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Research Article

A Mathematical Compartmental Model for Deradicalization in Indonesia: The SERTV Framework

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Abstract

Radicalism remains a critical threat to Indonesia's national security and social cohesion, necessitating urgent efforts to understand and mitigate its spread. This study develops a mathematical model to describe the dynamics of radicalization and deradicalization in Indonesia, using a compartmental structure that divides the population into susceptible, extremist, recruiter, treated, and vaccinated groups. The model incorporates a saturated incidence rate to capture the nonlinear effects of radical interactions. Numerical simulations are carried out using the fifth-order Runge–Kutta method to illustrate the transitions between population groups. The results indicate a significant decline in extremist and recruiter populations, while vaccination against radical ideas contributes to long-term resilience. Sensitivity analysis shows that the radicalization rate and recruitment effectiveness are the most influential parameters driving the spread of radicalism. These findings provide new insights into the mechanisms of radicalization and serve as a foundation for designing evidence-based preventive strategies.

Keywords: deradicalization, mathematical modeling, radicalism, saturated incidence rate, vaccination

1. INTRODUCTION

Radicalism and terrorism are two concepts that are often considered to be in opposition to one another. The term radical is usually associated with several different concepts, including political activity and extremism, increased religious fanaticism, and so forth [1]. Radicalism is an ideology that advocates for transformative change, restructuring, and the dismantling of existing systems and structures. Radicalism is characterized by a desire for comprehensive transformation, encompassing all aspects of society. From a linguistic perspective, radicalism diverges from terrorism [2]. Radicalism can be defined as a process of earnestly striving for success or ideals through positive actions, whereas terrorism is defined by its use of fear as a tool to achieve its goals. In addition to the dynamics and movement patterns of groups in society, the terms radicals and terror eventually become synonymous. This is because radicals can be considered the embryo of the terror movement. An individual with a radical mindset is at significant risk of engaging in acts of terror. The rapid dissemination of radical ideologies has precipitated a proliferation of terrorist attacks worldwide in recent years. Understanding the processes by which extremist tendencies develop and drive individuals to act is crucial from a cultural standpoint and for formulating effective response and prevention strategies.

As indicated by the Global Terrorism Index (2019), Indonesia occupies the 35th position out of 138 countries [3]. The country's terrorism index is classified as medium. Based on historical evidence, Indonesia has experienced four distinct periods of radical activity, the most prominent being the G/30/S/GKI. Indonesia remains vulnerable to radicalism and terrorism. The NGO Lazuardi Birru survey, conducted in 33 provinces with 1,240 respondents in 2011, revealed that the country's vulnerability index to radicalism is 43.6 points, with a safe level below 33.3 [4]. A further study conducted by the National Intelligence Agency (BIN) in 2017 revealed that approximately 39% of students from several universities had been exposed to radicalism [5].

Several prior studies have explored the mathematical modeling of radicalism. One notable example is Castillo's research, which focuses on modeling fanatical behavior as a possible precursor to radicalization. Similarly, Paul's study serves as an early effort to clarify the connection between

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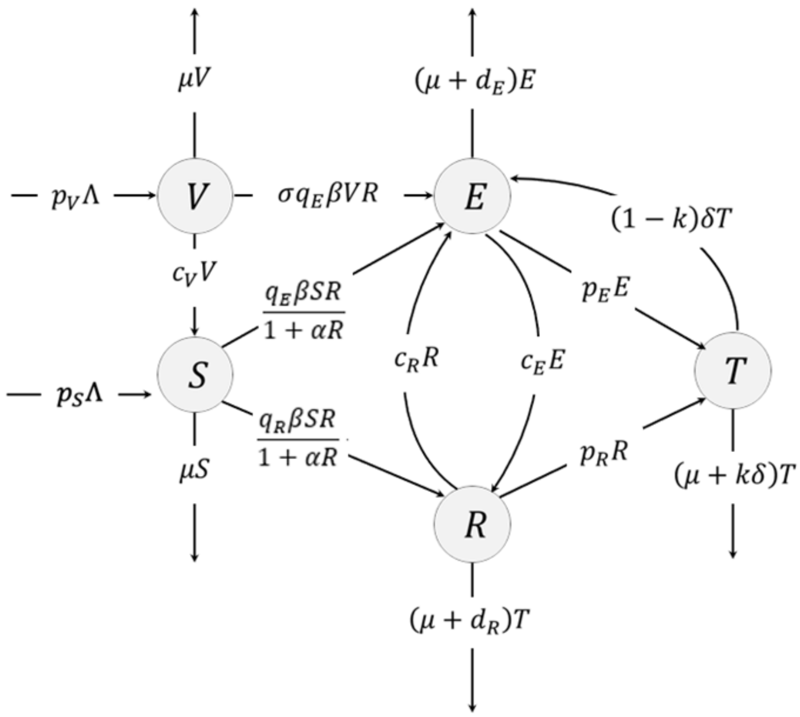

Figure 1. Flow diagram of the SERTV model.

modeling radicalism or terrorism and epidemiological principles. However, the conceptual framework used in this study largely relies on classical epidemic models [6][7]. The following research project employed the concept of epidemic disease modeling in a study conducted in Germany. However, the compartment represents an approach to the social domain [8][9]. This compartment employs a model that accommodates the SIR model, commonly used in epidemiological models [10]. Moreover, research conducted by Nathan has led to the development of not only a model of radicalism but also a model of de-radicalization. This has been achieved by including government intervention schemes for handling radicalism [11]-[16]. The following research by Chuang builds upon previous research on modeling radicalism using epidemiological models. In the context of deradicalization, it adds several additional compartments, including the recruiter, treatment, and vaccine compartments.

While previous studies have provided important foundations by adapting epidemiological models to the spread of radical ideas, they often rely on classical incidence assumptions and limited compartmental structures. These approaches may not fully capture the nonlinear effects of radical interactions or the complex pathways of deradicalization. To address these gaps, this research develops an extended compartmental model, i.e., susceptible–extremist–recruiter–treated –vaccinated (SERTV) that incorporates a saturated incidence rate to represent more realistic interaction patterns, where vaccination (anti-radical reasoning) is a proposed mitigation strategy. Numerical simulations are conducted using the fifth-order Runge–Kutta method, and sensitivity analysis is applied to identify the most influential parameters. Although previous studies have employed epidemic models to analyze radicalization, only a few have integrated a saturated incidence function along with treatment and vaccination strategies specifically tailored to Indonesia's socio-political context. This approach not only enhances the theoretical understanding of radicalization dynamics but also provides valuable insights for designing more effective future strategies to counter radicalism.

2. RESEARCH METHODS

The model developed in this study describes the dynamics of radicalization and deradicalization processes within the Indonesian population. The total population is divided into five distinct compartments: susceptible (S), extremists (E), recruiters (R), treated (T), and vaccinated (V). Each compartment represents a group of individuals characterized by specific behavioral attributes related to the radicalization process.

The S consists of individuals who are vulnerable to radicalization but have not yet been exposed to extremist ideologies. The E includes individuals who have adopted radical ideologies and may engage in extremist activities. The R represents individuals actively involved in recruiting others into radical groups, thereby contributing to the expansion of radical networks. The T comprises individuals who have undergone intervention or rehabilitation programs aimed at reducing radical tendencies, such as de-radicalization efforts. Finally, the V represents individuals who have received preventive measures, such as educational programs or community-based initiatives intended to build resilience against radicalization. The model illustrating the interactions among these compartments is presented in Figure 1.

The model utilizes a set of parameters to delineate the dynamics of individuals movement between compartments. The parameter μ denotes a typical mortality rate, which affects all compartments. The parameter β is defined as the rate of interaction between vulnerable individuals (S) and extremist individuals (E) as well as recruiters (R). This parameter quantifies the frequency vulnerable individuals are exposed to radical ideologies, which may escalate the risk of radicalization. The parameter denoted by δ, the radicalization mortality rate, indicates the mortality risk faced by treatment individuals (T).

Other parameters, such as p_V, denote the proportion of individuals entering the V compartment, and p_S denotes the proportion entering the S compartment, with $p_S = 1 - p_V$. q_E is the rate of recruitment of new individuals into the E compartment, while q_R is the rate of recruitment of new individuals into the R compartment with $q_R = 1 - q_E$ £ 0. It is imperative to understand the effectiveness of recruitment efforts made by radical groups, and these parameters are instrumental in doing so.

Furthermore, multiple parameters are capable of describing the rate at which individuals transition between the compartments above. The c_V denotes the rate at which individuals transition from the V to the S compartment, signifying the failure rate of vaccination in preventing radicalization. Conversely, c_E denotes the rate at which individuals transition from the E to the R compartment, thereby illustrating the recruitment process within extremist groups. The c_R is the rate at which individuals move from the R to the E compartment, indicating how recruits turn into extremists.

Furthermore, there are parameters d_E and d_R that describes the rate of death or life imprisonment for individuals in the E and R compartments. These parameters offer insights into the efficacy of law enforcement in addressing individuals engaged in radical activities. The parameter α_1 is defined as the saturated incidence rate, which quantifies the rate of radicalization incidents in the population that has reached a saturation state. The failure rate σ in the vaccination process, denoted by 0 £ σ £ 1 and representing the effectiveness of preventive measures in protecting individuals from radicalization, is another crucial metric. This diagram offers a visual depiction of the movement of individuals between different compartments, contingent on the parameters in place. To illustrate, individuals in the S compartment can transition to E or R through interactions with radicalized individuals, with the rate of this transition being determined by the parameter β. By comprehending these dynamics, researchers can formulate more efficacious intervention strategies to prevent and address the proliferation of radicalism.

The data utilized in this study were obtained from two primary sources: reports published by the National Counterterrorism Agency (BNPT) and population data provided by the Central Statistics Agency (BPS) of Indonesia. The total population is denoted by N , which represents the sum of all individuals across the five compartments, Equation 1.

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

The initial population values are set as $N(0)$ = 276343752, $E(0)$ = 12750, $R(0)$ = 4250, $T(0)$ = 1031, and $V(0) = 0$ [17]-[19]. The parameter values used in the model are adopted from several relevant studies on radicalization and are summarized in Table 1.

Table 1. Parameter values for the SERTV model.

Parameter	Value	Reference	Parameter	Value	Reference
Λ	7776	[17]	c_E	6×10^{-5}	[18]
μ	1.8×10^{-5}	[19]	c_R	8×10^{-5}	[18]
β	1.7×10^{-10}	Assumption	d_E	8.3×10^{-5}	[18]
δ	1.6×10^{-3}	[20]	d_R	8.3×10^{-5}	[18][21]
q_E	0.75	Assumption	p_V	0.3	[21]
q_R	0.25	Assumption	p_S	0.7	[21]
k	0.66	[20]	p_E	2.74×10^{-3}	[22]
σ	0.20	[21]	p_R	2.74×10^{-3}	[22]
c_V	5×10^{-5}	[21]	α_1	0.5	Assumption

This model is particularly salient in that it furnishes profound insight into the various factors that influence the spread of radicalization. This information can be used to design policies and programs to reduce the risk of radicalization in society. By comprehending the mechanisms through which individuals transition between different ideological categories and the factors that motivate these transitions, policymakers can formulate more effective measures to address the challenges posed by radicalization, thereby contributing to the preservation of security and social stability.

2.1. Mathematical Formulation of the Radicalization Model

In recent decades, epidemiological approaches have been employed to model the spread of radicalism. The model utilizes a compartmental diagram akin to those used in epidemiology to illustrate the spread of radicalism. Agents are analogous to ideologies, vectors to recruiters, and hosts to vulnerable individuals. While this analogy is indeed powerful, it is not entirely accurate. Vector -borne disease transmission, such as malaria, involves two species: the vector and the human host.

This radicalization model employs an analogy with tuberculosis (TB). The present study proposes a novel model to provide an overview of deradicalization. The model comprises five distinct compartments, namely *S*, *E*, *R*, *T*, and *V*. The incorporation of the *T* compartment serves to mitigate the influence of radicalization as a preventative program. The model is further enriched by incorporating a saturated incidence rate, which enhances the study's analytical rigor. The term vulnerable individual refers to those not influenced by extremist ideology. Individuals identified as extremists have been influenced by the ideology but have not taken action to disseminate it. Individuals identified as recruiters are those who proactively disseminate extremist ideology to vulnerable individuals. The accompanying Figure 1 offers a visual representation of this theoretical framework.

$$\frac{dS}{dT} = \dot{S} = L + p_S\Lambda + c_V V - \frac{q_E\beta SR}{1+\alpha_1 E} - \frac{q_R\beta SR}{1+\alpha_1 R} - \mu S \quad (2)$$

$$\frac{dE}{dT} = \dot{E} = \sigma q_E \beta VR + (1-k)\delta T + \frac{q_E\beta SR}{1+\alpha_1 E} + c_R R - c_E E - p_E E - (\mu + d_E)E \quad (3)$$

$$\frac{dR}{dt} = \dot{R} = \frac{q_R\beta SR}{1+\alpha_1 R} + c_E E - c_R R - p_R R - (\mu + d_R)R \quad (4)$$

$$\frac{dT}{dt} = \dot{T} = p_E E + p_R R - (1-k)\delta T - (\mu + k\delta)T \quad (5)$$

$$\frac{dV}{dt} = \dot{V} = p_V\Lambda - \sigma q_E \beta VR - \mu V - c_V V \quad (6)$$

As illustrated in Figure 1, the compartmental diagram provides a foundation for the subsequent mathematical model equation of deradicalization, expressed in Equations (2) – (6). In addition, the researcher implemented a numerical solution employing the Runge-Kutta method, which represents a refinement of the Euler method. The

RungeKutta method encompasses multiple orders, with the order selection determining the resulting numerical solution. In the context of the proposed radicalism model, the fifth-order Runge-Kutta method is employed to obtain numerical solutions. The fifth-order Runge-Kutta method has been demonstrated to be the most accurate method compared to the second, third, and fourth Runge-Kutta methods. The fifth-order Runge-Kutta method possesses five improvement coefficients, denoted by k_1, k_2, k_3, k_4, k_5. The improvement coefficient is an interrelated composition function. In this study, the fifth-order Runge-Kutta method is implemented. The numerical integration of the fifth Runge-Kutta method is as follows Equation 7.

$$y_{i+1} = y_i + \frac{h}{6}(k_1 + 4k_4 + k_5) \quad (7)$$

2.2. System Equilibrium Point

The equilibrium point of the model system can be obtained using Equations (2) – (6). It is imperative to establish that each equation is equivalent to zero . The objective is to ascertain the optimal condition, defined as the absence of change in the system's condition. To this end, the equilibrium point of the model system is obtained Eq. (8) – (12).

$$S^* = \frac{L + p_S\Lambda + c_V V}{\left(\left(\frac{q_E}{1+\alpha_1 E} + \frac{q_R}{1+\alpha_1 R}\right)\beta R + \mu\right)} \quad (8)$$

$$E^* = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \quad (9)$$

$$R^* = \frac{-B_2 + \sqrt{B_2^2 - 4A_2C_2}}{2A_2} \quad (10)$$

$$T^* = \frac{p_E E + p_R R}{\mu + \delta} \quad (11)$$

$$V^* = \frac{p_V \Lambda}{\sigma q_E \beta R + \mu + c_V} \quad (12)$$

with

$$A_1 = \alpha_1(c_E + p_E + \mu + d_E)$$

$$B_1 = (c_E + p_E + \mu + d_E) - \alpha_1 E(q_E\beta VR + (1-k)\delta T + c_R R)$$

$$C_1 = -q_E\beta SR + \sigma q_E \beta VR + (1-k)\delta T + c_R R$$

$$A_2 = \alpha_1(c_R + p_R + \mu + d_R)$$

$$B_2 = (c_R + p_R + \mu + d_R) - \alpha_1 c_E E - q_R\beta S$$

$$C_2 = -c_E E$$

The deradicalization model, formulated through an epidemiological approach, encompasses two system conditions: disease-free and epidemic states. When applied to the case under study, the system is characterized by radical-free and radicalism. In the radical-free condition, it is postulated that the population of extremist individuals and recruiters is nonexistent ($E = R = 0$). In the context of radicalism, the population sizes in each variable remain constant and equal to the initial value. Conversely, the equilibrium point is achieved when the system is devoid of radicals.

$$\xi_0 = (S_0^*; E_0^*; R_0^*; T_0^*; V_0^*) = (3.98 \times 10^8; 0; 0; 0; 3.43 \times 10^7)$$

The following equilibrium point is considered radical-free with respect to the number of individuals in treatment. The value of x is 0. This is consistent with the logical framework because if there are no radical individuals, there are also no individuals in treatment. Moreover, the condition of the system under the presence of radicalism is such that the equilibrium point is obtained:

$$\xi_1 = (S_1^*; E_1^*; R_1^*; T_1^*; V_1^*) = (3.98 \times 10^8; 27.50; 10.25; 63.93; 3.43 \times 10^7)$$

2.3. System Equilibrium Point

To analyze the stability properties of the system based on its conditions, it is necessary to perform a linearization process around the equilibrium point of the model system equation. The purpose of this process is to understand the general behavior of the system around the equilibrium point. The linearization process can be carried out using the Jacobian matrix of Equations (2) – (6). To ascertain the stability condition of the system concerning the equilibrium point, it is necessary to determine the eigenvector of the System Matrix (13):

$$J = \begin{pmatrix} \frac{\partial f_1}{\partial S} & \frac{\partial f_1}{\partial E} & \frac{\partial f_1}{\partial R} & \frac{\partial f_1}{\partial T} & \frac{\partial f_1}{\partial V} \\ \frac{\partial f_2}{\partial S} & \frac{\partial f_2}{\partial E} & \frac{\partial f_2}{\partial R} & \frac{\partial f_2}{\partial T} & \frac{\partial f_2}{\partial V} \\ \frac{\partial f_3}{\partial S} & \frac{\partial f_3}{\partial E} & \frac{\partial f_3}{\partial R} & \frac{\partial f_3}{\partial T} & \frac{\partial f_3}{\partial V} \\ \frac{\partial f_4}{\partial S} & \frac{\partial f_4}{\partial E} & \frac{\partial f_4}{\partial R} & \frac{\partial f_4}{\partial T} & \frac{\partial f_4}{\partial V} \\ \frac{\partial f_5}{\partial S} & \frac{\partial f_5}{\partial E} & \frac{\partial f_5}{\partial R} & \frac{\partial f_5}{\partial T} & \frac{\partial f_5}{\partial V} \end{pmatrix} \quad (13)$$

With f_i denotes the right-hand side of the Equations (2) – (6). The partial derivatives of f_i with respect to the variables *S, E, R, T,* and *V* are computed, and the resulting expressions are then evaluated at the radical free equilibrium point (ξ_0), yielding the Jacobian matrix $J(\xi_0)$ and at the radical existence equilibrium point (ξ_1), yielding the Jacobian matrix $J(\xi_1)$.

To evaluate the stability of the system, the eigenvalues are obtained by solving the characteristic equation derived from the Jacobian matrix, expressed in Equation (14).

$$|J(\xi_0) - \lambda I| = 0 \text{ and } |J(\xi_1) - \lambda I| = 0 \quad (14)$$

For the radical free condition, the eigenvalues obtained from $J(\xi_0)$: l_1 = -0.00001, l_2 = -0.00007, l_3 = 0.014, l_4 = -0.004, and l_5 = -0.0009. The presence of one positive eigenvalue ($l_3 > 0$) indicates that the system is unstable under radical-free conditions. This suggests that, in the absence of control measures, the radicalized population may continue to grow over time. In contrast, for the radical-existence condition, the eigenvalues obtained from $J(\xi_1)$ are: l_1 = -0.00002, l_2 = -0.002, l_3 = -0.001, l_4 = -0.005, and l_5 = -0.00007. Since all eigenvalues are negative, the system is asymptotically stable under these conditions. This result aligns with the expected dynamics, as continuous deradicalization programs, arrests, and preventive measures effectively reduce the populations of *E*, *R*, and *T* over time.

3. RESULTS AND DISCUSSIONS

3.1. Numerical Simulation

The simulation results obtained using the fifth-order Runge-Kutta method are illustrated in Figure 2. As the initial graph describes, the *S* group has demonstrated an escalation in figures, reaching approximately 2.78×10^8 with almost 2.9×10^8 over 7,000 days. The number of at-risk individuals has shown a consistent upward trend. This suggests that, despite factors such as extremist recruitment and vaccination failure that could reduce their numbers, the overall susceptible population continues to grow.

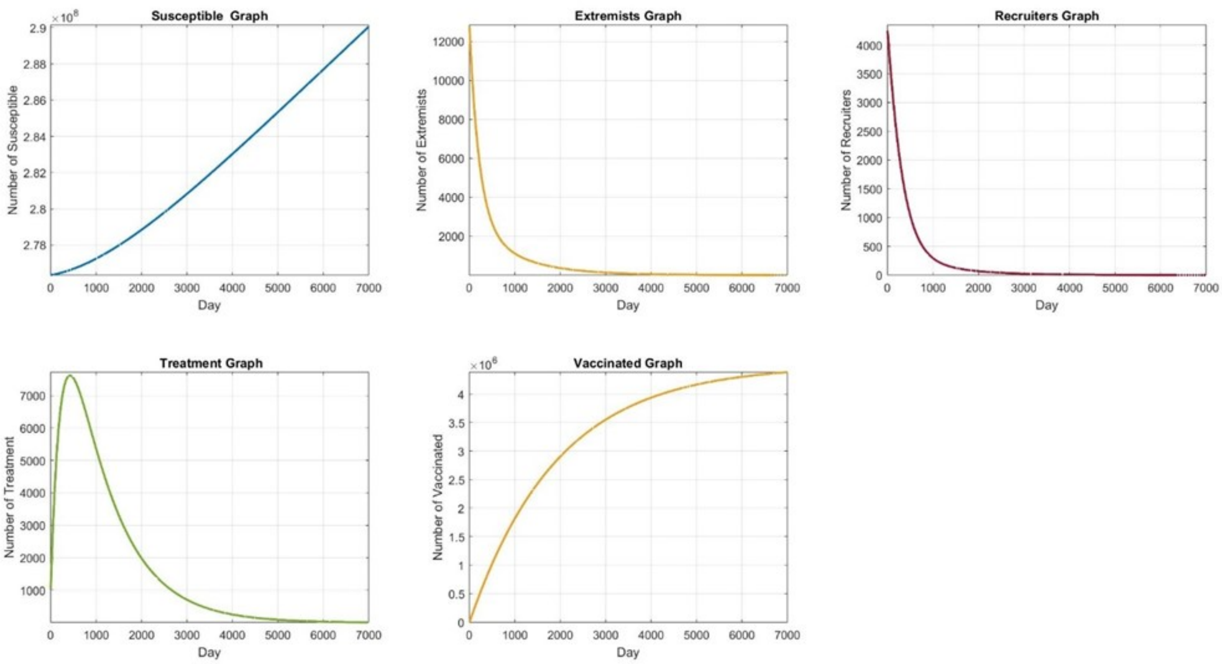

Figure 2. Simulation results illustrating population trend over time.

The second graph presents the modeling results of the *E* group, which exhibits a substantial decrease in the number of extremists from approximately 12,000 to nearly none over 7,000 days. This decline can be attributed to factors such as law enforcement interventions, successful treatment or deradicalization programs, and mortality among recruiters. These findings suggest that endeavors aimed at addressing extremist groups are efficacious in reducing the number of radical groups. This marked decrease may signify the efficacy of the deradicalization program. The third graph, *R* exhibits a precipitous decline from approximately 4,000 to nearly zero. As observed in the case of the extremist group, this decline is influenced by conversion to extremism, migration of individuals from *S* to *R* groups, and fatalities. Intensified efforts to address recruiters appear to be effective in reducing their numbers.

The fourth graph, designated as *T*, exhibits an initial increase in the number of treated individuals, reaching a peak of approximately 7,000 after 500 days, followed by a gradual decline to nearly zero. This initial increase might be attributed to the heightened surveillance and subsequent treatment of extremists and recruiters. The ensuing decline could indicate a reduction in the number of individuals requiring treatment over time. The *V* population graph displays a consistent increase in the vaccinated population, from an initial state of zero to approximately 4×10^6 over 7000 days. This outcome suggests the efficacy of the vaccination program despite potential failures in the vaccination process that could impede the rate of increase in the vaccinated population.

The influence of births, deaths, vaccination failure, and recruitment by extremist groups and recruiters on compartment *S* demonstrates the complexity of managing vulnerable populations to radicalism. This study underscores the importance of controlling these factors to prevent the increase of vulnerable populations. Vaccine failure, conversion to recruiters, capture to treated groups, and death are the primary factors affecting the *E* population. Effective management of these factors has proven critical in reducing the number of extremists.

The *R* group is subject to change, extremist influence, transfer from the *S* group, and death. The decline in recruiters signifies the efficacy of interventions directed toward this group. However, ongoing monitoring is necessary to avert an escalation in radicalism. The *T* group is impacted by the deaths and arrests of individuals belonging to the *E* and *R* groups. The decline in this group signifies the efficacy of deradicalization and rehabilitation programs in reducing the number of individuals requiring treatment. Births, deaths, and failures of the vaccination process influence the *V* group. The consistent increase in vaccinated individuals indicates the effectiveness of vaccination programs, which is an important step in reducing vulnerability to radicalism. The incorporation of saturated incidence rate (α_1) in this study demonstrates that the rate of radicalism transmission is reduced when the population of extremists or recruiters attains a certain level. The inclusion of the α_1 value has been shown to substantially impact the reduction of the transmission rate, thereby aiding in managing the number of populations exposed to radicalism. Furthermore, the incorporation of a_1 has been found to contribute to a decrease in the number of vulnerable populations using a reduction in the rate of transmission of radicalism. This, in turn, enhances the efficacy of interventions such as vaccination and treatment, which can assist in reducing the overall population of extremists and recruiters. Sustained efforts in vaccination and early intervention are imperative to attain long-term success, and the consistent improvement observed in vaccination efforts is a positive indication of the reduction of radicalism spread.

3.2. Basic Reproduction Number

The basic reproduction number (R_0) is a key parameter in understanding the spread of radicalization within a population. This value represents the average number of new individuals who become radicalized due to interactions with recruiters. If $R_0 > 1$, radicalization will spread within the population, whereas if $R_0 < 1$, radicalization will decline and eventually disappear. To compute R_0 , we use the Next Generation Matrix (NGM) method [23]. In this model, we consider three key compartments responsible for the spread of radicalization: *E*, *R*, and *T*.

Next, we define the X matrix as $(E, R, T)^t$, which

Table 2. The sensitivity index of each parameter.

Parameter	Sensitivity Index	Parameter	Sensitivity Index
Λ	1	c_E	0.01
μ	-1.07	c_R	-0.03
β	1	d_E	-4.52×10^{-4}
δ	6.68×10^{-5}	d_R	-0.03
q_E	9.42×10^{-3}	p_V	0.24
q_R	0.99	p_S	0.76
k	-0.01	p_E	-0.01
σ	1.60×10^{-4}	p_R	0.76
c_V	0.06		

represents the system's transition dynamics as $X = F - Z$, where: F is the transmission matrix, representing the rate at which individuals enter the E and R states due to interactions with recruiter individuals. Z is the transition matrix, describing the movement of individuals E, R, and T compartments.

Thus, the matrices are given as follows:

$$F = \begin{pmatrix} \sigma q_E \beta V R + \dfrac{q_E \beta S R}{1+\alpha_1 E} \\ \dfrac{q_R \beta S R}{1+\alpha_1 R} \\ 0 \end{pmatrix} \text{ and } Z = \begin{pmatrix} -(1-k)\delta T - c_R R + (c_E + p_E + \mu + d_E)E \\ -c_E E + (c_R + p_R + \mu + d_R)R \\ -p_E E - p_R R + (\delta + \mu)T \end{pmatrix}$$

The Jacobian matrices of F and Z at the radical-free equilibrium provide the dominant eigenvalue of FZ^{-1}, which determines the basic reproduction number: $R_0 = \frac{a}{b}$, with,

$$a = \beta\Lambda\big((c_E q_E + m_1 q_R)(p_S + p_V)c_V m_3 + \mu m_3(q_E c_E(p_V\sigma + p_S) + p_S q_R m_1) - (c_V(p_S + p_V) + p_S\mu)(1-k)p_E q_R \delta\big)$$

$$b = \mu(\mu + c_V)(m_3(m_1 m_2 - c_E c_R) - (c_E p_R + m_2 p_E)(1-k)\delta)$$

$$m_1 = c_E + p_E + \mu + d_E, m_2 = c_R + p_R + \mu + d_R, \text{ and } m_3 = \delta + \mu.$$

After some algebraic manipulation, we obtain:

$$\begin{aligned}(c_E q_E + m_1 q_R)(p_S + p_V)c_V m_3 + \mu m_3(q_E c_E(p_V\sigma + p_S) + p_S q_R m_1) \\ - (c_V(p_S + p_V) + p_S\mu)(1-k)p_E q_R \delta \\ = c_E q_E(p_S + p_V)c_V m_3 + (c_E + \mu + d_E)q_R(p_S + p_V)c_V\delta + m_1 q_R(p_S + p_V)c_V\mu \\ + \mu m_3 q_E c_E(p_V\sigma + p_S) + \delta\mu p_S q_R(c_E + \mu + d_E) + \mu^2 p_S q_R m_1 \\ + (c_V(p_S + p_V) + p_S\mu)p_E q_R \delta k\end{aligned}$$

$$\begin{aligned}m_3(m_1 m_2 - c_E c_R) - (c_E p_R + m_2 p_E)(1-k)\delta \\ = \delta(c_E(\mu + d_R) + (\mu + d_E)m_2) + \mu(c_E p_R + c_E(\mu + d_R) + (p_E + \mu + d_E)m_2) \\ + (c_E p_R + m_2 p_E)k\delta\end{aligned}$$

Hence, it is clear that $R_0 > 0$. Since the expression for R_0 remains positive for all valid parameter values, it follows that when $R_0 > 1$, radicalization will continue to increase within the population. Conversely, if $R_0 < 1$, radicalization can be suppressed and eventually eradicated from the system.

3.3. Sensitivity Analysis

After obtaining R_0, we conducted a sensitivity analysis to determine which parameters have the most significant influence on changes in R_0. The sensitivity analysis was performed using the method previously described [23]. Let m be the parameter under analysis. The sensitivity index of m is defined as:

$S^m = \frac{\partial R_0}{\partial m} \times \frac{m}{R_0}$ where S^m represents the sensitivity index of parameter m.

By computing this equation for all parameters in R_0 and substituting parameter values from Table 1, we obtained the sensitivity index values for each parameter, as presented in Table 2.

The interpretation of the sensitivity index is as follows: A positive sensitivity index indicates that an increase in the parameter leads to an increase in R_0, and vice versa. A negative sensitivity index implies that an increase in the parameter leads to a decrease in R_0, and vice versa. The largest positive and smallest (most negative) sensitivity values highlight the parameters that have the greatest influence on changes in R_0.

Hence, we conclude that parameters μ, Λ, β, and q_R are the most influential in determining the value of R_0. To further evaluate their impact, we conducted a comparative simulation to assess how variations in β and q_R as controllable parameters affect the E and R populations over time. The results are presented in Figure 3.

Figure 3 clearly demonstrates the nonlinear and time-dependent dynamics of radicalization. During the early phase (approximately the first 200 days), fluctuations in the extremist and recruiter populations remain relatively small, indicating a transient period where ideological transmission and recruitment are still stabilizing. However, the simulation results indicate that both the recruitment rate (q_R) and the radicalization transmission rate (β) significantly influence the growth of E and R populations. Higher values of q_R and β lead to a rapid increase in both populations, as seen in the red curves, while lower values (green and blue curves) result in a slower growth or even decline over time. The positive sensitivity indices of these parameters suggest that reducing recruitment effectiveness and limiting the spread of radical ideology can effectively suppress the extremist population. Specifically, lowering q_R leads to a reduction in recruiter numbers, which in turn weakens the extremist network, while decreasing β directly limits the spread of radicalization, preventing further growth of extremists. Therefore, intervention strategies should focus on disrupting recruitment processes and controlling exposure to radical influences to curb extremist expansion effectively.

Furthermore, our findings are consistent with and extend the theoretical frameworks developed by Castillo [6], Chuang & D'Orsogna [12], and Santoprete [24] who similarly emphasized the pivotal role of recruitment and ideological transmission in driving radicalization dynamics. In contrast to these prior models, our study integrates empirical deradicalization frameworks implemented by BNPT, particularly those emphasizing ideological vaccination through preventive education and community based rehabilitation for reintegration. This synthesis bridges mathematical modeling with real-world deradicalization practices, demonstrating that curbing recruitment and limiting ideological contagion are mathematically effective and practically aligned with Indonesia's national counter radicalization strategies.

These findings are consistent with Santoprete and Xu [18], who developed a deradicalization model using the SERT framework and demonstrated that radical-free stability can be achieved by strengthening intervention programs and reducing the efficiency of extremist ideological transmission. Their study highlights the crucial role of treatment as an active component in significantly decreasing the extremist population, which aligns with the Indonesian context, where the success of deradicalization programs implemented by BNPT reflects a real-world representation of the T compartment in our model. In addition, Wang and Bu [25] proposed a mathematical model of radicalization involving two ideologies that either compete or mutually reinforce each other, and their results indicate that an ideology with stronger cooperative structures and higher transmission effectiveness is more likely to persist and spread. This reinforces our sensitivity analysis, which shows that the transmission rate (β) and the proportion of individuals transitioning into extremism (q_E) are the most dominant parameters influencing R_0. Consequently, strategies that reduce recruitment effectiveness or disrupt the chain of radical ideological transmission become critically important for preventing the persistence and long-term sustainability of radicalism.

The findings also suggest that a higher rate of recruitment and a wider dissemination of radical ideology contribute to the rapid expansion of extremist and recruiter groups within society. When recruitment activities and ideological transmission occur intensively, extremist movements tend to grow swiftly, resembling the spread of an infectious social phenomenon. Conversely, when recruitment processes are effectively constrained and the propagation of radical narratives is controlled, the population of extremists and recruiters gradually declines over time [26].

While the numerical simulations and sensitivity analysis demonstrate that the proposed SERTV model effectively captures the core dynamics of radicalization and deradicalization in Indonesia, several limitations must be acknowledged when interpreting the results. First, the compartmental modeling framework necessarily simplifies complex human behaviors by representing radicalization and deradicalization processes as transitions between discrete population groups. In reality, these processes are shaped by multifaceted psychological, sociological, cultural, and ideological factors, as well as increasingly influential digital and social media ecosystems, which cannot be fully captured through aggregated compartments.

Second, several parameter values were adopted from existing literature or derived from demographic assumptions due to the limited availability of reliable empirical data on radicalization dynamics in Indonesia. Although this approach is common in mathematical modeling studies, such assumptions may affect the quantitative precision of the simulations and should be interpreted as illustrative rather than predictive. Third, the model assumes relatively stable policy and socio-political conditions, whereas in practice the effectiveness of deradicalization programs, law enforcement intensity, and preventive interventions may evolve over time in response to political, social, or technological changes.

These limitations suggest that the current findings should be viewed primarily as a theoretical and analytical framework to support understanding and strategic planning, rather than as exact forecasts of real-world outcomes. Future research could address these constraints by integrating psychological and sociological variables, incorporating digital radicalization pathways, and developing hybrid or agent-based models to capture individual-level heterogeneity. Moreover, the calibration of model parameters using empirical data from national deradicalization programs, including BNPT, Densus 88, and community-based interventions, would substantially enhance the policy relevance and empirical robustness of the proposed framework.

4. CONCLUSIONS

This study demonstrates that the implementation of deradicalization and prevention initiatives in Indonesia has produced positive outcomes, as reflected by a substantial decline in extremist and recruiter populations within the proposed SERTV mathematical framework. Numerical simulations indicate that law enforcement actions, deradicalization programs, and preventive vaccination strategies play a decisive role in suppressing radical dynamics. Although the susceptible population continues to increase, this finding underscores the need to strengthen preventive measures rather than questioning the effectiveness of existing interventions. The treated population initially increases in response to intensified intervention efforts and subsequently stabilizes, indicating a gradual reduction in individuals requiring rehabilitation. Meanwhile, the consistently increasing vaccinated population

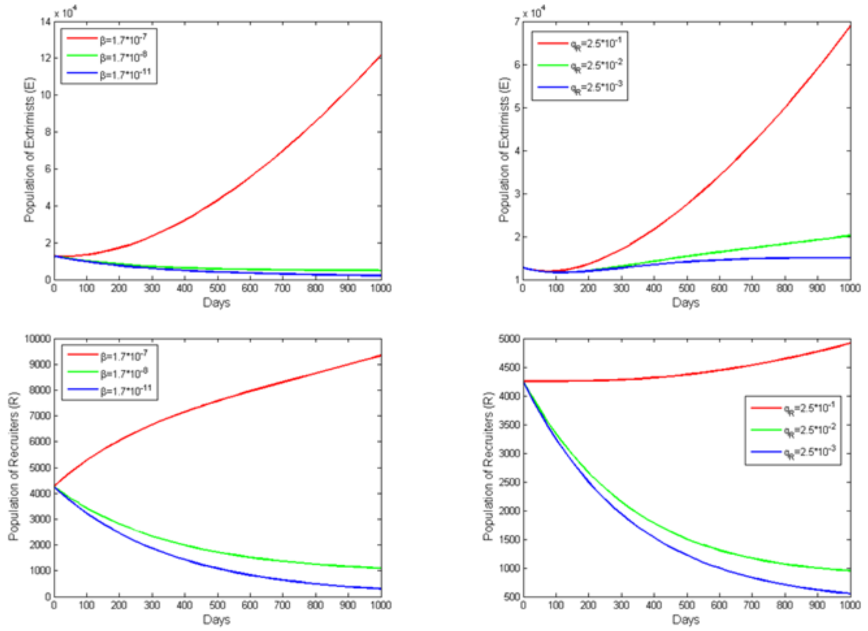

Figure 3. Impact of changes in parameter values β and q_R on populations E and R.

confirms the effectiveness of ideological vaccination programs in building long-term societal resilience against radicalization. The incorporation of a saturated incidence rate enhances model realism by demonstrating that radicalization transmission decreases at higher population levels, thereby improving the overall effectiveness of control strategies. Sensitivity analysis reveals that the recruitment rate and the radicalization transmission rate are the most influential parameters affecting the basic reproduction number and the growth of extremist and recruiter populations. Consequently, interventions aimed at disrupting recruitment networks and limiting ideological transmission emerge as the most effective deradicalization strategies. Overall, the SERTV model successfully fulfills the study's objectives by providing a robust analytical framework for understanding radicalization dynamics and supporting evidence-based policymaking in Indonesia.

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Conflicts of Interest

The authors declare no conflict of interest.

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DECLARATION OF GENERATIVE AI

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