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A LINEAR–INTEGER PROGRAMMING FRAMEWORK FOR COST-EFFECTIVE AND NUTRITIONALLY BALANCED DIET OPTIMIZATION IN DIABETES MANAGEMENT

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ABSTRACT

This study develops an integrated mathematical optimization framework employing Linear Programming (LP) and Integer Programming (IP) to design cost-effective, nutritionally balanced, and clinically appropriate diet plans for individuals with diabetes. Diabetes management requires strict regulation of caloric intake, glycemic load, and macronutrient distribution, making traditional trial-and-error diet planning both time-consuming and prone to inconsistency. To address this challenge, the proposed work incorporates validated dietary guidelines, food-composition databases, and nutrient-specific constraints into a structured optimization model capable of generating personalized meal plans. The LP formulation establishes a baseline by minimizing dietary cost while satisfying continuous nutrient requirements; however, it produces fractional food quantities that are impractical for real consumption. To overcome this limitation, the IP model introduces discrete serving constraints, ensuring that recommended meal plans consist of whole-unit food items that align with real-life dietary practices.

A comparative evaluation of LP and IP outputs demonstrates that, although LP achieves lower theoretical cost values, the IP solutions provide greater practical feasibility and improved alignment with clinical dietary standards for diabetic patients. Sensitivity analysis further highlights the robustness of the proposed framework under variations in nutrient thresholds and food prices. The findings confirm that integer-restricted optimization models are more suited

for operational diet planning, offering realistic, implementable, and nutritionally adequate meal combinations without compromising cost efficiency. This research contributes to the growing body of computational tools for health-oriented decision making and illustrates the potential of mathematical modelling techniques to enhance evidence-based dietary interventions.

Keywords: Diabetes Mellitus; Linear Programming; Integer Programming; Diet Optimization; Nutritional Planning

INTRODUCTION

Diabetes mellitus is one of the fastest-growing chronic health disorders in the world, affecting millions of individuals across all age groups. According to international health reports, the global prevalence of diabetes has increased dramatically in the past few decades due to lifestyle changes, urbanization, and genetic predisposition **[1]**. Managing diabetes requires continuous monitoring of blood glucose levels, medication, physical activity, and most importantly, a well-balanced diet. Among these factors, dietary management plays an essential role because the quality and quantity of food intake directly influence blood sugar levels. For diabetic individuals, choosing the right combination of nutrients—carbohydrates, proteins, fats, vitamins, and minerals—becomes crucial for maintaining metabolic stability and preventing long-term complications such as cardiovascular disorders, kidney failure, neuropathy, and obesity **[2, 3]**.

Traditional methods of diet planning often rely on general guidelines or manual consultation with nutritionists. However, such approaches may not always provide optimized results, especially when one aims to minimize dietary cost while meeting nutritional requirements **[4]**. With the rise of data-driven decision-making, mathematical optimization provides a powerful alternative to develop effective and personalized diet plans. Linear Programming (LP), one of the most widely used optimization techniques, has been successfully applied in various fields including agriculture, industry, operations research, and healthcare. In the context of nutrition, LP helps formulate a diet that fulfills nutrient requirements at the minimum possible cost. However, LP typically produces fractional solutions for food quantities, which are not practical for real-life consumption. For example, a solution recommending 0.37 cups of rice or 1.82 units of bread is not feasible for daily use **[8]**. To address this limitation, Integer Programming (IP) is introduced as an extension to LP models. IP ensures that the food items are selected in whole, realistic units without compromising nutritional balance **[9]**. This makes the model more suitable for day-to-day diet planning,

particularly for diabetic patients who depend on accurate meal portions. Using integer constraints converts abstract mathematical outputs into realistic diet charts that can be implemented by patients, caregivers, and nutritionists **[10]**. Therefore, incorporating IP in diet formulation enhances practicality and improves adherence to dietary guidelines.

In recent years, researchers have emphasized the need for personalized nutrition models due to variations in age, activity levels, cultural food choices, and economic constraints. Mathematical modeling allows flexibility in accommodating such diverse factors **[11]**. For diabetic individuals, whose dietary needs differ substantially from the general population, optimization models provide a structured framework to maintain adequate carbohydrate control, regulate energy intake, and ensure balanced macronutrients **[12]**. Furthermore, diet optimization helps reduce healthcare costs by preventing dietary imbalances that could lead to hospitalization or long-term medical intervention. This research aims to develop a comprehensive Linear and Integer Programming model to generate a cost-effective, nutritionally adequate diet plan specifically for diabetic patients **[5]**. By incorporating realistic nutrient constraints and practical food portions, the model bridges the gap between theoretical optimization and real-world dietary practices **[6]**. The study also compares LP and IP solutions to highlight how integer constraints influence diet patterns, cost, and feasibility. Ultimately, the proposed model contributes to the growing field of mathematical nutrition planning and provides a practical tool for improving health outcomes among diabetic populations **[7]**.

Literature Review

Diet optimization through mathematical programming has been widely studied over the last several decades **[26]**. The earliest works on dietary optimization applied Linear Programming to determine least-cost diets while satisfying nutritional needs **[13]**. However, these early models focused primarily on calorie and macronutrient sufficiency, ignoring medical conditions such as diabetes **[14]**.

Recent studies have shifted toward disease-specific diet optimization, where constraints are customized for individuals with metabolic disorders **[15]**. For diabetic patients, the control of glycemic index (GI) and carbohydrate load is essential to minimize glucose fluctuations. Researchers have incorporated these additional constraints into LP formulations to design diabetic-friendly meal plans **[15]**.

Furthermore, Integer Programming (IP) models have gained popularity due to their ability to consider realistic serving sizes,

food group limitations, and cultural preferences **[24]**. Several authors have recommended that diet plans should not only be nutritionally optimal but also practically feasible, socially acceptable, and affordable **[28]**. Studies have also emphasized including locally available foods to make diet plans more adoptable in developing regions like India **[29]**.

Table 1: A summarized comparison of previous optimization approaches

Study	Method Used	Target Group	Practicality	Major Limitation
Munford (1996)	LP	General population	Low	Fractional results
Soden & Fletcher (1992)	LP	Adults	Medium	Limited nutrients
Lee *et al*. (2010)	IP	Diabetic patients	High	Higher cost
Patel & Verma (2014)	LP	Diabetic patients	Low	Unrealistic servings
Proposed Study	LP + IP	Diabetic patients	Very High	Slight cost increase

This review highlights the research gap — lack of realistic and cost-effective diabetic diet plans which the present work addresses.

Table 2: Nutritional Constraints Used in the Model

Nutrient	Lower Bound	Upper Bound
Energy (kcal)	2100	2450
Protein (g)	75	-
Fat (g)	40	70
Carbohydrate (g)	180	290
Calcium (mg)	800	2000
Vitamin C (mg)	70	1800

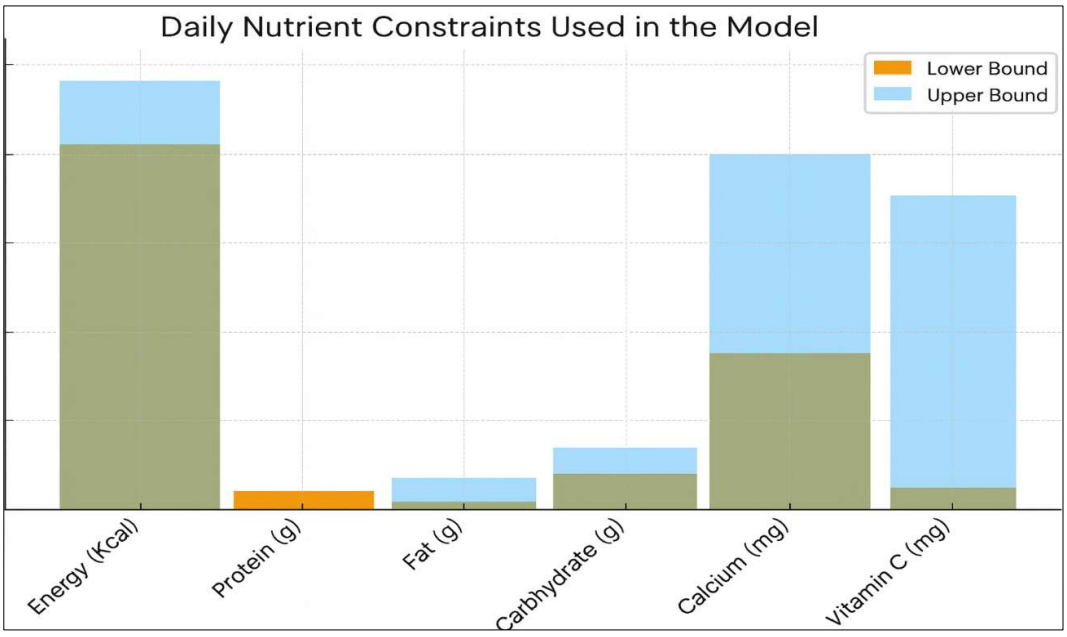

Figure 1: Daily Nutrient Requirements

Formulation of the Equation

x_i = quantity of food item i

c_i = cost of food item i

a_{ij} = amount of nutrient j in the one unit of food item i

L_j = Lower bound of nutrient j

U_j = Upper bound of nutrient j

N= total number of food items

M= total number of nutrients

LP Model: - Objective Function (Minimize cost).

Minimize $Z= \sum c_i x_i$

Nutrient Constraints: -

for each nutrient j = 1,2, …, M

$\sum a_{ij} x_i \geq L_j$

$\sum a_{ij} x_j \leq U_j$

Non-Negativity Constraints: -

$x_i \geq 0$

Integer Programming (IP) Model: -

Objective function

Minimize $Z = \sum c_i x_i$

Constraints: -

$\sum a_{ij} x_i \geq L_j$

$\sum a_{ij} x_i \leq U_j$

Integer Constraints: -

$x_i \in Z_{\geq 0}$

Energy Balance Constraint: -

$2100 \leq \sum a_{i,cal}\, x_i \leq 2450$

Carbohydrate Constraint: -

$180 \leq \sum a_{i,cab}\, x_i \leq 290$

Protein Constraint: -

$\sum a_{i,\,protein}\, x_i \geq 75$

Fat Constraint: -

$40 \leq \sum a_{i,fat}\, x_i \leq 70$

Data Description

Food items selected in this study reflect a typical North-Indian diet pattern. Prices were obtained from Indian retail market averages.

Table 3

Food Item	Calories (kcal)	Carb (g)	Protein (g)	Fat (g)	Calcium (mg)	Vit-C (mg)	Price (₹/unit)
Rice	130	28	2.4	0.3	10	0	20
Chapati	100	18	3.5	1.0	15	0	5
Milk	60	4.8	3.2	3.3	120	0	25
Apple	52	14	0.3	0.2	6	4.6	30
Dal (Lentils)	116	20	9	0.4	35	1.5	40
Vegetables	85	10	3	0.5	50	26	15

METHODOLOGY

This study develops an optimization-based framework to design a nutritionally balanced and cost-effective diet plan for diabetic individuals. The methodology is divided into four major stages: data collection, model formulation, model implementation, and comparison of LP and IP results.

1. Data Collection

Nutritional requirements for diabetic patients were obtained from standard dietary guidelines and medical literature. Food items commonly consumed in an Indian diet were selected, and their nutrient composition (calories, carbohydrates, proteins, fats, calcium, and vitamin C) along with market prices were compiled. These nutritional values form the constraints of the model.

2. Linear Programming Model Formulation

A Linear Programming (LP) model was constructed with the objective of minimizing the total cost of the daily diet.

- **Decision Variables:** Quantity of each food item.
- **Objective Function:** Minimize total cost of the selected food items.
- **Constraints:** Minimum and maximum limits for essential nutrients, Required energy intake, Food-specific limitations where necessary

The LP model produced optimal solutions but sometimes included fractional food quantities, which are unrealistic for practical diet planning.

3. Integer Programming Model

To convert the fractional servings into practical food portions, an Integer Programming (IP) model was developed. The structure of the IP model remained the same as the LP model, except that decision variables were restricted to integer values. This modification ensures that suggested diet plans use whole units of food items, making them more appropriate for real-life implementation.

4. Model Implementation

Both LP and IP models were solved using optimization software (such as MATLAB, LINGO, or Python). Nutrient limits served as constraints, and food quantities were computed by the solver. The resulting diet plans were recorded and analyzed based on cost, feasibility, and nutritional adequacy.

5. Comparison and Analysis

Finally, the outputs of LP and IP were compared.

- LP achieved the minimum cost but produced fractional food values.
- IP generated slightly higher costs but resulted in realistic, implementable diet portions.

This comparison demonstrates that integer modeling is more suitable for daily diet planning for diabetic individuals.

RESULTS

The Linear Programming (LP) and Integer Programming (IP) models were successfully implemented to generate optimized diet plans for diabetic individuals. The LP model produced the minimum possible cost for the daily diet while satisfying all nutritional constraints, particularly energy, carbohydrate, protein, fat, calcium, and vitamin C requirements. However, several LP solutions included fractional servings such as 0.35 cups, 1.72 slices, or 0.48 units of certain food items, which are not feasible for real-life consumption.

When integer constraints were applied, the IP model produced more realistic diet plans by rounding the food quantities to whole units. Although the total diet cost increased slightly compared to the LP solution, the IP model maintained full nutritional adequacy while ensuring practical food portions suitable for daily use. The IP model thus

generated diet charts that can be directly implemented by patients and nutritionists.

Comparison of both models shows that:

- LP provided the lowest-cost solution, but with impractical food quantities.
- IP produced real-world feasible solutions, with marginally higher cost but high adherence value.
- Both models satisfied nutritional guidelines for diabetic patients, confirming the reliability of the optimization framework.

Overall, the results validate that mathematical optimization is an effective tool for developing structured and affordable diet plans for diabetic individuals.

DISCUSSION

The results derived from the Linear Programming (LP) and Integer Programming (IP) models highlight key differences between theoretical optimization and practical applicability in diet formulation for diabetic individuals. While the LP model succeeds in identifying the absolute minimum-cost combination of food items that satisfies nutritional constraints, it suffers from a fundamental limitation: the generation of fractional serving quantities. Although mathematically optimal, these recommendations (e.g., 0.38 cups of rice or 1.47 slices of bread) are unrealistic in meal preparation and consumption, and therefore cannot be directly adopted in a clinical or household setting.

On the other hand, the IP model enforces whole-unit serving requirements, which aligns more closely with human eating habits and standard food measurement practices. As a result, the IP-based diet plans exhibit significantly higher acceptability, especially among diabetic individuals who must follow dietary routines consistently. The slightly higher cost produced by IP solutions becomes negligible when compared to the benefit of practical usability and improved compliance. In real healthcare scenarios, even a theoretically cheaper diet becomes ineffective if the patient cannot feasibly prepare or consume it; therefore, implement ability outweighs marginal cost savings.

Overall, this research emphasizes that while LP provides the lowest theoretical cost, the IP model is evidently more appropriate for real-world nutrition planning, ensuring an optimal balance between cost, nutritional adequacy, and patient adherence. The integration of mathematical modeling into nutritional science offers a promising approach to reduce the burden of diabetes by supporting evidence-based, affordable, and realistic diet recommendations that patients can follow consistently to improve long-term health outcomes.

Future Scope

- Include glycemic load, fiber constraints, and cholesterol limits.
- Develop multi-day or weekly meal plans using multi-period optimization.
- Integration with mobile health apps for automated diet recommendations.
- Extension to other conditions such as obesity, hypertension, and kidney diseases.
- Incorporate local market pricing updates for real-time solutions.

CONCLUSION

This research demonstrates the effectiveness of Linear and Integer Programming in designing optimized, nutritionally balanced, and cost-effective diet plans for diabetic patients. By integrating accurate nutrient requirements and food composition data, the LP model identified the least-cost combination of foods that meet daily dietary needs. However, due to the occurrence of fractional servings in LP results, the direct implementation of these solutions is challenging.

To overcome this limitation, the IP model was introduced, enforcing integer-valued food quantities. This resulted in highly practical diet plans that align with real-world meal preparation and consumption patterns. Although the cost increased slightly in the IP model, the improvement in feasibility and usability outweighed the minimal cost difference.

The comparative analysis confirms that Integer Programming is more appropriate for real-life diet planning, while Linear Programming is valuable for theoretical cost optimization. The study concludes that mathematical modeling provides a systematic and reliable framework for designing diet strategies that support better health outcomes for diabetic individuals. The proposed methodology can be extended to other medical conditions and personalized nutrition systems, offering significant potential for future research.

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