Stability Analysis of Rice-Rat-Snake Population Dynamics Using Three Species Lotka-Volterra Model

Zakaria[1] and Dian Savitri[1,*]

[1] *University State of Surabaya, Surabaya, Indonesia*

Article Info	ABSTRACT
Article history: Received April 17th, 2025 Revised October 9th, 2025 Accepted October 12th, 2025 ***Corresponding Author:*** diansavitri@unesa.ac.id	Rice production is frequently threatened by rat infestations that reduce yield and compromise food security. The use of natural predators, such as snakes, is considered an environmentally friendly strategy to suppress rat populations. This study investigates the stability of a rice–rat–snake ecological system using a three-species Lotka–Volterra mathematical model. Rice is modeled as the primary producer with logistic growth, rats as herbivorous consumers, and snakes as predators. The model is formulated based on a literature review and biologically reasonable parameter assumptions. Equilibrium points are determined analytically, and their local stability is examined through Jacobian matrix analysis and eigenvalue evaluation. Numerical simulations are performed to illustrate the dynamic behavior of the populations over time. The results indicate the existence of an interior equilibrium that is locally asymptotically stable, characterized by damped oscillations converging toward coexistence. These findings suggest that snake predation plays an important role in regulating rat populations and maintaining rice stability, highlighting the potential of biological control for sustainable rice farming systems. ***Keywords:*** Population dynamics; Lotka–Volterra model; Stability analysis; Biological control; Numerical simulation

Introduction

Agriculture plays a crucial role in ensuring food security in Indonesia, with rice production serving as the primary food source for the majority of the population (Susanti *et al.*, 2024). Despite continuous efforts to increase productivity, rice cultivation remains vulnerable to pest disturbances, particularly from rats (Rattus spp.), which are recognized as one of the most destructive agricultural pests in rice fields (Singleton *et al.*, 2021). Uncontrolled rat populations can cause significant yield losses, threatening both farmers' livelihoods and national food stability (Noor *et al.*, 2023). Within rice field ecosystems, snakes function as natural predators of rats and contribute to regulating rat population growth (Shine *et al.*, 2024). Consequently, the interaction among rice plants as producers, rats as herbivores, and snakes as predators forms a complex trophic system that strongly influences ecosystem stability and agricultural productivity (Mandal *et al.*, 2023).

Mathematical modeling has been widely employed as an effective approach to analyze population interactions and to provide quantitative insights into ecosystem dynamics (Diz-Pita & Otero-Espinar, 2021). Predator–prey models, particularly those based on the classical Lotka–Volterra framework, have been extensively used to describe biological interactions between consumers and predators (Din *et al.*, 2024; Grunert *et al.*, 2021; Rahman *et al.*, 2013) . Numerous studies have applied Lotka–Volterra-type models to investigate population oscillations, equilibrium behavior, and long-term coexistence in ecological systems (Diz-Pita & Otero-Espinar, 2021; Gómez-Hernández *et al.*, 2024).

Several researchers have extended predator–prey models to agricultural contexts (Panja, 2023). Previous studies have examined rice–rat interactions by modeling rats as herbivores that consume rice biomass, highlighting the potential for rapid rat population growth when natural controls are absent (Noor *et al.*, 2023). Other studies have incorporated predators such as snakes or owls to evaluate biological pest control mechanisms and their effectiveness in suppressing rat populations (Saufi *et al.*, 2020). These works demonstrate that predator presence can significantly alter system dynamics and improve ecological balance in agroecosystems (Ghosh & Borzee, 2024).

However, most existing studies focus either on simplified two-species predator–prey systems or emphasize numerical simulations without providing a comprehensive analytical investigation of system stability (Diz-Pita & Otero-Espinar, 2021; Gómez-Hernández *et al.*, 2024). In particular, mathematical models that explicitly integrate rice as a renewable producer, rats as herbivores, and snakes as higher-level predators within a unified dynamical system remain limited (Khalighi *et al.*, 2021; Panja, 2023). Moreover, stability analysis around equilibrium points—which is essential for understanding whether population disturbances will decay or amplify over time—has received relatively less attention in the context of rice field ecosystems (Bassim *et al.*, 2024; Gómez-Hernández *et al.*, 2024).

This study addresses these gaps by formulating a three-species predator–prey model that captures the interactions among rice, rats, and snakes using a system of nonlinear ordinary differential equations of Lotka–Volterra type. Rice growth is modeled explicitly through a logistic term, while rat herbivory and snake predation are incorporated as interaction mechanisms within the same analytical framework. Equilibrium points of the system are derived analytically, and their local stability properties are investigated using Jacobian matrix analysis and eigenvalue criteria. The novelty of this study lies in the explicit integration of rice as a dynamic producer variable within a three-species Lotka–Volterra framework and the complete analytical characterization of local stability conditions for all equilibrium points. Unlike previous studies that emphasize numerical simulations or simplified subsystems, this work provides explicit stability criteria that clarify the parameter regimes ensuring pest suppression and stable coexistence. By linking mathematical stability conditions with biologically interpretable parameters, the results offer theoretical support for predator-based pest management strategies and contribute to a deeper understanding of sustainable rice field ecosystem dynamics.

Methods

This study employs an analytical mathematical modeling approach to investigate the dynamics of a rice–rat–snake ecological system. A system of nonlinear ordinary differential equations of Lotka–Volterra type is formulated based on biologically reasonable assumptions derived from the literature. Equilibrium points are obtained analytically, and their local stability is examined using Jacobian matrix analysis and eigenvalue criteria. Numerical simulations are then performed to illustrate the theoretical results.

Based on these assumptions, a three-species Lotka–Volterra-type system of nonlinear differential equations is formulated to represent the interactions among rice as a producer, rats as herbivores, and snakes as predators. The equilibrium points of the system are obtained by imposing zero population growth conditions. Local stability properties are then analyzed through linearization using the Jacobian matrix evaluated at each equilibrium points, followed by eigenvalue analysis to determine the stability characteristics of each equilibrium. Finally, the mathematical results are interpreted within a biological context to assess the implications of predator–prey interactions for population regulation and sustainable pest control strategies in rice field ecosystems.

Results and Discussion

In this section, the mathematical formulation of the rice–rat–snake population dynamics is presented as the foundation for subsequent analytical and stability investigations. The model is constructed using a Lotka–Volterra-type framework with logistic growth for the rice population, allowing the interaction between agricultural production and pest dynamics to be represented explicitly. This formulation captures the trophic structure of the ecosystem, where rice acts as a primary producer, rats function as herbivores, and snakes serve as natural predators.

Let $P(t)$ denote the rice population, $T_i(t)$ the rat population, and $U(t)$ the snake population at time t. The interaction among these populations is described by the following system of nonlinear differential equations:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) - \alpha P T_i \,,$$
$$\frac{dT_i}{dt} = \beta\alpha P T_i - cT_i - mT_i U \,,$$
$$\frac{dU}{dt} = \gamma m T_i U - sU \,,$$

where r represents the intrinsic growth rate of rice, K is the carrying capacity, α denotes the consumption rate of rice by rats, β is the conversion efficiency of consumed rice into rat biomass, c is the natural mortality rate of rats, m represents the predation rate of rats by snakes, γ is the conversion efficiency of prey into predator biomass, and s denotes the natural mortality rate of snakes.

The parameter values used in this study are adopted from the predator–prey model presented in (Rahmawati & Savitri, 2023), as summarized in Table 1.

Table 1. Model parameters, biological interpretations, and assumed values adopted from Rahmawati (2023)

Parameters	Assumption	Value
r	Intrinsic growth rate of rice	1
K	Rice availability	2000
α	The rate of price	0.0005
β	Conversion of rice consumption into rat births	0.30
c	Natural death of rats	0.20
m	Rate of predation of rats by snakes	0.001
γ	Conversion of mice into rats	0.40
s	Natural death of snakes	0.10

The model is analyzed under biologically reasonable initial conditions representing a moderate level of rice availability, a controlled rat population, and a relatively small predator population at the initial time. Specifically, the initial conditions are given by

$$P(0) = 1500,\ T_i(0) = 100,\ U(0) = 10$$

These values are chosen to reflect a typical rice field scenario in which rice biomass is below carrying capacity while pest and predator populations are present at nonzero levels, allowing the dynamical behavior of the system to be meaningfully examined.

To investigate the long-term behavior of the system, equilibrium points are determined by imposing the zero-growth conditions

$$\frac{dP}{dt} = 0,\ \frac{dT_i}{dt} = 0,\ \frac{dU}{dt} = 0$$

which correspond to states where all population densities remain constant over time. The resulting equilibrium points form the basis for subsequent stability analysis.

Local Stability Analysis

In this subsection, the equilibrium points of the rice–rat–snake model are analyzed to understand the local dynamical behavior of the system near steady states. Equilibrium analysis plays a central role in population dynamics, as it reveals whether small perturbations around biologically meaningful states will decay or amplify over time. The model admits the following equilibrium points:

$$E_0 = (0,0,0)$$

$$E_P = (K, 0,0)$$
$$E_{PT} = \left(\frac{c}{\beta a}, \frac{r}{a}\left(1 - \frac{c}{\beta a K}\right), 0\right)$$
$$E_{int} = \left(P^*, \frac{s}{\gamma m}, \frac{\beta a P^* - c}{m}\right)$$

where

$$P^* = K\left(1 - \frac{as}{r\gamma m}\right)$$

To investigate the local stability of each equilibrium point, linearization of the nonlinear system is performed. This is achieved through the Jacobian matrix, which captures the first-order partial derivatives of the system and provides a linear approximation of the dynamics near an equilibrium. Local stability is then determined by analyzing the eigenvalues of the Jacobian matrix evaluated at each equilibrium point: an equilibrium is locally asymptotically stable if all eigenvalues have negative real parts, unstable if at least one eigenvalue has a positive real part, and non-hyperbolic if eigenvalues with zero real parts exist.

The Jacobian matrix of the system is given by

$$J = \begin{pmatrix} r\left(1 - \frac{2P}{K}\right) - aTi & -aP & 0 \\ \beta a Ti & \beta a P - c - mU & -mTi \\ 0 & \gamma m U & \gamma m Ti - s \end{pmatrix}$$

Boundedness of Solutions

Before discussing stability at each equilibrium point, it is important to establish that the solutions of the system are biologically feasible. Since the rice population follows logistic growth and all interaction terms are nonnegative for positive populations, the solutions remain nonnegative for all $t > 0$. Moreover, the rice population is bounded above by the carrying capacity K, while the rat and snake populations are indirectly bounded through their dependence on rice availability and predation interactions. Therefore, all solutions of the system are positive and bounded in the biologically relevant region, ensuring the validity of the local stability analysis.

Local Stability of the Trivial Equilibrium E_0

The equilibrium point $E_0 = (0,0,0)$ represents the extinction of all populations. Substituting E_0 into the Jacobian matrix yields

$$J(E_0) = \begin{pmatrix} r & 0 & 0 \\ 0 & -c & 0 \\ 0 & 0 & -s \end{pmatrix}$$

The corresponding eigenvalues are

$$\lambda_1 = r, \lambda_2 = -c, \lambda_3 = -s$$

Since $r > 0$, at least one eigenvalue has a positive real part. Therefore, the equilibrium point $E_0$is unstable. This result indicates that the complete extinction state is not sustainable, as the rice population tends to grow when it is near zero, which is consistent with biological expectations.

Lemma (Local Stability Criterion)

Let E be an equilibrium point of the system. If all eigenvalues of the Jacobian matrix evaluated at E have negative real parts, then E is locally asymptotically stable. If at least one eigenvalue has a positive real part, then $E$is unstable. This lemma forms the basis for analyzing the stability of the remaining equilibrium points E_P, E_{PT}, and E_{int}, which are examined in the subsequent analysis.

Stability of the Rice-Only Equilibrium $E_P = (K, 0{,}0)$

The equilibrium point $E_P = (K, 0{,}0)$ represents a rice-only ecosystem in the absence of rats and snakes. Substituting E_P into the Jacobian matrix yields

$$J(E_P) = \begin{pmatrix} -r & -aK & 0 \\ 0 & \beta aK - c & 0 \\ 0 & 0 & -s \end{pmatrix}$$

The corresponding eigenvalues are

$$\lambda_1 = -r, \lambda_2 = \beta aK - c, \lambda_3 = -s$$

Since $\lambda_1 < 0$and $\lambda_3 < 0$, the local stability of $E_P$depends on the sign of λ_2. If $\beta\alpha K - c < 0$, then all eigenvalues have negative real parts and $E_P$is locally asymptotically stable. Conversely, if $\beta\alpha K - c > 0$, then $E_P$becomes unstable, indicating that the rat population can invade the rice-only equilibrium when its growth rate exceeds its natural mortality.

Stability of the Rice–Rat Equilibrium E_{PT}

The equilibrium point

$$E_{PT} = \left(\frac{c}{\beta a}, ., \frac{r}{a}\left(1 - \frac{c}{\beta aK}\right) ., 0\right)$$

corresponds to the coexistence of rice and rats in the absence of snakes. Evaluating the Jacobian matrix at E_{PT}gives

$$J(E_{PT}) = \begin{pmatrix} -\frac{rc}{\beta aK} & -\frac{c}{\beta} & 0 \\ \beta r\left(1 - \frac{c}{\beta aK}\right) & 0 & -\frac{mr}{a}\left(1 - \frac{c}{\beta aK}\right) \\ 0 & 0 & \gamma m\frac{r}{a}\left(1 - \frac{c}{\beta aK}\right) - s \end{pmatrix}$$

The eigenvalues consist of those associated with the upper-left 2×2block and the lower-right diagonal entry

$$\lambda = \gamma m\frac{r}{a}\left(1 - \frac{c}{\beta aK}\right) - s,$$

For the 2×2 block, the trace is negative and the determinant is positive provided that

$$\frac{r}{a}\left(1 - \frac{c}{\beta aK}\right) > 0,$$

which ensures that both eigenvalues have negative real parts. Consequently, the local stability of E_{PT} is governed by λ_3. If

$$\gamma m\frac{r}{a}\left(1 - \frac{c}{\beta aK}\right) - s < 0.$$

then E_{PT} is locally asymptotically stable. Otherwise, if $\lambda_3 > 0$, the equilibrium becomes unstable with respect to snake invasion. Biologically, this result indicates that although the rice–rat subsystem may reach equilibrium, sufficiently strong snake predation relative to snake mortality will drive the system toward a state in which snakes persist.

Stability of the Interior Equilibrium E_{int}

The interior equilibrium

$$E_{int} = \left(P^*, \frac{s}{\gamma m}, \frac{\beta a P^* - c}{m}\right),\ P^* = K\left(1 - \frac{as}{r\gamma m}\right)$$

represents the coexistence of rice, rats, and snakes. Provided that the existence conditions $P^* > 0$ and $\beta\alpha P^* > c$ are satisfied, the Jacobian matrix evaluated at E_{int} yields eigenvalues with negative real parts. Therefore, the interior equilibrium E_{int} is locally asymptotically stable, indicating a stable coexistence among all three populations.

Numerical Simulation

To complement the analytical results and to illustrate the dynamical behavior of the proposed model, numerical simulations are conducted in this subsection. Numerical simulation serves to visualize the temporal evolution of the rice–rat–snake populations and to validate the local stability results obtained from the equilibrium and eigenvalue analysis. Since this study is theoretical in nature, the parameter values used in the simulations are selected based on commonly adopted assumptions in predator–prey modeling and values reported in previous studies, rather than site-specific field data (Rahman et al., 2013; Windawati et al., 2020; Din et al., 2024). All simulations are performed using biologically reasonable initial conditions to ensure consistency with the analytical framework.

The primary objective of the numerical simulation is to examine how changes in key ecological parameters influence population stability and long-term coexistence. In particular, the simulations focus on the effects of (i) predation intensity of snakes on rats and (ii) natural mortality rates on system dynamics. These parameters are chosen because the analytical stability conditions explicitly indicate their critical role in determining whether boundary equilibria or interior equilibria are stable.

Time-Series Dynamics

Figure 1 illustrates the time-series dynamics of rice $P(t)$, rat $T_i(t)$, and snake $U(t)$ populations using the baseline parameter set

$$r = 0.8, K = 100, \alpha = 0.01, \beta = 0.02, c = 0.5, m = 0.005, \gamma = 0.03, s = 0.4,$$

with initial conditions $P(0) = 50$, $T_i(0) = 20$, and $U(0) = 10$. These values represent a moderate rice availability with relatively small initial pest and predator populations. The trajectories demonstrate the temporal evolution of all populations and show convergence toward a stable coexistence equilibrium, which is consistent with the local stability analysis of the interior equilibrium.

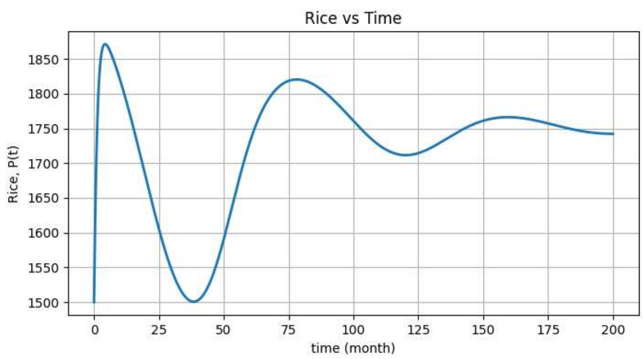

Figure 1. Time-series dynamics of rice, rat, and snake populations showing convergence toward the interior equilibrium.

Effect of Parameter Variation

To investigate the influence of parameter changes on system behavior, a second simulation is performed by modifying the predation rate $m$and the mortality parameters $c$and s, while keeping other parameters fixed. This modification is motivated by the analytical results, which indicate that these parameters govern the invasion or extinction of predators and the stability of the rice–rat equilibrium.

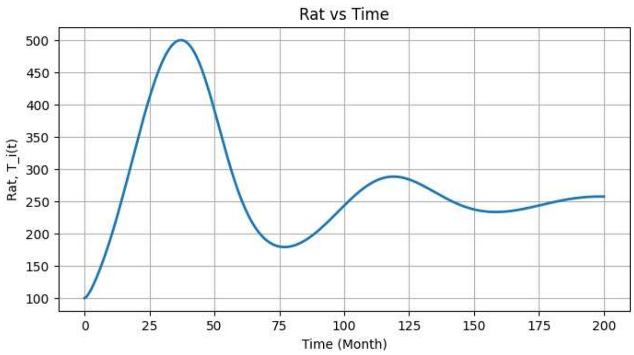

Figure 2. Time-series dynamics under modified parameter values showing the effects of predation and mortality on population stability and long-term coexistence.

Figure 2 shows that increasing the predation rate and predator efficiency alters the amplitude of population oscillations and accelerates convergence toward equilibrium, whereas higher mortality rates tend to suppress predator persistence. These results highlight the sensitivity of the system to predator–prey interaction strength and confirm the analytical conditions derived for local stability.

Phase Portrait Analysis

To further visualize the interaction structure of the system, phase portraits are presented. Figure 3 displays the phase portrait of the rice–rat subsystem in the (P, T_i)plane for the baseline parameter values. The trajectory shows convergence toward the rice–rat equilibrium, indicating stable interaction dynamics between rice growth and rat consumption.

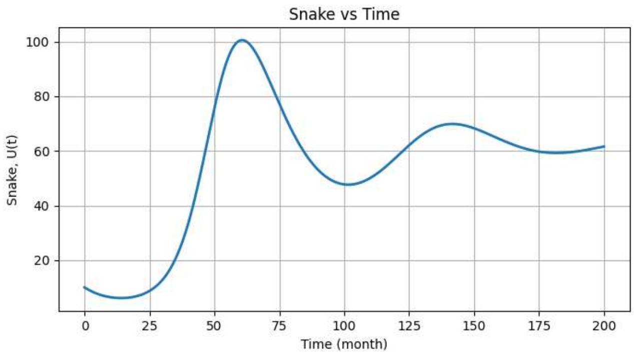

Figure 3. Phase portrait of the rice–rat subsystem in the (P, T_i)phase plane for the baseline parameter values, illustrating convergence toward the equilibrium point.

Figure 4 presents the phase portrait of the full rice–rat–snake system in the (T_i, U)phase space. The trajectory demonstrates the coupled predator–prey dynamics between rats and snakes and illustrates the system's approach toward the interior equilibrium, confirming the analytical prediction of stable coexistence.

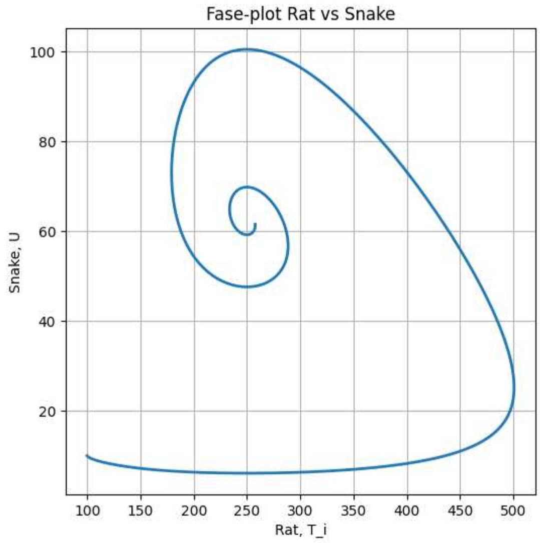

Figure 4. Phase portrait of the rice–rat–snake system in the (T_i, U)phase space, showing convergence toward the interior equilibrium of the three-species model.

The numerical simulations presented in Figures 1–4 illustrate the dynamic response of the rice–rat–snake system under both baseline and modified parameter settings. Among the model parameters, the predation rate of snakes on rats (m), the conversion efficiency of prey into predator biomass (γ), and the natural mortality rate of snakes (s) emerge as the most influential factors governing the stability of the equilibrium points. These parameters explicitly appear in the analytical stability conditions of both the rice–rat equilibrium and the interior coexistence equilibrium.

As shown in Figures 1 and 2, an increase in the predation-related parameters $m$and γenhances the ability of snakes to suppress rat population growth, leading to reduced oscillation amplitudes and faster convergence toward equilibrium. Conversely, higher snake mortality rates $s$weaken predator persistence and may destabilize the rice–rat equilibrium, allowing rat populations to increase. These numerical observations are fully consistent with the analytical condition

$$\gamma m \frac{r}{a}\left(1 - \frac{c}{\beta a K}\right) - s < 0.$$

which determines whether the rice–rat equilibrium remains stable against snake invasion.

The time-series simulations in Figure 1 demonstrate that the rat population initially increases due to abundant rice availability, followed by a gradual decline as snake predation becomes effective. The rice *population* experiences a temporary decrease caused by herbivory but subsequently stabilizes, while the snake population grows slowly and eventually reaches equilibrium. The gradual decay of oscillations observed in the simulations indicates that the system converges toward the interior equilibrium.

Phase portraits in Figures 3 and 4 further support this conclusion by showing trajectories that spiral toward equilibrium points in both the $(P, T_i)$and (T_i, U)phase planes. These results confirm the analytical finding that the interior equilibrium is locally asymptotically stable under biologically reasonable parameter values.

In summary, both analytical and numerical results demonstrate that predator-related parameters—particularly the predation rate m, predator efficiency γ, and predator mortality s—play a decisive role in determining the stability of equilibrium points in the rice–rat–snake system. The numerical *simulations* validate the theoretical predictions by illustrating how appropriate parameter regimes lead to stable coexistence among all three populations. From a biological perspective, these findings emphasize the importance of natural predators in regulating pest populations and maintaining ecological balance in rice field ecosystems, thereby supporting sustainable pest control strategies based on ecological principles.

Conclusion

This study investigates the local stability of a three-species rice–rat–snake population model based on a Lotka–Volterra food-chain structure, where rice acts as the producer, rats as herbivores, and snakes as natural predators. The analysis focuses on local stability properties of equilibrium points and their biological interpretation, supported by numerical simulations. The results demonstrate the existence of an interior equilibrium that is locally asymptotically stable under biologically reasonable conditions, indicating that sustainable coexistence among the three species is achievable.

The local stability of the system is primarily governed by a set of key parameters that directly influence pest control effectiveness. In particular, the predation rate of snakes on rats (m), the conversion efficiency of prey into predator biomass (γ), and the natural mortality rate of snakes (s) play a decisive role in determining whether rat populations can be suppressed. Numerical simulations confirm that higher predation intensity and predator efficiency, combined with sufficiently low predator mortality, lead to reduced rat population levels and damped oscillations toward equilibrium. These parameters are ecologically interpretable and, to some extent, controllable through habitat management strategies, such as conserving predator habitats or reducing practices that increase predator mortality.

From an agricultural perspective, the findings indicate that maintaining favorable conditions for natural predators can effectively prevent rat population outbreaks and protect rice yields without relying solely on chemical pest control. Therefore, local stability analysis of the proposed model provides a meaningful theoretical basis for understanding how controllable ecological parameters can be leveraged to achieve a rice production system that is resilient to rat infestations.

Future research may extend this framework by incorporating additional control mechanisms, seasonal effects, or environmental disturbances, as well as by calibrating the model with field data to enhance its applicability to real-world agricultural management.

Acknowledgements

The authors would like to express sincere gratitude to Universitas Negeri Surabaya (UNESA) for the institutional support provided during the preparation of this article.

References

Bassim, W. B., Salem, A. J., & Ali, A. H. (2024). A new analytical study of prey–predator dynamical systems involving the effects of Hide-and-Escape and predation skill augmentation. *Results in Control and Optimization*, *16*(100449).

Din, Q., Naseem, R. A., & Shabbir, M. S. (2024). Predator–Prey Interaction with Fear Effects: Stability, Bifurcation and Two-Parameter Analysis Incorporating Complex and Fractal Behavior. *Fractal and Fractional*, *8*(4). https://doi.org/10.3390/fractalfract8040221

Diz-Pita, É., & Otero-Espinar, M. V. (2021). Predator–prey models: A review of some recent advances. *Mathematics*, *9*(15). https://doi.org/10.3390/math9151783

Ghosh, D., & Borzee, A. (2024). Biological pest regulation can benefit from diverse predation modes. In *Royal Society Open Science* (Vol. 11, Number 9). Royal Society Publishing. https://doi.org/10.1098/rsos.240535

Gómez-Hernández, E. A., Moreno-Gómez, F. N., Córdova-Lepe, F., Bravo-Gaete, M., Velásquez, N. A., & Benítez, H. A. (2024). Eco-epidemiological predator–prey models: A review of models in ordinary differential equations. *Ecological Complexity*, *57*(101071).

Grunert, K., Holden, H., Jakobsen, E. R., & Stenseth, N. C. (2021). Evolutionarily stable strategies in stable and periodically fluctuating populations: The Rosenzweig-MacArthur predator-prey model. *Proceedings of the National Academy of Sciences (PNAS)*, *118*(4). https://doi.org/10.1073/pnas.2017463118/-/DCSupplemental.y

Khalighi, M., Eftekhari, L., Hosseinpour, S., & Lahti, L. (2021). Three-species lotka-volterra model with respect to caputo and caputo-fabrizio fractional operators. *Symmetry*, *13*(3), 1–22. https://doi.org/10.3390/sym13030368

Mandal, S., Oberst, S., Biswas, M. H. A., & Islam, M. S. (2023). Dynamic analysis and control of a rice-pest system under transcritical bifurcations. *PeerJ*, *11*. https://doi.org/10.7717/peerj.16083

Noor, H. M., Burhanuddin, M., Salim, H., Asrif, N. A., Jamian, S., & Azhar, B. (2023). Pest Rodents' Responses to Rice Farming in Northern Peninsular Malaysia. *Agronomy*, *13*(1). https://doi.org/10.3390/agronomy13010085

Panja, P. (2023). Dynamics of a crop, pest and predator model in an agricultural system. *Results in Control and Optimization*, *12*.

Rahman, H. A., Bahar, A., & Rosli, N. (2013). Jurnal Teknologi Parameter Estimation of Lotka-Volterra Model : A Two-Step Model. *Jurnal Teknologi*, *63*(2), 2180–3722. www.jurnalteknologi.utm.my

Rahmawati, R., & Savitri, D. (2023). Model Lotka-Volterra Yang Mempertimbangkan Efek Ketakutan Pada Prey Dengan Fungsi Respon Holling Tipe II. In *Jurnal Ilmiah Matematika* (Vol. 11).

Saufi, S., Ravindran, S., Hamid, N. H., Zainal Abidin, C. M. R., Ahmad, H., Ahmad, A. H., & Salim, H. (2020). Diet composition of introduced barn owls (Tyto alba javanica) in urban area in comparison with agriculture settings. *Journal of Urban Ecology*, *6*(1). https://doi.org/10.1093/jue/juz025

Shine, R., Dunstan, N., Abraham, J., & Mirtschin, P. (2024). Why Australian farmers should not kill venomous snakes. In *Animal Conservation* (Vol. 27, Number 4, pp. 415–425). John Wiley and Sons Inc. https://doi.org/10.1111/acv.12925

Singleton, G. R., Lorica, R. P., Htwe, N. M., & Stuart, A. M. (2021). Rodent management and cereal production in Asia: Balancing food security and conservation. *Pest Management Science*, *77*(10), 4249–4261.

Susanti, W. I., Cholidah, S. N., & Agus, F. (2024). Agroecological Nutrient Management Strategy for Attaining Sustainable Rice Self-Sufficiency in Indonesia. In *Sustainability (Switzerland)* (Vol. 16, Number 2). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su16020845