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Numerical solution of fractional order SIR model of dengue fever disease via Laplace optimized decomposition method

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Abstract

In this research article, we handle the susceptible infected-recovered (SIR) model of the dengue fever epidemic under Caputo Fabrizio fractional derivative. The dengue fever disease is a complicated disease because of the connection it creates between humans and mosquitoes. This encouraged scientists to understand the various factors that influence the recurrence of dengue fever. A new technique called the Laplace Optimized Decomposition (LODM) is used to solve this model numerically and compared with the 4^{th} order Runge-Kutta Method (RKM). The solution in the proposed method is in the form of a convergent series with easily computable components. We present the solution via graphs and hence give some remarks about the nature of the solutions.

Keywords: Laplace optimized decomposition method (LODM), Caputo Fabrizio fractional derivative (CFFD), dengue fever epidemic model.

2020 MSC: 49M27, 44A10, 26A33, 92D30.

1. Introduction

Infectious diseases are disorders caused by organisms such as bacteria, viruses, fungi or parasites. Many of these organisms live in and on our bodies. In general, they are harmless but sometimes they may cause a serious disease. Some of infectious diseases are transmitted from person to person or from insects and animals to humans or by consuming contaminated food or water or being exposed to organisms in the environment. The flu, measles, HIV, strep throat, COVID-19, Dengue fever and salmonella are all examples of infectious diseases. Dengue fever is an infectious disease transmitted by mosquito and it occurs in several areas of the world. It causes a high fever and flu symptoms but sometimes it causes a serious bleeding, a sudden drop in blood pressure and death [3, 8, 16, 18]. Dengue fever is most common in Southeast Asia, the western Pacific islands, Latin America and Africa. It is also spreading to new areas such as Europe and southern parts of the United States. Scientists are working on dengue fever vaccines but for now, the best ways to prevent infection are to avoid being bitten by mosquitoes and to take steps to reduce the mosquito population. Calculus of non-integer order differentiation and integration has

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been identified as a useful tool for describing the properties of complicated dynamical processes more effectively than standard integer order derivatives and integrals in last few decades. In the literature of fractional calculus, numerous fractional derivatives have been introduced, with Caputo, Caputo-Fabrizio, and Atangana-Baleanu being the most often used derivatives in diverse domains. Many research projects have been carried out with the use of fractional-order derivatives [4–6, 11, 12, 15, 22].

The Adomian decomposition method (ADM) was introduced by G. Adomian in the 1980s. The nonlinear fractional differential equations could be solved using this method, which demonstrated its usefulness [1, 2, 21]. As a result of the additions and modifications made to the Laplace-Adomian decomposition method (LADM) in this situation, this hybrid method has become a potent tool for locating an approximation that is both accurate and valid for a large number of (FPDEs) [10, 20]. Additionally, Odibat proposed the optimal decomposition approach, which introduced a new idea for the analytical treatment of nonlinear problems. The fundamental principle of the (ODM) is the linear approximation of a nonlinear operator, which is used to decompose the solution in series form [13, 14].

In this paper, we offer the following system of differential equations of SIR of dengue disease. The dengue fever epidemic model is divided into three classes:

$S(t)$: the susceptible people to catch infection;
$I(t)$: the infected people with dengue virus;
$R(t)$: the recovered people from dengue virus.

The differential equation system of dengue fever is shown here [9]

$$\begin{cases} \frac{dS(t)}{dt} = \nu - (\nu - \lambda R(t))S(t), \\ \frac{dI(t)}{dt} = \lambda S(t)R(t) - \xi I(t), \\ \frac{dR(t)}{dt} = \rho I(t) - (\rho I(t) + \omega)R(t), \end{cases} \tag{1.1}$$

where ξ is the infection rate coefficient, ρ is the recover rate after infection, ν is the death rate of the susceptible host, λ is the average number of bites per infected mosquito and ω is the number of deaths among the susceptible mosquito.

We use the preceding model (1.1) to expand under (CFFD) as follows [19]

$$\begin{cases} D^{\beta}S(t) = \nu - (\nu - \lambda R(t))S(t), \\ D^{\beta}I(t) = \lambda S(t)R(t) - \xi I(t), \\ D^{\beta}R(t) = \rho I(t) - (\rho I(t) + \omega)R(t), \end{cases} \tag{1.2}$$

where the initial conditions ae given by

$$S(0) = N_1, \qquad I(0) = N_2, \qquad R(0) = N_3,$$

$\beta \in (0, 1]$ and the total population N is given by

$$N(t) = S(t) + I(t) + R(t).$$

To be brief and to remember some details, the Caputo Fabrizio fractional integral and the (CFFD) of order $\beta \in (0, 1]$ of a function $f \in \mathcal{H}^1(a, b)$, where $a < b$, are expressed altogether as

$$\begin{cases} I^{\beta}f(t) = \frac{2(1-\beta)}{(2-\beta)M(\beta)}f(t) + \frac{2\beta}{(2-\beta)M(\beta)}\int_a^t f(\varphi)d\varphi, \\ D^{\beta}f(t) = \frac{M(\beta)}{1-\beta}\int_a^t f'(\varphi)\exp\left[-\beta\frac{t-\varphi}{1-\beta}\right]d\varphi, \end{cases}$$

where $M(\beta)$ is the normalization function with $M(1) = M(0) = 1$. Whilst the Laplace transform of $f(t)$ is $\mathcal{L}[f(t)] = F(t)$ and

$$\mathcal{L}\left[D^{\beta}f(t)\right] = \frac{s\mathcal{L}[f(t)] - f(0)}{s + \beta(1-s)}. \tag{1.3}$$

Besides the first section, the paper is organized as follows. Section 2 presents the essential steps of the (LODM) to solve nonlinear fractional differential operator equations. In Section 3, the fractional dengue fever epidemic model is solved with the proposed technique, and the graphics of the numerical solution are presented and discussed. We finalize our study with a conclusion in Section 4.

2. The algorithm of the (LODM)

Laplace Optimized Decomposition Method (LODM) is one of the effective and straight forward techniques to solve nonlinear fractional-order ordinary differential equations. This method combines two powerful methods for getting approximate solutions for systems of fractional ordinary differential equations: the Laplace transform method and the optimized decomposition method [7, 9, 10, 13, 14, 17, 19, 22]. To explain the basic steps of the Laplace optimized decomposition method, we will use the following nonlinear fractional-order ordinary differential equation

$$D^{\beta}\chi(t) + \mathcal{N}(\chi(t)) = g(t), \quad t > 0, \quad \text{and} \quad 0 < \beta \leqslant 1, \tag{2.1}$$

subject to the initial conditions

$$\chi(0) = \alpha_0, \tag{2.2}$$

where $\mathcal{N} : \mathbb{R} \mapsto \mathbb{R}$ is the nonlinear term, $g(t) : (0, \infty) \mapsto \mathbb{R}$ is a given function, and $\alpha_0 \in \mathbb{R}$. Applying the Laplace transform to both sides of equation (2.1) and using the linearity of Laplace transforms, the result is

$$\mathcal{L}\left[D^{\beta}\chi(t)\right] + \mathcal{L}\left[\mathcal{N}(\chi(t))\right] = \mathcal{L}\left[g(t)\right],$$

based on (1.3), we have

$$\frac{s\mathcal{L}\left[\chi(t)\right] - \chi(0)}{s + \beta(1-s)} = \mathcal{L}\left[g(t)\right] - \mathcal{L}\left[\mathcal{N}(\chi(t))\right]$$

and so,

$$s\mathcal{L}\left[\chi(t)\right] = \chi(0) + (s + \beta(1-s))\left(\mathcal{L}\left[g(t)\right] - \mathcal{L}\left[\mathcal{N}(\chi(t))\right]\right).$$

Thus,

$$\mathcal{L}\left[\chi(t)\right] = \frac{\chi(0)}{s} + \frac{s + \beta(1-s)}{s}\left(\mathcal{L}\left[g(t)\right] - \mathcal{L}\left[\mathcal{N}(\chi(t))\right]\right). \tag{2.3}$$

The (LODM) assumes that we can decompose the solution of (2.3) by the infinite series as

$$\chi(t) = \sum_{k=0}^{\infty} \vartheta_k(t), \tag{2.4}$$

where $\mathcal{N}(\chi(t))$ is represented by

$$\mathcal{N}(\chi(t)) = \sum_{k=0}^{\infty} Q_k(t) \tag{2.5}$$

such that $Q_k(t)$, which are called the Adomian polynomials and can be determined from the relation

$$Q_k(t) = \frac{1}{k!}\frac{d^k}{d\mu^k}\left[\mathcal{N}\left(\sum_{k=0}^{\infty}\mu^k\vartheta_k(t)\right)\right]|_{\mu=0}.$$

Substituting (2.4) and (2.5) into (2.3) and using the initial conditions given in (2.2), we get

$$\mathcal{L}\left[\sum_{k=0}^{\infty}\vartheta_k(t)\right] = \frac{\alpha_0}{s} + \frac{s + \beta(1-s)}{s}\left(\mathcal{L}\left[g(t)\right] - \mathcal{L}\left[\sum_{k=0}^{\infty}Q_k(t)\right]\right). \tag{2.6}$$

As a result, the iteration is defined by the recursive algorithm below

$$\begin{cases} \mathcal{L}\left[\vartheta_0(t)\right] = \psi(t), \\ \mathcal{L}\left[\vartheta_1(t)\right] = -\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_0(t)\right], \\ \mathcal{L}\left[\vartheta_2(t)\right] = -\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_1(t)+\zeta(\vartheta_1(t))\right], \\ \mathcal{L}\left[\vartheta_{k+1}(t)\right] = -\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_k(t)+\zeta(\vartheta_k(t)-\vartheta_{k-1}(t))\right]\right], k \geqslant 2, \end{cases} \tag{2.7}$$

where $\psi(t)$ and ζ are

$$\psi(t) = \frac{\alpha_0}{s} + \frac{s+\beta(1-s)}{s}\mathcal{L}\left[g(t)\right] \quad \text{and} \quad \zeta = \frac{\frac{\partial\Omega}{\partial\chi}\left(D^\beta\chi(t),\chi(t)\right)}{\frac{\partial\Omega}{\partial D^\beta\chi}\left(D^\beta\chi(t),\chi(t)\right)},$$

such that we assume that the function $\Omega\left(D^\beta\chi(t),\chi(t)\right) = D^\beta\chi(t) + \mathcal{N}(\chi(t))$ can be linearized by a 1^{st}-order Taylor series expansion at $t = 0$. Solving $\Omega\left(D^\beta\chi(0),\chi(0)\right) = 0$, thus, the Taylor series expansion of the function $\Omega\left(D^\beta\chi(t),\chi(t)\right)$ near (φ_0,α_0), where $\varphi_0 = D^\beta\chi(0)$ and $\alpha_0 = \chi(0)$ is

$$\Omega\left(D^\beta\chi(t),\chi(t)\right) \approx \frac{\partial\Omega}{\partial D^\beta\chi(t)}(\varphi_0,\alpha_0)D^\beta\chi(t) + \frac{\partial\Omega}{\partial\chi(t)}(\varphi_0,\alpha_0)\chi(t).$$

Applying the inverse Laplace transform to (2.7), we gain

$$\begin{cases} \vartheta_0(t) = \mathcal{L}^{-1}\left[\psi(t)\right], \\ \vartheta_1(t) = -\mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_0(t)\right]\right], \\ \vartheta_2(t) = -\mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_1(t)+\zeta(\vartheta_1(t))\right]\right], \\ \vartheta_{k+1}(t) = -\mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_k(t)+\zeta(\vartheta_k(t)-\vartheta_{k-1}(t))\right]\right], k \geqslant 2. \end{cases} \tag{2.8}$$

To facilitate the calculations, we can express the function $\psi(t)$ in Taylor series as $\psi(t) = \sum_{j=0}^{\infty}\psi_j(t)$ and so, (2.8) can transform to

$$\begin{cases} \vartheta_0(t) = \mathcal{L}^{-1}\left[\psi_0(t)\right], \\ \vartheta_1(t) = \mathcal{L}^{-1}\left[\psi_1(t)\right] - \mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_0(t)\right]\right], \\ \vartheta_2(t) = \mathcal{L}^{-1}\left[\psi_2(t)\right] - \mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_1(t)+\zeta(\vartheta_1(t))\right]\right], \\ \vartheta_{k+1}(t) = \mathcal{L}^{-1}\left[\psi_{k+1}(t)\right] - \mathcal{L}^{-1}\left[\frac{s+\beta(1-s)}{s}\mathcal{L}\left[Q_k(t)+\zeta(\vartheta_k(t)-\vartheta_{k-1}(t))\right]\right], k \geqslant 2. \end{cases}$$

3. Numerical results

In this section, some investigations are considered to demonstrate the applicability and effectiveness of the (LODM) for the disease model of dengue fever. The obtained findings show that the (LODM) is precise, efficient, and systematic in dealing with a variety of essential fractional calculus difficulties. All the numerical computations were performed by using the Mathematica 12 software package.

3.1. Solutions steps

First, applying the Laplace transform to both sides of (1.2) gives

$$\begin{cases} \mathcal{L}\left[D^\beta S(t)\right] = \mathcal{L}\left[\nu - (\nu+\lambda R(t))S(t)\right], \\ \mathcal{L}\left[D^\beta I(t)\right] = \mathcal{L}\left[\lambda S(t)R(t) - \xi I(t)\right], \\ \mathcal{L}\left[D^\beta R(t)\right] = \mathcal{L}\left[\rho I(t) - (\rho I(t)+\omega)R(t)\right]. \end{cases}$$

In view of (1.3), we have

$$\begin{cases} \mathcal{L}[S(t)] = \frac{N_1}{p} + \frac{(p+\beta(1-p))\nu}{p^2} + \frac{p+\beta(1-p)}{p}\mathcal{L}[-(\nu-\lambda R(t))S(t)], \\ \mathcal{L}[I(t)] = \frac{N_2}{p} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\lambda S(t)R(t) - \xi I(t)], \\ \mathcal{L}[R(t)] = \frac{N_3}{p} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\rho I(t) - (\rho I(t)+\omega)R(t)]. \end{cases} \tag{3.1}$$

Assume the series solution has the form

$$S(t) = \sum_{i=0}^{\infty} \upsilon_i(t), \quad I(t) = \sum_{i=0}^{\infty} \vartheta_i(t), \quad R(t) = \sum_{i=0}^{\infty} \psi_i(t).$$

Because of (2.6), (3.1) transforms to

$$\begin{cases} \mathcal{L}[\sum_{i=0}^{\infty}\upsilon_i(t)] = \frac{N_1}{p} + \frac{(p+\beta(1-p))\nu}{p^2} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\sum_{i=0}^{\infty}\Theta_i(t)], \\ \mathcal{L}[\sum_{i=0}^{\infty}\vartheta_i(t)] = \frac{N_1}{p} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\sum_{i=0}^{\infty}\Psi_i(t)], \\ \mathcal{L}[\sum_{i=0}^{\infty}\psi_i(t)] = \frac{N_3}{p} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\sum_{i=0}^{\infty}\Lambda_i(t)]. \end{cases}$$

By some computation, one can simplify

$$\begin{cases} \mathcal{L}[\upsilon_0(t)] = \frac{N_1}{p}, \\ \mathcal{L}[\upsilon_1(t)] = \frac{(p+\beta(1-p))\nu}{p^2} + \frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_0(t)], \\ \mathcal{L}[\upsilon_2(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_1(t) + (\nu+\lambda(\upsilon_0(t)+\vartheta_0(t)))\upsilon_1(t)], \\ \mathcal{L}[\upsilon_{i+1}(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_i(t) + (\nu+\lambda(\upsilon_0(t)+\vartheta_0(t)))(\upsilon_i(t)-\upsilon_{i-1}(t))], i \geqslant 2, \end{cases}$$

$$\begin{cases} \mathcal{L}[\vartheta_0(t)] = \frac{N_2}{p}, \\ \mathcal{L}[\vartheta_1(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Psi_0(t)], \\ \mathcal{L}[\vartheta_2(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Psi_1(t) + (\xi-\lambda(\upsilon_0(t)+\vartheta_0(t)))\vartheta_1(t)], \\ \mathcal{L}[\vartheta_{i+1}(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Psi_i(t) + (\xi-\lambda(\upsilon_0(t)+\vartheta_0(t)))(\vartheta_i(t)-\vartheta_{i-1}(t))], i \geqslant 2, \end{cases}$$

$$\begin{cases} \mathcal{L}[\psi_0(t)] = \frac{N_3}{p}, \\ \mathcal{L}[\psi_1(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Lambda_0(t)], \\ \mathcal{L}[\psi_2(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Lambda_1(t) + (\omega-\rho(1-\vartheta_0(t)-\psi_0(t)))\psi_1(t)], \\ \mathcal{L}[\psi_{i+1}(t)] = \frac{p+\beta(1-p)}{p}\mathcal{L}[\Lambda_i(t) + (\omega-\rho(1-\vartheta_0(t)-\psi_0(t)))(\psi_i(t)-\psi_{i-1}(t))], i \geqslant 2, \end{cases}$$

where the Adomian polynomials Θ_i, Ψ_i, and Λ_i are given by

$$\Theta_i(t) = \frac{-1}{i!}\frac{d^i}{d\mu^i}[(\nu-\lambda\psi_0(t))\upsilon_0(t) + (\nu-\lambda(\psi_0(t)+\mu\psi_1(t)))(\upsilon_0(t)+\mu\upsilon_1(t)) + \cdots]|_{\mu=0},$$

$$\Psi_i(t) = \frac{1}{i!}\frac{d^i}{d\mu^i}[\lambda\upsilon_0(t)\psi_0(t) - \xi\vartheta_0(t) + \lambda(\upsilon_0(t)+\mu\upsilon_1(t))(\psi_0(t)+\mu\psi_1(t)) - \xi(\vartheta_0(t)+\mu\vartheta_1(t)) + \cdots]|_{\mu=0},$$

$$\Lambda_i(t) = \frac{1}{i!}\frac{d^i}{d\mu^i}[\rho\vartheta_0(t) - (\rho\vartheta_0(t)+\omega)\psi_0(t) + \rho(\vartheta_0(t)+\mu\vartheta_1(t)) - \rho(\vartheta_0(t)+\mu\vartheta_1(t))(\psi_0(t)+\mu\psi_1(t)) + \cdots]|_{\mu=0}.$$

As a result, the terms of the Laplace optimized decomposition series are given as follows

$$\begin{cases} \upsilon_0(t) = N_1, \\ \upsilon_1(t) = \mathcal{L}^{-1}\left[\frac{(p+\beta(1-p))\nu}{p^2}\right] + \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_0(t)]\right], \\ \upsilon_2(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_1(t) + (\nu+\lambda(\upsilon_0(t)+\vartheta_0(t)))\upsilon_1(t)]\right], \\ \upsilon_{i+1}(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}[\Theta_i(t) + (\nu+\lambda(\upsilon_0(t)+\vartheta_0(t)))(\upsilon_i(t)-\upsilon_{i-1}(t))]\right], i \geqslant 2, \end{cases}$$

$$\begin{cases} \vartheta_0(t) = N_2, \\ \vartheta_1(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Psi_0(t)\right]\right], \\ \vartheta_2(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Psi_1(t) + (\xi - \lambda(\upsilon_0(t) + \vartheta_0(t)))\vartheta_1(t)\right]\right], \\ \vartheta_{i+1}(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Psi_i(t) + (\xi - \lambda(\upsilon_0(t) + \vartheta_0(t)))(\vartheta_i(t) - \vartheta_{i-1}(t))\right]\right], i \geqslant 2, \end{cases}$$

$$\begin{cases} \psi_0(t) = N_3, \\ \psi_1(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Lambda_0(t)\right]\right], \\ \psi_2(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Lambda_1(t) + (\omega - \rho(1 - \vartheta_0(t) - \psi_0(t)))\psi_1(t)\right]\right], \\ \psi_{i+1}(t) = \mathcal{L}^{-1}\left[\frac{p+\beta(1-p)}{p}\mathcal{L}\left[\Lambda_i(t) + (\omega - \rho(1 - \vartheta_0(t) - \psi_0(t)))(\psi_i(t) - \psi_{i-1}(t))\right]\right], i \geqslant 2. \end{cases}$$

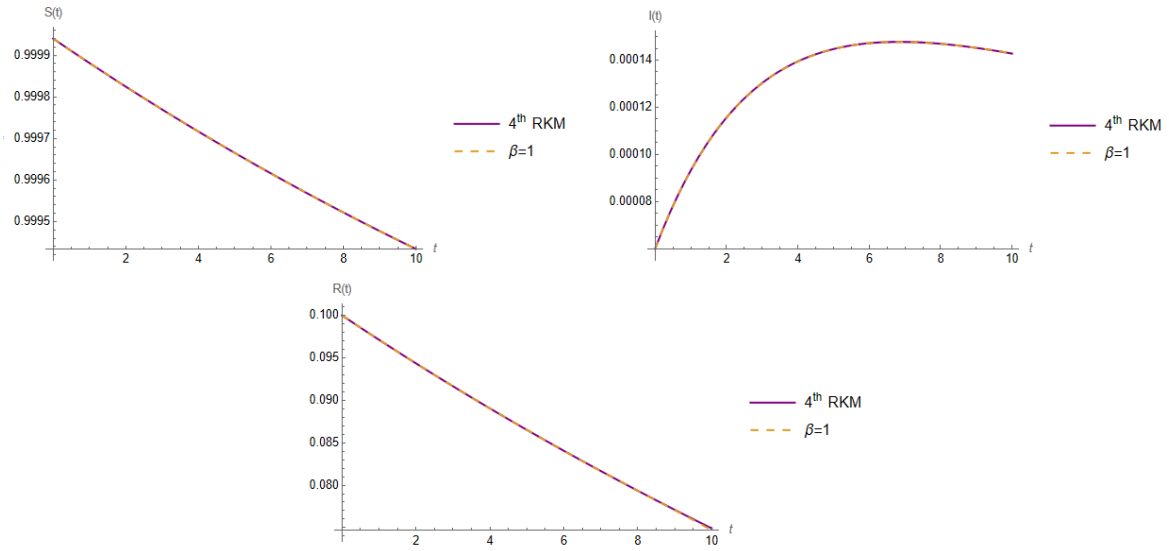

Figure 1: The 4^{th} RKM solution versus the (LODM) solution for $\beta = 1$.

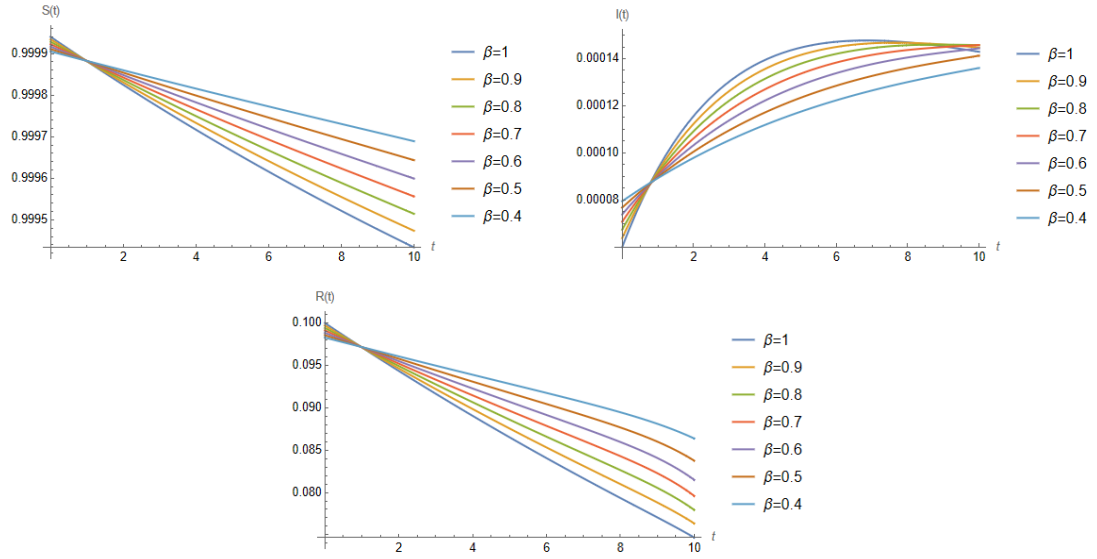

Figure 2: The solution of the model by the (LODM) for some cases of fractional order β.

3.2. Simulation results

In this part, we examine the fractional order SIR model of dengue fever disease to show the effectiveness of the (LODM). We use initial conditions and parameter values from [2] to execute numerical simulation: $N_1 = 0.9999400528$, $N_2 = 0.0000599472$, $N_3 = 0.1$, $\lambda = 0,0006$, $\xi = 0,333$, $\rho = 0.375$, $\omega = 0,02941$, $\nu = 0,0045$.

In Figure 1, we plotted the 4^{th} RKM solution versus the (LODM) solution for $\beta = 1$, we notice from the graphs that the two methods are in good agreement, while in Figure 2 we have plotted the resultant solutions of the susceptible class $S(t)$, the infected class $I(t)$ and the recovered class $R(t)$ for different fractional-order by using (CFFD). Figure 2 shows how the disease is spread in a community that we assume is susceptible to infection, when the virus attacks, the number of susceptible people decreases because they turn into an infected people, and thus the decomposition of the susceptible leads to infected growth. If the appropriate treatment is not applied, the number of people who recover will decrease. The rate of increase and decrease of the various curves is faster in the lower order, while as the order increases the process becomes slower and vice versa.

4. Conclusion

In this study, we used (CFFD) to provide an analytical solution for a fractional order model of dengue fever disease. A comparison between the (LODM) and the 4^{th}order RKM method is mapped. This study shows that the (LODM) has a significant impact on the accuracy of efficient solutions in the fundamental spread of dengue illness. Finally, we conclude that the (LODM) is a very dependable approach for solving a wide range of dynamical issues due to its consistency over a longer time frame and can be a useful complement in achieving a model for the dengue virus, thereby assisting in the complete eradication of the disease.

Data availability

The data (Mathematica code) used to support the findings of this study are available from the corresponding author upon request. The data was generated by Mathematica 13.1 software version.

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