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Mathematical Modelling of a Delay Prey-Predator System using Caputo Fractional Derivatives

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***Abstract:** In this paper introduces a nonlinear fractional-order prey–predator model to describe the interaction between one prey species and two predator species in an ecological system. These model are formulated with the use of Caputo fractional derivative with time delay to represent memory and hereditary effects that naturally arise in biological processes. The model includes prey growth dynamics and nonlinear interaction terms among the three species. Local stability of the system is examined at different equilibrium points using the Jacobian matrix method. Numerical solutions of the fractional delay system are obtained using the fractional Adams–Bash forth –Moulton predictor–corrector scheme. The influence of different fractional orders $0 < \alpha < 1$is investigated and the results are compared with those of the classical integer-order model. Validation is carried out through comparisons with the fourth-order Runge – Kutta and classical Adams–Bash forth–Moulton methods. Numerical simulations confirm the accuracy, stability, and effectiveness of the proposed approach.*

***Keywords:** Prey–Predator Model; Caputo Fractional Derivative; Time Delay; Stability Analysis; Fractional Adams–Bash forth–Moulton Method; Runge – Kutta Method.*

I. INTRODUCTION

Applied mathematics provides powerful tools for describing natural phenomena and predicting the evolution of complex dynamical systems over time. In particular, mathematical modelling plays a significant role in ecology and economics, where population growth, species interactions, and system stability are influenced by multiple biological and environmental factors. Among these models, predator–prey systems are widely used to understand interaction mechanisms and long-term population behaviour. Several studies have investigated predator–prey dynamics under different ecological and mathematical assumptions. Agarwal and Pathak [1] examined optimal harvesting strategies in predator–prey models with Holling type-III functional response. Toaha et al. [2] performed stability analysis of predator–prey systems, emphasizing the dependence of predators on prey populations and the regulatory role of predation. It has been observed that excessive predation, limited prey availability, or slow prey growth may result in population decline or extinction.

The classical Lotka – Volterra model has been extensively modified to incorporate realistic features such as harvesting, time delays, and nonlinear functional responses. Srinivasu et al. [3] analyzed harvesting control mechanisms within the Lotka – Volterra framework, while Kar [4] studied selective harvesting with time delays. Didiharyono [5] investigated the stability of a one-prey two-predator system with Holling type-III response and harvesting, and later extended the analysis to constant harvesting strategies [6]. Kunal et al. [7] considered optimal harvesting in stage-structured predator–prey systems, and Li and Kaitai [8] derived conditions for positive and stable equilibria in multi-species interaction models. In parallel, various analytical and numerical techniques have been developed for solving nonlinear and fractional differential equations arising in population dynamics. Abd-Elhameed et al. [9,10] introduced spectral and operational matrix methods based on Chebyshev polynomials for solving Emden–Fowler and fractional Riccati equations. Abdallah et al. [11] applied the Fractional Reduced Differential Transform Method (FRDTM) to nonlinear fractional mutualism models. Hadziabdic et al. [12] analyzed a Lotka – Volterra system with two predators and one prey, while Noori et al. [13] studied convergence properties of reduced differential transform methods. Recent research has focused on fractional-order predator–prey models to capture memory and hereditary effects that cannot be described by classical integer-order systems. Abdallah and Ishag [14] proposed fractional predator–prey models, Romero-Ordonez et al. [15] investigated prey fear effects, and Zabidi et al. [16] and Bhalekar and Daftardar -Gejji [17] developed predictor–corrector numerical schemes for fractional differential equations. Motivated by these studies, the present work formulates a delayed prey–predator model consisting of one prey and two predator populations using the Caputo fractional derivative. The fractional Adams–Bash forth–Moulton (FABM) predictor–corrector method is employed to obtain accurate numerical solutions, particularly in the presence of time delays.

The proposed method is validated through comparison with classical numerical schemes, including the fourth-order Runge –Kutta method, demonstrating its accuracy, stability, and computational efficiency.
We consider a prey–predator system consisting of one prey population x(t) and two predator populations y(t) and z(t). The dynamics with constant time delay τ and harvesting effects are governed by the following system of differential equations:

$$\frac{dx}{dt} = a\,x(t)\left[1-\frac{x(t)}{k}\right] - \beta x(t-\tau)y(t-\tau) - \gamma x(t)z(t) - E_1\,x(t)$$
$$\frac{dy}{dt} = -by(t) + \beta x(t-\tau)y(t-\tau) - dy(t) - E_2\,y(t) \qquad [1]$$
$$\frac{dz}{dt} = -cz(t) + \gamma(t)z(t) - dy(t) - E_3\,z(t)$$

Here, a denotes the intrinsic growth rate of the prey, k is the carrying capacity, and b and c represent the natural death rates of the predators. The parameters β and γ are predation coefficients, d denotes the conversion rate from the first predator to the second predator, and E1, E2, E3 represent harvesting rates. The time delay τ accounts for delayed predator–prey interactions.
To incorporate memory effects, the classical model is extended to a fractional-order framework using the Caputo derivative of order $0 < \omega < 1$:

The equation is

$$D_t^{\omega}\,x(t) = \alpha_1 x(t) - x^2(t)\delta - \beta x(t-\tau)y(t-\tau) - \gamma x(t)z(t)$$
$$D_t^{\omega}\,y(t) = -\alpha_2 y(t) + \beta x(t-\tau)y(t-\tau) \qquad [2]$$
$$D_t^{\omega}\,z(t) = -\alpha_3 z(t) + \gamma x(t)z(t) + dy(t) \qquad 0 < \omega < 1.$$

The initial functions are defined on the interval $t \in [-\tau, 0]$. This fractional formulation allows the model to capture nonlocal temporal effects and provides a more realistic description of population dynamics.

II. PRELIMINARIES

In this section, we recall some fundamental definitions from fractional calculus that are required for the formulation of the proposed fractional prey–predator model and the development of the numerical scheme.

1) *Definition 1*

The Caputo fractional derivative of order α is defined as the n^{th} integer derivative of the function by an integral with a fractional power in the kernel

$$cD_a^{\alpha}\ f(x) = \frac{1}{\Gamma(n-\alpha)}\int_a^x \frac{f^n(t)}{(x-t)^{\alpha-n+1}}\ dt$$

Where $n-1 < \alpha < n\ \forall n \in N$
In case n=1 the Caputo fractional derivative reduces to

$$cD_a^{\alpha}\ f(x) = \frac{1}{\Gamma(1-\alpha)}\int_a^x \frac{f'(t)}{(x-t)^{\alpha}}\ dt \quad [3]$$

The Caputo derivative is particularly suitable for physical and biological applications, since it allows the use of classical initial conditions.

2) *Definition 2*

A fractional Volterra integral equation of order α is expressed as

$$D^{\alpha}(u(x)) = f(x) + \lambda\int_0^x k(x.t)u(t)dt \ [4]$$

Where u(x) is the unknown function, D^{α} is a fractional order derivative , f(x),k(x , t) is a known continuous function and λ is a constant.
Fractional Volterra integral equations naturally arise in the numerical treatment of fractional differential equations and play an important role in the formulation of predictor–corrector schemes.

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III. METHODOLOGY

A. Lotka – Volterra Predator–Prey Model with Delay

In this section we have examined the classical model of the lotka - volterra equation in one prey and two predators in the non linear differential equation of delay.

$X(t) = \alpha_1 x(t) - x(t-\tau)y(t-\tau) - x(t)z(t)$
$Y(t) = -\alpha_2 y(t) - y(t-\tau)x(t-\tau)$
$Z(t) = -\alpha_3 z(t) - z(t)x(t)$

Where $\tau > 0$ is a constant time delay . we will represent the delayed equation can be proved the stability conditions also

$$F(t) = \begin{bmatrix} \alpha_1 x(t) - x(t-\tau)y(t-\tau) - x(t)z(t) \\ -\alpha_2 y(t) - y(t-\tau)x(t-\tau) \\ -\alpha_3 z(t) - z(t)x(t) \end{bmatrix} \qquad [5]$$

Therefore x, y, z are the population of prey and predators and the parameters of $\alpha_1, \alpha_2, \alpha_3 \geq 0$.

B. Local Stability Analysis

The local stability of the equilibrium points of system (5) is analyzed using the Jacobian matrix technique. This approach describes the behaviour f the system in a small neighbourhood around each equilibrium point. For linearization, the delay terms are neglected, and the Jacobian matrix of system (5) is obtained as

$$J(t) = \begin{bmatrix} \alpha_1 - z(t) & -x(t) & -x(t) \\ y(t) & -\alpha_2 + x(t) & 0 \\ z(t) & 0 & -\alpha_3 - x(t) \end{bmatrix} \qquad [6]$$

The local stability of each equilibrium point is determined by evaluating the eigen values of the Jacobian matrix at that point. An equilibrium point is locally asymptotically stable if all eigen values have negative real parts otherwise it is unstable.

C. Equilibrium Points

The equilibrium points of system (5) are obtained by setting and solving the resulting algebraic equations yields the following equilibrium points:

1) Trivial equilibrium (extinction state):
   $t_0 = (0,0,0)$
2) Prey-only equilibrium:
   $t_1 = (\alpha_1, 0, 0)$,which corresponds to the absence of both predator species.
3) Prey–first predator equilibrium:
   $t_2 = (\alpha_2, \alpha_1, 0)$ representing coexistence of the prey and the first predator only.
4) Prey–second predator equilibrium:
   $t_3 = (\alpha_3, 0, \alpha_1)$, representing coexistence of the prey and the second predator only.

These equilibrium points form the basis for the subsequent stability and bifurcation analysis of the delayed predator–prey system.

a) Theorem 1

Given the nonlinear differential equation of the system of eq [5] and therefore the equilibrium point is (0,0,0) is unstable.

Proof :

The Jacobian matrix of system

$$J(t) = \begin{bmatrix} \alpha_1 - z(t) & -x(t) & -x(t) \\ y(t) & -\alpha_2 + x(t) & 0 \\ z(t) & 0 & -\alpha_3 - x(t) \end{bmatrix}$$

and the equilibrium point of t_0 is given by

$$J(t_0) = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & -\alpha_2 & 0 \\ 0 & 0 & -\alpha_3 \end{bmatrix}$$

The corresponding eigen values are$\lambda 1 = \alpha 1 > 0, \lambda 2 = -\alpha 2 < 0$, $\lambda 3 = -\alpha 3 < 0$. Since at least one eigen value has a positive real part, so the equilibrium point of t_0 is unstable .

b) Theorem 2

Given the nonlinear differential equation of the system of eq [5] and therefore the equilibrium point is (α_1,0 ,0) is unstable.

Proof ;

The Jacobian matrix of system

$$J(t) = \begin{bmatrix} \alpha_1 - z(t) & -x(t) & -x(t) \\ y(t) & -\alpha_2 + x(t) & 0 \\ z(t) & 0 & -\alpha_3 - x(t) \end{bmatrix}$$

and the equilibrium point of t_1 is given by

$$J(t_1) = \begin{bmatrix} \alpha_1 & -\alpha_1 & -\alpha_1 \\ 0 & \alpha_2 - \alpha_1 & 0 \\ 0 & 0 & -\alpha_3 - \alpha_1 \end{bmatrix}$$

The eigen values are$\lambda 1=\alpha_1$,$\lambda 2=\alpha_1 - \alpha_2$,$\lambda 3=\alpha_1 - \alpha_3$. Since at least one eigenvalue is positive ($\lambda 1>0$), the prey-only equilibrium t_1 is unstable.

c) Theorem 3

Given the nonlinear differential equation of the system of eq [5] and therefore the equilibrium point (α_2,α_1,0), is locally asymptotically stable provided that $\alpha_2<\alpha_1$and$\alpha_2<\alpha_3$.

Proof:

The Jacobian matrix of system

$$J(t) = \begin{bmatrix} \alpha_1 - z(t) & -x(t) & -x(t) \\ y(t) & -\alpha_2 + x(t) & 0 \\ z(t) & 0 & -\alpha_3 - x(t) \end{bmatrix}$$

and the equilibrium point of t_2 is given by

$$J(t_2) = \begin{bmatrix} \alpha_1 & -\alpha_2 & -\alpha_2 \\ \alpha_1 & 0 & 0 \\ 0 & 0 & -\alpha_2 - \alpha_3 \end{bmatrix}$$

The characteristic equation yields three eigen values. Two eigen values associated with the prey–first predator subsystem have negative real parts under the condition $\alpha_2<\alpha_1$. The third eigenvalue is given by $\lambda 3=\alpha_2 - \alpha_3$.Hence, all eigen values have negative real parts if $\alpha_2<\alpha_3$. Therefore, under the conditions$\alpha_2<\alpha_1$and $\alpha_2<\alpha_3$the equilibrium point of $t_2$is locally asymptotically stable.

d) Theorem 4

Given the nonlinear differential equation of the system of eq [5] and therefore the equilibrium point (α_3,0,α_1), is not locally asymptotically stable .

Proof :

The Jacobian matrix of system

$$J(t) = \begin{bmatrix} \alpha_1 - z(t) & -x(t) & -x(t) \\ y(t) & -\alpha_2 + x(t) & 0 \\ z(t) & 0 & -\alpha_3 - x(t) \end{bmatrix}$$

and the equilibrium point of t_3 is given by

$$J(t_3) = \begin{bmatrix} 0 & -\alpha_3 & -\alpha_3 \\ 0 & \alpha_3 - \alpha_2 & 0 \\ \alpha_1 & 0 & 0 \end{bmatrix}$$

The characteristic equation of this matrix admits at least one eigen value with zero or purely imaginary real part, depending on the parameter values. Consequently, the equilibrium point $t_3$does not satisfy the conditions required for asymptotic stability.Hence, t_3 is not asymptotically stable.

D. Fractional Adams-Bash forth - Moluton (ABM) PECE Method

Let us define a fractional differential equation of order $\alpha \epsilon (0,1)$ in caputo sense

$cD_t^{\alpha}\ y(t) = f(t, y(t)) \quad y(0) = y_0$

Volterra integral equation

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$y(t) = y_0 + \frac{1}{\Gamma(\alpha)}\int_0^t t - \tau^{\alpha-1} f(\tau, y(\tau))\ d\tau$ [7]

Where $\Gamma(\alpha)$ is the gamma function.

1) Adams-Bash Forth Predictor

$$y_{n+1}^P = y_0 + \frac{1}{\Gamma(\alpha)}\sum_{j=0}^{n}\int_{t_j}^{t_{j+1}} (t_{n+1} - \tau)^{\alpha-1} f(\tau, y(\tau))\ d\tau$$

$$\int_0^t t - \tau^{\alpha-1} f(\tau, y(\tau))\ d\tau = \frac{h^\alpha}{\alpha}\left[b_{n-j} f(t_j, y_j) + b_{n-j-1} f(t_{j+1}, y_{j+1}{}^p) + \cdots\right]$$

$y_{n+1}^P = y_0 + \frac{1}{\Gamma(\alpha)}\sum_{j=0}^{n} b_{j,n+1} f(t_j, y_j)$ [8]

2) Adams-Bash forth Corrector

$$y_{n+1}^c = y_0 + \frac{1}{\Gamma(\alpha)}\int_0^{t^n} (t_{n+1} - \tau)^{\alpha-1} f(\tau, y(\tau))\ d\tau + \int_{t_n}^{t_{n+1}} (t_{n+1} - \tau)^{\alpha-1} f(\tau, y(\tau))\ d\tau$$

$$y_{n+1}^c = y_0 + \frac{h^\alpha}{\Gamma(\alpha+1)}\ f(t_{n+1}, y_{n+1}{}^p) + \frac{h^\alpha}{\Gamma(\alpha+2)}\sum_{j=0}^{n} a_{n-j} f(t_j, y_j)$$

$y_{n+1}^c = y_0 + \frac{h^\alpha}{\Gamma(\alpha+1)}\left[\sum_{j=0}^{n} a_{0,n+1} f(t_{n+1}, y_{n+1}^P) + \sum_{j=0}^{n} a_{j,n+1} f(t_j, y_j)\right]$ [9]

3) Numerical Simulation

To validate the proposed fractional Lotka – Volterra prey–predator model with delay, numerical simulations are performed using the Fractional Adams–Bash forth–Moulton (FABM) predictor–corrector (PECE) method. The obtained fractional-order solutions are compared with those computed using the fourth-order Runge – Kutta (RK4) method, which serves as a benchmark for validation. The system parameters are selected a$\alpha_1 = \alpha_2 = \alpha_3 = 0.0001$, $\beta = 0.003$, $\gamma = 0.005$, $d = 0.005$, $\delta = 0.005$ and the initial state $x_0 = 4$, $y_0 = 2$, $z_0 = 2$, $\tau = 0$, $x(t-\tau) = x(t)$ $\omega = 0.9$. For numerical simulations, the system is integrated over the time interval t∈[0,100]. The choice of the final simulation time T=100 is made to ensure that the long-term dynamical behaviour of the fractional-order prey–predator system is adequately captured.

	W=0.9	W=0.9	W=0.9
TIME	FAB PR (X)	FAB CR (X)	RK4 (X)
0.0	4.000	4.000	4.000
1.0	3.851	3.709	3.859
2.0	3.721	3.467	3.726
3.0	3.599	3.249	3.597
4.0	3.480	3.480,	3.426
5.0	3.357	3.357	3.282
6.0	3.244	3.244	3.138
7.0	3.137	3.137	2.995
8.0	3.029	3.029	2.851
9.0	2.930	2.930	2.708
10.0	2.813	2.813	2.564

Table 1 indicates Time Evolution of Prey Population

TIME	W=0.9 FAB PR (Y)	W=0.9 FAB CR (Y)	W=0.9 RK4 (Y)
0.0	2.000	2.000	2.000
1.0	2.0247	2.048	2.024
2.0	2.046	2.090	2.046
3.0	2.066	2.128	2.069
4.0	2.086	2.086	2.095
5.0	2.107	2.107	2.119
6.0	2.125	2.125	2.143
7.0	2.143	2.143	2.167
8.0	2.161	2.161	2.190
9.0	2.177	2.177	2.214
10.0	2.197	2.197	2.238

Table 2 indicates Time evolution of First Predator Population

TIME	W=0.9 FAB PR (Z)	W=0.9 FAB CR (Z)	W=0.9 RK4(Z)
0.0	2.000	2.000	2.000
1.0	2.052	2.103	2.049
2.0	2.096	2.192	2.098
3.0	2.139	2.275	2.148
4.0	2.181	2.181	2.199
5.0	2.223	2.223	2.249
6.0	2.262	2.262	2.299
7.0	2.299	2.299	2.349
8.0	2.337	2.337	2.398
9.0	2.177	2.177	2.448
10.0	2.412	2.412	2.498

Table 3 indicates Time evolution of second Predator Population

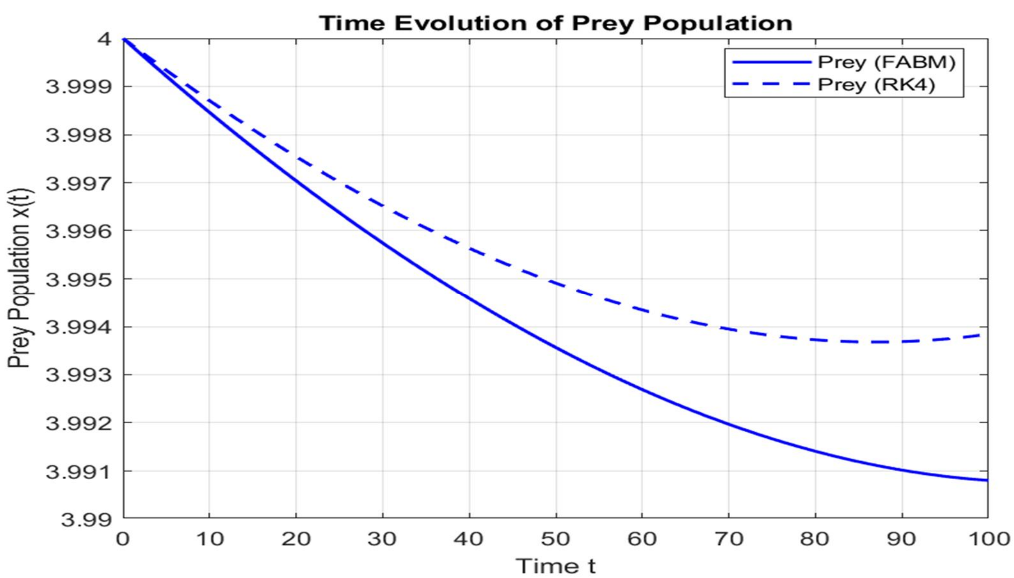

Figure 1: Time Evolution of Prey Population

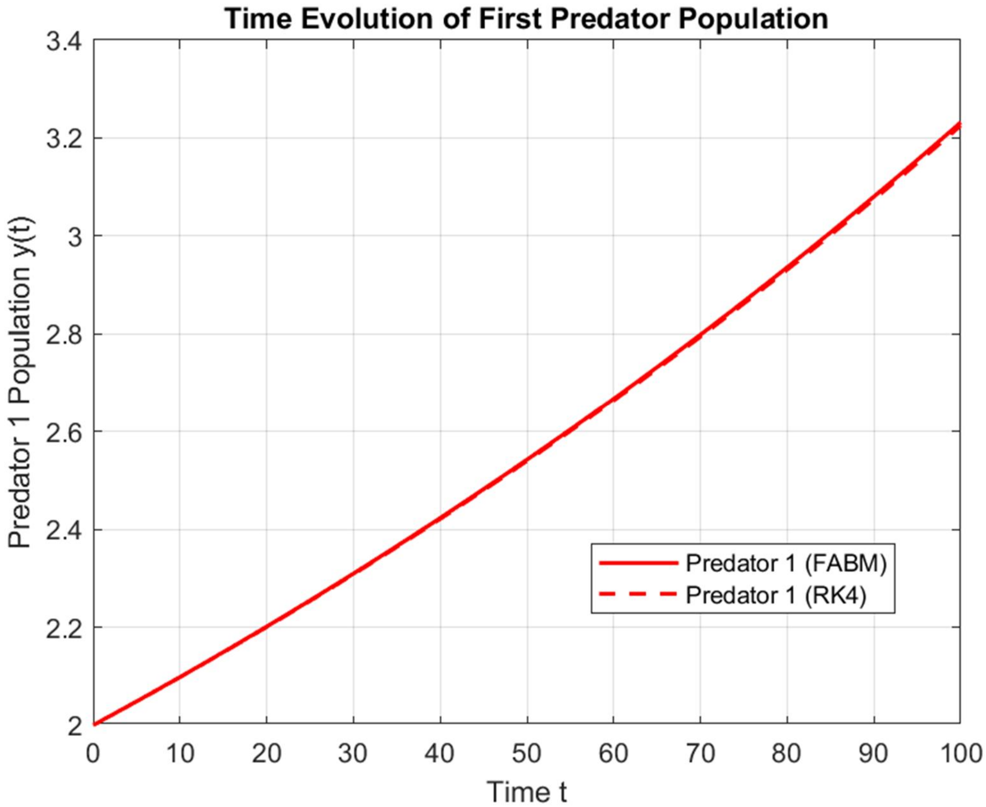

Figure 2: Time Evolution of First Predator Population

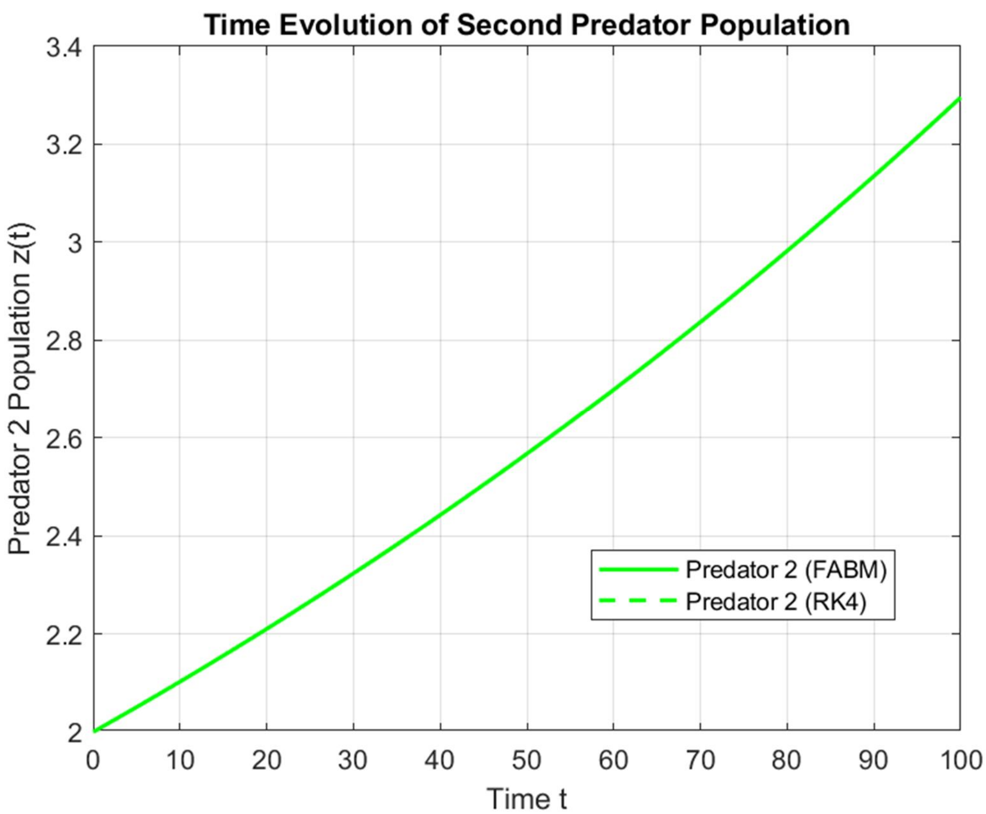

Figure 3: Time Evolution of Second Predator Population

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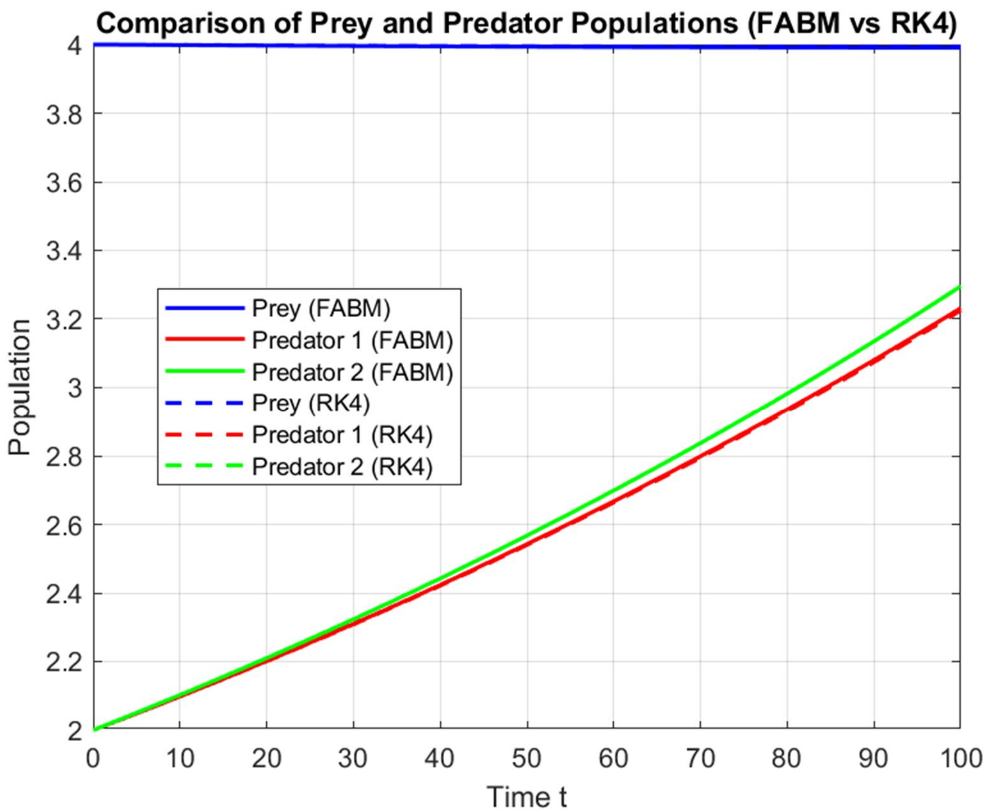

Figure 4: Comparsion of Prey and Predator Populations (FABM vs RK4)

IV. CONCLUSION

In this paper, a delayed Caputo fractional-order prey–predator model was analyzed to describe population interactions with memory and time-delay effects. The local asymptotic stability of the equilibrium points was examined using the Jacobian matrix approach. Numerical solutions were obtained by employing the Fractional Adams–Bash forth–Moulton (FABM) predictor–corrector method. The numerical simulations demonstrate that the FABM scheme produces stable and accurate approximations for the nonlinear fractional system considered. The results confirm that fractional-order models offer a robust mathematical framework for studying complex dynamical behaviours in prey–predator interactions that are not adequately captured by classical integer-order formulations.

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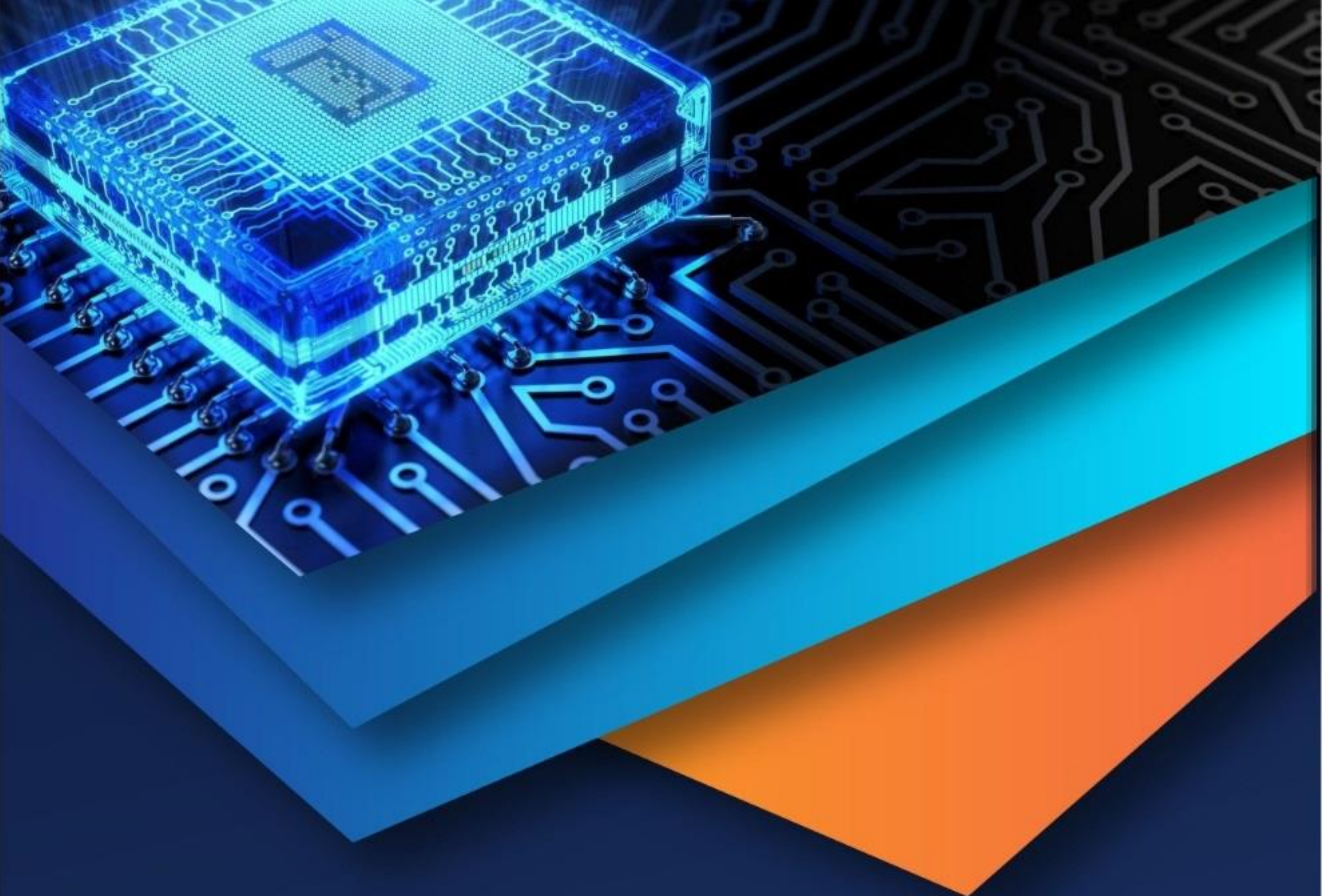

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