 & 0 & \theta \\ \alpha U & \alpha S - (\beta+\mu+\sigma) & 0 & 0 & 0 \\ 0 & \beta & -(\delta+\mu) & 0 & 0 \\ 0 & 0 & \delta & -(\gamma+\mu) & 0 \\ \omega & \sigma & 0 & \gamma & -(\theta+\mu) \end{bmatrix} \tag{5}$$

By substituting Eq. (2) to Eq. (5), the Jacobian at around the sexual violence-free equilibrium point is given by:

$$\mathcal{J}_{E_0} = \begin{bmatrix} -q_1 & -q_2 & 0 & 0 & \theta \\ 0 & q_2 - q_3 & 0 & 0 & 0 \\ 0 & \beta & -q_4 & 0 & 0 \\ 0 & 0 & \delta & -q_5 & 0 \\ \omega & \sigma & 0 & \gamma & -q_6 \end{bmatrix} \tag{6}$$

where $q_1 = \omega + \mu, q_2 = \frac{\alpha b(\theta+\mu)}{\mu(\omega+\mu+\theta)}, q_3 = \beta + \mu + \sigma, q_4 = \delta + \mu,\ \ q_5 = \gamma + \mu,$ $q_6 = \theta + \mu$.

The characteristic equation for this matrix is

$$\big(\lambda - (q_2 - q_3)\big)(\lambda + q_4)(\lambda + q_5)(\lambda^2 + r_1\lambda + r_2) = 0 \tag{7}$$

where $r_1 = 2\mu + \omega + \theta$ and $r_2 = \mu^2 + \mu\theta + \mu\omega$. So, the eigenvalues are given by:

- $\lambda_1 = (q_2 - q_3)$. For $\lambda_1 < 0$, we get

$$\frac{\alpha b(\theta + \mu)}{\mu(\omega + \mu + \theta)} - \beta + \mu + \sigma < 0$$
$$\Leftrightarrow \frac{\alpha b(\theta + \mu)}{\mu(\omega + \mu + \theta)(\beta + \mu + \sigma)} < 1$$
$$\Leftrightarrow \Re_0 < 1$$

- $\lambda_2 = -q_4 = -\delta - \mu < 0$
- $\lambda_3 = -q_5 = -\gamma - \mu < 0$
- Using Lemma 3.2, the eigenvalues associated with $\lambda^2 + r_1\lambda + r_2 = 0$, denoted as λ_4 and λ_5, are guaranteed to be negative if $r_1 > 0$ and $r_1 r_2 > 0$. These conditions are satisfied since both r_1 and r_2 are positive.

Therefore, with $\Re_0 < 1$, the system of Eq. (1) at the sexual violence-free equilibrium gives all eigenvalues with a negative real part, so it is locally asymptotically stable.

Theorem 3.2: *If* $\Re_0 > 1$, *the gender based sexual violence endemic equilibrium point is locally asymptotically stable.*

Proof: The endemic equilibrium exists when $U^* > 0$ and $V^* > 0$. As established in the preceding subsection, V^* can be further simplified as follows:

$$V^* = \frac{\beta(\alpha b\mu + \alpha b\theta - \beta\mu^2 - \beta\mu\omega - \beta\mu\,\theta - \mu^3 - \mu^2\omega - \mu^2\sigma - \mu^2\theta - \mu\omega\sigma - \mu\sigma\theta)(\mu + \gamma)}{\alpha\mu\Delta}$$
$$= \frac{\beta\mu(\mu+\theta+\omega)(\mu+\sigma+\beta)\left(\frac{\alpha b(\theta+\mu)}{\mu(\omega+\mu+\theta)(\beta+\mu+\sigma)} - 1\right)(\mu+\gamma)}{\alpha\mu\Delta}$$
$$= \frac{\beta\mu(\mu+\theta+\omega)(\mu+\sigma+\beta)(\Re_0 - 1)(\mu+\gamma)}{\alpha\mu\Delta}$$

Since $U^* > 0$ and $V^* > 0$, it follows $\Re_0 > 1$. Moreover, the Jacobian evaluated at the endemic equilibrium is formulated as in Eq. (8) where $s_1 = \alpha U^* + \omega + \mu,\ s_2 = -(\alpha S^* - \beta - \mu - \sigma),\ s_3 = \delta + \mu, s_4 = \gamma + \mu, s_5 = \theta + \mu$.

$$\mathcal{J}_{E_*} = \begin{bmatrix} -s_1 & -\alpha S^* & 0 & 0 & \theta \\ \alpha U^* & -s_2 & 0 & 0 & 0 \\ 0 & \beta & -s_3 & 0 & 0 \\ 0 & 0 & \delta & -s_4 & 0 \\ \omega & \sigma & 0 & \gamma & -s_5 \end{bmatrix} \quad (8)$$

The eigenvalue equation is

$$\lambda^5 + m_1\lambda^4 + m_2\lambda^3 + m_3\lambda^2 + m_4\lambda + m_5 = 0$$

with

$$m_1 = s_1 + s_2 + s_3 + s_4 + s_5$$
$$m_2 = s_1(s_2 + s_3 + s_4 + s_5) + s_2 s_3 + s_4 s_5 + (s_2 + s_3)(s_4 + s_5) + \alpha^2 S^* U^* - \omega\theta$$
$$m_3 = s_3(s_1 + s_2)(s_4 + s_5) + s_4 s_5(s_1 + s_2 + s_3) - \omega\theta(s_2 + s_3 + s_4) + (s_1 s_2 + \alpha^2 S^* U^*)(s_3 + s_4 + s_5) - \alpha\sigma\theta U^*$$

$$m_4 = s_3 s_4 s_5 (s_1 + s_2) - \omega\theta(s_2 s_3 + s_2 s_4 + s_3 s_4) + (s_1 s_2 + \alpha^2 S^* U^*)(s_3 s_4 + s_3 s_5 + s_4 s_5) - \alpha\sigma\theta U^*(s_3 + s_4)$$
$$m_5 = s_1 s_2 s_3 s_4 s_5 - s_2 s_3 s_4 \omega\theta + s_3 s_4 s_5 \alpha S^* U^* - s_3 s_4 \alpha^2 \sigma\theta U^* - \alpha\beta\delta\gamma\theta U^*.$$

Using Lemma 3.2, the real part of the eigenvalues of the matrix $\mathcal{J}_{E_*}$ is negative if

$$m_1 > 0,$$
$$m_1 m_2 - m_3 > 0,$$
$$m_1 m_2 m_3 - m_1^2 m_4 - m_3^2 + m_5 m_1 > 0, \tag{9}$$
$$m_1 m_2 m_3 m_4 - m_5 m_1 m_2^2 - m_1^2 m_4^2 + 2 m_5 m_1 m_4 - m_3^2 m_4 + m_5 m_2 m_3 - m_5^2 > 0,$$
$$m_1 m_2 m_3 m_4 m_5 - m_5^2 m_1 m_2^2 - m_5 m_1^2 m_4^2 + 2 m_5^2 m_1 m_4 - m_5 m_3^2 m_4 + m_5^2 m_2 m_3 - m_5^3 > 0$$

for $\Re_0 > 1$. Therefore, the endemic equilibrium point is asymptotically stable.

3.4 *Numerical Simulation*

A numerical simulation is conducted using MAPLE to validate the analytical findings. For the model defined in Eq. (1), initial conditions and parameter values are adopted from Tables 2 and 3.

Table 2

Initial Conditions for Variables

Variable	Value	Source
$S(0)$	0.992696762	Estimated
$U(0)$	0.004820511	Estimated
$V(0)$	0.002053538	Estimated
$P(0)$	0.000390172	Estimated
$R(0)$	0.000039017	Estimated

Table 3

Parameter Value for Model Simulation

Parameter	Value	Parameter	Value
b	0.00800 [Estimated]	γ	0.06985 [Assumption]
α_1	0.00029 [Estimated]	ω	0.00004 [Assumption]
α_2	0.01000 [Assumption]	σ	0.00442 [Assumption]
β_1	0.00117 [Estimated]	θ	0.46560 [Assumption]
β_2	0.00600 [Assumption]	μ	0.003287 [Estimated]
δ	0.04424 [Assumption]		

Substituting the parameters from Table 3 into system (1) yields the following model:

$$\frac{dS}{dt} = 0.008 - \alpha SU + 0.04656R - 0.00404S,$$
$$\frac{dU}{dt} = \alpha SU - (\beta + 0.00842)U,$$

$$\frac{dV}{dt} = \beta U - 0.04824V,$$
$$\frac{dP}{dt} = 0.04424V - 0.07385P$$
$$\frac{dR}{dt} = 0.00442U + 0.06985P + 0.00004S - 0.46960R$$

Using Eq. (3), the basic reproduction number is calculated based on the condition of simulation below

(1) $\alpha_1 = 0.00029, \beta_1 = 0.00117 \Rightarrow \Re_0 = 0.0117309 < 1$

(2) $\alpha_2 = 0.01000, \beta_2 = 0.00600 \Rightarrow \Re_0 = 1.10671391 < 1.$

For Simulation 1, by using Eq. (2), we derive the sexual violence-free equilibrium point $E_0 = (1.99983, 0, 0, 0, 0.00017)$, and for Eq. (7), we get:

- $\lambda_2 = -\delta - \mu = -0.04824 < 0$
- $\lambda_3 = -\gamma - \mu = -0.07385 < 0$
- $r_1 = 2\mu + \omega + \theta = 0.47364 > 0$
- $r_1 r_2 = (2\mu + \omega + \theta)(\mu^2 + \mu\theta + \mu\omega) = 0.00089 > 0$

In this context, the Routh-Hurwitz criterion confirms that the fourth Equation in Eq. (7) yields eigenvalues that have negative real parts. Thus, when $\Re_0 < 1$, all eigenvalues are negative, indicating that the sexual violence-free equilibrium is asymptotically stable. The corresponding numerical simulation results are illustrated in Figure 2.

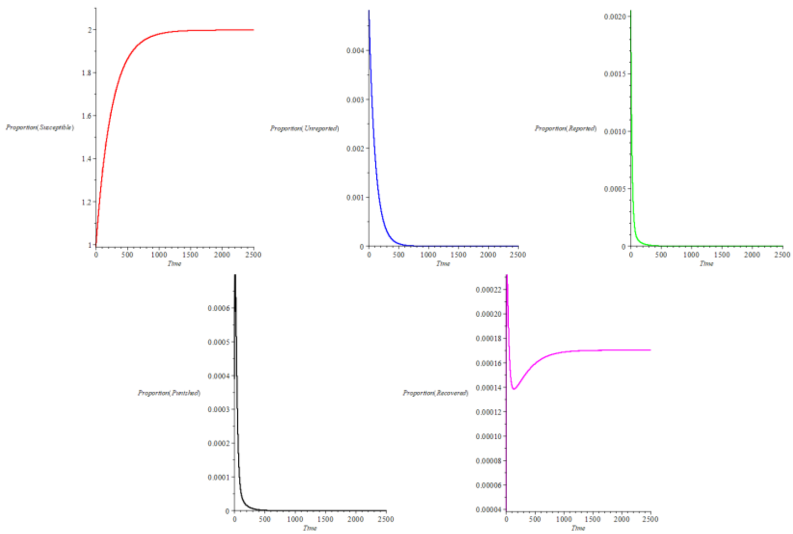

Figure 2
Solution graph of SUVPR model for gender based sexual violence-free equilibrium point

As shown in Figure 2, the populations of susceptible and recovered perpetrators increase toward the sexual violence-free equilibrium, while the numbers of unreported, reported, and punished perpetrators decline at a similar rate. This dynamic reflects the condition $\mathfrak{R}_0 = 0.0117309 < 1$, supporting the theorem that guarantees the sexual violence-free equilibrium stability occurs when $\mathfrak{R}_0 < 1$. Using Equation (4) in Simulation 2, the endemic equilibrium point is identified as $E_* = (1.44200, 0.45751, 0.05690, 0.03409, 0.00950)$.

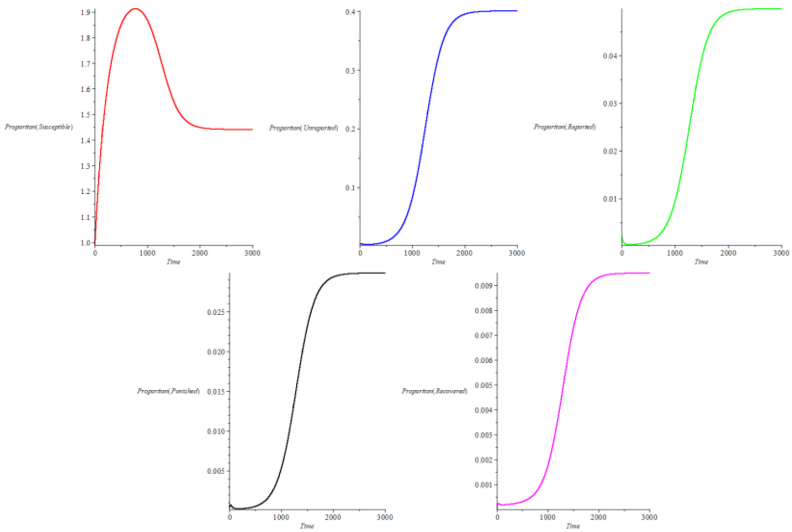

Figure 3
Solution graph of SUVPR model for gender based sexual violence endemic equilibrium point

Figure 3 displays the simulation results, indicating that all subpopulations converge to the endemic equilibrium due to $\mathfrak{R}_0 = 1.106713911$. This supports the theorem asserting that the endemic equilibrium is stable when $\mathfrak{R}_0 > 1$. In such conditions, each unreported or reported perpetrator, on average, leads to more than one new perpetrator, promoting the sustained transmission of sexual violence within the community.

4. Conclusion

The deterministic model in this study is employed to analyze the dynamics of sexual violence. The model's epidemiological and mathematical validity was established within a defined domain. Key parameters, including the basic reproduction number ($\mathfrak{R}_0$), the violence-free equilibrium (E_0), and the endemic equilibrium (E_*), were determined. Results show that E_0 is locally asymptotically stable when $\mathfrak{R}_0 < 1$, whereas E_* is stable when $\mathfrak{R}_0 > 1$.

This study identifies parameters α and β as critical drivers in the spread of sexual violence, where α denotes the effective contact rate from susceptible individuals to unreported perpetrators, and β represents the transition rate from unreported to reported perpetrators. Reducing these parameters is essential to curb the transmission of sexual violence within the population effectively.

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