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A HYBRID ANALYTICAL TECHNIQUE FOR TIME-FRACTIONAL MODELING OF COMPUTER VIRUS PROPAGATION

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Abstract. *The study of epidemic dynamics of computer viruses is an evolving discipline focused on studying the propagation of computer viruses across networks. This work aims to develop a series of epidemic models for computer viruses utilizing the Katugampola fractional derivative. This study aims to resolve the time-fractional computer virus propagation model using a hybrid approach that integrates the residual power series method with the generalized Laplace transform. In addition, an example demonstrates the fractional order α and the parameter ρ influence the dynamic behavior of the computer virus propagation model.*
Keywords: The Katugampola fractional derivative in Caputo form, Residual power series method, Generalized Laplace transform, Computer virus propagation model

1. **Introduction.** Nowadays, the information technology has developed daily services, but it has also led to the spread of computer viruses, which can result in significant financial loss and data corruption. Various types of computer viruses, including worm, Trojan horses, file virus, boot sector, macro, and script, have the ability to self-replicate and infect other devices, leading to data loss and file displacement. The study of the dynamic propagation of computer viruses is crucial, and epidemiology models and mathematical models have been developed to address infectious diseases and study computer viruses, enabling rapid predictions about virus transmission dynamics [1]. The correlation between biological and computer viruses was introduced by Cohen [2]. Based on this analogy, the computer virus propagation model can be mathematically formulated as a system of nonlinear ordinary differential equations (ODEs), given by

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$$\begin{aligned} \frac{dS(t)}{dt} &= d - \eta S(t)I(t) - \mu S(t), \\ \frac{dI(t)}{dt} &= \eta S(t)I(t) - (\xi + \mu)\, I(t), \\ \frac{dR(t)}{dt} &= \xi I(t) - \mu R(t), \end{aligned} \tag{1}$$

with the initial condition: $S(0) = P_1,\ I(0) = P_2,\ R(0) = P_3,$ (2)

where $S(t)$, $I(t)$, and $R(t)$ indicate the number of susceptible computers (vulnerable, not infected), infected computers (can transmit virus), and recovered computers (immune, non-infectious), respectively, d is the rate of external computers connecting to the network, η is the average contact rate causing infection, μ is the recovery rate via antivirus, and ξ is the removal rate from the network.

Numerous studies have used epidemiological methods to investigate the spread of computer viruses. Murray [3] was the first to propose a comparison between biological epidemics and computer viruses, and Mishra and Saini [4] created mathematical models to analyze the dynamics of transmission. Fractional calculus has been used to better capture complex behaviors [5,6]. In order to address uncertainty, Alhebshi et al. [9] added fuzzy parameters, while Bonyah et al. [7] and Hoang [8] developed models utilizing fractional Caputo and β derivatives. Understanding has been further improved by numerical methods such as the finite-difference method [10] and control strategies for systems with delays [11]. Furthermore, [12] used numerical simulations and examined stability conditions to examine various virus propagation scenarios. More recently, Farman et al. [13] used fractional derivatives to model the long-memory effects of virus spread. Saptaningtyas et al. [14] suggested an optimal control framework with saturated incidence, vaccination, and treatments. These recent developments highlight the increasing innovation in mathematical modeling and inspire the current study to further advance this dynamic research field.

The analytical and numerical techniques have been applied to solving time-fractional computer virus propagation models. The typical techniques include generalized differential transform methods (GDTM) [5], Laplace and homotopy-based techniques [7], finite difference methods (FDM) [9] and the Adomian decomposition method (ADM) [15]. The choice of method depends on the model complexity, required accuracy results, and the strengths of each method. The residual power series (RPS) method, which was introduced in [16], is regarded as an effective optimization technique for determining and defining the coefficient values of the power series solution. Building upon this foundation, this study extends upon the previous research of [17] and presents modifications to the classical model of computer virus propagation. We specifically integrate the time-fractional derivative (1) and (2) by substituting the time fractional Caputo derivative with the time fractional Katugampola derivative in the Caputo form, as demonstrated in the subsequent systems:

$$\begin{aligned} {}^{KC}D_t^{\alpha,\rho} S(t) &= d - \eta S(t)I(t) - \mu S(t), \\ {}^{KC}D_t^{\alpha,\rho} I(t) &= \eta S(t)I(t) - (\xi + \mu) I(t), \\ {}^{KC}D_t^{\alpha,\rho} R(t) &= \xi I(t) - \mu R(t), \end{aligned} \tag{3}$$

with the initial condition: $S(0) = P_1,\ I(0) = P_2,\ R(0) = P_3,$ (4)

where ${}^{KC}D_t^{\alpha,\rho}$ represents the operator of fractional Katugampola derivative in the Caputo term.

The stability analysis of the time-fractional computer virus propagation model (3) is inspired by the method in [17], which focuses on analyzing the boundedness of solutions and their asymptotic behavior toward equilibrium. This study presents an analytical solution for the computer virus propagation model using a hybrid approach, combining

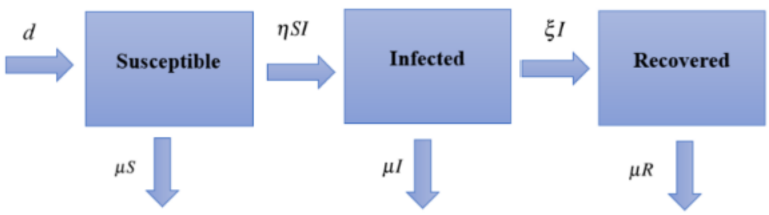


Figure 1. Process diagram of the computer virus propagation system

the residual power series (RPS) method with the generalized Laplace transform. In addition, the Adomian polynomial is utilized in the proposed method because the system of model propagation has a nonlinear term. Although deriving analytical solutions is often more challenging than numerical computation, they are a powerful tool for analyzing and interpreting the propagation models.

The remainder of the paper is structured as follows. Section 2 introduces the fundamental concepts and essential terminology concerning fractional calculus, the generalized Laplace transform, and fractional power series. In Section 3, a general fractional differential equation is solved using a hybrid analytical approach. Section 4 explores the influence of the fractional order α and parameter ρ on the dynamics of the model. The paper concludes with a summary of the main findings in the final section.

2. **Preliminaries and Notations.** Definitions, theorems, and lemmas for the generalized Laplace transform, fractional derivatives and integrals, and fractional power series are briefly discussed in this section. The concept of fractional derivatives used in this study is based on the works in [18-21]. Let α be a fractional order such that $0 < \alpha \leq 1$, and let ρ and T be the constant. Denote the Gamma function as $\Gamma(\cdot)$.

Definition 2.1. [19,20] *The following expression represents the Katugampola fractional derivative in Caputo type operator of order α for a function g whose domain is $[0,\infty)$ and codomain is $\mathbb{R}$:*

$$^{KC}D_t^{\alpha,\rho} g(t) = \frac{1}{\Gamma(1-\alpha)} \int_0^t \left(\frac{t^\rho - \varepsilon^\rho}{\rho}\right)^{-\alpha} \frac{d}{d\varepsilon} g(\varepsilon) d\varepsilon$$

Moreover, the Kapugampola fractional derivative reduces to the Caputo derivative when the parameter $\rho = 1$ as shown in [16].

Lemma 2.1. [19,20] *Let ρ, α, η, κ be constants and $g(t) \in C[0,\infty)$, where $0 < \alpha, \eta \leq 1$, $\rho > 0$, $\kappa \neq \alpha - 1$, we get 1) $^{KC}D_t^{\alpha,\rho} c = 0$, where c is constant; 2) $^{KC}D_t^{\alpha,\rho} \left(\frac{t^\rho}{\rho}\right)^\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa+1-\alpha)} \left(\frac{t^\rho}{\rho}\right)^{\kappa-\alpha}$; 3) $^{KC}D_t^{\alpha,\rho} \left(^{KC}D_t^{\eta,\rho} g(t)\right) = {}^{KC}D_t^{\alpha+\eta,\rho} g(t)$; 4) $^{KC}I_t^{\alpha,\rho} \left(^{KC}D_t^{\alpha,\rho} g(t)\right) = g(t) - g(0)$, where $^{KC}I_t^{\alpha,\rho}$ is the operator of the Katugampola fractional integral in Caputo type.*

Definition 2.2. [21] *Let $g : [0,\infty) \to \mathbb{R}$. The function g possesses $\frac{t^\rho}{\rho}$-Laplace transform, denoted by $\mathcal{L}_{\frac{t^\rho}{\rho}}\{g(t)\}(s)$ or $G(s)$, which is defined by*

$$G(s) = \mathcal{L}_{\frac{t^\rho}{\rho}}\{g(t)\}(s) = \int_0^t e^{-s\frac{t^\rho}{\rho}} g(t) \frac{dt}{t^{1-\rho}}, \quad s > 0,$$

where s denotes the transform parameter associated with the $\frac{t^\rho}{\rho}$-Laplace transform.

Lemma 2.2. [22] *Let $A(s) = \mathcal{L}_{\frac{t^\rho}{\rho}}\{a(t)\}(s)$, where $s > 0$ and $0 < \alpha < 1$. Then,*

$$1)\ \mathcal{L}_{\frac{t^\rho}{\rho}}\{\omega_1 a(t) + \omega_2 b(t)\}(s) = \mathcal{L}_{\frac{t^\rho}{\rho}}\{\omega_1 a(t)\}(s) + \mathcal{L}_{\frac{t^\rho}{\rho}}\{\omega_2 b(t)\}(s),$$

2) $\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{\left(\frac{t^\rho}{\rho}\right)^{\kappa}\right\}(s)=\frac{\Gamma(1+\kappa)}{s^{1+\kappa}}$,

3) $\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{{}^{KC}D_t^{\alpha,\rho}a(t)\right\}(s)=s^{\alpha}A(s)-s^{\alpha-1}a(0)$,

4) $\mathcal{L}_{\frac{t^\rho}{\rho}}\{1\}(s)=\frac{1}{s}$,

5) $\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{{}^{KC}D_t^{m\alpha,\rho}a(t)\right\}(s)=s^{m\alpha}A(s)-\sum_{n=0}^{\infty}s^{(m-n)\alpha-1}\ {}^{KC}D_t^{n\alpha,\rho}a(0)$,

where ${}^{KC}D_t^{m\alpha,\rho}=\underbrace{{}^{KC}D_t^{\alpha,\rho}\cdot{}^{KC}D_t^{\alpha,\rho}\cdots{}^{KC}D_t^{\alpha,\rho}}_{(m\text{-times})}$.

The concept from [24] is extended to define a fractional power series (FPS) characterized by the parameter ρ, for any $t\in[0,T]$.

Theorem 2.1. *Assume that $\varphi(t)$ can be indicated as a generalized FPS centered at $t=0$ with the parameter ρ in the form: $\varphi(t)=\sum_{n=0}^{\infty}\omega_n\left(\frac{t^\rho}{\rho}\right)^{n\alpha}$. If the function $\varphi(t)$ and its Katugampola fractional derivative on ${}^{KC}D_t^{\alpha,\rho}\varphi(t)$ are continuous functions on $[0,T]$, and ${}^{KC}D_t^{\alpha,\rho}\varphi(t)$ is $(m-1)$ times differentiable on the $(0,T)$, then the coefficients ω_n of the FPS with parameter ρ are defined as follows: $\omega_n=\frac{{}^{KC}D_t^{\alpha,\rho}\varphi(0)}{\Gamma(n\alpha+1)}$, for any n being a non-negative integer.*

Proof: The proof of this theorem follows a procedure similar to that used in [24].

Theorem 2.2. *Suppose that $\varphi(t)$ can be indicated by an FPS centered around $t=0$ with a parameter ρ, and the operator ${}^{KC}D_t^{\alpha,\rho}\varphi(t)$ exists on the interval $[0,T]$. Then, $\Phi(s)=\mathcal{L}_{\frac{t^\rho}{\rho}}\{\varphi(t)\}(s)$ can be defined utilizing the following fractional expansion: $\Phi(s)=\sum_{n=0}^{\infty}\frac{q_n}{s^{1+n\alpha}}$, $s>0$, where $q_n={}^{KC}D_t^{n\alpha,\rho}\varphi(0)$ for any n is a non-negative integer.*

Proof: The proof of this theorem is derived straightforwardly from the results established in Theorem 2.1 and the property of $\frac{t^\rho}{\rho}$-Laplace transform in Lemma 2.2.

3. **The Basic Procedure of Generalized Residual Power Series Method.** The primary objective of this part is to describe the generalized residual power series method (GLRPS) for solving a fractional differential equation based on the Katugampola fractional derivative in the Caputo form.

For any $t\in[0,T]$, we consider the generalized fractional differential equation:

$$ {}^{KC}D_t^{\alpha,\rho}\varphi(t)+L[\varphi(t)]+N[\varphi(t)]=g(t), \tag{5}$$

and the initial condition:

$$\varphi(0)=\xi, \tag{6}$$

where $L[\varphi]$ is a linear function, $N[\varphi]$ is a nonlinear function, ${}^{KC}D_t^{\alpha,\rho}\varphi(t)$ denotes the Katugampola fractional derivative in the Caputo form of order α, and φ and g are given functions.

The GLRPS procedure is initiated by assuming that the solution φ of the fractional differential equation takes the following form $\varphi(t)=\sum_{n=0}^{\infty}\frac{q_n}{\Gamma(1+n\alpha)}\left(\frac{t^\rho}{\rho}\right)^{n\alpha}$, where the function q_n is obtained by the process described below. Evidently, the initial condition $\varphi(0)=\xi$ implies that $q_0=\xi$.

Step 1. Using the $\frac{t^\rho}{\rho}$-Laplace transform with respect to the time variable t, Equation (5) is transformed as follows:

$$\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{{}^{KC}D_t^{\alpha,\rho}\varphi(t)\right\}=\mathcal{L}_{\frac{t^\rho}{\rho}}\{g(t)-L[\varphi(t)]-N[\varphi(t)]\},\quad 0<t<T.$$

Subsequently, using the differentiation property of the $\frac{t^\rho}{\rho}$-Laplace transform in relation to the fractional Katugampola derivative in the Caputo form and the initial condition (6), we obtain

$$s^\alpha \mathcal{L}_{\frac{t^\rho}{\rho}}\{\varphi(t)\} - s^{\alpha-1}\varphi(0) = \mathcal{L}_{\frac{t^\rho}{\rho}}\{g(t) - L[\varphi(t)] - N[\varphi(t)]\},$$

or

$$\Phi(s) = \frac{\xi}{s} + \frac{1}{s^\alpha}\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{g(t) - L\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right] - N\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right]\right\}, \tag{7}$$

where $\Phi(s) = \mathcal{L}_{\frac{t^\rho}{\rho}}\{\varphi(t)\}$. It is important to recognize that Equation (7) is equivalent to the nonlinear ODEs presented in Equations (5) and (6).

Step 2. Utilizing the GLRPS approach, the function $\Phi(s)$ can be expressed through the subsequent expansion

$$\Phi(s) = \sum_{n=0}^{\infty} \frac{q_n}{s^{1+n\alpha}}, \quad s > 0. \tag{8}$$

The infinite series, as described by Equation (8), is referred to as the Laplace series solution, and $\lim_{n\to\infty} s\Phi(s) = q_0$. The initial k terms of the Laplace series solution, represented as $\Phi_k(s)$, will be expressed as

$$\Phi_k(s) = \sum_{n=1}^{k} \frac{q_n}{s^{1+n\alpha}}, \quad s > 0. \tag{9}$$

For determining the coefficients q_n of the series solution (9), we need to establish the $\frac{t^\rho}{\rho}$-Laplace residual function (GLRF). The GLRF of Equation (7) is as follows:

$$\mathcal{L}_{\frac{t^\rho}{\rho}} Res(s) = \Phi(s) - \frac{\xi}{s} - \frac{1}{s^\alpha}\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{g(t) - L\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right] - N\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right]\right\}, \tag{10}$$

and the k terms of GLRF (k-th GLRF) will be as

$$\mathcal{L}_{\frac{t^\rho}{\rho}} Res_k(s) = \Phi(s) - \frac{\xi}{s} - \frac{1}{s^\alpha}\mathcal{L}_{\frac{t^\rho}{\rho}}\left\{g(t) - L\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right] - N\left[\mathcal{L}^{-1}{}_{\frac{t^\rho}{\rho}}\{\Phi(s)\}\right]\right\}. \tag{11}$$

Step 3. The properties of $\mathcal{L}_{\frac{t^\rho}{\rho}} Res(s)$ and $\mathcal{L}_{\frac{t^\rho}{\rho}} Res_k(s)$ employed in this study are referred in [21]. The coefficient functions q_n can be derived recursively via the subsequent equation:

$$\lim_{n\to\infty}\left(s^{1+k\alpha}\mathcal{L}_{\frac{t^\rho}{\rho}} Res_k(s)\right) = 0, \tag{12}$$

for $0 < \alpha \leq 1$, $k \in \mathbb{N}$.

A similar approach to the proof of these properties can be found in [25,26].

Step 4. The solution $\varphi(t)$ of the fractional differential equation (5) subject to the initial condition (6) is obtained by utilizing the inverse $\frac{t^\rho}{\rho}$-Laplace transform to $\Phi(s)$.

4. **Numerical Results and Discussion.** According to the GLRS method in Section 3, the solution of the time-fractional computer virus propagation models (3) with the initial condition (4) is derived by the following system:

$$S(t) = P_1 + \frac{b - \eta P_1 P_2 - \mu P_1}{\Gamma(1+\alpha)}\left(\frac{t^\rho}{\rho}\right)^\alpha + \sum_{n=2}^{\infty}\frac{a_n}{\Gamma(1+n\alpha)}\left(\frac{t^\rho}{\rho}\right)^{n\alpha},$$

$$I(t) = P_2 + \frac{\eta P_1 P_2 - (\xi+\mu)P_2}{\Gamma(1+\alpha)}\left(\frac{t^\rho}{\rho}\right)^\alpha + \sum_{n=2}^{\infty}\frac{b_n}{\Gamma(1+n\alpha)}\left(\frac{t^\rho}{\rho}\right)^{n\alpha},$$

$$R(t) = P_3 + \frac{\xi P_2 - P_1 P_3}{\Gamma(1+\alpha)}\left(\frac{t^\rho}{\rho}\right)^\alpha + \sum_{n=2}^{\infty}\frac{c_n}{\Gamma(1+n\alpha)}\left(\frac{t^\rho}{\rho}\right)^{n\alpha},$$

where

$$a_n = \begin{cases} -\eta[P_1 b_1 + a_1 P_2] - \mu a_1, & \text{if } n = 2 \\ -\eta\left[P_1 b_{n-1} + b_1 \sum_{i=2}^{n-2} a_i + a_{n-1} P_2\right] - \mu a_{n-1}, & \text{if } n \geq 3 \end{cases},$$

$$b_n = \begin{cases} \eta[P_1 b_1 + a_1 P_2] - (\xi + \mu) b_1, & \text{if } n = 2 \\ \eta\left[P_1 b_{n-1} + b_1 \sum_{i=2}^{n-2} a_i + a_{n-1} P_2\right] - \mu a_{n-1}, & \text{if } n \geq 3 \end{cases},$$

and $c_n = \xi b_{n-1} - \mu c_{n-1}$, if $n \geq 2$.

This section examines the distinct impact of the fractional order α and the parameter ρ on the concentrations of susceptible (S), infected (I), and recovered (R) computers within the network. The focus is placed on the behavior of the system under different types of motion, specifically when both ρ and α are set to $1/3$ and $2/3$, representing fractional Brownian motions (fBm), as well as the classical Brownian motion case, where $\rho = \alpha = 1$. Through this comparative analysis, the influence of memory and long-range dependence introduced by the fractional derivative and the parameter ρ is explored. The simulations use specific values for the parameters, including the basic reproduction number R_0 which corresponds to Theorem 1 in [17]: external contact rate $d = 0.4$, removal rate $\mu = 0.02$, average contact rate $\eta = 0.01$, recovery rate $\xi = 0.2$, and initial populations $P_1 = 20$, $P_2 = 18$, and $P_3 = 16$ which represent the starting numbers of susceptible, infected, and recovered computers, respectively. These settings provide a controlled framework to assess how varying α and ρ affect the propagation dynamics and stability of the system over time.

Figures 2 and 3 show that the interaction between susceptible and infected computers and susceptible and recovered computers increases as the fractional order α and parameter ρ decrease. This behavior reveals the significant influence of fractional order α and parameter ρ on the dynamic response of the system, indicating how memory effects impact transmission and recovery processes. The fractional order system, represented as an integer order system when α and ρ are equal to 1, is influenced by the computer virus propagation model at values of $1/3$, $2/3$, and 1, focusing the dynamics of susceptible, infected, and recovered computers.

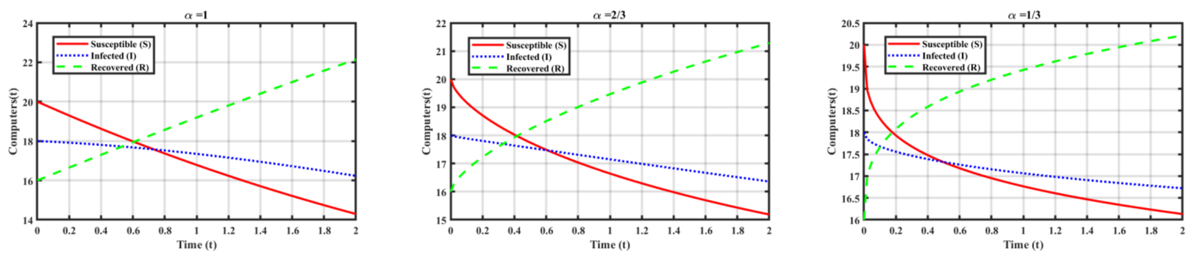


FIGURE 2. The approximate solution of susceptible, infected, and recovered computers at different fractional order α when $\rho = 1$

The number of susceptible computers decreases significantly over time when $\alpha = 1/3$ and $\rho = 1/3$, as illustrated in Figure 4(a). This suggests that the reduction occurs at a faster rate under stronger memory effects. As shown in Figure 4(b), the number of infected computers tends to decrease over time. However, this decrease becomes slower and the number of infections even increases when the fractional order α and the parameter ρ are reduced, making the impact of these parameters more noticeable. The rate of recovery is higher for smaller values of α, and the number of recovered computers increases rapidly with time, as illustrated in Figure 4(c). The behavior of the system is strongly

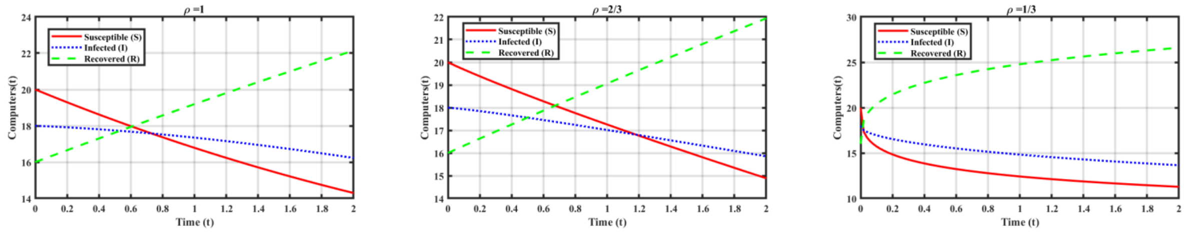
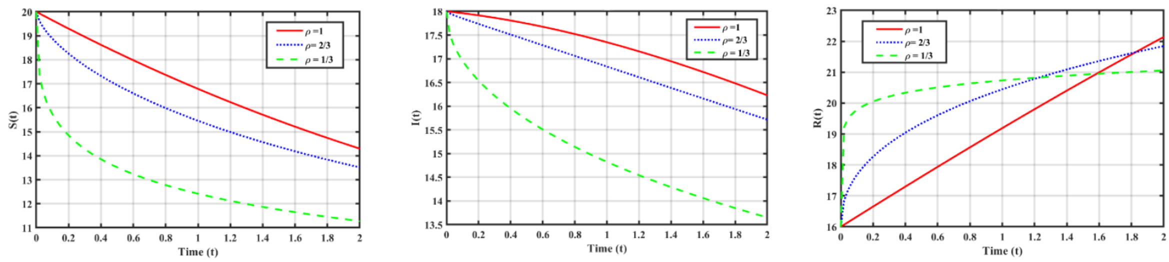


Figure 3. The approximate solution of susceptible, infected, and recovered computers at different parameters ρ when $\alpha = 1$



(a) Susceptible $S(t)$ (b) Infected $I(t)$ (c) Recovered $R(t)$

Figure 4. Approximate solutions of $S(t)$, $I(t)$, and $R(t)$ with varying ρ, where $\alpha = 1$

influenced by the fractional order α of the time derivative and the parameter ρ. The approximate solutions are continuously dependent on these values, highlighting the importance of fractional-order modeling in capturing the system's memory and hereditary characteristics.

Table 1 shows the approximate solution of the susceptible (S), infected (I), and recovered (R) by varying the parameter ρ while fixing the fractional order at 1. The GLRPS method can generate solutions with high accuracy with only three iterations, as shown in graphic and tabular presentations. Adding the number of iteration terms can make the numerical results more accurate. The fractional order has a significant impact on the number of susceptible, infected, and recovered computers, as shown in [17]. This study utilized the Katugampolatype fractional derivative in the Caputo form, incorporating the parameter ρ which effectively reduced the number of susceptible and infected computers, while increasing the number of recovered computers more rapidly compared to using the fractional order.

Table 1. An approximate solution of $S(t)$, $I(t)$ and $R(t)$ at different parameters ρ

t	$S(t)$			$I(t)$			$R(t)$		
	$\rho = 1/3$	$\rho = 2/3$	$\rho = 1$	$\rho = 1/3$	$\rho = 2/3$	$\rho = 1$	$\rho = 1/3$	$\rho = 2/3$	$\rho = 1$
0	20	20	20	18	18	18	16	16	16
0.2	14.846252	18.256335	19.295779	16.537319	17.734819	17.915409	21.444116	17.661794	16.653083
0.4	13.854564	17.326310	18.622851	15.950822	17.509694	17.806541	22.724269	18.614740	17.299693
0.6	13.232365	16.598262	17.98076	15.507768	17.285615	17.674765	23.582076	19.398204	17.938913
0.8	12.776606	15.987310	17.368981	15.141161	17.060919	17.521464	24.240240	20.084026	18.569884
1	12.416899	15.457156	16.786915	14.824540	16.835703	17.348034	24.778556	20.702289	19.191806

5. **Conclusions.** This study solves the time-fractional computer virus model using the Katugampola derivative in Caputo form and introduces the analytical method, which combines the generalized Laplace transform with the residual power series technique. The

system derived from the proposed method provides the analytical solution in terms of the parameter ρ. Thus, the numbers of susceptible, infected, and recovered computers are influenced by the fractional order α and the parameter ρ of the Katugampola fractional derivative in the Caputo form. The variations in these parameters affect the number of susceptible, infected, and recovered computers, as demonstrated in Section 3. Future research using alternative derivatives, numerical methods, and real-world applications could transform strategies for managing transmission dynamics and open new paths for exploration.

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