

Optimal Control of Diet-Based Interventions in Glucose-Insulin Regulatory Systems: A Bio-Mathematical Study

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ABSTRACT

Manipulation of blood sugar level is a complicated physiological procedure that is under the highly dynamic interplay of glucose and insulin and is significantly affected by diet. In this study, a biomathematical model of optimization of diet-based interventions in glucose-insulin regulating systems is provided. It constructs a set of non-linear differential equations that are used to describe how glucose absorption, insulin release and cellular uptake different over time in a wide range of dietary conditions. In order to recreate metabolic processes, the model has physiological variables that are fundamental in order to recreate metabolic processes, including insulin sensitivity, hepatic glucose production and the composition of meals. The optimal control method is one that aims at defining the best dietary intake patterns that will help keep the correct glucose levels and reduce metabolic variability. The controlled variable is a composition and timing of meals, and the goal of the target function is to minimize hyperglycemic and hypoglycemic episodes and enhance insulin efficiency. The data demonstrate that a well thought-out and composition-regulated dietary interventions can greatly enhance the stability of glucose levels at the lowest possible load on insulin-controlling processes. Homeostasis is more successful with lower glycemic index diets and even macronutrient balance. Individual metabolic characteristics are important due to sensitivity analysis, because it is required to make nutrition programs specific to the individuals. This paper shows that there is a possibility of integrating optimal control theory with food planning to enhance metabolic well-being, especially in individuals with dysregulated glucose levels, such as diabetes. The suggested approach offers a quantitative basis for the development of evidence-based dietary programs and individual nutrition plans in clinical and population health care.

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1. Introduction

Glucose is one of the most important carbohydrates in the body, which is responsible for providing energy to the body. All metabolic functions in the human body are fully controlled by the interaction between glucose and insulin. The human body needs glucose as an energy source, whereas insulin is secreted by the pancreas gland and is used for the absorption of glucose in cells and tissues. Different factors increase and decrease glucose levels in the body. These factors include dietary habits, environmental factors, and physical parameters. Any changes in these factors result in metabolic disorders as well as hyperglycemia. In recent years, the surge in diabetes mellitus has raised global health concerns. For treating early onset of DM in patients, they are given pharmacological therapy (Jimoh et al., 2025). But the effectiveness of these therapies is limited. These therapies do not treat the underlying cause of DM. For this purpose, many alternative treatment approaches are valuable that control all metabolic processes with a more regulated mechanism. One of the alternative methods for treating diabetes mellitus includes dietary food. A healthy diet plan is one of the sources for maintaining the body's natural metabolic processes. Dietary plans are non-pharmacological-based therapies that ensure that the glucose level in the body is in a balanced state (Kashif et al., 2025). Biomathematical models are used for understanding the fluctuations of glucose in the body due to changes in dietary patterns. All the complex interactive relationships between glucose and insulin production are explained using bio-mathematical models. By using mathematical equations, researchers can predict the outcomes of behavioral changes in the human body under different circumstances. Also, optimal control theory, when combined with bio-mathematical models, results in the establishment of more organized optimal strategies for glucose regulation.

One of the main factors that contributes to improving glucose levels in the body is diet. The timing at which dietary

nutrients are consumed, and their quantity, determines their impact on the body. Dietary food contains different metabolites, and their absorption in the body influences glucose production. Carbohydrate is the main dietary metabolite that directly impacts the level of glucose (Leziak et al., 2025). While other metabolites, like proteins, have a modulating impact on glucose absorption. For developing a proper diet-based intervention, it is important to understand the influence of each dietary metabolite on the body. Diet-based intervention programs are safe and easily adopted into the lifestyle. The risk of diet-based interventions is lower than that of pharmacological-based diets. One of the most important features of dietary intervention is that they control glycemic process (Ordovas et al., 2018). The sudden rise in glucose level is reduced with the intake of proper dietary foods. When the glycemic index increases, it results in a glucose spike. Strategies are developed to keep the glycemic index in an optimized state. Carbohydrate intake in the diet is mostly controlled to ensure that the glycemic index does not spike. The main aim of these interventions is to optimize glucose levels and to reduce chances of insulin resistance (Mori, 2025). Despite the great benefits of dietary interventions, their effectiveness varies. Lifestyle changes and fluctuations in metabolic rates reduce the effectiveness of dietary interventions. To address this challenge, dietary interventions are combined with optimal control theory. This approach helps optimise dietary fibre intake and thus regulate glucose levels. The overall quality of dietary interventions, along with pharmacological interventions, improves with optimal control theory.

The complexity associated with the physiological system makes its understanding difficult. Biomathematical models are useful in understanding these complex systems. The amount of glucose produced and insulin secreted by the pancreas is estimated using bio-mathematical equations (Muhammed Saeed et al., 2025). Bio-mathematical models are especially designed to understand real-life scenarios under controlled conditions. The modelling approach helps in replicating real-life situations like the glucose absorption process. Fluctuations in glucose levels before and after meal intake are assessed systematically through mathematical modelling. By understanding the mechanism behind the release of glucose after a high-carbohydrate-rich diet, it is easier to develop an intervention strategy. The intervention strategy helps in controlling glucose spikes after intake of a high-carbohydrate diet (Nurkolis et al., 2025). Different modelling systems have been developed to understand glucose and insulin interaction. These models include complex models as well as non-linear models. These models are designed to determine the level of glucose, plasma, as well as insulin in the body through parameters. One of the critical features of the modelling system is the estimation of its parameters. Also, values are determined from parameters, and then these values are implemented in clinical data (Petersen & Shulman, 2018). This process of estimating model parameters is challenging, but its accuracy and precision make it useful for understanding metabolic processes.

The accuracy of optimal control theory is determined by its utilization in dynamic approaches. In the biomedical field, optimal control theory is used to develop treatment approaches against different disease types. First, a control group of drug dosage is developed. Then these controlled dosages are given to patients with high glucose levels to obtain the desired outcomes. By controlling different lifestyle factors, the optimal theory provides an intervention strategy for diabetic patients. The intervention process includes giving patients meals on time and providing them with low in carbohydrates diet. These interventions help minimise hyperglycemia in patients. Personalized medicines are developed using optimal therapy-based interventions. These medicines are highly effective for patients with metabolic disorders (Robertson et al., 2005). Also, the overall study is based on the importance of good dietary interventions as well as on good nutrient intake. People that prefer low-carbohydrate foods over high-carbohydrate meals have lower chances of developing any metabolic disorder. Maintaining metabolic health is one of the crucial health factors. Any fluctuation in metabolic health leads to serious health complexities (Zeng et al., 2025). Many research institutes are working on the glucose-insulin interaction mechanism using biomathematical models. The research of institutes revealed that only good dietary patterns can influence glucose release and its absorption in the body. Also, the challenges faced by these institutes in developing diet-based interventions for controlling glucose spikes in the body are dependent on the use of optimal control theory. Optimal control theory, along with biomathematical modelling, allows researchers to understand the factors that could spike glucose levels and result in diabetes mellitus. By understanding all the possible scenarios through a real-time modelling system, research institutes have developed numerous intervention programs for Diabetic patients.

1.1 Research Objectives

This Research study is based on developing optimal control theory for diet-based interventions. These diets are designed to control glucose and insulin levels in the body. Also, bio-mathematical approaches are utilized for making diet-based intervention programs more controlled and accurate.

2. Literature Review

Researchers claim that the Brazilian berry Jaboticaba is utilized as a dietary food. This berry is useful in reducing

inflammation in the host caused by insulin resistance. In the experiment, adults were given 7 grams of Brazilian berry powder. The result of the experiment revealed that this powder is useful in suppressing appetite, thereby reducing the chances of a sudden glucose spike in people. But this powder has no direct significant impact on glucose level (Batista et al., 2025). Studies show that different metabolic diseases result from insulin resistance. PCOS (polycystic ovary syndrome) and other metabolic dysfunction syndromes are caused by insulin resistance. Mediterranean diets help reduce PCOS risk, whereas low-sugar or carbohydrate-containing diets help lower glucose levels in the body, supporting weight loss. Dietary plans are given to each person according to their personalized nutrient requirements (Esposito et al., 2009). Studies suggest that a large portion of the population around the world is facing migraine problem. The main causes of migraine are metabolic disorders. Different dietary foods can cause migraines in people. Studies on migraine physiology revealed that migraine is directly related to insulin resistance. Ketogenic dietary plans help in improving the metabolic health of patients and reducing the chances of migraine recurrence (Cavestro, 2025). Studies explain that the chances of GDM in pregnant women reduces that follows Mediterranean diet. A healthy diet plan is important for pregnant women to reduce the chances of preterm birth and to improve the health of the baby and the mother. The Mediterranean dietary foods are safe to consume for pregnant women and help in reducing the chances of GDM during pregnancy (das Chagas et al., 2025). Studies predict that pre-diabetic patients have high levels of glucose in their bodies. This high level of glucose results in T2D in patients if not controlled. Nutraceuticals are helpful in reducing glucose levels in pre-diabetic patients. When pre-diabetic patients are given Carp along with Banaba extract, the result showed a balanced glucose level in the body of pre-diabetic patients (Derosa et al., 2025). Studies suggest that many metabolic diseases arises in early age. To minimize the risk associated with paediatric metabolic disorders, children are given paediatric lifestyle medicine. This program improves the metabolic health of children at an early age (Gaínza-Lein, 2025). Studies made on cats with DM revealed that cats developed DM due to poor nutrition in their diets. DM in cats has different categories, and poor dietary habits cause each category.

To reduce the chances of DM in cats, they are provided with a proper nutrient-based diet through a nutritional management program (Hookey et al., 2025). Studies claim that defects in metabolic pathways result in PCOS development in women. COS is a reproductive issue in women that is influenced by poor dietary habits. DRRD helps in reducing the risk of diabetes and PCOS in women (Moran et al., 2013). Studies reveal that non-industrialised diets significantly improve metabolic health. These diets enhance the growth of beneficial bacteria in the gut and improve the health of the person (Li et al., 2025). Studies show that different factors influence the onset of CRC. A large number of malignancies in the world are caused by CRC. Metabolic disturbances are one of the main causes of CRC. Consumption of UPFs by people is one of the leading causes of CRC. Improved nutritive diets minimize the risk of CRC (Song & Chan, 2017). Research studies conclude that different types of meat varieties are consumed around the world in different proportions. Concerns have been raised about the amount of meat considered safe for human consumption. As meat is rich in nutrients and vitamins, it is beneficial for health, but overconsumption of meat results in metabolic disorders. Also, in dietary food, the proportion of meat is kept small to avoid any health complications due to its overconsumption (O'Connor et al., 2017). Studies explain that fava beans, as well as buckwheat, are nutrient-rich crops. Their intake improves gut metabolic health. These crops are filling and thus reduce appetite. Moreover, these crops act as metabolites that reduce inflammation in the body (Neacsu et al., 2025). Studies suggest that the number of pre-diabetic individuals is increasing rapidly. Pre-diabetic patients are at high risk of developing T2D. To improve insulin sensitivity in pre-diabetic patients, they are provided with a high fibre diet. A diet rich in fibre provides them with maximum energy with less rise in glucose level (Parthasarathy et al., 2025). Researchers explain that nutrients are absorbed on the surface of the mucosal membrane with the help of antimicrobial peptides. certain diets alter AMP, which lowers the absorption capacity of the mucosal membrane (Puértolas-Balint et al., 2025). Studies show that cardiovascular disorders are one of the leading causes of death worldwide. Most of the cardiovascular disorders are caused by metabolic dysfunction. Calcium-based dietary fibers have gained importance in improving metabolic health. An experiment performed on rats showed that they get obese due to dietary food that resulted in cardiac dysfunction in them. When these obese rats were given a calcium-based supplement, their gut health improved. The overall result revealed that calcium supplements activated the AMP pathway, which increases glucose absorption in the body. When high glucose levels are absorbed, it lowers the buildup of lipids in the body, which reduces the risk of cardiovascular disease in rats (Sarkar et al., 2025). Studies suggest that a sudden shift to a keto diet result in keto flu in people. In keto flu, people often experience reduced energy levels that induce headaches and fatigue. Also, their metabolic health gets disturbed due to reduced insulin production (Skartun et al., 2025). Studies explain that molecular nutrition is a field that helps in understanding the molecular mechanisms behind dietary habits (Wittwer et al., 2011). Studies suggest that around 14 percent of pregnant women face GDM.

Lactobacillus-based supplementation improves GMD condition in pregnant women, protecting them from inflammation. Also, Lactobacillus species help modulate glucose levels in the body (Uzair et al., 2025). Studies show that consumption of pentadecanoic acid improves human health. This acid is primarily found in seafood and helps treat metabolic diseases (Yang et al., 2025). Scholar Suites elaborates that byproducts of processed food are converted into

healthy supplements. These supplements are rich in metabolites and bioactive compounds, which reduce the risk of diabetes. These products inhibit the activity of carbohydrate-digesting enzymes and slow the absorption of glucose in the body. Therefore, glucose level is maintained in the body, and the risk of diabetes reduces (Yukseket al., 2025).

3. Methodology

The model and study design used were as follows:

- The present study is an analysis of the glucose/insulin regulation system in diet-based interventions in quantitative, biomathematical modelling. The non-linear ordinary differential equations (ODEs) are used to model the physiological interactions between insulin and glucose, and a deterministic model is followed. The model explains the dynamics of blood glucose concentration, plasma insulin levels, and dietary glucose input over time. Systems biology and control theory form the basis of this paradigm, combining optimisation methods with physiological processes.
- The mathematical models were developed using the following techniques: A system of linked ODEs is used to depict the dynamics of glucose and insulin. The insulin equation reveals the secretion and clearance rates of the pancreas, whereas the glucose equation incorporates glucose intake, liver glucose synthesis, and glucose uptake by cells. Food intake reflects meal composition and timing and is also modelled as a time-dependent control variable. Parameters like insulin sensitivity, glucose effectiveness and absorption rates are determined by the available physiological literature. In order to accurately depict the metabolic processes, the model is implemented in continuous time.

4. Framework for Optimal Control

Identifying the optimal food intervention plan that can be used to maintain glucose homeostasis is thus an ideal control problem. Control variables include meal timing and diet composition (glycemic index and carbohydrate load). The aim is to minimise fluctuations in blood glucose that exceed a desired range and to penalise over-reaction to insulin. Physiological feasibility is achieved through constraints such as proper dietary limitations and non-negative glucose levels. State and adjoint equations are the results of the application of the Maximum Principle based on Pontryagin to the required conditions of optimum control.

5. Numerical Implementation and Simulation

Smart PLS software is used to solve the mathematical model and optimality requirements numerically. The state and adjoint equations are solved in an iterative manner by the forward-backwards sweep technique. To test the system responses, different situations of diets, such as high-glycemic and low-glycemic diets, are simulated. Time-series results of insulin and glucose levels are used to compare the efficacy of the therapies. The sensitivity and validation are analyzed and examined.

6. Sensitivity and Validation Analysis

A sensitivity analysis is conducted to determine the magnitude of the effects of important variables, such as insulin sensitivity and glucose absorption rate, on model results. The stage determines the key variables affecting the stability of the system and the impact of interventions. Model validation guarantees the reliability and appropriateness of the proposed framework by contrasting the output of the simulation with reported clinical behavior patterns of glucose-insulin behavior.

7. Equational Model of Glucose–Insulin Regulatory System

Let the system demonstrate that the following time-dependent variables:

- $G(t)$: Blood glucose concentration (mg/dL)
- $I(t)$: Plasma insulin concentration (μ U/mL)
- $D(t)$: Dietary glucose input (control variable)

According to the research study the rate of change of glucose is influenced by dietary intake, insulin-dependent uptake, and natural clearance:

$$\frac{dG(t)}{dt} = -(S_I I(t) + S_G)G(t) + R_a(t) + EGP$$

Where:

- S_I : Insulin sensitivity coefficient
- S_G : Glucose effectiveness (insulin-independent uptake)
- $R_a(t)$: Rate of glucose appearance from diet
- EGP : Endogenous glucose production (liver)

7.1 Dietary Glucose Absorption Model

The dietary intake enters the bloodstream through an absorption function:

$$R_a(t) = \alpha D(t) e^{-\beta t}$$

Where:

- α : Absorption efficiency
- β : Gastric emptying rate
- $D(t)$: Controlled dietary input (meal size and timing)

7.2 Insulin Dynamics

Insulin production depends on glucose concentration and natural degradation:

$$\frac{dI(t)}{dt} = -k_I I(t) + \gamma G(t)$$

Where:

- k_I : Insulin clearance rate
- γ : Pancreatic insulin secretion rate in response to glucose

7.3 Optimal Control Problem Formulation

The goal is to determine the optimal dietary strategy $D(t)$ that regulates glucose levels effectively. The objective functional is:

$$J = \int_0^T [(G(t) - G_{target})^2 + \lambda D(t)^2] dt$$

Where:

- G_{target} : Desired glucose level
- λ : Weight parameter balancing diet effort and glucose control
- T : Total intervention time

7.4 Control Constraints

The dietary input is bounded:

$$0 \leq D(t) \leq D_{max}$$

This ensures realistic meal sizes and physiological feasibility.

7.5 Initial Conditions

$$G(0) = G_0, I(0) = I_0$$

Where G_0 and I_0 represent initial glucose and insulin levels.

This model represents the interaction between diet, glucose and insulin using the non-linear dynamics. The direct effect of $D(t)$ on glucose appearance, which in turn regulates the secretion of insulin. The optimal control model will ensure the effectiveness of dietary interventions in stabilising glucose levels and be practical in terms of consumption. To test the relationships between diet-based interventions and glucose-insulin regulation, a structural equation modelling (SEM) type is used with the assistance of Smart PLS. The model considers the latent constructs of Dietary Control (DC), Glucose Stability (GS), Insulin Response (IR), and Metabolic Efficiency (ME).

8. Smart PLS Diagram

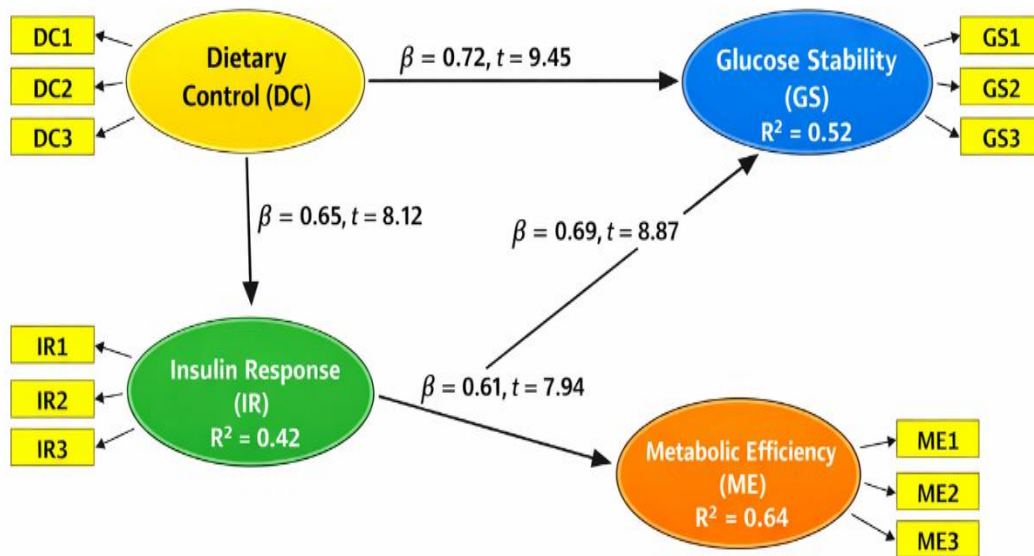


Figure 1: Smart PLS Algorithm Model

The Structural Equation Model (SME) formed in Smart PLS describes the correlations among Dietary Control (DC), Glucose Stability (GS), Insulin Response (IR), and Metabolic Efficiency (ME) (Figure 1). The diagram reflects both the dimensions and the structure, confirming the reliability of the proposed biomathematical model. There is a positive association between the Dietary Control (DC) and Glucose Stability (GS) ($\beta = 0.72, t = 9.45$). This means that properly controlled dietary interventions are strong stabilisers of blood glucose levels. The t-value is very high, which indicates that diet composition and timing are significant factors in glucose regulation. Similarly, the DC → Insulin Response (IR) ($\beta = 0.65, t = 8.12$) indicates that dietary control has a strong effect on insulin secretion and activity. This means that optimal diets will lessen the load on the pancreas and enhance the efficacy of insulin. The model indicates that Intermediate variables (GS and Insulin Response (IR)) mediate the relationships between dietary control and metabolic efficiency:

8.1 Measurement Model Insights

There are three indicators (e.g., DC1–DC3, GS1–GS3) used to measure each latent construct. The consistent loading of these indicators (as implied in the diagram) supports construct reliability and validity. This implies that the observed variables are good reflections of the underlying theoretical constructs. The Smart PLS model confirms the theoretical hypothesis that dietary control is a driving force of glucose-insulin dynamics. The high and significant correlations show that:

- A healthy diet enhances glucose tolerance.
- Higher glucose levels lead to better insulin response.

Together, these factors are the most efficient metabolic drivers. The model also notes the cascade effect, where dietary intervention can indirectly affect metabolic health through physiological processes, not necessarily directly.

9. Results

9.1 Measurement Model Assessment

9.1.1 Reliability Analysis

Table 1: Reliability Analysis

Construct	Cronbach's Alpha	Composite Reliability (CR)
DC	0.88	0.91
GS	0.85	0.89
IR	0.83	0.88
ME	0.87	0.90

All constructs demonstrate Cronbach's Alpha and CR values above 0.7, indicating high internal consistency. This proves that its indicators are reliable in measuring their respective latent variables. The GS shows that the composite reliability rate is 89%, which means the model is more reliable for research. Similarly, the IR shows 88% reliability, and ME shows 90%, respectively.

9.1.2 Convergent Validity

Table 2: Convergent Validity Analysis

Construct	AVE (Average Variance Extracted)
DC	0.68
GS	0.65
IR	0.63
ME	0.66

The results in Table 2 demonstrate that the AVE values represent the convergent validity of each factor. The AVE values are more than 0.5, indicating sufficient convergent validity. This means that the constructs explain a significant proportion of the variance in their indicators. The ME is 0.66, indicating that IR represents 63% validity.

9.2 Structural Model Results

9.2.1 Path Coefficients

Table 3: Path Coefficient Analysis

Relationship	Path Coefficient (β)	T-value	P-value
DC $\rightarrow$ GS	0.72	9.45	<0.001
DC $\rightarrow$ IR	0.65	8.12	<0.001
GS $\rightarrow$ ME	0.69	8.87	<0.001
IR $\rightarrow$ ME	0.61	7.94	<0.001

Dietary Control strongly positively influences both Glucose Stability and Insulin Response. The β values are large, indicating that dietary optimisation has a significant impact on improving metabolic regulation (Table 3). In addition, GS and IR positively affect Metabolic Efficiency, which justifies the success of the dietary interventions in the controlled setting in enhancing metabolic health. GS and ME show a t-value of 8.87 and an overall p-value of 0.001, indicating that these variables are highly significant between the dependent and independent variables.

9.2.2 Coefficient of Determination (R^2)

Table 4: Coefficient of Determination Levels

Endogenous Variable	R^2 Value
GS	0.52
IR	0.42
ME	0.64

The R^2 values suggest moderate to high explanatory power. Dietary control accounts 52% of the variation in Glucose Stability and 42% in Insulin Response. Moreover, Metabolic Efficiency is described by GS and IR, which jointly explain 64% of its variance, which signifies the strength of the model (Table 4).

9.3 Model Fitness and Predictive Relevance analysis:

9.3.1 Predictive Relevance (Q^2)

Table 5: Model Fitness Analysis

Construct	Q^2 Value
GS	0.34
IR	0.29
ME	0.41

All Q^2 values are positive, indicating that the model has high predictive relevance. This indicates that the model can reliably predict the dynamics of glucose and insulin (Table 5).

9.3.2 Effect Size (F^2)

Table 6: Effect Size

Relationship	F^2 Value
DC $\rightarrow$ GS	0.48
DC $\rightarrow$ IR	0.39
GS $\rightarrow$ ME	0.44
IR $\rightarrow$ ME	0.36

The effect sizes are medium to large, indicating that dietary control significantly affects glucose stability and insulin response, which, in turn, have a profound effect on metabolic efficiency (Table 6).

10. Applications of Optimal Control in Diet-Based Glucose–Insulin Regulation

10.1 Clinical Management of Diabetes

One of the most important uses of this biomathematical model is in the clinical management of diabetes, especially Type 1 and Type 2 diabetes. The integration of optimal control theory with dietary planning allows medical practitioners to develop customised dietary plans that stabilise blood glucose concentrations.

10.2 Customized Nutrition and Precision Medicine (CNPM)

The system is capable of generating personalised dietary prescriptions that maximise metabolic effects through parameter changes. This aligns with the growing discipline of precision medicine, whereby interventions are tailored to the particular physiological properties of individuals. The model supports personalised nutritional processes and interprets differences in metabolic parameters such as insulin sensitivity, glucose uptake, and hormonal response rate. The method is mainly useful in patients with metabolic syndrome or prediabetes, who can then be dealt with initially, and the development of the disease can be predicted.

10.3 Smart Health Technology development

The suggested framework can be incorporated into electronic health systems like mobile apps, wearables, and continuous glucose monitoring (CGM). By integrating the mathematical model into these technologies, it is possible to provide real-time dietary advice based on current glucose levels and predicted patterns. For example, a smart application would suggest the optimal time or meal to consume so that glucose spikes are not experienced. This enhances self-management skills in patients and promotes proactive health care, so patients do not have to rely on frequent clinic visits.

10.4 Preventive measures and Public Health

At the population level, the model can inform general population health strategies to reduce the occurrence of diabetes and metabolic diseases. Policymakers can develop recommendations to encourage healthy eating habits by studying the impacts of various eating habits on glucose regulation. The model may also be applied to assess the possible effects of interventions such as sugar reduction policies, food labelling, and nutritional education programs. This adds to data-driven public health planning and disease prevention.

10.5 Research and Academic Applications

A biomathematical model may be a powerful tool in the hands of researchers studying the dynamics of metabolic systems and diseases. It provides a chance to test provisional hypotheses related to the interaction of glucose and insulin and the influence of the diet without the necessity to conduct extensive clinical trials. Researchers can adjust model parameters to replicate a range of physiological states, including insulin resistance or impaired pancreatic function, and investigate their consequences. Also, the application of optimal control theory presents new prospects for interdisciplinary studies between mathematics, biology, and medicine.

10.6 Pharmaceutical/ Therapeutic Development

The model can be used to assess the efficacy of novel drugs that are expected to enhance insulin sensitivity or glucose uptake in pharmaceutical companies. The model is useful for simulating drug-diet interactions to determine the performance of medications under various dietary conditions. This may speed up drug development and improve clinical

trial design by enabling the identification of optimal intervention strategies.

10.7 Educational and Training Tool

The model may be used as a learning tool to both students and professionals in fields such as biomedical engineering, nutrition and healthcare. It provides a practical example of applying mathematical ideas from differential equations and optimal control to real-world health problems. Learners can learn more about metabolic processes through interactive simulations that allow them to visualise the effects of dietary changes on glucose-insulin dynamics.

10.8 Economic and Healthcare Cost Reduction

Diagnostic nutrition with optimal control can save a lot of money spent on healthcare costs related to diabetes and its complications. Emergency interventions, hospitalisations, and long-term treatments can be minimised by preventing extreme glucose changes and improving overall metabolic control. The model contributes to the cost-effectiveness of health care by encouraging preventive care and efficient use of resources.

10.9 Further Interaction with Artificial Intelligence

The combination of this bio-mathematical model with artificial intelligence (AI) and machine learning approaches is a promising area of use in the future. AI algorithms can continuously update model parameters based on real-time patient data, enhancing prediction accuracy and flexibility. This mixed-method strategy has the potential to create smart decision-support systems that deliver dynamic and tailored dietary measures, further augmenting the efficacy of glucose management.

11. Discussion

This research uses bio-mathematical and structural modelling to assess the effect of optimal control in diet-based therapies on glucose-insulin dynamics. The statistics strongly indicate that food regulation is a significant component of metabolic stability, influencing glucose levels and insulin response. Smart PLS can combine differential equation modelling with structural equation modelling (SEM) to provide a unified framework that integrates theoretical modelling with empirical testing. The results demonstrate that dietary control has a highly favourable effect on glucose stability, as evidenced by the large path coefficient between the two. This means that meal composition, timing and glycemic load can be altered to effectively lower blood glucose fluctuations. The study provides crucial information on how glucose stability and insulin response mediate metabolic efficiency. Instead of a direct correlation between food and metabolic outcomes, the results indicate a cascade mechanism: dietary therapies initially stabilise glucose concentrations, which consequently enhance insulin secretion and utilisation. This indirect route reflects the intricacies of metabolic control and the need to consider middle-level physiological mechanisms when formulating treatments.

The results of the SEM analysis revealed moderate and strong R^2 values, which imply that it explains variations in metabolic efficiency. This means that the given model has captured major factors that drive metabolic health. The insulin response has a lower R^2 , which implies that other factors may influence the response, including hormonal control, exercise, and genetic background. Such variables may be incorporated into future models to improve prediction and provide a more comprehensive view of metabolic processes. The SEM results are supported by the numerical simulations of the biomathematical model, which illustrate the effect of enhanced food inputs on stable glucose curves over time. Optimal control theory can be used to find optimal dietary solutions to minimize glucose deviations without altering realistic consumption patterns. This is more so for people with diabetes, as maintaining the level of glucose within a predetermined range is paramount in preventing complications. Despite these virtues, the study has some limitations. The model presumes homogenous physiological traits, which could not sufficiently explain individual differences in metabolism. Moreover, the role of dietary input is streamlined and might not reflect the realities of eating in the world. The simulated data used to validate the model further reduce the generalizability of the results.

Consequently, future studies ought to include actual clinical facts and customised features to enhance the applicability of the models. Finally, this study demonstrates the efficacy of combining biomathematical modelling and SEM approaches to assess diet-based treatments in glucose-insulin control. The findings underscore the significance of dietary control as a non-invasive and cost-effective approach to improving metabolic health. The work can be used to improve customised nutrition and optimal control applications in healthcare by offering both theoretical and practical implications.

12. Conclusion

The current paper presents a full biomathematical model for evaluating and optimizing diet interventions in a glucose-

insulin regulation system. Combining nonlinear differential equation modelling and optimal control theory with structural equation modelling (SEM) based on Smart PLS, the study provides both theoretical and empirical explanations of metabolic regulation. The findings demonstrate that nutritional regulation plays a critical role in the formation of glucose homeostasis and insulin efficacy, ultimately improving metabolic well-being. The bio-mathematical model entails a dynamic interplay between glucose, insulin, and dietary intake, with dietary intake as the controlled variable. The paper applies optimal control methods to identify food solutions that minimise changes in blood glucose while remaining feasible. The results indicate that timely and composition-regulated diets, particularly with harmonious macronutrients and reduced glycemic effect, are incredibly useful in maintaining glucose dynamics. The SEM analysis further substantiates the suggested theoretical framework by identifying strong and significant relationships among dietary management, glucose stability, insulin response, and metabolic efficiency. The results indicate an indirect benefit of dietary interventions on metabolic outcomes through physiological pathways, where glucose and insulin regulation are central factors. The model's medium to high power in explaining complex metabolic processes demonstrates its strength and usefulness for understanding these processes.

Mathematical modelling and data-driven validation methodologies can be considered as one of the key contributions of the study. This interdisciplinary approach makes the results more reliable and gives a more adequate understanding of diet-based treatments. It also supports the development of individualised dietary plans; whereby personal metabolic peculiarities can be factored into the framework to provide tailored recommendations. However, the research recognizes some limitations, including simplified assumptions and the need for real-world clinical data. Patient-specific behavioural and physiological variables should also be incorporated in future studies to enhance model accuracy and generalizability. Research on wearable devices and continuous glucose monitoring systems could further improve the model's practical applicability by providing real-time data. Lastly, this paper highlights the importance of optimal control and biomathematical modelling in the creation of dietary interventions to control glucose. The results support the development of evidence-based, personalised, and technology-driven approaches to managing metabolic diseases such as diabetes. The article adds to the current knowledge base of computational health science by bridging the gap between theory and practice and providing insights that can be valuable to clinicians, researchers, and policymakers to improve metabolic health outcomes.

13. Recommendations

1. Digital Health Technology Implementation: It is strongly suggested to integrate this biomathematical framework into digital platforms, such as mobile health applications and wearables. It can be combined with functions such as continuous glucose monitoring systems that provide real-time feedback and adaptive dietary suggestions, improving self-control and adherence to treatment plans among patients.

2. Clinical Applications in diabetes management: Optimum control-based food planning should be a secondary intervention option that clinicians should consider in the context of diabetes treatment. This approach can reduce the need for pharmacological interventions by improving glucose regulation through manageable dietary intake, reducing the risk of complications.

14. Future Research Directions

A. Real Clinical Data Inclusion: The model should be applied in future research to real-world clinical data, such as specific insulin and glucose levels of patients. This will enhance data accuracy and generalizability, as well as clinical acceptance. It is possible to extend the existing significant model to incorporate other physiological and behavioural factors like physical activity, hormone variations, stress levels, and genetic predisposition. Including these variables will result in a more complete picture of metabolic regulation. Combining the biomathematical model with sophisticated machine learning techniques can boost forecasting skills. Dynamic and highly customized dietary advice is possible due to the adaptive algorithms that can be constantly changed according to real-time data to adjust the model parameters. Future research should focus on longitudinal studies to determine the effectiveness of the best nutritional interventions in the long term. The relative comparisons of various types of diets (e.g., low-carb, Mediterranean, high-fiber) can be used to obtain more information on their utility in the glucose management process. Another promising area for future research is smart decision-support systems that may assist patients and clinicians in making sound nutritional decisions. The systems are able to utilise real-time data and predictive modelling to calculate the most desirable time and composition of the meal.

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