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A linear programming approach for designing nutritionally adequate and cost-effective vegetarian diets in Nepal

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Abstract

Adequate nutrition is fundamental to maintaining health and overall well-being. This study aimed to identify the cost-minimizing combination of locally available vegetarian foods in Nepal that meets the recommended dietary requirements for adults. Food items were selected based on their local availability, and price data were collected from the Kalimati Vegetable and Fruit Market in Kathmandu. A linear programming model was employed to optimize daily dietary intake across breakfast, lunch, snacks, and dinner, while ensuring that nutritional constraints for energy, macronutrients, and key micronutrients-including iron, calcium, vitamin A, and vitamin C-were satisfied. The analysis revealed that a minimum daily expenditure of Rs. 262.2 per person is sufficient to meet all nutritional requirements, which corresponds to Rs. 1,048.8 per day for a four-member household. The study focuses solely on food costs and excludes other household expenditures such as fuel, education, healthcare, and clothing. These findings offer guidance for affordable dietary planning and can support the formulation of policies aimed at enhancing nutritional security in Nepal.

Keywords: Linear programming; Mathematical model; Constraints; Balanced diet; Minimum expenditure.

2020 Mathematics Subject Classification. *Primary: 90B10, 90C27, 68Q25; Secondary: 90B06, 90B20.*

1. Introduction

Adequate nutrition is a fundamental determinant of health, productivity, and overall well-being. A balanced diet supplies the essential macronutrients and micronutrients required for normal physiological functioning, disease prevention, and improved quality of life. However, in many low-and middle-income countries, including Nepal, achieving adequate nutrition remains a persistent challenge due to economic constraints, limited access to diverse foods, and seasonal variations in availability. According to national dietary guidelines, a healthy adult diet should meet minimum daily requirements for energy, macronutrients (carbohydrates, proteins, and fats), and key micronutrients such as calcium, iron, vitamin A, and vitamin C, [1, 2].

Dietary patterns in Nepal are predominantly plant-based, relying heavily on locally available and seasonal foods. While this offers certain nutritional and environmental advantages, rising food prices and household budget limitations make it difficult for many families to meet recommended dietary allowances. Identifying affordable combinations of commonly consumed foods that satisfy nutritional requirements can provide a foundation for dietary planning and policy interventions aimed at improving food and nutrition security [1, 3].

Linear programming has been widely applied in diet optimization studies to determine the lowest-cost combination of foods that meet nutritional standards. By systematically incorporating nutrient requirements and food prices, linear programming models can generate cost-effective dietary plans that are both nutritionally adequate and context-specific. This study applies a linear programming model to estimate the minimum daily cost of a vegetarian diet that meets recommended nutrient intakes for adults in Nepal. Price data were obtained from the Kalimati Vegetable and Fruit Market - one of the country's major wholesale markets. The findings offer valuable insights for households, nutrition planners, and policymakers seeking to promote affordable and nutritionally balanced diets [4, 5].

1.1. Literature review

The origins of linear programming (LP) trace back to Soviet mathematician and economist Leonid Kantorovich in 1939, who formulated a problem equivalent to the general LP problem. During World War II, Kantorovich adapted this technique to strategically plan army expenditures, minimize costs, and maximize enemy losses. Concurrently, Frank Lauren Hitchcock applied LP to transportation problems in 1941, proposing a solution akin to the simplex method [6, 7].

In 1947, George B. Dantzig introduced the simplex method, revolutionizing optimization by efficiently solving LP problems. His collaboration with John von Neumann led to the development of duality theory, linking LP with game theory. The computational efficiency of LP was further enhanced by Leonid Khachiyan's 1979 demonstration of polynomial-time solvability, followed by Narendra Karmarkar's 1984 introduction of the interior-point method [6, 7, 8].

The application of LP to diet optimization began with George Stigler's 1945 formulation of the "diet problem," aiming to determine the least-cost combination of foods meeting specified nutritional requirements. Utilizing heuristic methods, Stigler identified a cost-effective solution. The subsequent development of the sim-

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plex method enabled more precise solutions to such dietary optimization problems [3, 6, 9].

Recent advancements in LP have expanded its application to diet optimization, addressing nutritional adequacy, cost-effectiveness, and environmental sustainability. Studies have employed LP to design diets that meet recommended dietary allowances while minimizing costs. For instance, research has focused on optimizing diets considering factors like nutrient intake, food variety, and cultural acceptability [5, 9, 10].

1.2. Problem statement

In nutrition, vegetarians often face the challenge of meeting dietary requirements while adhering to budget constraints. Although dietary guidelines exist, cost-effective solutions tailored to the financial realities and food availability in Nepal are limited. Current approaches to vegetarian diet planning may not sufficiently balance nutritional adequacy with affordability in the Nepali context. There is therefore a need for a systematic, mathematical methodology that employs linear programming to optimize vegetarian diets, ensuring both nutritional completeness and minimal cost. This study addresses this gap by developing and implementing a linear programming model, supported by appropriate software tools, to provide practical, tailored dietary solutions for Nepali individuals committed to a vegetarian lifestyle within constrained budgets.

2. Materials and methods

2.1. Study design

This study employed a linear programming (LP) approach to determine the minimum daily cost of a nutritionally adequate vegetarian diet for Nepali adults. The model was designed to identify an optimal combination of locally available foods that meets recommended dietary allowances while minimizing total cost. The analysis focused on a single adult, and results were subsequently scaled to estimate costs for a four-member household.

2.2. Data sources

2.2.1. Food selection

Locally consumed vegetarian foods were selected based on interviews with lecturers and students from multiple campuses in the Kathmandu Valley. The selection emphasized habitual dietary patterns, local availability, and regular consumption to reflect realistic dietary practices.

2.2.2. Price data

Price information was collected from the Kalimati Vegetable and Fruit Market, one of Nepal's largest wholesale markets, and adjusted by 20% to approximate local retail prices and account for minor daily fluctuations. Prices were expressed in Nepali Rupees (Rs.) per standard unit (e.g., kilogram or litre).

2.2.3. Nutrient composition

Nutritional data were obtained from the Nepal Food Composition Table (Department of Food Technology and Quality Control, 2012) and FAO/INFOODS resources [11]. Data included energy (calories), macronutrients (carbohydrates, protein, fat), and selected micronutrients (iron, calcium, vitamin A, and vitamin C).

2.3. Nutritional requirements

Nutritional constraints were based on the Recommended Dietary Allowances (RDA) for healthy Nepali adults. The model incorporated minimum daily requirements for energy, macronutrients, and essential micronutrients, ensuring alignment with national dietary guidelines and FAO/WHO recommendations [9].

Table 1: Data sources for the linear programming model.

Data Type	Source / Reference	Notes / Adjustments
Food Selection	Interviews with lecturers and students (Kathmandu Valley)	Commonly consumed vegetarian foods.
Price Data	Kalimati Vegetable and Fruit Market	Adjusted +20% for local retail prices and daily fluctuations.
Nutrient Composition	Nepal Food Composition Table (2012), FAO/INFOODS	Energy, macronutrients, iron, calcium, vitamin A, vitamin C.
Nutritional Requirements	RDA for Nepali adults (20–45 years), FAO/WHO	Minimum daily requirements for energy and key nutrients

2.4. Mathematical model of LPP

In this study, the standard linear programming problem (LPP) was employed to optimize vegetarian diets. The model minimizes the total food cost while satisfying specified nutritional requirements. Decision variables represent the quantities of each food item, and the objective function coefficients correspond to their respective costs. Nutritional constraints ensure that the diet meets or exceeds recommended daily allowances [4, 6, 7]. The model is formulated as follows:

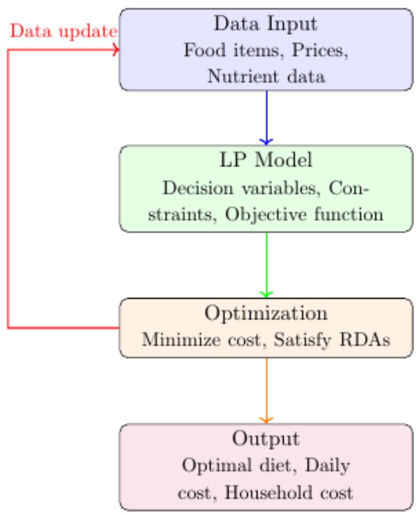

Figure 1: Workflow of the linear programming model.

Objective functions:

$$\text{Minimize } Z = \sum_{j=1}^{n} C_j X_j$$

Subject to the constraints:

$$\sum_{j=1}^{n} a_{ij} X_j \geq b_i, i = 1, 2, \ldots, m$$

$$X_j \geq 0, j = 1, 2, \ldots, n.$$

Where:

Table 2: Breakfast ingredients.

Food Item	Cost/kg	Calories	Carbs	Protein	Fat	Calcium	Iron	Vit A(mcg)	Vit C(mg)
Sprout	200	42	5.0	3.4	1.0	120	0.05	22	11
Fruit Salad	100	89	22.8	1.1	0.3	5	0.3	60	90
Ginger tea	50	70	97	0	0	0.9	0.11	0	1

Table 3: Lunch ingredients.

Food Item	Cost/kg	Calories	Carbs	Protein	Fat	Calcium	Iron	Vit A(mcg)	Vit C(mg)
Rice	150	195	43.05	3.6	0.45	15	0.3	0	0
Lentils (dal) cooked with ghee	240	174	30.0	13.5	20.6	28.5	4.95	8	1.5
Spinach	150	23	3.6	2.9	0.4	99	2.7	469	28.1
Mixed vegetables with paneer	750	140	14	4.0	40.4	60	1.4	400	30
Curd (plain yogurt)	160	122	9.4	7	6.6	242	0.2	27	1

Table 4: Snacks ingredients.

Food Item	Cost/kg	Calories	Carbs	Protein	Fat	Calcium	Iron	Vit A(mcg)	Vit C(mg)
Boiled beans	150	20.7	35	7.1	0.4	1.4	0	25	4
Potatoes pickle	100	87	20.1	1.9	0.1	5	0.8	15	14
Bara	500	194	24.3	10.3	6.4	28.6	3.3	4	1

Table 5: Dinner ingredients.

Food Item	Cost/kg	Calories	Carbs	Protein	Fat	Calcium	Iron	Vit A(mcg)	Vit C(mg)
Roti (whole wheat)	150	297	59.0	9.0	3.0	30	3.5	0	0
Tofu (sabji)	200	144	1.9	15.7	8	350	5.4	0	0.1
Carrots (raw)	100	41	9.6	0.9	0.2	33	0.3	935	5.9
Milk (cow)	120	152.5	12	8	8.25	282.5	0	46	0

- Z is the total cost of the diet.
- C_j is the cost of the j^{th} food item.
- X_j is the quantity of the j^{th} food item in the diet.
- a_{ij} represents the nutritional content of the j^{th} food item for the i^{th} nutrient.
- b_i is the recommended level of the i^{th} nutrient.
- m is the number of nutritional constraints.
- n is the number of food items.

This model captures the essence of the optimization problem, aiming to find the values of X_j that minimize the total cost while satisfying the nutritional constraints.

This study focused on key nutritional components, including carbohydrates, protein, fat, iron, vitamin A, vitamin C, and total caloric intake. Dietary recommendations for breakfast, lunch, snacks, and dinner were developed based on food availability, seasonal fruits in the Nepali market, surveys of adults, and consultations with nutritionists, ensuring alignment with established nutritional requirements. Nutritional values for all selected foods were obtained from the Food Composition Table published by the FAO, providing standardized data on macronutrients, micronutrients, and caloric content for accurate and consistent dietary calculations.

2.5. Mathematical formulation

The proposed model includes fifteen decision variables, each representing a food item, and eight nutritional constraints for key nutrients-calories, carbohydrates, protein, fat, calcium, iron, vitamin A, and vitamin C. Non-negativity constraints ensure that all food quantities are non-negative. Together, these constraints guarantee that the selected combination of foods meets the recommended dietary allowances for an adult, maintaining nutritional adequacy while minimizing the total diet cost.

Decision variables:

$$X_1 = \text{Sprout}, \quad X_2 = \text{Fruit Salad}, \quad X_3 = \text{Ginger tea}, \quad X_4 = \text{Rice}$$
$$X_5 = \text{Lentil}, \quad X_6 = \text{Spinach}, X_7 = \text{Mix Vegetable}, X_8 = \text{Curd}$$
$$X_9 = \text{Boiled beans}, X_{10} = \text{Potato achar}, X_{11} = \text{Bara},$$
$$X_{12} = \text{Roti}, X_{13} = \text{Tofu}, \quad X_{14} = \text{Carrot}, \quad X_{15} = \text{Milk}.$$

Objective function:

$$\begin{aligned}\text{Minimize } C = 0.2X_1 + 0.3X_2 + 0.05X_3 + 0.15X_4 + \\ 0.24X_5 + 0.15X_6 + 0.75X_7 + 0.16X_8 + \\ 0.15X_9 + 0.1X_{10} + 0.5X_{11} + 0.15X_{12} \\ + 0.2X_{13} + 0.1X_{14} + 0.12X_{15}.\end{aligned}$$

Key constraints:

(i) Calorie constraint:

$$\begin{aligned}42X_1 + 89X_2 + 70X_3 + 194X_4 + \\ 174X_5 + 23X_6 + 140X_7 + 122X_8 + 207X_9 \\ +87X_{10} + 194X_{11} + 297X_{12} \\ +144X_{13} + 41X_{14} + 152.5X_{15} \geq 1800.\end{aligned}$$

(ii) Carbohydrate constraint:

$$\begin{aligned}5X_1 + 22.8X_2 + 97X_3 + 43.05X_4 \\ +30X_5 + 3.6X_6 + 14X_7 + 9.4X_8 + 35X_9 \\ +20.1X_{10} + 24.3X_{11} + 59X_{12} \\ +1.9X_{13} + 9.6X_{14} + 12X_{15} \geq 250.\end{aligned}$$

(iii) Protien constraint:

$$3.4X_1 + 1.1X_2 + 0X_3 + 3.6X_4 + 13.5X_5 + 2.9X_6 + 4X_7 + 7X_8 + 7.1X_9 + 1.9X_{10} + 10.3X_{11} + 9X_{12} + 15.7X_{13} + 0.9X_{14} + 8X_{15} \geq 56.$$

(iv) Fat constraint:

$$0.1X_1 + 0.3X_2 + 0X_3 + 0.45X_4 + 20.6X_5 + 0.4X_6 + 40.4X_7 + 6.6X_8 + 0.4X_9 + 0.1X_{10} + 6.4X_{11} + 3X_{12} + 8X_{13} + 0.2X_{14} + 8.25X_{15} \geq 60.$$

(v) Calcium constraint:

$$120X_1 + 5X_2 + 0.9X_3 + 15X_4 + 28.5X_5 + 99X_6 + 60X_7 + 242X_8 + 1.4X_9 + 5X_{10} + 28.6X_{11} + 30X_{12} + 350X_{13} + 33X_{14} + 282.5X_{15} \geq 1200.$$

(vi) Iron constraint:

$$0.05X_1 + 0.3X_2 + 0.11X_3 + 0.3X_4 + 4.95X_5 + 2.7X_6 + 1.4X_7 + 0.2X_8 + 0X_9 + 0.8X_{10} + 3.3X_{11} + 3.5X_{12} + 5.4X_{13} + 0.3X_{14} + 0X_{15} \geq 18.$$

(vii) Vitamin A constraint:

$$22X_1 + 60X_2 + 0X_3 + 0X_4 + 8X_5 + 469X_6 + 400X_7 + 27X_8 + 25X_9 + 15X_{10} + 4X_{11} + 0X_{12} + 0X_{13} + 835X_{14} + 46X_{15} \geq 700.$$

(viii) Vitamin C constraint:

$$11X_1 + 90X_2 + 1X_3 + 0X_4 + 1.5X_5 + 28.1X_6 + 30X_7 + 1X_8 + 4X_9 + 14X_{10} + 1X_{11} + 0X_{12} + 0.1X_{13} + 5.9X_{14} + 0X_{15} \geq 90.$$

(ix) Non-negative constraint:

$$50 \leq X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15} \leq 100.$$

3. Solution

There are several tools to solve this LP model. In this work, we applied LINDO to solve it. The LINDO code this model is as follows:

$MIN = 0.20*X1+0.30*X2+0.05*X3+0.15*X4+0.24*X5+0.15*X6+0.75*X7+0.16*X8+0.15*X9+0.10*X10+0.50*X11+0.15*X12+0.20*X13+0.10*X14+0.12*X15;$

Calorie constraint ;

$0.42*X1+0.89*X2+0.70*X3+1.94*X4+1.74*X5+0.23*X6+1.40*X7+1.22*X8+2.07*X9+0.87*X10+1.94*X11+2.97*X12+1.44*X13+0.41*X14+1.525*X15 >= 1800;$

Protein ;

$0.034*X1+0.011*X2+0.00*X3+0.036*X4+0.135*X5+0.029*X6+0.04*X7+0.07*X8+0.071*X9+0.019*X10+0.103*X11+0.09*X12+0.157*X13+0.009*X14+0.08*X15 >= 56;$

Fat ;

$0.001*X1+0.003*X2+0.000*X3+0.0045*X4+0.206*X5+0.004*X6+0.404*X7+0.066*X8+0.004*X9+0.001*X10+0.064*X11+0.003*X12+0.008*X13+0.002*X14+0.00825*X15 >= 60;$

Carbohydrate ;

$0.005*X1+0.228*X2+0.97*X3+0.4305*X4+0.30*X5+0.036*X6+0.14*X7+0.094*X8+0.35*X9+0.201*X10+0.243*X11+0.59*X12+0.019*X13+0.096*X14+0.12*X15 >= 250;$

Calcium ;

$1.20*X1+0.05*X2+0.009*X3+0.15*X4+0.285*X5+0.99*X6+0.60*X7+2.42*X8+0.014*X9+0.05*X10+0.286*X11+0.30*X12+3.50*X13+0.33*X14+2.825*X15 >= 1200;$

Iron ;

$0.0005*X1+0.003*X2+0.0011*X3+0.003*X4+0.0495*X5+0.027*X6+0.014*X7+0.002*X8+0.000*X9+0.008*X10+0.033*X11+0.035*X12+0.054*X13+0.003*X14+0.000*X15 >= 18;$

Vitamin A ;

$0.22*X1+0.60*X2+0.00*X3+0.00*X4+0.08*X5+4.69*X6+4.00*X7+0.27*X8+0.25*X9+0.15*X10+0.04*X11+0.00*X12+0.00*X13+8.35*X14+0.46*X15 >= 700;$

Vitamin C ;

$0.11*X1+0.90*X2+0.01*X3+0.00*X4+0.015*X5+0.281*X6+0.30*X7+0.01*X8+0.04*X9+0.14*X10+0.01*X11+0.00*X12+0.001*X13+0.059*X14+0.00*X15 >= 90;$

Bounds ;

$50 <= X1 <= 100;$
$50 <= X2 <= 100;$
$50 <= X3 <= 100;$
$50 <= X4 <= 100;$
$50 <= X5 <= 100;$
$50 <= X6 <= 100;$
$50 <= X7 <= 100;$
$50 <= X8 <= 100;$
$50 <= X9 <= 100;$
$50 <= X10 <= 100;$
$50 <= X11 <= 100;$
$50 <= X12 <= 100;$
$50 <= X13 <= 100;$
$50 <= X14 <= 100;$
$50 <= X15 <= 100;$

4. Results and discussion

Objective (minimum cost): 262.216586
Decision variables:

- X1 = 85.913868
- X2 = 50.000000
- X3 =100.000000
- X4 =100.000000
- X5 =100.000000
- X6 = 50.000000
- X7 = 61.625838
- X8 =100.000000
- X9 =100.000000
- X10 =100.000000
- X11 = 68.628867
- X12 =100.000000
- X13 =100.000000
- X14 =100.000000
- X15 =100.000000

Constraint LHS checks (all $\geq$ RHS):

- Calories: $1800.00 (\geq 1800)$
- Protein: $81.155 (\geq 56)$
- Fat: $60.00 (\geq 60)$
- Carbs: $355.984 (\geq 250)$
- Calcium: $1200.00 (\geq 1200)$
- Iron: $20.230 (\geq 18)$
- Vitamin A: $1488.650 (\geq 700)$
- Vitamin C: $115.175 (\geq 90)$

4.1. Optimal result

Objective (minimum cost) = Rs. 262.216586 per day.

The model reached a feasible solution where Calories, Fat, and Calcium are exactly at their required minima-these three constraints are binding. All other nutrient constraints exceed their minima by comfortable margins (protein, carbs, iron, vitamin A, vitamin C).

Many decision variables are at their upper bound (100) or lower bound (50). Only three variables are strictly interior (not exactly 50 or 100):

X1 = 85.913868
X7 = 61.625838
X11 = 68.628867

4.2. Interpretation

The requirements for calories, fat, and calcium are exactly satisfied, making these nutrients the binding constraints that determine the composition of the optimal food combination and the corresponding total cost. An increase in any of these nutrient requirements would lead to a higher overall cost. The associated shadow prices for these constraints are positive, reflecting the marginal increase in cost per unit rise in the respective nutrient requirement.

As shown in Figure 3, the optimized diet provides nutrient levels that exceed the minimum requirements for protein (81.155 vs 56), carbohydrates (355.984 vs 250), vitamin A, vitamin C, and iron. This indicates that the model's selected combination of food items results in an oversupply of these nutrients. Such outcomes are likely due to the inclusion of low-cost foods that are inherently rich in these nutrients or because foods chosen to satisfy calorie, fat, and calcium requirements simultaneously contribute additional amounts of these micronutrients.

Many foods stuck at bounds-likely artificial constraints. A large number of $Xj = 100$ or $Xj = 50$ suggests the lower/upper bounds are strongly shaping the solution.

Foods at 100 (upper bound): solver wants more of them but can't increase beyond enforced cap-they are "fully used."

Foods at 50 (lower bound): solver keeps them at the minimum allowed; some may be forced into the diet by lower-bound rules (cultural/availability constraints).

With most variables at bounds and only X1, X7, X11 interior, the current feasible basis is narrow. Small changes to prices or RHS could change which foods are selected.

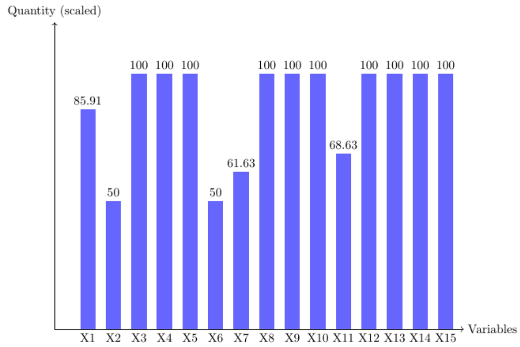

Figure 2: Optimal decision variable values (X1-X15).

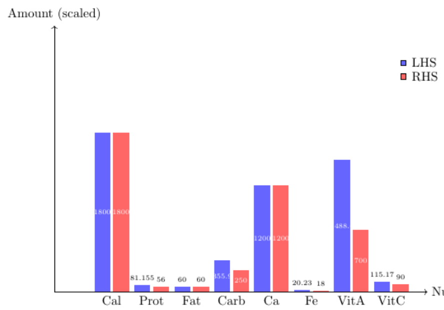

Figure 3: Nutrient intake (LHS) vs requirement (RHS) with smaller numbers inside bars.

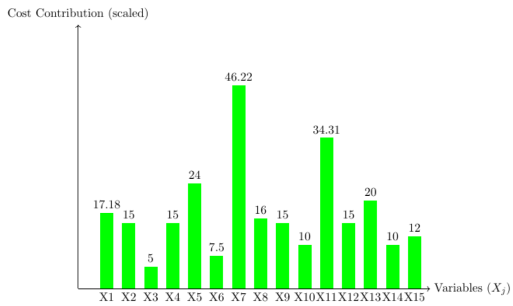

Figure 4: Cost contribution of each food item (X1-X15).

5. Conclusion

A balanced diet plays a crucial role in maintaining health and well-being by ensuring an adequate intake of essential nutrients on a daily basis. This study aimed to identify the optimal combination of vegetarian food items that a typical Nepali adult can consume for breakfast, lunch, snacks, and dinner to meet recommended nutritional requirements at the minimum possible cost. The selection of food items was based on their local availability in Nepal, and price data were obtained from the Kalimati Vegetable and Fruit Market, which is one of the major wholesale markets in Kathmandu. Using a linear programming model, the analysis revealed that a daily expenditure of Rs. 262.2 per person is required to satisfy all nutritional constraints. For a household of four members, this translates to a total daily cost of Rs. 1,048.8. It is important to note that this estimate only covers food costs and excludes other household expenditures such as fuel, education, healthcare, clothing, and miscellaneous expenses. These findings provide insights that can inform dietary planning and policy formulation aimed at improving nutritional security in Nepal, particularly in the context of affordability and resource allocation.

Conflict of interest

Authors declares that there is no conflict of interest.

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