FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 22, November, 2026, pp 326 – 331
DOI: https://doi.org/10.33003/fjs-2026-1022-6070

Mathematical Model of Canine Rabies Transmission Dynamics with Combined Pre and Post Exposure Vaccination

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Received: 03 Oct. 2026
Accepted: 30 Oct. 2026
Published: 04 Nov. 2026

ABSTRACT
Canine rabies remains an important public health concern, and mathematical modeling provides a useful framework for understanding its transmission dynamics and evaluating vaccination strategies. This study develops a deterministic mathematical model for canine rabies transmission incorporating pre- and post-exposure vaccination. The positivity and boundedness of the model solutions are established, the rabies-free equilibrium is determined, and the effective reproduction number is derived. The rabies-free equilibrium is shown to be locally asymptotically stable whenever $R_e < 1$ and unstable whenever $R_e > 1$. The condition for the existence of an endemic equilibrium is established, and sensitivity analysis indicates that R_e increases with the transmission contact rate β, whereas increasing the disease-induced death rate α reduces R_e. Numerical simulations are conducted to examine the effects of pre- and post-exposure vaccine effectiveness on rabies transmission dynamics. The results show that increasing the effectiveness of both vaccination strategies reduces rabies transmission and increases the number of protected dogs. However, pre-exposure vaccination has a greater effect on the protected dog population than post-exposure vaccination.

Keywords: Effective Reproduction Number, Local Stability Analysis, Sensitivity Analysis

INTRODUCTION

Rabies is a severe zoonotic viral disease that affects numerous domestic and wild mammalian species and continues to pose a significant public health and veterinary challenge worldwide. The disease is caused by the rabies virus, which targets the central nervous system and is almost always fatal after the onset of clinical symptoms. Although rabies can be effectively prevented through vaccination and appropriate control strategies, the disease remains endemic in many regions, particularly in areas where vaccination programs are insufficient and dog population management is inadequate (Hampson et al., 2015; World Health Organization, 2024).

Among domestic animals, dogs serve as the primary reservoir and source of transmission, largely because rabies spreads efficiently through interactions between infectious and susceptible dogs. The transmission of rabies among dogs is a key factor in sustaining the disease within canine populations. Following exposure to the virus from an infectious dog, a susceptible dog enters an incubation period before becoming capable of transmitting the infection. This transmission cycle enables rabies to persist even when the number of infectious animals remains relatively low. Several factors contribute to the maintenance of rabies within dog populations, including population recruitment, transmission rates, progression from exposure to infectiousness, disease-related mortality, natural death rates, and vaccination coverage levels (Layan et al., 2021; Hampson et al., 2015).

Vaccination remains the most effective strategy for controlling rabies in dogs. Both theoretical and empirical studies have shown that achieving and maintaining high vaccination coverage can significantly reduce disease transmission and eventually eliminate rabies from canine populations (Cleaveland et al., 2003; Layan et al., 2021). However, the success of vaccination programs depends on several factors beyond vaccine efficacy, including the proportion of dogs immunized, the frequency of vaccination campaigns, population turnover, and the ability to reach susceptible animals. Consequently, unvaccinated dogs continue to serve as a reservoir of susceptibility, allowing ongoing disease transmission. Pre-exposure vaccination is designed to protect susceptible dogs before contact with the rabies virus occurs. Within a mathematical modeling framework, this intervention can be represented by the transfer of susceptible individuals into a protected or vaccinated class at a rate determined by vaccination efforts and vaccine effectiveness. By decreasing the pool of susceptible dogs, pre-exposure vaccination reduces the likelihood of rabies spread through dog-to-dog contact. Previous investigations have consistently emphasized that maintaining high vaccination coverage is critical for suppressing rabies transmission and sustaining rabies-free canine populations (Cleaveland et al., 2003; Cleaveland et al., 2006; WHO, 2024).

Apart from pre-exposure vaccination, vaccination of dogs after exposure may also be considered as a potential intervention. The interpretation of this strategy depends on the vaccination history of the exposed animal. Veterinary recommendations differentiate between previously vaccinated dogs, for which immediate booster vaccination is advised following rabies exposure, and previously unvaccinated dogs, for which vaccination alone is generally not regarded as a dependable post-exposure measure (Centers for Disease Control and Prevention, 2025). Nevertheless, from a mathematical perspective, an intervention pathway involving exposed dogs can be incorporated to explore its potential influence on disease dynamics. Such an approach allows the assessment of the population-level impact of removing exposed individuals from the pathway that leads to

infectiousness. Mathematical modeling offers a valuable framework for understanding rabies transmission dynamics and evaluating control measures. Islam et al. (2026) developed deterministic SEI and SEIV models to assess dog-to-dog rabies transmission and the effects of pre- and post-exposure vaccination. Their findings showed that pre-exposure vaccination had a stronger control effect than post-exposure vaccination, while combining both strategies enhanced rabies control. The proposed model explicitly distinguishes between the pre- and post-exposure vaccination rates $v_1$and v_2 and their respective vaccine effectiveness parameters $\eta_1$and η_2, thereby enabling a more comprehensive assessment of the effects of imperfect vaccine effectiveness on rabies transmission and control. Therefore, this study aims to develop and analyze a deterministic mathematical model of canine rabies transmission incorporating both pre-exposure and post-exposure vaccination strategies.

MATERIALS AND METHODS

Model Assumptions

The assumptions of the model are presented below:

i. There is no recovery of infectious dogs
ii. The recruitment of the dog population is Λ
iii. Susceptible and exposed dogs are vaccinated
iv. Vaccinated dogs are assumed to remain protected and do not return to the susceptible class
v. All parameters are non-negative
vi. The initial conditions are non-negative with $S_d(0) > 0$, so that $N_d(0) > 0$.

Description of the Model

A deterministic compartmental model is formulated to describe the transmission dynamics of rabies within a dog population. The dog population is divided into four epidemiological compartments: susceptible dogs $S_d(t)$, exposed dogs $E_d(t)$, infectious dogs $I_d(t)$, and protected dogs $R_d(t)$. Thus, the total dog population at time t is given by

$$N_d(t) = S_d(t) + E_d(t) + I_d(t) + R_d(t) \quad (1)$$

Susceptible dogs become exposed through contact with infectious dogs at the force of infection

$$\lambda_d = \frac{\beta I_d}{N_d} \quad (2)$$

where β is the transmission contact rate. Susceptible dogs are vaccinated at rate v_1, with effectiveness η_1, and consequently move to the protected compartment. Exposed dogs are vaccinated at rate v_2, with effectiveness η_2, and also move to the protected compartment. Exposed dogs progress to the infectious class at rate δ. Infectious dogs experience disease-induced mortality at rate α, while all dog compartments are subject to natural mortality at rate μ and the dogs are recruited into the susceptible compartment at a constant rate Λ.

Schematic Diagram of the Model

The flow diagram of the model is presented in Figure 1

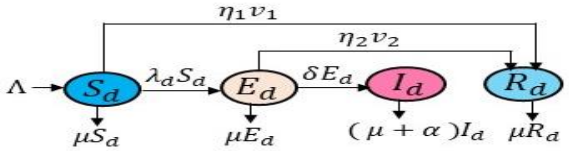


Figure 1: Model Diagram

Model Equations

The model equations are given below

$$\frac{dS_d}{dt} = \Lambda - (\lambda_d + \eta_1 v_1 + \mu) S_d \quad (3)$$

$$\frac{dE_d}{dt} = \lambda_d S_d - (\eta_2 v_2 + \delta + \mu) E_d \quad (4)$$

$$\frac{dI_d}{dt} = \delta E_d - (\alpha + \mu) I_d \quad (5)$$

$$\frac{dR_d}{dt} = \eta_1 v_1 S_d + \eta_2 v_2 E_d - \mu R_d \quad (6)$$

with initial conditions $S_d(0) > 0$, $E_d(0) \geq 0$, $I_d(0) \geq 0$, $R_d(0) \geq 0$

Parameters of the Model

The model parameters and their baseline values are presented in Table 1

Table 1: Model Parameters

Symbols	Descriptions	Baseline value	Source
Λ	Recruitment rate of dogs	3300 y^{-1}	Assumed
β	Transmission contact rate	$47y^{-1}$	Calculated
α	Disease-induced death rate	$64\,y^{-1}$	Islam *et al.* (2026)
μ	Per-capita natural death rate of dogs	$0.33\,y^{-1}$	Islam *et al*. (2026)
v_1	Pre-exposure vaccination of susceptible dogs	$0.18\,y^{-1}$	Islam et al. (2026)
v_2	Post-exposure vaccination of exposed dogs	$0.09\,y^{-1}$	Islam *et al*. (2026)
η_1	Effectiveness of the pre-exposure vaccination of susceptible dogs	0.9	Assumed
η_2	Effectiveness of the post exposure vaccination of exposed dogs	0.9	Assumed
δ	Progression rate from exposed to infectious dogs	$6\,y^{-1}$	Islam *et al*. (2026)

Positivity and Boundedness

Theorem 1

(Positivity of solutions). *For the model system (3)-(6), with non-negative initial conditions* $S_d(0) > 0$, $E_d(0) \geq 0$, $I_d(0) \geq 0$, $R_d(0) \geq 0$, *and non-negative model parameters, the solutions* $S_d(t)$, $E_d(t)$, $I_d(t)$, $R_d(t)$ *remain non-negative for all* $t \geq 0$.

Proof: Since $N_d(t) > 0$ then $0 \leq I_d(t) \leq N_d(t)$ and the force of infection λ_d is bounded above as follows: $\lambda_d = \frac{\beta I_d(t)}{N_d(t)} \leq \beta$ (7)

By the comparison theorem, from the susceptible dog equation (3), we have

$\frac{dS_d}{dt} \geq -(\lambda_d + \eta_1 v_1 + \mu)S_d$ (8)

$\frac{dS_d}{S_d} \geq -(\beta + \eta_1 v_1 + \mu)\mathrm{dt}$ (9)

Integrating equation (9), we obtain

$S_d(t) \geq S_d(0)e^{-t(\beta+\eta_1 v_1+\mu)} > 0$ (10)

following the same procedure on the remaining equations (4), (5) and (6) it follows that

$E_d(t) \geq E_d(0)e^{-t(\eta_2 v_2+\delta+\mu)} \geq 0$ (11)

$I_d(t) \geq I_d(0)e^{-t(\alpha+\mu)} \geq 0$ (12)

$R_d(t) \geq R_d(0)e^{-t\mu} \geq 0$ (13)

for all $t \geq 0$. Hence, the solutions of the model remain nonnegative.

Theorem 2 (Invariant Region)

For the model system (3)-(6), *the solutions remain bounded and the feasible region* Ω *is positively invariant,*

where $\Omega = \left\{(S_d, E_d, I_d, R_d) \in \mathbb{R}^4_+ : S_d + E_d + I_d + R_d \leq \frac{\Lambda}{\mu}\right\}$

Proof: Suppose $N_d(t) = S_d(t) + E_d(t) + I_d(t) + R_d(t)$ is bounded for all $t \geq 0$. Adding equations (3)-(6), we obtain

$\frac{dN_d}{dt} = \Lambda - \mu N_d - \alpha I_d$ (14)

$\frac{dN_d}{dt} \leq \Lambda - \mu N_d$ (15)

Solving equation (15), we obtain

$\mathrm{N_d(t)} \leq \frac{\Lambda}{\mu} + \left(\mathrm{N_d(0)} - \frac{\Lambda}{\mu}\right)\mathrm{e^{-t\mu}}$ (16)

Now, as $t \to \infty$ then $N_d(t) \leq \frac{\Lambda}{\mu}$. Thus, the solutions of the model are bounded in the feasible region Ω.

Rabies-Free Equilibrium (RFE)

The rabies-free equilibrium represents the state in which there is no rabies infection among the dog population. Therefore, the infected compartments are zero, such that ($E_d = I_d = 0$) which implies that the $\lambda_d^0 = 0$. Consequently, the post-exposure vaccination term ($\eta_2 v_2 E_d$) is zero because there are no exposed dogs, whereas pre-exposure vaccination of susceptible dogs remains active; thus, ($\eta_1 v_1$) need not be zero. Suppose the RFE of the model is defined as: $E^0 = (S_d^0, E_d^0, I_d^0, R_d^0)$ (17)

Setting the left-hand sides of the model equations (3)-(6) to zero and solving the resulting equilibrium equations with $N_d^0 = \Lambda/\mu$, we obtain

$E^0 = \left(\frac{\Lambda}{\eta_1 v_1+\mu},\ 0,\ 0,\ \frac{\Lambda\eta_1 v_1}{\mu(\eta_1 v_1+\mu)}\right)$ (18)

Effective Reproduction Number

The effective reproduction number (R_e) is determined using the approach adopted by Abubakar et al. (2025) and Bako et al. (2025). Let F denote the matrix of new infection terms, V the matrix of transfer terms, and ρ the spectral radius.

The effective reproduction number R_e is given by $R_e = \rho(FV^{-1})$. Where

$\mathrm{F} = \begin{pmatrix} 0 & \frac{\beta\mu}{\eta_1 v_1+\mu} \\ 0 & 0 \end{pmatrix}$ (19)

$\mathrm{V} = \begin{pmatrix} \eta_2 v_2 + \delta + \mu & 0 \\ -\delta & \alpha + \mu \end{pmatrix}$ (20)

$V^{-1} = \begin{pmatrix} \frac{1}{\eta_2 v_2+\delta+\mu} & 0 \\ \frac{\delta}{(\eta_2 v_2+\delta+\mu)(\alpha+\mu)} & \frac{1}{(\alpha+\mu)} \end{pmatrix}$ (21)

$\mathrm{FV^{-1}} = \begin{pmatrix} \frac{\beta\mu\delta}{(\eta_1 v_1+\mu)(\eta_2 v_2+\delta+\mu)(\alpha+\mu)} & \frac{\beta\mu}{(\eta_1 v_1+\mu)(\alpha+\mu)} \\ 0 & 0 \end{pmatrix}$ (22)

then

$R_e = \frac{\beta\mu\delta}{(\eta_1 v_1+\mu)(\eta_2 v_2+\delta+\mu)(\alpha+\mu)}$ (23)

Existence of Endemic Equilibrium

The endemic equilibrium of rabies represents the state in which rabies infection is present in the dog population. Therefore, the infected compartments are greater than zero, that is, $E_d^* > 0$ and $I_d^* > 0$. Consequently, the force of infection satisfies $\lambda_d^* > 0$. Let E^* represent the endemic equilibrium, defined by:

$E^* = (S_d^*, E_d^*, I_d^*, R_d^*)$ (24)

At equilibrium, the left-hand sides of the model equations (3)-(6) are zero. Solving the resulting equilibrium equations, we obtain

$S_d^* = \frac{\Lambda}{\lambda_d^*+\eta_1 v_1+\mu}$ (25)

$E_d^* = \frac{\Lambda\lambda_d^*}{(\lambda_d^*+\eta_1 v_1+\mu)(\eta_2 v_2+\delta+\mu)}$ (26)

$I_d^* = \frac{\Lambda\delta\lambda_d^*}{(\alpha+\mu)(\lambda_d^*+\eta_1 v_1+\mu)(\eta_2 v_2+\delta+\mu)}$ (27)

$R_d^* = \frac{\eta_1 v_1 S_d^* + \eta_2 v_2 E_d^*}{\mu}$ (28)

Theorem 3

The model described by equations (3)-(6) admits a positive endemic equilibrium if and only if $R_e > 1$.

Proof. From equation (14), at the endemic equilibrium, we have

$N_d{}^* = \frac{\Lambda - \alpha I_d^*}{\mu}$ (29)

Using equation (2) at the endemic equilibrium and substituting equation (29), we obtain

$\lambda_d^* = \frac{\mu\beta I_d^*}{\Lambda - \alpha I_d^*}$ (30)

From equation (30), it follows that

$I_d^* = \frac{\Lambda\lambda_d^*}{\mu\beta + \alpha\lambda_d^*}$ (31)

Equating the expressions for I_d^* obtained from equations (27) and (31) and solving for λ_d^*, we obtain

$\lambda_d^* = \frac{\beta\mu\delta - (\eta_1 v_1+\mu)(\eta_2 v_2+\delta+\mu)(\alpha+\mu)}{(\alpha+\mu)(\eta_2 v_2+\delta+\mu) - \alpha\delta}$ (32)

Using the effective reproduction number in (23), the numerator in equation (32) is expressed as $(\eta_1 v_1 + \mu)(\eta_2 v_2 + \delta + \mu)(\alpha + \mu)(R_e - 1)$ and the denominator is positive. Therefore, $\lambda_d^* > 0$. Hence the model admits a unique positive endemic equilibrium if and only if $R_e > 1$.

Local Stability of the Rabies-Free Equilibrium

Theorem 4

The rabies-free equilibrium E^0 *is locally asymptotically stable if* $R_e < 1$, *and unstable if* $R_e > 1$.

Proof. From the next-generation matrix method, the effective reproduction number is given in equation (23). Therefore, by the theorem of van den Driessche and Watmough (2002), the rabies-free equilibrium E^0 is locally asymptotically stable whenever $R_e < 1$ and unstable whenever $R_e > 1$.

RESULTS AND DISCUSSION

Sensitivity Analysis

A local sensitivity analysis was conducted to assess the influence of model parameters on the effective reproduction number (R_e). Normalized sensitivity indices were computed by evaluating the relative change in R_e resulting from a small perturbation in each parameter around its baseline value, while keeping the other parameters fixed. Parameters with larger absolute sensitivity indices have a greater influence on R_e near the baseline parameter values. The normalized local sensitivity indices of R_e are presented in equations (33)-(40)

$$\mathcal{S}_{\beta}^{\mathrm{Re}} = 1 \quad (33)$$

$$\mathcal{S}_{\mu}^{\mathrm{Re}} = 1 - \frac{\mu}{\eta_1 v_1 + \mu} - \frac{\mu}{\eta_2 v_2 + \delta + \mu} - \frac{\mu}{\alpha + \mu} \quad (34)$$

$$\mathcal{S}_{\delta}^{\mathrm{Re}} = \frac{\eta_2 v_2 + \mu}{\eta_2 v_2 + \delta + \mu} \quad (35)$$

$$\mathcal{S}_{\eta_1}^{\mathrm{Re}} = -\frac{\eta_1 v_1}{\eta_1 v_1 + \mu} \quad (36)$$

$$\mathcal{S}_{v_1}^{\mathrm{Re}} = -\frac{\eta_1 v_1}{\eta_1 v_1 + \mu} \quad (37)$$

$$\mathcal{S}_{\eta_2}^{R_e} = -\frac{\eta_2 v_2}{\eta_2 v_2 + \delta + \mu} \quad (38)$$

$$\mathcal{S}_{\alpha}^{R_e} = -\frac{\alpha}{\alpha + \mu} \quad (39)$$

$$\mathcal{S}_{v_2}^{R_e} = -\frac{\eta_2 v_2}{\eta_2 v_2 + \delta + \mu} \quad (40)$$

The sensitivity indices in Table 2 are generated by substituting the corresponding baseline parameter values from Table 1 into equations (33)-(40)

Table 2: Sensitivity Indices

Symbols	Sensitivity index	Remark
β	1.000	positive
α	-0.995	negative
μ	0.273	positive
v_1	-0.329	negative
v_2	-0.013	negative
η_1	-0.329	negative
η_2	-0.013	negative
δ	0.064	positive

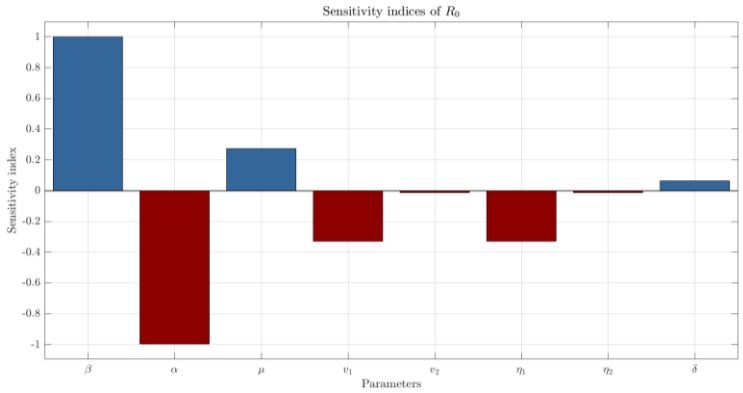


Figure 2: Local sensitivity indices of the effective reproduction number R_e

The sensitivity analysis indicates that the transmission rate β has the strongest positive influence on R_e, with a sensitivity index of $+1.000$. Meanwhile, the disease-induced death rate α has the strongest negative influence, with an index of -0.995, these findings are presented in Table 2 and illustrated in Figure 2. The pre-exposure vaccination rate v_1 and its effectiveness η_1 have moderate negative effects on R_e, while the post-exposure vaccination parameters v_2 and η_2 have relatively weak negative effects. The natural death rate μ and progression rate δ have relatively small positive influences on R_e. Overall, the results show that R_e is most sensitive to changes in β, α, and the pre-exposure vaccination parameters.

Numerical Simulation

Numerical simulations are performed to illustrate the transmission dynamics of canine rabies and examine the effects of combined pre- and post-exposure vaccination. Figure 3 shows the dynamics under the baseline parameters and the model equations (3) -(6) are solved numerically using the fourth-order Runge-Kutta method implemented in MATLAB R2024a. The baseline parameter values presented in Table 1 and the initial conditions $S_d(0) = 9500$, $E_d(0) = 300$, $I_d(0) = 200$ and $R_d(0) = 0$ are used in the simulations. The results show that increasing the effectiveness of both pre- and post-exposure vaccination increase the number of protected dogs. However, under the specified baseline parameter values and model assumptions, pre-exposure vaccination produced a greater increase in the protected dog population than post-exposure vaccination, as shown in Figure 4. Furthermore, the number of protected dogs under post-exposure vaccination gradually declined over time despite the initial increase associated with improved vaccine effectiveness.

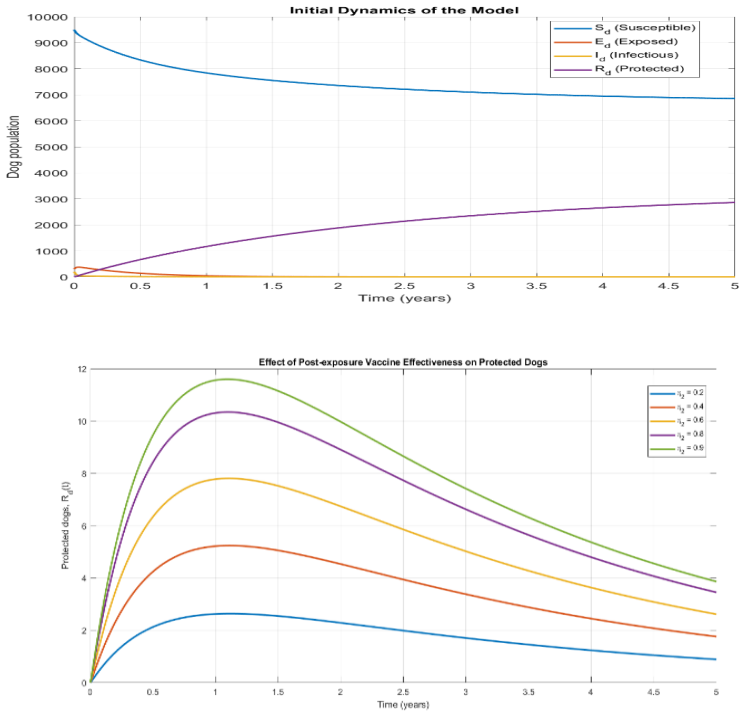


Figure 3: Initial dynamics of the canine rabies model

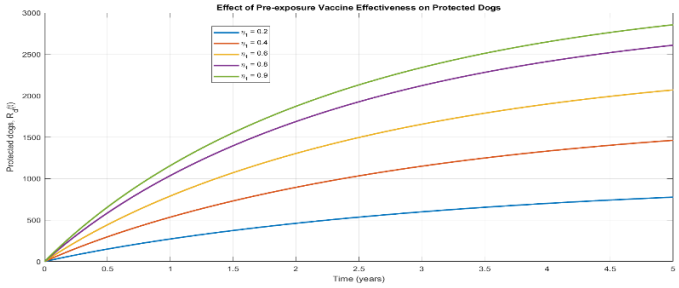


Figure 4: Numerical simulations with varying pre- and post-exposure vaccine effectiveness

(a) Effectiveness of v_1 on $R_d(t)$ (b) Effectiveness of v_2 on $R_d(t)$

Conclusion

This study developed a mathematical model for canine rabies transmission incorporating pre- and post-exposure vaccination. The positivity and boundedness of the model solutions were established, the rabies-free equilibrium was determined, the effective reproduction number was derived, the condition for the existence of an endemic rabies equilibrium was established, and local sensitivity analysis was performed. The study is limited by the assumption of homogeneous mixing among dogs and parameter uncertainty, which may affect the accuracy and generalizability of its findings. Future studies should calibrate and validate the model using empirical canine rabies data to improve its reliability and predictive capability.

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