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Full Length Research

Assessing the impact of treatment on the dynamics of Diabetes mellitus and its complications: A mathematical model approach

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ABSTRACT: Diabetes is a disorder in which the body becomes unable to control the amount of sugar in the blood. The pancreas (beta-cells) is not functioning normally, resulting in a partial or total lack of insulin, which is the key to the mechanism converting sugar to energy. Consequently, the system is no longer self-regulated, and the level of sugar in the blood goes beyond the limits. This paper proposes a mathematical model for the dynamics of diabetes mellitus and its complications incorporating treatment. The human population were divided into four compartments, namely: susceptible, diabetics without complications, diabetics with complications and diabetics with complications undergoing treatment. The system of ordinary differential equations describing the dynamics of diabetes mellitus was derived. The analytical solution of the model equations was obtained using the Homotopy Perturbation Method. Numerical simulation of the solution was carried out, and results were obtained. The results show that diabetes can be controlled and the complications arising from it can be cured with effective treatment.

Keywords: Complications, diabetes mellitus, Homotopy Perturbation Method, numerical simulation, treatment.

INTRODUCTION

Diabetes Mellitus (DM) is simply caused by the failure of the body to produce the right amount of insulin to stabilise the amount of sugar in the body (Patil *et al.,*2010). The pancreas β-cells (beta-cells) are not functioning normally, resulting in a partial or total lack of insulin, which is the key to the mechanism converting sugar to energy. Consequently, the system is no longer self-regulated, and the level of sugar in the blood goes beyond the limits (threshold).

According to the World Health Organisation (WHO, 2014), diabetes can be classified into TYPE I diabetes, TYPE II diabetes and gestational diabetes. Most patients who suffer from the failure of the body to produce the right amount of insulin to stabilise the amount of sugar in the body are recommended to take insulin injections. This is called Diabetes TYPE I. Diabetes TYPE II is the patient's body's rejection of insulin. This type of patient is recommended to undergo a certain health meal program as well as performing exercises to lose weight in addition to oral medication (Zecchin *et al*., 2011). Gestational diabetes can occur temporarily during pregnancy, which is due to hormonal changes and usually begins in the fifth or sixth month of pregnancy (between 24th and 28th weeks). Gestational diabetes usually resolves once the baby is born. However, 25-50% of women with gestational diabetes will eventually develop diabetes later in their life, especially those who require insulin during pregnancy and those who are overweight after their delivery (Sharief and Sheta, 2014).

Mathematical models have been developed by various Mathematicians and Biomathematicians to study the dynamics of diabetes. They formulated models that deal with incidence, progression and control of diabetes.

Wild *et al (*2004) studied how to approximate the incidence of diabetes and the number of diabetic people of all ages for the years 2000 and 2030. As per the data collected for all age groups, the incidence of diabetes mellitus worldwide was estimated to be 2.8% in 2000 and 4.4% in 2030. The incidence of diabetes is higher in men than women, but as per the record, there are more diabetic women as compared to men. These findings indicate that the “diabetes occurrence” will continue even if levels of obesity remain constant.

Adeyemo *et al* (2024) proposed a suitably and mathematically well-posed model of the dynamics of diabetes mellitus, incorporating three control parameters. The obtained equilibrium point shows that there is no disease-free equilibrium (DFE) but an endemic equilibrium point (EEP) of the model. The analysis of the model shows that the endemic equilibrium point of the model is both locally asymptotically stable (LAS) and globally asymptotically stable (GAS). The Homotopy Perturbation Method was used to obtain the model solution. Nigeria diabetes values and parameters are used to obtain the sensitivity analysis of the sensitive parameters, and graphical simulations of the numerical solution of the state variables. The study provides comprehensive guidance for the prevention and control of Type 1, Type 2 and gestational diabetes.

Aye *et al.* (2025) proposed and analysed an optimal control model for diabetes management, focusing on minimising complications and treatment costs. The model is structured around a population of diabetic patients, incorporating dynamic interactions between healthy, susceptible, diabetic, complication, and treatment populations. An objective functional is defined, integrating costs associated with complications and treatment efforts, and is subjected to optimisation through control strategies aimed at enhancing patient education, regular monitoring, and comprehensive care. The application of the Pontryagin Maximum Principle provides a solid theoretical foundation for identifying optimal control strategies. Utilising a fourth-order Runge-Kutta method, the model is simulated under varying control conditions to assess the impact of interventions. The results demonstrate that increasing control measures significantly reduces the incidence of complications while improving treatment rates. The findings highlight the importance of strategic health management interventions in mitigating the burden of diabetes-related complications and emphasise the model's applicability in real-world healthcare settings. This research provides a robust framework for policymakers and healthcare providers to devise effective strategies that enhance the quality of care for diabetic patients.

Homotopy Perturbation Method (HPM), which was first proposed by Ji-Huan He (Babolian *et al*., 2009; He, 1999; He, 2000), for solving differential and integral equations, has successfully been applied to solve many types of linear and nonlinear functional equations. This method, which is a combination of homotopy in topology and classic perturbation techniques, provides us with a convenient way to obtain analytic or approximate solutions for different kinds of problems arising in different fields.

He used HPM to solve Lighthill equation (He, 2003a), Duffing equation (He, 2003b) and Blasiusequation (He, 2005), and then the idea found its way into sciences and has been used to solve nonlinear wave equations (He, 2006), boundary value problems (Yildirim, 2008a); Abbasbandy, 2006), quadratic Riccati differential equations (Golbabai and Keramati, 2008), integral equations (Ghasemi *et al*., 2007; Biazar and Ghazvini, 2007; 2009), Klein-Gordon and sine-Gordon equations (Odibat and Momani, 2007; Chowdhury and Hashim, 2007), initial value problems(Chowdhury and Hashim, 2007), Schrödinger equation (Abdulaziz *et al*., 2008), Emden-Fowler type equations (Chowdhury & Hashim, 2007), nonlinear evolution equations (Ganji *et al*., 2007), differential-difference equations (Yildirim, 2008b), modified KdV equation (Yildirim, 2008b) and many other problems. This wide variety of applications shows the power of HPM in solving functional equations.

In this study, we extended the work of Boutayeb *et al.* (2004) by carrying out a mathematical study of diabetes and its complications, as well as incorporating treatment, using the Homotopy Perturbation Method.

METHODOLOGY

Mathematical model

The population is compartmentalised into four. Namely: Susceptible population $S(t)$, Diabetics without Complications $D(t)$, Diabetics with Complications $C(t)$, and Diabetics with Complications that undergo Treatment $T(t)$. Where t, represents time as continuous independent variable and the parameters incorporated are β (Birth rate), α (probability rate of Incidence of diabetes), μ (Natural mortality rate), λ (Probability of a diabetic person developing a complication), γ (Rate at which diabetics with complications undergo treatment), v (Rate at which diabetics with complication become severely disabled), ω (Rate at which diabetics with complication that recovered after treatment return to diabetics without complications class), and δ (Mortality rate due to complications). Figure 1 shows the pictorial interactions of the different compartments with the system dynamics of diabetes mellitus and its complications

Assumption of the model

The model was formulated based on the following assumptions:

1. The population of diabetics is finite.
2. Natural death is constant.
3. The rate of developing complications is constant.
4. The rate of recovery from complications after

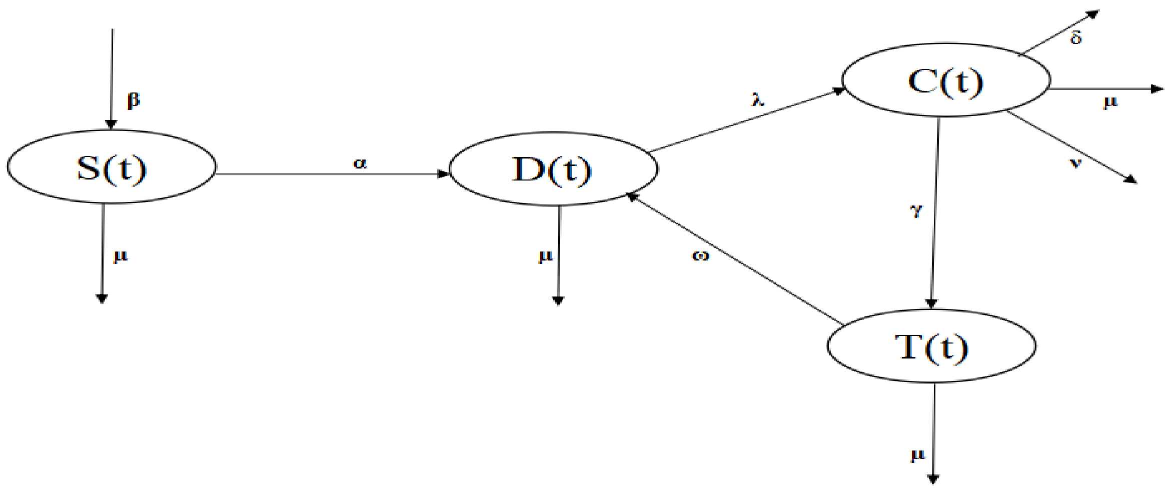

Figure 1. Schematic diagram of the model.

treatment is constant.

5. Death due to complications occurred.
6. Complications can be treated.
7. The recovered individual after treatment can develop complications again.
8. Incidence of the disease occurs without complications.
9. Complications develop over time.

The mathematical equation describing the dynamics of diabetes and its complications is given by the ordinary differential equations.

$$\left.\begin{aligned} \frac{dS(t)}{dt} &= \beta - \mu S(t) - \alpha S(t) \\ \frac{dD(t)}{dt} &= \alpha S(t) - \mu D(t) - \lambda D(t) + \omega T(t) \\ \frac{dC(t)}{dt} &= \lambda D(t) - \mu C(t) - v\, C(t) - \delta C(t) - \gamma C(t) \\ \frac{dT(t)}{dt} &= \gamma C(t) - \mu T(t) - \omega T(t) \end{aligned}\right\} \quad (1)$$

With the initial conditions $S(0) = S_o$, $D(0) = D_o$, $C(0) = C_o$, $T(0) = T_o$.

Analytical solution of the model using Homotopy Perturbation Method (HPM)

To illustrate the ideas of this method, the following non-linear differential equation was considered (He, 2000).

$$A(u) - F(r) = 0,\ r \in \Omega \qquad (2)$$

Subject to the boundary condition of:

$$B\left(U, \frac{\partial u}{\partial n}\right) = 0, \qquad r \in \Gamma \qquad (3)$$

Where ***A*** is a general differential operator, ***B*** is a boundary operator, ***F(r)*** is a known analytical function, and ***Γ*** is the boundary of the domain ***Ω***. The operator ***A*** can be divided into two parts, ***L*** and ***N***, where ***L*** is the linear part, and ***N*** is the nonlinear component. Equation (2) may therefore be rewritten as:

$$L(u) + N(u) - F(r) = 0, r \in \Omega \qquad (4)$$

Using the Homotopy technique, we construct a Homotopy $v(r, p) : \Omega \times [0,1] \rightarrow R$, which satisfies

$$H(v, p) = (1 - p)\,[L(v) - L(u_o)] + p\,[L(v) + N(v) - F(r)] = 0 \qquad (5)$$

$$H(v, p) = L(v) - L(u_o) + pL(u_o) + p\,[N(v) - F(r)] = 0 \qquad (6)$$

Where: $L(u)$ is the linear part; $L(u) = L(v) - L(u_o) + pL(u_o)$

And $N(u)$ is the nonlinear part; $N(u) = pN(v)$

In equation (5), $p \in [0, 1]$ is an embedding parameter, and u_o is the first approximation that satisfies the boundary condition. Obviously, considering equations (5) and (6), we will have:

$$H(v, 0) = L(v) - L(u_o) = 0 \qquad (7)$$

$$H(v, 1) = L(v) + N(v) - F(r) = 0 \qquad (8)$$

The changing process of p from zero to unity is just of $H(v, r)$ from $u_o(r)$ to $u(r)$. In topology, this is called deformation and $L(v) - L(u_o)$ and $A(v) - F(r)$ are called homotopy.

According to HPM, we can first use the embedding parameter p as a small parameter, and it can be assumed that the solutions of equations (5) and (6) can be written as power series as follows:

$$v = v_o + p^1 v_1 + p^2 v_2 + \ldots \qquad (9)$$

The best approximation for the solution is:

$$u = \lim_{p \to 1} v = v_o + v_1 + v_2 + \ldots \qquad (10)$$

According to He (He, 2000; He, 2006), series *(10)* is convergent for most cases. However, the convergence rate depends on the nonlinear operator *A(v).*

The analytical solution of the model equations in (1) was solved using the Homotopy Perturbation method, and the solution obtained is presented in (11).

$$\left.\begin{array}{l} S(t) = S_o + (\beta - qS_o)t - \frac{1}{2}q(\beta - qS_o)t^2 + \ldots \\ D(t) = D_o + (\alpha S_o + \omega T_o - mD_o)t + \frac{1}{2}\{\alpha(\beta - qS_o) + \\ \omega(\gamma C_o - rT_o) - m(\alpha S_o + \omega T_o - mD_o)\}t^2 + \ldots \\ C(t) = C_o + (\lambda D_o - nC_0)t + \frac{1}{2}\{\lambda(\alpha S_o + \omega T_o - mD_o) - \\ n(\lambda D_o - nC_0)\}t^2 + \ldots \\ T(t) = T_o + (\gamma C_o - rT_o)t + \frac{1}{2}\{\gamma(\lambda D_o - nC_0) - r(\gamma C_o - rT_o)\}t^2 + \ldots \end{array}\right\} \quad (11)$$

Where $q = \mu + \alpha$, $m = \mu + \lambda$, $n = \mu + v + \delta + \gamma$ *and* $r = \mu + \omega$

Numerical simulation

The numerical simulation of the four compartments ***S(t), D(t), C(t),*** and ***T(t)*** was done with the use of a Mathematical Software (Maple 18), and the results obtained are presented in graphical form. The values of parameters used for numerical simulation are shown in Table 1.

RESULTS AND DISCUSSION

The numerical simulation of the analytical solutions obtained in Equation (11) was carried out using the parameter values presented in Table 1. The graphical responses of the system are presented in Figures 2–11. The results show how variations in the model parameters affect the dynamics of the susceptible population, diabetics without complications, diabetics with complications, and diabetics with complications undergoing treatment.

Figure 2 shows that, as the probability rate of incidence of diabetes (α) increases, the susceptible population decreases. This is attributable to the fact that a higher incidence rate increases the movement of individuals from the susceptible class to the diabetic class. The result may also be associated with unhealthy lifestyles such as alcoholism, smoking, overeating, and lack of physical exercise, which are important factors associated with the occurrence and progression of diabetes. This observation is consistent with Widyaningsih *et al*. (2018), who developed a mathematical model of diabetes mellitus incorporating lifestyle and genetic factors and showed the importance of these factors in the dynamics of diabetes.

Figure 3 shows that, as the probability rate of incidence of diabetes increases, the population of diabetics without complications also increases. This is expected because an increase in the incidence rate results in more susceptible individuals becoming diabetic. Thus, the increase in the

Table 1. Values of parameters used for numerical simulation.

Parameters	Values	Source
β	0.01623	Widyaningsih *et al*. (2018)
α	0.05	Enagi *et al*. (2017)
μ	0.02	Enagi *et al*. (2017)
λ	0.05	Enagi *et al*. (2017)
γ	0.08	Enagi *et al*. (2017)
v	0.05	Enagi *et al*. (2017)
ω	0.08	Permatasari *et al*. (2018)
δ	0.05	Enagi *et al*. (2016)

diabetic population observed in Figure 3 corresponds to the decline in the susceptible population shown in Figure 1. This finding agrees with the general behaviour reported in mathematical models of diabetes, including the study of Enagi *et al*. (2017), which examined the dynamics of diabetes and its complications and demonstrated the importance of disease-transition parameters in determining the size of diabetic populations.

Figure 4 shows that, as the probability rate of incidence of diabetes increases, the population of diabetics with complications also increases. This indicates that increasing diabetes incidence can eventually increase diabetes-related complications because more individuals enter the diabetic population and subsequently become exposed to the risk of developing complications. The increase may be associated with both genetic and lifestyle factors such as smoking, alcoholism, overeating, and lack of physical exercise. The finding is consistent with Adeyemo *et al*. (2024), who emphasised the importance of controlling the dynamics of diabetes mellitus and its complications through appropriate control measures. It also agrees with Boutayeb *et al*. (2004), who demonstrated through mathematical modelling that the progression of diabetes and its complications contributes substantially to the overall burden of the disease.

Figure 5 shows that, as the probability rate of diabetics developing complications increases, the population of diabetics without complications decreases faster. This occurs because an increase in the complication-development rate causes more individuals to move from the diabetics-without-complications class to the diabetics-with-complications class. The result indicates that the rate of progression to complications is an important parameter in determining the dynamics of diabetes. Therefore, effective management of diabetes at the early stage may help to reduce the transition of individuals from uncomplicated diabetes to more severe complications. This observation is in agreement with Enagi *et al*. (2017), whose mathematical study considered the progression of diabetes and its complications.

Figure 6 shows that, as the probability rate of diabetic persons developing complications increases, the population of diabetics with complications also increases. This translates to the need to control the transition from

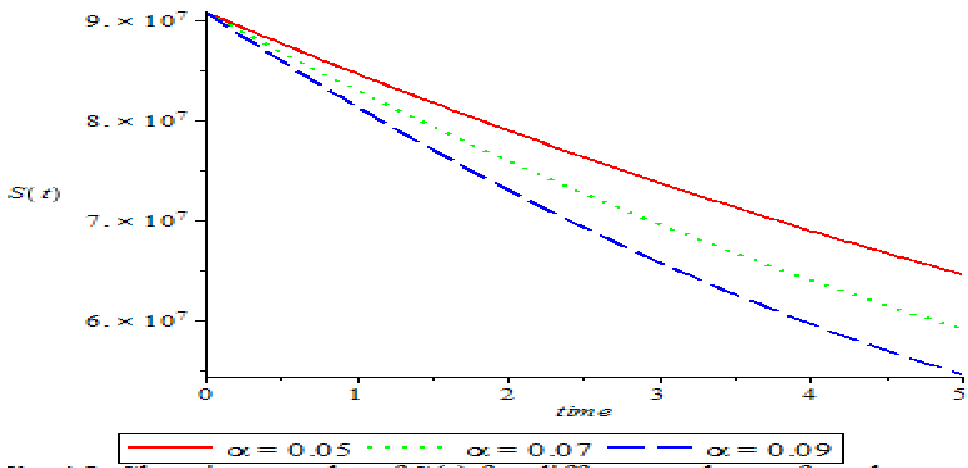

Figure 2. Graphs of S(t) for different values of α when $\nu = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \lambda = 0.05$

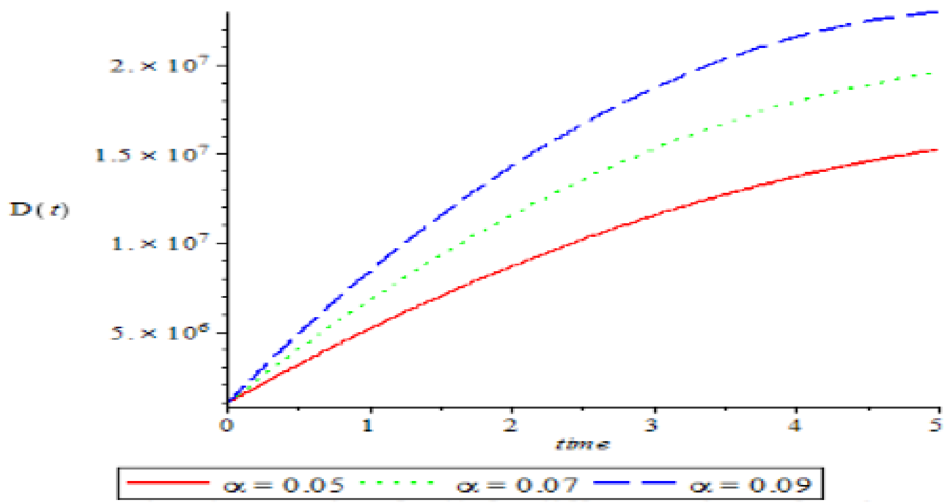

Figure 3. Graph of *D(t)* for different values of α when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \lambda = 0.05$

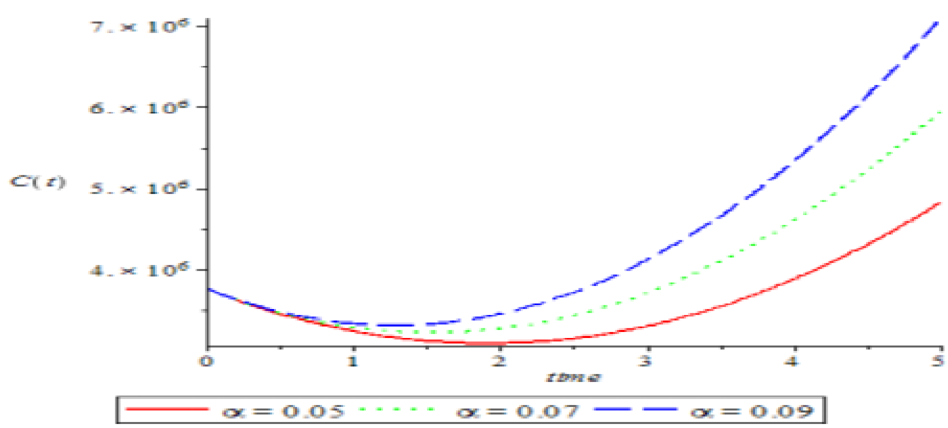

Figure 4. Graph of C*(t)* for different values of α when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \lambda = 0.05$

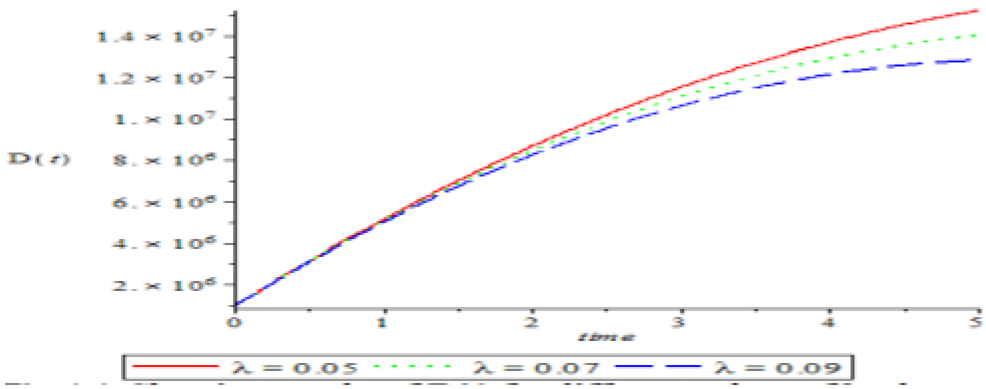

Figure 5. Graph of *D(t)* for different values of λ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \alpha = 0.05$

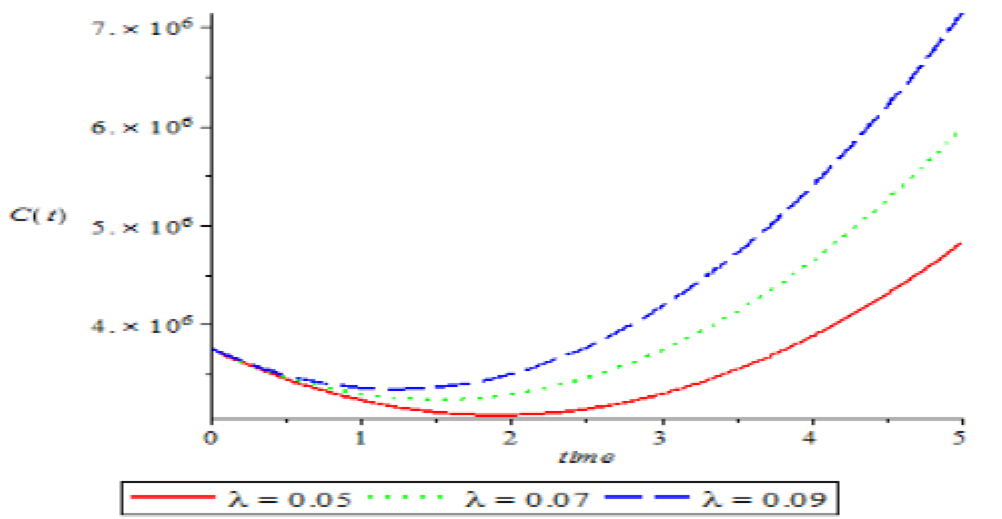

Figure 6. Graph of C*(t)* for different values of λ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \alpha = 0.05.$

diabetics without complications to diabetics with complications through effective management of diabetes. The result is consistent with Boutayeb *et al*. (2004), who developed a mathematical model to examine the burden of diabetes and its complications and demonstrated the importance of disease progression in determining the population affected by complications. Similarly, Adeyemo *et al*. (2024) reported that appropriate control strategies are important for reducing the burden associated with diabetes and its complications.

Figure 7 shows that, as the probability rate of a diabetic person developing complications increases, the population of diabetics with complications undergoing treatment also increases. This shows that more diabetics with complications move into the treatment class to receive medical care. The increase in the treatment population is expected because a higher rate of complication development produces more individuals requiring treatment. However, this result also emphasises the importance of preventing complications, rather than depending only on treatment after complications have developed. The importance of treatment and control measures is supported by Aye *et al*. (2025), who reported that increasing control measures significantly reduces the incidence of complications while improving treatment rates among diabetic patients.

Figure 8 shows the effect of the treatment rate on the population of diabetics without complications. The result shows that a high treatment rate increases the population of diabetics with complications undergoing treatment. This indicates that effective treatment facilitates the movement of individuals with complications into the treatment class. Effective treatment helps to control the menace of diabetes and may reduce the number of deaths associated with diabetes and its complications. This finding agrees with Aye *et al*. (2025), who demonstrated that strategic control

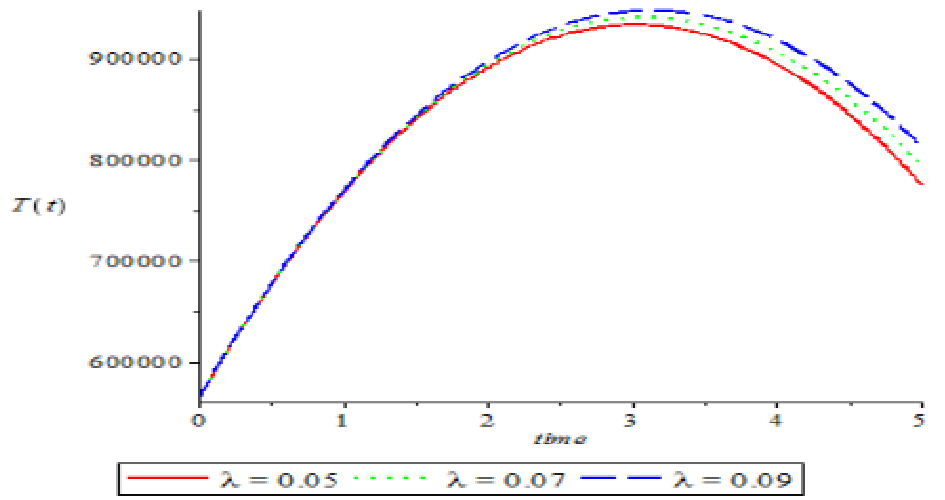

Figure 7. Graph of T*(t)* for different values of λ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \gamma = 0.08, \omega = 0.08, \alpha = 0.05$

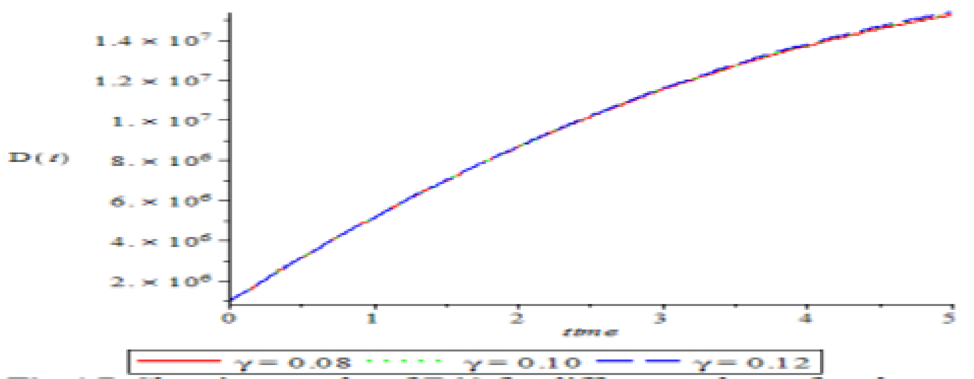

Figure 8. Graph of D*(t)* for different values of γ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \lambda = 0.05, \omega = 0.08, \alpha = 0.05$.

measures, including treatment and patient management, can reduce diabetes-related complications and improve treatment outcomes.

Figure 9 shows that, as the rate of diabetics with complications undergoing treatment increases, the population of diabetics with complications decreases. This shows that more diabetics with complications move into the treatment class for effective treatment. The decline in the complications population indicates that increasing the treatment rate can help to reduce the number of individuals remaining in the complications class. This finding supports the results of Adeyemo *et al*. (2024), who showed through mathematical modelling that effective control strategies can reduce the burden of diabetes and its complications.

Figure 10 shows that, as the rate of diabetics with complications undergoing treatment increases, the treatment population increases. This shows that more diabetics with complications migrate into the treatment class for effective treatment of complications and medical care. The result demonstrates the important role of treatment in controlling the progression of diabetes-related complications. This finding is in agreement with Aye *et al*. (2025), who reported that increasing control measures improves treatment rates and reduces the incidence of complications in diabetic populations.

Figure 11 shows that, as the rate of recovery from complications increases, the population of diabetics with complications undergoing treatment decreases. This shows that the more diabetics with complications recover following treatment, the fewer individuals remain in the treatment class. Recovered individuals subsequently move to the diabetics-without-complications class, thereby reducing the population exposed to complication-related mortality. This result is consistent with the model developed by Permatasari *et al*. (2018), which considered the dynamics and controllability of diabetic populations and emphasised the importance of transitions between different disease states.

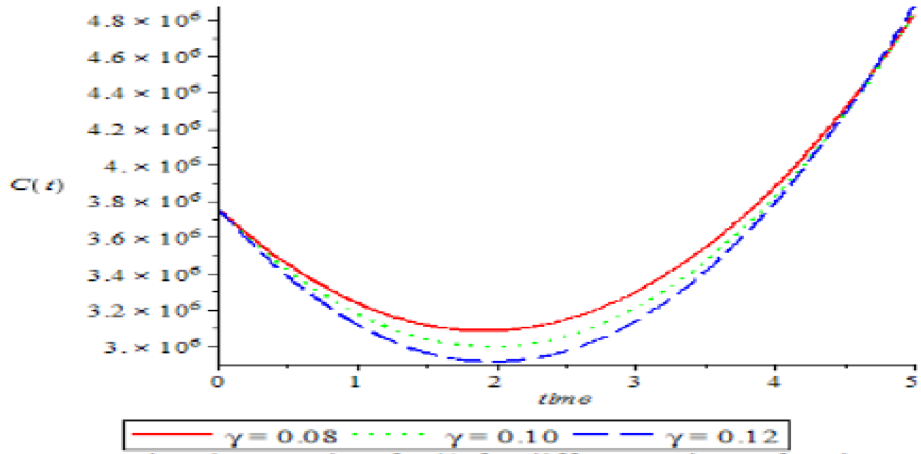

Figure 9. Graph of C*(t)* for different values of γ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \lambda = 0.05, \omega = 0.08, \alpha = 0.05$.

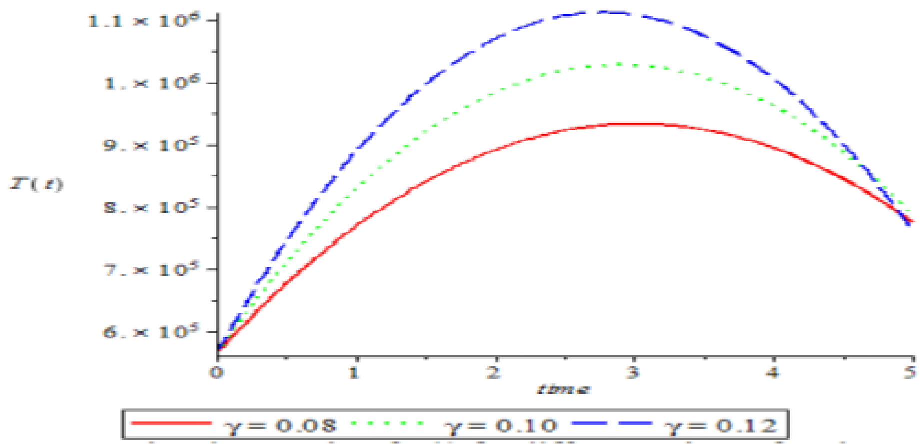

Figure 10. Graph of T*(t)* for different values of γ when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \lambda = 0.05, \omega = 0.08, \alpha = 0.05$

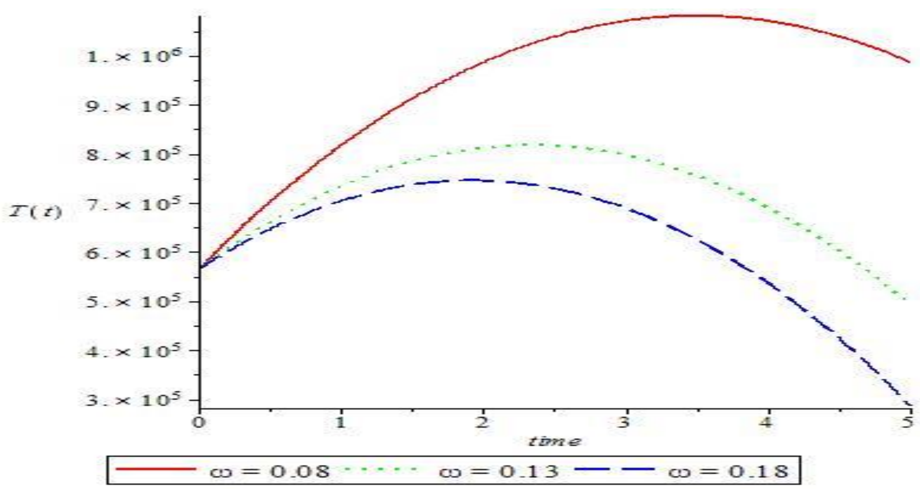

Figure 11. Graph of T*(t)* for different values of ω when $\upsilon = 0.05, \delta = 0.05, \mu = 0.02, \lambda = 0.05, \gamma = 0.08, \alpha = 0.05$

The findings of this research work justify the position of Adeyemo *et al*. (2024) and Aye *et al*. (2025), which stated that if diabetics with complications are subjected to effective treatment and the incidence of diabetes complications is controlled, the number of deaths attributed to complications of diabetes mellitus can be drastically reduced. The present results further demonstrate that controlling the incidence of diabetes, reducing the progression from uncomplicated diabetes to complications, and improving treatment and recovery rates are important strategies for controlling the dynamics of diabetes mellitus. Therefore, sustained and effective management of diabetes can reduce the burden of complications and enable diabetic patients to enjoy a longer and better quality of life.

COMPETING INTEREST

The authors declare that they have no conflict of interest.

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