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Review Article

A Systematic Review of Linear Programming Techniques as Applied to Diet Optimisation and Opportunities for Improvement

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Background. Food provides the required nutrients for adequate growth and development. However, meeting the recommended nutrients while considering environmental sustainability can be complicated and challenging. Previously, trial-and-error methods were used for product development, but these are tedious and time-consuming. Mathematical techniques such as linear programming offer an alternative and rapid approach to developing products with nutritional/or sustainability considerations. This method has been extensively used in diet optimisation but does not sufficiently address dietary problems with more than one objective function. *Aim*. The review aimed to explore the extent of mathematical approaches to address dietary problems. *Methodology*. A systematic review approach was adopted for the research. The major search engines used were Scopus, PubMed, and Science Direct, based on selected keywords. A stepwise structural method was used to obtain articles. Articles that contained the search keywords but applied in nonhuman cases were excluded. Duplicated articles were also excluded and accounted for as one. All articles were subjected to further review based on their abstract and complete titles before passing them for data analysis. *Results*. The total number of articles obtained from the search activity was 280. Fifty-six were retained after the criteria for inclusion were applied to them. Out of the 56 articles retained, only two studies used goal programming and nonlinear generalised mathematical approaches to address dietary problems. All other studies used the linear programming approach, focusing mainly on one or two constraints (nutrients and/or acceptability), highlighting the limitations of linear programming in addressing the multiple factors of a sustainable diet. Several researchers have proposed using multiobjective optimisation, an extension of linear programming, to address challenges with sustainable diets. These approaches can be further explored to address sustainable dietary problems.

1. Introduction

Good nutrition, a critical component of good health, is achieved when consumers access healthy diets. A population that consumes a healthy diet reduces the burden of malnutrition and its related diseases. However, access to a healthy diet is constrained by many factors, including cost, especially for low-income earners [1]. Socioeconomic status affects food choices and healthy diets due to the cost of food commodities [1–3], causing some consumers to purchase energy-dense over nutrient-dense foods. Healthy diets have been found to have a higher cost [4]. This and other factors like what consumers want and the environment pose dietary problems that need to be addressed to lessen the burden of malnutrition on the population while safeguarding the environment.

Trial-and-error and optimisation methods have been used to solve these dietary problems. Trial-and-error methods used for product development to resolve dietary problems mentioned above can be tedious [5] since they are typically completed manually [6]. Mathematical diet optimisation techniques can better solve complex dietary problems than the tedious trial-and-error method.

Diet optimisation has been identified as one of the best approaches to address dietary problems and ensure that sustainable diets are achieved for individuals or groups based on locally available and culturally specific foods [7, 8]. The Food and Agriculture Organisation (FAO) defines a sustainable diet as a diet with a low environmental impact that is nutritionally adequate, accessible, economically fair, affordable, safe, and healthy [9]. When planning food for any defined population, mathematical diet optimisation models can be used to design food plans that best look like the current eating patterns of the people while meeting prespecified nutrition and cost constraints [10].

From a literature search, the basic approach to diet optimisation is linear programming (LP), which has three main components: an objective function, decision variable(s), and constraints [3, 11]. Jones and Tamiz [12] stated that the decision variables are factors that the decision maker has control over and must be determined to solve a linear programming problem. Constraints are restrictions usually imposed on the decision variables [12, 13]. An objective function indicates the contribution of the decision variables to the value of the function to be optimised (minimised or maximised), with examples being cost, profits, etc. [14]. Linear programming is a mathematical approach that enables obtaining ideal solutions simultaneously while satisfying several constraints [11]. Karloff [15] also defined linear programming as minimising or maximising a linear objective function with a finite number of linear equality and inequality constraints imposed on it. Diet optimisation models have been developed for different nutrient needs for different age groups that satisfy different constraints. In diet optimisation, nutrient-based references are translated into practical nutritionally optimum food combinations based on locally available foods within a defined geographic location [16].

However, diet optimisation goes beyond nutrition and cost. It includes acceptability and environmental friendliness and incorporates all constraints defined for diet optimisation by the World Health Organisation [17]. Although linear programming methods can solve dietary problems, they can only optimise problems with a single objective function [11, 15]. As such, linear programming is not enough when there is more than one objective function to be optimised.

Moreover, what happens when an optimisation problem has multiple objective functions? Ferguson et al. [18], Jayaraman et al. [19], and Gazan et al. [3] proposed the multiobjective criteria approach to this question. These are considered as an extension of LP problems [20], and they are continuous problems [21] that cut across areas of engineering, mathematics, economics, etc. and have more than one objective function to be addressed. When there are multiple objectives that conflict with each other, multiobjective decision making is employed [22]. Some examples of multiobjective optimisation methods are the goal programming [23], weighted sum approach [24], and the epsilon constraint (ε-constraint) methods. When goals are multiple and conflict with each other, goal programming (GP) is used [23]. Goal programming (GP) is an extension of LP and a multiobjective optimisation tool used to minimise deviations between achievements and goals [19, 23]. Even beyond goal programming, other multiobjective optimisation approaches like epsilon (ε) constraint [25] and weighted sum approach [24] methods can be used to address complex dietary problems.

This paper therefore analyses different studies that used linear programming to address dietary problems. It highlights the most considered objectives, cost, environment, deviations between observed and optimised patterns, and maximising nutrients.

2. Review Approach

The systematic research technique was explored for this review work. The search selection method used for this review was the Preferred Reporting Items for the Systematic Reviews and Meta-Analyses (PRISMA) framework [26]. PRISMA can be used as a basis for reporting systematic reviews of other types of research and is suitable for evaluating published systematic reviews [26]. The PRISMA method followed a modified version of the one used by van Dooren [11]. The search method used for the literature search focused on using defined keywords in specific search engines. The language of selection was English, regardless of the origin or setting of the research work. The method followed a structural approach briefly explained below.

2.1. Article Search by Keyword(s). The search included the use of specific keywords, "*linear programming,*" "*sustainable diet,*" and "*diet optimisation*" in Scopus, PubMed and Science Direct, within the search windows of 2000 – to date (2023).

2.2. Data Search and Evaluation. The first search using the defined terminologies in the search engines yielded 280 articles within the defined timeframe. Open-access articles were focused on, and articles that had linear programming but not diet optimisation were excluded. Also, annual meetings, poster presentations, and conference publications were also excluded because they did not provide sufficient details for further discussion, reducing the articles size to 137. The 137 articles were accessed and further scrutinised for inclusion or exclusion. Duplicated publications were removed and accounted for as one. This was followed by excluding articles that employed diet optimisation but for nonhuman settings, bringing the total number of articles to 73.

2.3. Data Screening and Analyses. The 73 articles retained were screened for analysis. The criteria for the screening stage were the review of abstracts to ascertain if the article fit the description of having a defined objective, decision variable(s), and constraint(s). This resulted in the retention of 56 articles which were analysed for discussion. The details extracted were the objective(s), decision variables, imposed constraints, study locations, and mathematical techniques used for diet optimisation. An Excel worksheet was used to aid in extracting data from the articles selected for the review. Figure 1 gives a schematic flow of the systematic method adopted for the review.

3. Results and Discussion

3.1. Summary of Findings. Two hundred and eighty (280) publications were obtained from PubMed, Scopus, and Science Direct. Fifty-six (56) empirical studies published from 2000 to date (2023) were obtained for data extraction and discussion (Figure 1). Results from reviewing the selected articles showed the versatility of applying the technique in different settings. The countries where mathematical diet optimisation has been applied include Korea [27], Australia [28], Malaysia [29], Philippines [16, 30], France [31, 32], New Zealand [33, 34], Ghana [1, 35], Kenya [36], Canada [10], Malawi [37], Czech Republic [38], Brazil [39], Hungary [40], and Nepal [41].

The reviewed articles were further classified under the different objective functions defined by researchers for discussion. Other details extracted from the reviewed articles include the decision variables, constraints, and modelling approach (Tables 1–5).

From the articles reviewed, researchers had different objectives they set out to achieve. Results showed 43 (84%) articles focused on minimising objective functions, 4 (11%) on maximising objective functions, and the remaining 3 (5%) did not have a clearly defined minimisation or maximisation direction (Figure 2).

The first component of a linear programming model is the objective function. According to Verly-Jr et al. [39], a linear programming model is defined by an objective function optimised and dependent on decision variables constrained by some defined constraints. In optimisation problems, objective functions are essential because they show how each variable contributes to the optimised value [57]. The optimisation of the objective function could either be to minimise or maximise the function [14]. When researchers are concerned with profits and increasing revenue, setting an objective function will be to maximise profits. When a diet optimisation problem concerns cost, the objective would be to minimise cost because researchers are interested in delivering healthy meals at minimum cost to consumers.

3.2. Objective Functions. Out of the 56 studies analysed for discussion, 47 articles minimised their objective functions, 6 maximised their objective functions, and 3 did not have a definitive objective of minimisation or maximisation. Objective functions are needed to show the direction of a linear programming optimisation model. Regardless of the direction, there could be different functions that can be minimised or maximised. For example, an objective could be to minimise cost, environmental function, or even deviations between an observation and a modelled function, as represented in Tables 1–5.

3.2.1. Cost Minimisation. Out of 48 studies that minimised their objective functions, 20 articles focused on minimising the cost of the modelled diet (Table 1). Highlighting a few, some of the studies minimised the cost of food baskets for a family [1, 38], others minimised the cost of RUTFs to treat malnutrition [44, 46, 59, 65], and Mejos et al. [30] minimised the cost of complementary feeding. All the studies that minimised the objective function (Table 1) obtained results that aligned with their defined study focus. According to Drewnowski and Specter [82], food prices remain one major factor affecting dietary quality, consumers' choices, and corresponding dietary patterns. Hence, it is very valuable and important that these studies were directed at minimising the cost of diets. Although these studies highlighted in Table 1 did not clearly define any limitations, one of the major limitations of these studies in addressing complex sustainable diet issues is that only objective function was optimised. Furthermore, minimising an objective function does not only mean achieving a minimum diet cost, but it could also mean minimising deviations between an observed and modelled pattern.

3.2.2. Deviation Minimisation. Studies that sought to minimise the deviations between the observed and modelled patterns were 20 from the results obtained (Table 2). Some studies [10, 37, 43, 47, 54] [16, 27, 40, 39, 69, 73–76, 80, 81] assessed the dietary patterns of a defined population, modelled diets that meet nutritional requirements for the said population, and then set objective functions to minimise the deviation between the observed and patterns and modelled diets. From these studies, dietary intake data collected from the population served as observed data. They then modelled a diet that met the constraints they defined. The approach adopted by these studies was a good way to address dietary problems encountered in different settings for different population groups; they also considered only a single objective function, which made it impossible to meet the four main dimensions of a sustainable diet (cost, environment, acceptability, and nutrition).

3.2.3. Environmental Factor Minimisation. Furthermore, only 4 studies set to minimise environmental factors as their objective function (Table 3). There is an increasing concern for the environment due to growing consumption patterns, Patterson et al. [83]; Ferrari et al. [50]; Larrea-Gallegos and Vázquez-Rowe [49]; whereas Tompa et al. [40] minimised the water footprint of the optimised diet. Springmann et al. [84] highlighted that there is a tendency that the impact of consumers on the environment may worsen as the world population grows exponentially and dietary patterns continue to change. For this reason, it is necessary that research gears toward the minimisation of environmental factors to ensure consumers are considerate of them. However, like the studies that minimised cost, these studies also focused on minimising only environmental factors against certain constraints, which leaves the gap and question of the other dimensions of a sustainable diet.

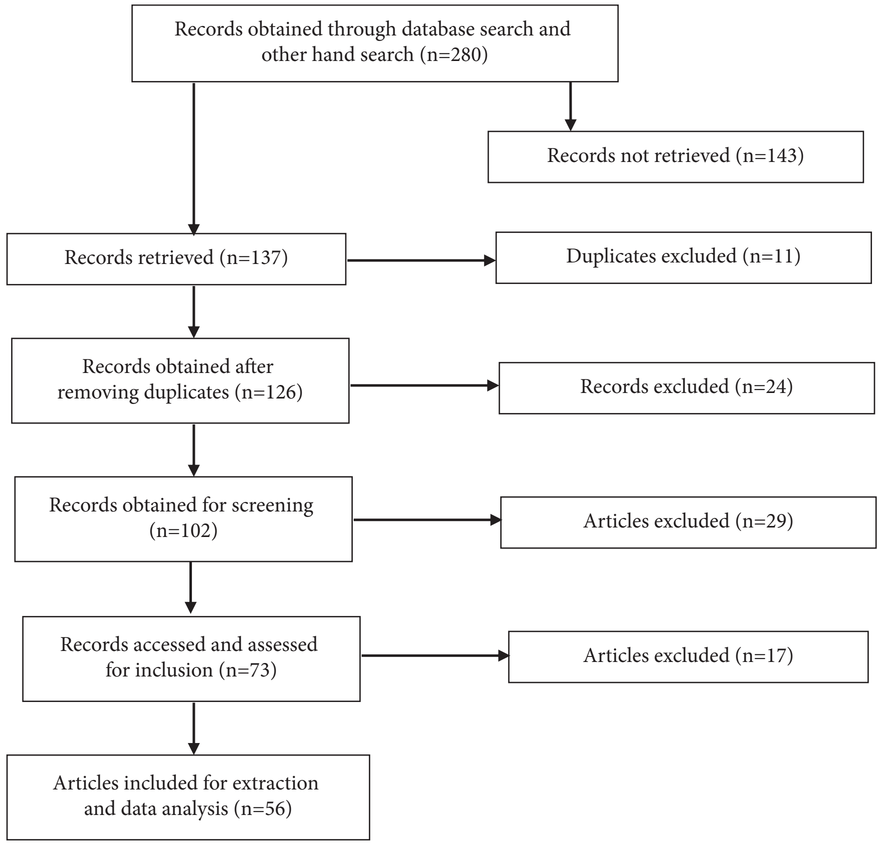

Figure 1: A schematic representation of the procedure followed to retrieve publications for the review, showing the stepwise criteria used to eliminate and obtain the final articles.

3.2.4. Maximisation. Six (6) studies maximised the nutritional requirements for defined populations, subject to defined constraints (Table 4). All these 6 studies set objective functions to maximise objective functions, thus not considering other dimensions of a sustainable diet like environment, acceptability, and cost. Even though van Dooren et al. [52] considered nutrients, cost, and GHGE, they were considered constraints, further supporting the limitation of linear programming in addressing the four dimensions (cost, nutrient, acceptability, and environment) of a sustainable diet.

3.2.5. Others. Two (2) studies from the articles analysed did not clearly state their linear programming model equations to show the direction of the objective function (Table 5). Ferguson et al. [36] aimed at meeting nutrient needs while considering locally available food-based recommendations. Even though the study did not clearly define the objective function mathematically, the direction could be assumed as maximisation since it aimed at ensuring that recommended nutrient needs were met. However, there was no consideration for the environment nor a clearly defined cost dimension. McMahon et al. [28] also minimised sodium intake while maintaining iodine intake; it did not clearly indicate these mathematically. It could be assumed that the direction of the objective function was that of minimisation.

On the other hand, Pasic et al. [54] sought to minimise the deviations between defined nutrients and food cost. This was the single study in the 56 articles analysed that adopted a multiobjective approach to solve the dietary problem using the goal programming approach. Even though this study adopted, it only considered cost and nutrient, without acceptability and the environment.

3.3. Decision Variables. Decision variables in mathematical diet optimisation are important because they are the factors a decision maker can control while searching for an optimal solution for defined objectives [12, 14]. Data extracted from articles obtained and used for discussion showed that all studies had at least one decision variable. A common decision variable that ran through all these studies was the weight or amount of individual food available for optimisation (Table 1). Out of the 56 articles retained for data extraction and discussion, 54 had weight or amount of the individual food as a single decision variable, whereas 3 of the studies [1, 42, 52] had price as an additional decision variable. Though these 3 studies had cost as an extra decision variable, they set a limit to the total cost, which they did not want the modelled diet to exceed. This shows that the weights of different food items are essential in addressing any dietary problem.

Table 1: Summary of details retrieved from articles that minimised cost.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Maillot et al. [42]	Minimum cost of diet that met increasing levels of nutritional constraints	Amount of food and energy cost	Nutrient, social acceptability	Demonstrate that foods with good nutritional quality compared to their cost can be easily identified using their nutrient profiles and energy cost	Linear programming
Pirički et al. [43]	Minimum price	Amount of food in FB	Nutrients, energy, and palatability (quantity of food consumed)	Design a diet that combines different food groups and has minimum fat (especially reduced saturated fatty acids) and cholesterol	Linear programming
Dibari et al. [44]	Lowest formulation price	Weights of the chosen commodities	UN recommendations for the macronutrient content of therapeutic food included palatability, texture, and maximum food ingredient weight criteria	Design a RUTF prototype for treating wasting in East African children and adults	Linear programming
Brimblecombe et al. [45]	The minimum cost of a diet	Amount of food consumed	Nutrient adequacy, nutrient density	To observe the dietary change required to achieve nutrient requirements at minimum cost	Linear programming
Ryan et al. [46]	Minimise ingredient cost of the ready-to-use therapeutic foods	Ingredient weight, the usage rate of foods available	Nutritional, product quality (food taste and processing considerations)	Novel ready-to-use therapeutic foods for Ethiopia	Linear programming
De Carvalho et al. [56]	The minimum cost of porridge mix	Weight/amount of food	Constraints on the weight of starch, limiting dry matter to 25%, a limit on the total mass of reconstituted porridge, and nutrient constraints	To extend LP methodology to food formulation by selecting ingredients to make up food with acceptable consistency for the intended consumer group	Linear programming
Parlesak et al. [57]	Cost-minimised nutritionally adequate food basket	Amount of food	Cultural, dietary guidelines, nutrient recommendations	FBDGs	Linear programming
Deptford et al. [58]	Least cost of diet	Energy and nutrient specifications, predefined groups within households, portion sizes, and currency conversion factors	Nutrient requirements and amounts per meal	Applying linear programming to understand better how poverty may affect people's ability to meet their nutritional specifications	Linear programming
Brixi [59]	Low cost	Nutritional value, price, and water efficiency of suitable ingredients	Nutrient, flavour, crop water efficiency	Ready-to-use therapeutic foods optimised at low cost using locally grown crops	Linear programming
Nykänen et al. [1]	The sum of cost of eating food (minimum cost)	Weight of each food, cost of each food	Energy and nutrient recommendations, minimum deviations from the food balance sheet for Ghana	Food basket for a family of 4 (mother, father, and male and female children) that has low cost	Linear programming
Ghazaryan [60]	Minimise cost	Portion (amount/weight) of the food product	Nutrient (tolerable levels), an upper limit imposed on the quantity of food product	Achieve minimum cost of diet while satisfying some constraints	Linear programming

Table 1: Continued.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Faksová et al. [38]	The minimum cost of a diet	The amount of food	Nutrient deviations from eating patterns	Obtain a food basket for a family of four (mother, husband, son, and daughter)	Linear programming
Hamid et al. [29]	Minimise food cost	The portion size of the food	Nutritional (amount of nutrient), acceptability (portion size)	To determine if an ideal diet that meets nutrient intake for pregnant women and is affordable can be created from locally available foods in Malaysia	Linear programming
Gurmu et al. [61]	The minimum cost of the optimised food basket	Weight of food	Estimated energy requirement, recommended macro and micronutrient requirement	Develop a basis for food-based dietary guidelines for Ethiopia	Linear programming
Verly-Jr et al. [62]	Minimise cost while minimising negative and positive deviations	Amount of food	Constraints on nutrient (RDIs), constraints on food group selection	To estimate the possibility of meeting dietary requirements and measure the correlation between the cost of menus and their adequacy	Linear programming
Alaini et al. [63]	Lowest cost for cancer prevention diet	Amount of food and nutrient	Energy, portion size	This study is aimed to build a healthy and balanced menu with minimal cost based on individual needs and focused on preventing cancer (100 people from a university)	Linear programming
Ibrahim et al. [64]	The minimum cost of the healthiest menu from McDonald's	Amount of food	Recommended nutrients, the lower and upper bound for nutrients	To find the minimum cost of McDonald's healthy combinations	Linear programming
Lauk et al. [65]	Lowest cost	Amount of food in FB	Nutrient recommendations, acceptability (dietary patterns)	Optimise food basket for Estonian family of four	Linear programming
Mejos et al. [30]	The minimum cost of diet complementary feeding recommendations	Amount of food	Constraints on nutrients, the lower and upper limits	To recognise problem nutrients in complementary diets and formulate feeding recommendations for children aged 6 to 23 months in the rural Philippines	Linear programming
Bai et al. [66]	Least cost of diets	Quantity of foods	Constraints on nutrient requirements (lower and upper bounds)	Identify populations whose nutrient needs are difficult to meet with the current challenges of the food systems	Linear programming

FB—food basket, UN—United Nations, FBDGs—food-based dietary guidelines, and RDIs—recommended dietary intakes.

Table 2: Summary of details retrieved from articles that minimised deviations between the observation and the modelled function.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Darmon et al. [47]	Minimise total departure from the mean food intake	Amount/weight of food	Constraints of energy content, food constraints to ensure compatibility with observed dietary patterns, cost constraints set at a maximum level		Linear programming
Ferguson et al. [38]	Minimise difference in the mean percentage of energy contributed by different food groups between modelled and observed diets	Weights of different foods	Nutrient (energy constraint, RNIs for macro and micronutrients), acceptability (portion size, percentiles on food groups)	To develop a rigorous, reproducible, and objective approach based on linear programming analysis, which can be used to formulate practical FBDGs for high-risk populations	Linear programming
Darmon et al. [32]	Minimised diet changes needed to meet nutritional requirements		Palatability, nutritional, cost	Isoenergetic diets that meet the current nutrition requirements	Linear programming
Masset et al. [10]	Minimise departure of optimised diet from the observed quantity of food eaten by the reference population	Quantity of food	Nutritional (energy, macro, and micronutrient constraints)	To use mathematical optimisation tools for dietary guidelines to prevent cancer	Linear programming
Maillot et al. [67]	Optimise diet close to observed diet	Quantity of foods	Dietary energy, nutritional targets, maximal quantities of foods, diet weight	Describe dietary changes needed to achieve nutritional recommendations	Linear programming
Clerfeuille et al. [68]	Minimise deviations between optimised and observed diet	Weight of foods	Nutritional adequacy (selected nutrients), the constraint on food quantities	To estimate the number of portions of the different milk-based food categories that fit into nutritionally adequate diets	Linear programming—BASAL model
Metzgar et al. [69]	Minimise the sum of differences in food intake	Amount of food	Cost (does not exceed a maximum level), the constraint on some food categories (kept at a maximum of 0), nutrient (minimum and maximum levels, DRIs)	This dietary optimisation program uses common food choices to build a suitable diet (Paleolithic diet)	Linear programming
Okubo et al. [16]	Minimise the deviation in food intake between the observed and optimised food intake patterns	Quantity of food	Nutritional (meet DRIs), upper limits of each food	To translate nutrient-based recommendations into realistic nutritionally optimum combinations of food by integrating local and culture-specific foods	Linear programming (infused goal programming)
Perignon et al. [70]	Minimise departure from the observed diet	Food price	Nutrition	To evaluate the compatibility among the affordability dimensions of diet sustainability	Linear programming
Horgan et al. [71]	Minimising dietary changes from their current reported intake (to meet dietary recommendations and GHGE targets)	Weight of food	Nutrient constraints based on dietary reference intake, constraint set on meat and fish, 25% reduction constraint on GHGE, the lower and upper limit on individual foods	To determine the range of dietary changes that achieve dietary recommendations and reduce GHGE (making little changes to current dietary intakes)	Linear programming

Table 2: Continued.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Scarborough et al. [72]	Minimise deviation between the cost of observed and modelled diets	Amount of food	Dietary recommendations	To model food group consumption and price of diet associated with meeting dietary recommendations with minimum deviation from current diet to redevelop FBDGs (setting, UK)	Nonlinear generalised reduced gradient algorithm
Maillot et al. [33]	A nutritionally adequate isocaloric diet that stayed close to the observed diet	The amount of food available	Acceptability (food most frequently eaten), nutrient constraint (based on dietary reference)	Nutritionally adequate isocaloric diet (a modelled diet that came as close as possible to the corresponding observed diet)	Linear programming
Raymond et al. [73]	An affordable diet that achieves DRIs for selected nutrients (objective function was to minimise deviations between populations' food groups and dietary standards)	Grams of food	Amount of food used by the population, so it does not exceed nutrient constraint, acceptability (constraints were set on grams on each food group)	The primary objective of this study was to ascertain if a practical and affordable diet that meets DRIs for some selected nutrients can be developed for rural 6–23-month-old children in Tanzania	Linear goal programming
Kramer et al. [74]	Minimisation of changes to the current average diet	Weight of food	Nutritional requirements, environmental targets	The model was done to mimic the current consumer behaviour	Linear programming
Raymond et al. [75]	Minimise deviation between modelled and observed diet patterns while meeting dietary standards	Quantity of food	Nutritional (RNIs)	To establish if a realistic and inexpensive diet that meets set nutritional goals for rural women (pregnant and lactating) can be formulated from locally available foods in Tanzania	Linear programming (using goal programming)
Barré et al. [76]	Minimum deviation from the observed diet	Quantities of food	Environmental, constraint on dietary macronutrients and RDA, acceptability (a constraint on quantities of food subgroups, bovine meat, and dairy products co-constrained), cost (to remain lower or equal to observed current cost)	The objective was to evaluate the impact of nutrient bioavailability and co-production links considerations on the dietary changes needed—especially regarding meat—to improve diet sustainability	Linear and nonlinear programming
Brink et al. [77]	Sustainable diets that are close to the observed patterns	Amount of food groups	Constraints on food groups, environmental considerations, the minimum and maximum constraints on nutrients and energy, acceptability (closeness of modelled diets to current pattern)	To obtain healthy and sustainable food-based dietary guidelines (FBDGs) for different target groups in the Netherlands	Linear programming
Kim and Kim [27]	Optimal nutrient levels (minimise deviations)	Amount of food	The upper and lower limits of calories, consumption, and amount of nutrient	An absolute optimal decision that provides the best possible nutrient combination	Linear programming

Table 2: Continued.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Johnson-Down et al. [78]	The deviation between modelled and observed diet	Gram of food	Cost, nutrient requirement (EAR)	Satisfy medicine macro and micronutrient requirements in healthy individuals based on available foods consumed by the defined population (at minimum cost)	Linear programming
Verly-Jr et al. [39]	Optimised diets with food quantities at the lowest deviation from the observed diets	The amount of food	Nutrient (WHO guidelines for NCDs, recommended requirements), acceptability (boundaries limiting changes in food quantities, STRICT and FLEX models on foods), GHGE (stepwise reduction from 10%)	Identify the dietary changes to improve nutrition and reduce diet-related greenhouse gas emissions (GHGE) in Brazil, with consideration given to food habits and prices	Linear programming
Gazan et al. [79]	Minimise deviation between observed and optimised diets	Quantity of foods	Constraint on recommended intakes, 30% reduction of carbon impact constraint	Explore the feasibility of plant-based "dairy-like" products in achieving sustainable diets	Linear programming
Rocabois et al. [80]	Minimise deviation between observed and modelled diet	Quantity of foods	Constraints on nutritional requirements and environmental impact targets	Develop an approach (INDIGOO) to design sustainable diets with nutrient requirements and achieve set environmental targets	Linear programming
Vasilogou et al. [81]	To minimise the deviation between modelled and typical diet consumed in America	Quantity of food	Nutrient and food group constraints	Assess the quality of simulated food patterns that have reduced animal protein using NHANES data from 2017-2018	Mixed integer linear programming

GHGE—greenhouse gas emission, FBDGs—food-based dietary guidelines, DRIs—dietary recommended intakes, UK—United Kingdom, WHO—World Health Organisation, NCDs—noncommunicable diseases, RNIs—recommended nutrient intakes, EAR—estimated average recommendations, and INDIGOO—individual diet including global objectives optimisation.

Table 3: Summary of details retrieved from articles that minimised environmental factors.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Colombo et al. [48]	Reduce GHGE	Amount of food	Nutrition, affordability, cultural	The model that had lower GHGE levels and was nutritionally adequate and affordable	Linear programming
Larrea-Gallegos and Vázquez-Rowe [49]	Minimise the total amount of GHGE of optimised diets	Amount of food, carbon emission for the foods	Nutritional, environment, and quantity of foods		Linear programming with the integration of Monte Carlo simulation
Ferrari et al. [50]	Minimise GHGE while satisfying nutritional (RDIs), acceptability, and health constraint	Amount of food	Nutritional (nutrient and energy), acceptability (mean total amount of food and beverage that was constrained between 80 and 140% of observed intake and percentile on calculated mean observed diet), and healthy constraints (established lower and upper limit)	To create a sustainable and healthy Italian diet with low GHGE that meets dietary requirements and reflects current food intake patterns	Linear programming
Tompa et al. [40]	Reduced dietary water footprint and minimise the deviation between observed and model diets	Weight of subgroups	Constraints on nutrient requirements, cultural acceptability, and stepwise environmental reduction	Design sustainable diets that minimise dietary water footprint in Hungary	Linear programming

GHGE—greenhouse gas emission; RDIs—recommended dietary intakes.

Table 4: Summary of details retrieved from articles that maximised objective function.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Rambeloson et al. [51]	Maximum nutritional requirement	Edible grams of the selected foods	Nutrient	Investigate the nutritional quality of FB food aid delivered in France	Linear programming
Wilson et al. [35]	Maximum nutritional requirement	The amount of food	Nutrient, cost	A dietary pattern that met the essential nutritional requirements for New Zealand men	Linear programming
van Dooren et al. [52]	Maximise most consumed foods	Price of food, amount of food	Energy and nutrient, cost, GHGE	Find low-priced diets with low climate impact yet fulfil all nutritional needs	Linear programming
dos Santos et al. [7]	Maximum nutritional requirement		Nutrient deviations from observed dietary patterns	A diet that does not vary much from the observed dietary pattern	Linear programming
Morrison et al. [41]	Maximise the iron content of food	Quantity of foods	Nutrient constraint, intake constraint (median portion size, upper and lower bounds on frequency)	Develop strategies to address anaemia in pregnancy in rural plains in Nepal	Linear programming
van Wonderen et al. [53]	Maximise the iron content of diets	Quantity of foods	Constraints on DRIs	Plan a 2-week menu to estimate the iron bioavailability of different diets for women of reproductive age	Mixed integer linear programming

GHGE—greenhouse gas emission, FB—food basket, and DRIs—dietary recommended intakes.

Table 5: Summary of details retrieved from articles that did not specify minimisation or maximisation.

Reference	Objective function (s)	Decision variable (s)	Constraint (s)	Focus	Mathematical approach used
Pasic et al. [54]	Minimise variations from the defined nutrients (micro and macro), food cost	Food commodities	Recommended nutrient intake, upper limits of nutrients		Goal programming
Ferguson et al. [37]	Meet nutrient needs (while considering locally appropriate FBR that are low cost and can enhance nutrient adequacy)	Amount of food item	Energy content, minimum and maximum number of servings from food groups, grams of each food item	Find realistic food-based recommendations (FBRs) and ascertain how they could ensure intake adequacy for 12 nutrients	Linear programming (Optifood software)
McMahon et al. [28]	Minimise sodium intake while maintaining iodine intake	Reduction in sodium content in different foods	Nutrient intake (allowable levels, recommended dietary intake, upper limits)	To evaluate the intake of sodium and iodine against requirements and then model the possible impacts of salt-reduction strategies on estimated sodium and iodine intakes in indigenous Australian communities	Linear programming

FBRs—food-based recommendations.

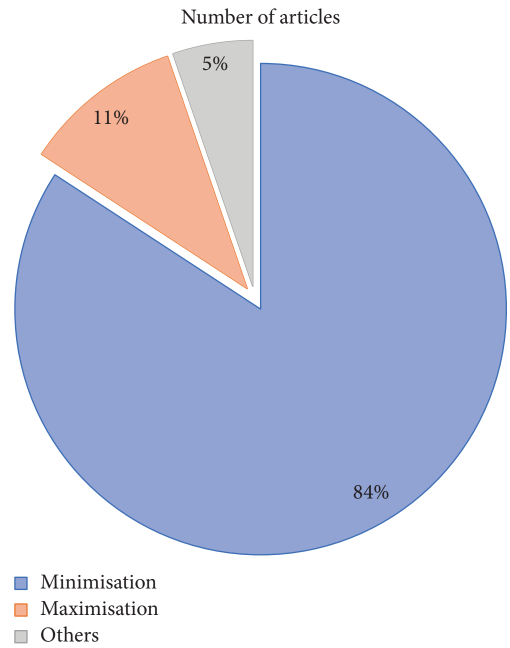

Figure 2: Graph showing the distribution of direction of the objective functions from articles analysed.

3.4. Constraints. In linear programming, there is the need for constraints to be imposed, and these constraints must be respected to obtain the defined optimal solution for the objective function set [14]. These multiple constraints are linear equations and inequalities that must be respected for optimal solutions. Some of these constraints can be set on nutritional needs, food acceptability or cultural requirements, environment, and the cost of diet [13, 39, 52]. All the studies had one thing in common: constraints that were defined to ensure some nutrients.

Most nutrition-related studies have focused on achieving nutritional constraints, regardless of the objective function (Tables 1–5). Masset et al. [10] set constraints to ensure modelled diet meets the nutritional requirement for cancer treatment. Dibari et al. [44] and Ryan et al. [46] also set constraints to meet the nutritional requirements for ready-to-use-therapeutic foods, Brixi [59] imposed constraints that ensure that the diet modelled met the nutritional requirements necessary to treat acute malnutrition, and Morrison et al. [41] set constraints to ensure that maximum iron content of modelled diets is obtained in an attempt to address anaemia among women of pregnancy age in Nepal. Other forms of nutritional constraint can be on macro and micronutrient requirements in the form of meeting recommended nutrient intakes (RNIs), as exhibited by Ferguson et al. [38]; Raymond et al. [75]; Verly-Jr et al. [39]; and van Wonderen et al. [53]. Similarly, Okubo et al. [16] and Horgan et al. [71] imposed nutritional constraints that satisfied dietary reference intakes (DRIs), Ghazaryan [60] did the same for tolerable levels of selected nutrients, and McMahon et al. [28] imposed constraints to ensure allowable levels were achieved and not exceeded. In other studies [10, 39, 43, 47, 50, 61, 63, 77], constraints were imposed on energy requirements to ensure diets modelled were less energy dense. To ensure the optimised diets did not exceed a set cost budget to ensure affordability, some studies [32, 48, 52] put a cost constraint to make it possible.

Also, constraints on culture or acceptability can be actualised in different ways. To ensure that optimised diets still stayed within the consumption pattern of the population or target group, researchers imposed a constraint on portion size [37, 38, 43, 63]. Another means of imposing ensuring the acceptability of an optimised diet is to impose a constraint on each food group, as done by Metzgar et al. [69]; Okubo et al. [16]; Horgan et al. [71]; Raymond et al. [73]; Ghazaryan [60]; and Mejos et al. [30].

Out of the 56 articles analysed, only 10 had a component of acceptability factored into their optimisation problems. Acceptability constraints are difficult to ensure in addressing dietary problems due to the varying needs of consumers and the different food items from one geographic area to another. However, acceptability is vital in ensuring that the sociocultural aspects of sustainable diets are achieved. For example, van Doren et al. [52] stated one limitation: the nonconsideration of cultural or social factors for dietary choices. van Dooren et al. [52] considered three more constraints besides the nutrient: energy, cost, and GHGE. This implies that there is room for more than only nutrients to be considered as constraints.

Computational models have been extensively applied in diet optimisation, primarily linear programming, under different settings. According to Beheshti et al. [85], these mathematical tools can simulate different scenarios in dietary choices and other diet optimisation problems at low cost with minimal risk. Though these studies either minimised or maximised an objective function, researchers had different scenarios and settings for their works (Table 1). Except for Pasic et al. [54] and Scarborough et al. [72] who used goal programming and a nonlinear generalised reduced gradient algorithm to find optimal solutions for the objectives they set, all studies (Table 1) used the linear programming approach. Linear programming has been used to address many diet-related problems [11, 14]. Though many of the studies analysed in this write-up employed linear programming to address a problem they intended to solve, the articles did not define mathematical equations that represent the physical problems.

From findings obtained from the review, LP has been successfully applied in solving diet optimisation problems. Though the LP is a robust and widely applied algorithm [86] suitable for diet optimisation problems, it becomes limited when more than one objective function is to be optimised. This can be seen from Tables 1–3 as almost all the studies had only one objective. One of the major hurdles in using linear programming to address the complexity of sustainable diets lies in resolving the multiple objectives. Almost all the research discussed in the review has addressed one or two dimensions of a sustainable diet, but not all (Table 1). With current challenges being faced by global food systems to ensure the provision of sustainable diets, the question of what mathematical approach can be employed offers room for more work. To achieve sustainable diets, researchers need to consider satisfying different conflicting goals like nutrition, cost, environment, and acceptability, making this a multi-objective diet optimisation problem. While single-objective optimisation problems generate a unique optimal solution, multiobjective optimisation yields a set of solutions through the Pareto optimality theory [87], making it a key point researchers should identify when solving a multiobjective optimisation problem. The Pareto optimal solution set obtained from solving the multiobjective problem is nondominated [24]. Chiandussi et al. [87] further indicated that some methods that have been used to solve these types of problems include the linear combination of weights, the multiobjective genetic algorithm, and the ε-constraint methods. Goal programming is another approach to solving multiobjective optimisation problems by minimising deviations between the individual goals obtained and the set targets [88]. Though many scholars have solved multiobjective optimisation problems, one challenge that could be encountered with its applications is the burden of computation when the number of objectives increases [89]. According to Nakayama [90], the weighted sum approach is well known but reveals the decision maker's subjective evaluation of the weights assigned. In addition, Zhen et al. [91] found that decision makers commonly assume that multiobjective optimisation problems have conflicting objectives when this is not always true. A review by Gazan et al. [3] showed the need for all the relevant aspects of a sustainable diet to be factored into mathematical diet optimisation. Although multiobjective optimisation has been widely used in various fields, its application in addressing intricate dietary issues remains limited. It would benefit future research to consider the various components of a sustainable diet and utilise a multiobjective optimisation approach.

4. Conclusion

Good nutrition is essential for obtaining nutrients to nourish the human body and ensure general well-being. However, current consumer dietary patterns raise concerns due to their environmental impact. As a result, there is increasing advocacy for sustainable diets which meet nutrient needs and consider the environment. Although there has been no definitive definition for sustainable diets, the different dimensions, including nutrition, economics (cost), environment, and sociocultural factors, make them complex.

The LP tool has been efficiently used to minimise cost, maximise nutrient requirement, and minimise deviations between set targets and achieve objectives. This handy tool can perfectly complement the tedious trial-and-error method used in addressing diet problems by providing the optimal solution for diet combinations in a shorter time. The tool has been efficiently used to address dietary problems by proposing diets that come at the least cost while meeting nutrient constraints or diets with low greenhouse gas emission values while meeting certain defined constraints. However, looking at how LP tools have extensively used, and some limitations highlighted, it is only able to solve problems with only one objective.

Therefore, challenges lie in its ability to solve more complex problems with multiple objective functions that may be conflicting, hence the advocacy for adopting multiobjective optimisation models in solving complex dietary problems with conflicting objectives.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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