Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review

Rozenn Gazan,[1,2] Chloé MC Brouzes,[3] Florent Vieux,[1] Matthieu Maillot,[1] Anne Lluch,[4] and Nicole Darmon[5]

[1] MS-Nutrition, Marseille, France; [2] Aix Marseille University, INSERM, INRA, C2VN, Marseille, France; [3] UMR PNCA, AgroParisTech, INRA, Université Paris-Saclay, Paris, France; [4] Danone Nutricia Research, Centre Daniel Carasso, Palaiseau, France; and [5] MOISA, INRA, CIHEAM-IAMM, CIRAD, Montpellier SupAgro, University of Montpellier, Montpellier, France

ABSTRACT

A sustainable diet is, by definition, nutritionally adequate, economically affordable, culturally acceptable, and environmentally respectful. Designing such a diet has to integrate different dimensions of diet sustainability that may not be compatible with each other. Among multicriteria assessment methods, diet optimization is a whole-diet approach that simultaneously combines several metrics for dimensions of diet sustainability. This narrative review based on 67 published studies shows how mathematical diet optimization can help with understanding the relations between the different dimensions of diet sustainability and how it can be properly used to identify sustainable diets. Diet optimization aims to find the optimal combination of foods for a population, a subpopulation, or an individual that fulfills a set of constraints while minimizing or maximizing an objective function. In the studies reviewed, diet optimization was used to examine the links between dimensions of diet sustainability, identify the minimum cost or environmental impact of a nutritionally adequate diet, or identify food combinations able to combine ≥2 sustainability dimensions. If some constraints prove difficult to fulfill, this signals an incompatibility between nutrient recommendations, over-monotonous food-consumption patterns, an inadequate supply of nutrient-rich foods, or an incompatibility with other dimensions. If diet optimization proves successful, it can serve to design nutritionally adequate, culturally acceptable, economically affordable, and environmentally friendly diets. Diet optimization results can help define dietary recommendations, tackle food security issues, and promote sustainable dietary patterns. This review emphasizes the importance of carefully choosing the model parameters (variables, objective function, constraints) and input data and the need for appropriate expertise to correctly interpret and communicate the results. Future research should make improvements in the choice of metrics used to assess each aspect of a sustainable diet, especially the cultural dimension, to improve the practicability of the results. *Adv Nutr* 2018;9:602–616.

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Introduction

Obesity and noncommunicable diseases are increasingly prevalent in high-income countries (1), whereas undernutrition and obesity coexist in low-income populations (2). The current food production system in more economically developed countries carries a significant burden of environmental impacts, which is further accentuated by intensification of industrial and agricultural production in fast-developing countries such as China and India (3). Given this context, the concept of sustainable diets—that is, diets that are "protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources"—is gaining attention in both high-income and low-income countries (4).

Assessing diet sustainability entails simultaneously exploring their health/nutrition, economic, cultural, and environmental dimensions. Research investigating the relation between the health and economic dimensions, both in observational or modeling studies, has found that nutritionally adequate diets (i.e., diets covering a set of nutrient recommendations) are often more expensive than unhealthy diets (5). Research tackling the challenge of climate change

has explored the relation between the nutritional quality and environmental impact of self-selected diets, and the results showed that nutritionally adequate diets are not necessarily associated with low dietary greenhouse gas emissions (GHGEs) (6, 7). Different dimensions of diet sustainability may not be compatible with each other, so no aspect of a sustainable diet should be left out (6). It is now necessary to imagine tomorrow's diets by establishing the best balance between the different dimensions of a sustainable diet with the use of multicriteria assessment methods.

Operational research encompasses several advanced analytical methods that help to identify optimal or near-optimal solutions to solve complex problems (8). Operational research methods offer suitable tools for integrating the multidimensional complexity of sustainable diets. Among many other operational research methods, substitution and mathematical optimization are common problem-solving techniques used for designing healthier diets. Substitution approaches can test an "a priori hypothesis" by replacing one or several foods with others, on the basis of a priori reasoning. Food-substitution methods have been used to assess nutritional (9–11) and economic (12–14) or environmental (15, 16) impacts of dietary changes. An alternative substitution method used an iterative process to identify, without a priori reasoning, the best food and beverage substitutions required within a diet to improve a nutritional quality score (17). However, these heuristic approaches require multiple steps to finally identify a diet that is not always the optimal one. In order to find the very best way to simultaneously fulfill a given set of constraints, researchers have used mathematical optimization to model theoretical diets (18). Mathematical diet optimization ("diet optimization") tackles the challenge of identifying the optimal combination of foods to answer a given question under a set of predefined constraints (e.g., imposed nutrient recommendations, a total diet cost, an environmental target, etc.). Diet optimization has, for instance, been used to answer questions, such as the following: Is it feasible to achieve all the nutritional recommendations (i.e., nutritional adequacy) with the current food supply (19)? What is the minimum cost of a nutritionally adequate diet (20–22)? Which optimal food combinations would be required to reach nutritional adequacy while staying as close as possible to the current diet (23, 24)? What is the optimal combination of foods to reduce environmental impact while fulfilling nutrient recommendations and departing the least from an existing diet (25, 26)?

Diet optimization is increasingly used in the field of public health nutrition. There is a need to establish a general picture of the numerous ways to mathematically optimize diets, especially in the context of sustainable diets.

On the basis of 67 relevant original publications, this narrative review shows how mathematical diet optimization can help understand the links between the different dimensions of diet sustainability, and how it can be properly used to identify sustainable diets. The focus of this study is to provide an overview of the best practices when modeling sustainable diets ("methodology oriented") but not to summarize food combinations that enable to answer specific public health and/or sustainability issues for a given population ("results oriented").

Introduction to Diet Optimization

Mathematical diet optimization, also called diet modeling or diet optimization, started in the 1940s with Georges Stigler (27), who chose diet as an example to translate a complex problem into a mathematical model called the "diet problem." The goal of the diet problem was to find the set of foods that satisfied daily nutritional requirements at minimum cost. The technical solution for solving this problem was developed by Dantzig (18) through the Simplex algorithm, which is the backbone of linear programming. Dantzig indicated that the optimal solution of the "diet problem" was finally reached by Laderman, who showed the solving capacity of the Simplex algorithm (18). Today, optimization problems can take other forms than linear functions, such as quadratic programming (28), mixed-integer programming when using integer variables (29), or goal-programming to solve problems with multiple objectives (30, 31). All of these different approaches are covered in this review.

The parameters of a mathematical optimization problem are the decision variables, the constraints, and the objective function. Mathematically, an optimization model aims to find the unique combination of values for decision variables that generates the optimal value for one objective function, while fulfilling a set of equalities or inequalities, called constraints. Applied in nutrition, a diet optimization model aims to find the unique combination of foods that minimizes or maximizes an objective (e.g., total diet cost, energy content or the content of a given nutrient, total deviation from the observed diet), while fulfilling nutritional recommendations and/or maximal amounts of foods, food groups, and/or other constraints. An illustration of a diet optimization with its parameters is presented in **Figure 1**. The model has a feasible solution when at least one combination of decision variables can simultaneously meet all the constraints. When there are multiple combinations that fulfill the set of constraints, the model selects the unique solution that best answers the objective function. However, it may happen that a model has no feasible solution, meaning that ≥2 constraints are not compatible using the decision variables. Special attention must be given to each parameter of the model, in particular to avoid getting unrealistic and extreme solutions. For instance, in 1959, after obtaining for a British family a nutritionally adequate and affordable diet that contained only 6 foods out of 73, Smith (34) had the idea of introducing food-habit constraints in order to obtain a more realistic diet—dubbed the "palatable human diet"—which would be more acceptable.

Throughout this review, "observed" diet refers to the current diet of a given population, a subpopulation, or an individual, whereas "optimized" diet refers to one theoretical diet obtained after running one diet optimization model. A diet optimization model is usually designed for a daily (or weekly) diet or a food basket. Here we consider diet optimization as "population-based optimization" when applied
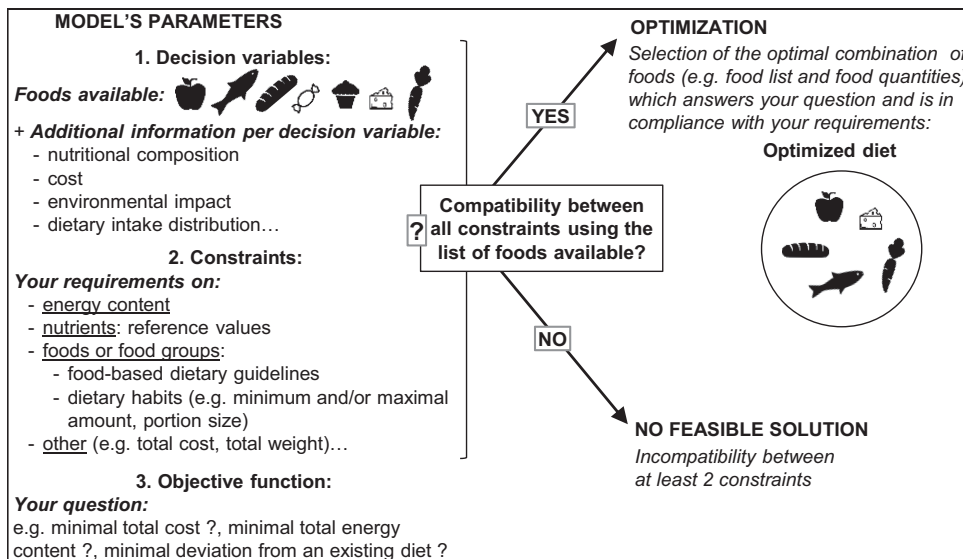
FIGURE 1 Schematic representation of mathematical diet optimization. Adapted from reference 32. Copyright © 2008 Elsevier Masson SAS. All rights reserved. Food images are from reference 33.

to a given population or subpopulation, and as "individual-based optimization" when applied to each individual of a population. In population-based optimization, only one diet is modeled for the whole population. The decision variables are the foods, food items, or food groups that are mostly consumed—or potentially available—in the population of interest. With this approach, it is assumed that all foods are potentially acceptable for all individuals from the population of interest. In individual-based optimization, one diet is modeled for each individual of the population. For each model, the decision variables are the foods consumed by the individual, completed, if necessary, by "new" foods (i.e., foods not currently consumed by the individual but consumed in the wider population). When the aim of the model is to stay closer to the current diet, the objective function in population-based optimization aims to stay as close as possible to the average observed diet, whereas in individual-based optimization the model for each individual aims to deviate the least from each individual observed diet, thus better taking individual food habits into account. When dealing with public health and nutrition issues, applying diet optimization at the individual level creates a diverse range of optimized diets, which can be statistically analyzed, thus providing robustness in the conclusion.

The literature strategy used to compile the 67 relevant original publications using mathematical diet optimization is presented in **Supplemental Methods 1**. Studies using mathematical optimization without a whole-diet approach were excluded from this review. A description of each of the 67 studies reviewed can be found in the **Supplemental Tables 1–3**, which detail the population studied, type of modeling (individual or population-based), objective function, constraints for each dimension of diet sustainability (health/nutrition, culture, economy, environment), and the software programs used. Not all software programs can

address all dimensions of diet sustainability. Preconceived software programs such as Optifood (35) can take into account metrics related to nutrition, cost, and food habits. Flexible software programs (such as R or SAS) can be used to take into account as many dimensions as desired. To date, only flexible software programs allow conducting individual-based diet optimization models, which can include complex equations [e.g., to consider nutrient bioavailability (36)], and to perform statistical analysis on model outputs.

Dimensions and Metrics of Diet Sustainability

Appropriate metrics need to be chosen to assess each dimension of diet sustainability, namely health/nutrition, culture, economy, and environment. All 67 studies in this review considered the nutrition and cultural dimensions, and some studies also included the economic and/or environmental dimensions (Supplemental Tables 1–3). The cultural dimension, also called "cultural acceptability," was taken into account in various ways that will be described and discussed in the following sections. Foods habits of the population studied were considered a proxy for cultural acceptability. The nutrition dimension was studied through nutritional quality or adequacy of diets. Because diet optimization rarely considers the health aspect, it is only addressed in the Discussion section. The economic dimension was depicted via economic affordability using diet cost. The environmental dimension was assessed through ≥1 diet-related environmental metrics (e.g. GHGEs, indirect land use, water use).

Nutritionally Adequate Diets

A nutritionally adequate diet is compliant with nutritional recommendations, meaning that it fulfills a set of reference values (RVs). RVs refer to quantitative values of nutrient intakes for healthy individuals given for different population

groups and derived from health-related criteria (37). Diet optimization can translate nutrient recommendations into an optimal combination of foods. It has been used to answer the following questions:

- Is reaching nutritional adequacy feasible, and what are the implications for food choices?
- Which nutrient recommendations are the most difficult to fulfill or, in the case of infeasibility, what are the "problem nutrients"?

Identifying the food combinations required to reach a nutritionally adequate diet

When nutritional recommendations are reachable with available foods, diet optimization can translate the full set of nutrient-based recommendations into food combinations (type and amount), which can potentially serve as a basis for developing food-based recommendations (FBRs). Working on specific subpopulations and/or at an individual level may then help to improve the acceptability of the optimal food combinations identified.

Models optimizing a given nutritional characteristic (e.g., minimizing total energy content) have been used to identify food combinations that reach nutritional adequacy starting from a simple list of foods. For example, from the list of locally available foods in Malawi, linear programming was applied for each season (harvest and nonharvest) to select foods satisfying nutritional and food-habit constraints at a minimal amount of energy (24). Food-habit constraints were introduced to avoid departing too much from current food habits. Results showed that the minimum energy intake required to meet all constraints was realistic (i.e., below the average energy intake observed in the population) in the harvest season but consistently higher than the average energy intake in the nonharvest season unless the energy from vegetables or meat, fish, and eggs was >75th percentile observed in the population. In France, the minimum energy needed to fulfill French recommended nutrient intakes and food-habit constraints was estimated at 1500 kcal/d for women and 1700 kcal/d for men (19).

Models minimizing dietary changes from an average observed diet were developed to better take into account cultural acceptability when designing a nutritionally adequate diet. For example, in 1993, an acceptable nutritionally adequate diet was designed to stay closer to the average diet of US women (23). Results helped to gain insight for promoting nutrition education messages by identifying the food changes required to reach nutritional adequacy (namely more fruit and vegetables and milk, and less cheese and composite dishes). In Japan, nutritionally adequate optimized diets were built for different age and sex groups, deviating as little as possible from the average observed diet of each subpopulation (38). Among Japanese adults, food changes were smaller for older (women especially) than for younger groups who had to greatly increase their fruit and vegetable consumption. Two pioneering studies, one using data from Malawi (39) and the other using data from Australia (40), applied diet optimization to help design practical FBRs, which are usually burdensome and time-consuming to develop (41). The FBRs were created in several steps: *1)* using diet optimization to design a nutritionally optimal diet that respects population food-habit constraints and then using this optimized diet as a basis to create draft FBRs, re-expressed as frequency of consumption of typical serving sizes; *2)* testing whether fulfilling the draft FBRs ensures nutritional adequacy; and *3)* adjusting the FBRs on the basis of expert feedback (30, 40). On the basis of this approach, a pre-set software program called "Optifood" was created specifically for designing FBRs, taking into account subpopulation specificities (e.g., age, sex, food habits, and food supply) in low-income countries (35). Optifood's modules are further detailed in **Supplemental Methods 2**. The Optifood software program has been extensively used for developing FBRs for children aged <2 y [e.g., in Kenya (42, 43), Guatemala (44), Indonesia (30, 45), Cambodia (46), and in 5 Southeast Asian countries (47)], for older children [in specific regions of Malawi (39) or Kenya (48)], and for women in Guatemala (44). Diet optimization also contributed to the development of a food guide in Benin for several adult age and sex subpopulations (49). Diet optimization can also be used to test the coherence and efficacy of FBRs, which are usually developed via collective expertise on the basis of scientific evidence linking diet to health and diseases. For example, the compatibility between nutritional requirements and meeting the 2005 US Food Guide Pyramid (50), the 2007 US cancer prevention recommendations (51), or a specific US recommendation on solid fats and added sugars (52) was checked using diet optimization. Diet optimization was also used in the United Kingdom to assess the nutritional efficacy and cost implications of new updated UK dietary guidelines on sugar and fiber (53). In 2010, the European Food Safety Authority advocated the use of modeling techniques to test whether FBRs meet nutrient recommendations and to adapt them as appropriate (54). Diet optimization can greatly improve the FBR development process, but the results still warrant careful expert examination to potentially re-adjust them in order to craft concise, realistic, and readily understandable food-guidance messages specific to the population of interest.

Individual-based diet optimization accounts for individual variability in food consumption, which is a way to improve cultural acceptability. In 1990, diet optimization was applied for the first time at the individual level in a clinical study to show the potential value of diet optimization for pediatric dietitians. Tailored and nutritionally adequate optimized diets were designed by maximizing a preferential score for the diet (after assigning a preference score to each food) (55). Individual-based optimization was then applied to minimize the deviations from each individual's observed diet in clinical and interventional studies on small samples of individuals (56, 57). More recently, individual-based optimization was developed in the field of nutritional epidemiology for public health and research purposes, and was first applied to 1171 individuals from a representative sample of the French population (58). Through

this approach, average dietary changes required to reach nutritional adequacy were identified and quantified in the whole population or by subpopulation, while accounting for the interindividual variability in food consumption (58–60). On average, in the population, the dietary changes required to fulfill nutritional constraints using individual-based optimization were consistent with usual dietary advice (more fruit and vegetables, fish, and unsalted nuts; fewer sweet products, meat, and animal fat) (58). There are actually multiple ways to reach nutritional adequacy from the same set of nutrient constraints, food-habit constraints, and foods available depending on the observed diets. Individual food changes can be assessed per subpopulation. For example, specific food changes to reach nutritional adequacy were obtained by comparing average dietary changes among French individuals with or without excessive intakes of free sugars (≤10% or >10% dietary energy according to the WHO recommendation, respectively) (61). An increase in vegetables and decreases in sugar-sweetened beverages, sweet products, and fruit juices were specifically required to reach nutritional adequacy for individuals with excessive free-sugar intakes. Another study used individual-based optimization to design nutritionally adequate diets among UK children aged 12–18 mo and compared average optimized diets between subpopulations on the basis of their current consumption of young child formula (YCF) and/or supplements. Food changes were greater for children who did not initially consume YCF or supplements than for children who did, with a switch from cow milk to YCF (62).

Identifying binding constraints and problem nutrients to reach nutritional adequacy

One RV can be difficult to reach or even unattainable, either due to an insufficient amount of nutrients in the food supply or incompatibility with another constraint applied in the model. Higher-income countries enjoy a diverse and nutrient-rich food supply that makes it easier to attain a nutritionally adequate diet than in low-income countries, but the fulfillment of some nutrient constraints may still be a concern. When all RVs cannot be met simultaneously with the current food supply, specific models can be conducted to obtain the best near-optimal solution. Another possibility for solving an unfeasible model is to allow new food variables in the model.

When a nutritionally adequate diet is feasible, some RVs can have a higher influence on food selection than others, in which case they are identified as the most difficult RVs to fulfill. A nutrient constraint is called a "binding constraint" (or "active constraint") when the amount of the nutrient in the optimized diet is just equal to the imposed value (i.e., RV), meaning that fulfillment of its RV strongly influences the food content in the optimized diet. Binding constraints can be identified and ranked by assessing the dual values, also known as shadow costs, which give the impact on the objective function when the constraint is relaxed by 1 unit. Zinc, riboflavin, vitamin B-6, and iron were identified as binding nutrient constraints when modeling a

nutritionally adequate diet while minimizing the total diet cost for French children aged 1–3 y (63). When designing nutritionally adequate diets that depart the least from the average observed diet in adults, the upper limit on sodium and SFAs and the minimal content of fiber were binding in France and Japan (26, 38), and the minimal content of iron and vitamin A were binding in the United States and Japan (38, 52, 64). In France, controversial macronutrient recommendations (i.e., total fat, total carbohydrates, MUFAs, and cholesterol) were investigated by imposing various combinations of macronutrient constraints in an individual-based optimization (59). The constraint applied on MUFAs (≥15% of total energy) was shown to be very difficult to satisfy, and MUFA content in optimized diets without this constraint was consistently reduced.

A too-high (or too-low) nutrient level imposed as a constraint is problematic, because it can lead to unrealistic optimized diets or may even make the model infeasible (meaning that this nutrient constraint is incompatible with at least one other constraint of the model). To test the compatibility between 1 specific nutrient recommendation and the others, one can either assess whether the recommendation is reached when maximizing the value of the nutrient while fulfilling the other nutrient constraints or assess the impact of varying or removing the value of this nutrient constraint on the model's feasibility. The US RV for vitamin E, which was criticized as unattainable, was compared with the highest vitamin E level achievable while meeting different sets of RVs and food-habit constraints for different age and sex groups (65). Although meeting the US RV for vitamin E was achievable for all age-sex strata, it was only feasible with dramatic dietary changes, including a strong increase in rarely consumed foods such as nuts and seeds. Two US studies explored the compatibility between the maximal recommended sodium intake and the nutritionally adequate potassium intake. The sodium and potassium goals (≤2300 and ≥4700 mg/d, respectively) were theoretically compatible with other RVs for all age and sex subpopulations but required strong deviations from average observed diets (66, 67). The more restrictive recommended amount of sodium (<1500 mg/d) was not compatible with the potassium goal and other RVs for several US subpopulations except for men aged >51 y (66, 67). Sometimes it can be impossible to reach nutritional adequacy, either because of incompatibility between RVs imposed in constraints or a problem with food availability, especially when background poverty limits physical or financial access to nutrient-rich foods. Nevertheless, one way to improve nutritional quality is to seek the "nutritionally best diet" by maximizing nutrient coverage itself while respecting food-habit constraints (30, 42). Nutrients for which RVs are not fulfilled in the "nutritionally best diets" are defined as "problem nutrients" (42). For example, this approach integrated in the Optifood software program (Supplemental Methods 2) helped to highlight iron as a "problem nutrient" because the nutritionally best diets only reached 21–66% of the iron RV depending on age-district subgroup in Bogota (Colombia) (42). Iron, zinc, and calcium

were common problem nutrients in children aged 6–23 mo living in Indonesia (68), in 5 Southeast Asian countries (47), and in Kenya (42, 43), whereas vitamin A and zinc were problematic for Kenyan children aged 4–6 y (48). Thiamin was identified as the only "problem nutrient" for a population of children from Bogota (Colombia) aged 12 mo (69). When nutrient gaps remain with locally available food sources, there is evidence for advocacy to modify the food supply in order to reach nutritional adequacy. In the context of severe malnutrition, it was shown that no combination of local foods was able to achieve a nutrient density as high as diets promoted by the WHO, thus showing the need for fortified foods in this specific health condition (70). Several others studies have found that nutritional adequacy was only attainable via the inclusion of fortified products (47, 48, 69). For example, in Kenya, with no zinc-fortified water, only 76% of the zinc RVs could be covered in the nutritionally best diet for young children, which was improved to 101% with the fortified product (48). Individual-based optimization can test whether the foods consumed by an individual are sufficient to build nutritionally adequate diets or if he or she needs to expand his or her habitual food repertoire. To achieve nutritional adequacy, the introduction of new foods was necessary for 78% and 92.5% of individuals in France (71) and the United Kingdom (72), respectively. Among UK children, nutritional adequacy was almost impossible to reach without introducing YCFs and/or supplements, especially for children whose observed diets lacked YCFs and supplements (62).

Affordable Diets

A positive association between diet cost and nutritional quality is a consistent finding worldwide (5). Because price could be a strong barrier to healthier food choices, the relation between diet cost and nutritional adequacy has been a focus of interest in several diet optimization applications to answer the following questions:

- What would be the influence of a cost constraint on the nutritional adequacy and cultural acceptability of diets?
- What is the minimum cost of a nutritionally adequate diet?
- How can we design a low-cost diet that would also be culturally acceptable and nutritionally adequate?

Impact of a cost constraint on nutritional quality and cultural acceptability of a diet

Healthy diets generally cost more than unhealthy diets (5). However, with transversal and observational data, causality (i.e., whether healthy diets cost more due to their high dietary quality) cannot be addressed. Even longitudinal studies cannot show a causal link between diet cost and dietary quality, because any reduction in food budget (e.g., due to job loss) will induce a number of changes in everyday life other than just dietary behavior. In that respect, mathematical diet optimization is a tool of interest for simulating the impact of varying 1 isolated factor on the outcomes of the model.

For instance, several isoenergetic diets were designed to be as close as possible to the French average observed diet (73, 74). Then, to assess the relation between diet cost and nutritional adequacy, a cost constraint alone (i.e., without any nutritional constraints) was imposed and strengthened (by steps of €0.50) until no solution was feasible (73, 74). Strengthening the cost constraint had a negative influence on food selection, because it impaired nutritional adequacy and diet quality, mainly through a decrease in most micronutrients and an increase in amount of fat and carbohydrates (including sugars) at the expense of proteins (73) and an increase in energy density (74). In the United States, food selection obtained from diet modeling with a cost constraint alone did not fulfill most of the nutrient RVs and did not provide the recommended quantity for each MyPyramid food group (64). In both the French and the US studies, forcing the cost to decrease also expanded the distance from the average observed diet, thus compromising cultural acceptability (64, 73).

Minimum cost of a nutritionally adequate diet

Given that food prices influence food choices, studies have compared the price of nutritious food baskets (75, 76) or diets (77) designed by experts against the budgets of poor people in different populations. Results consistently showed that poor people cannot afford a nutritious food basket or diet. However, the cost of these nutritious baskets or diets was not necessarily minimal. This is where diet optimization can be used to identify the minimum cost of a nutritionally adequate diet and assess whether the lowest-cost nutritionally adequate diet would be affordable for poor people and under which conditions it would be culturally acceptable.

Studies have shown that it is possible to achieve nutritional adequacy at a very low cost, but the realism of the optimized diet was highly dependent on food-habit constraints (22, 78–80). For instance, in the United Kingdom, nutritional adequacy was reachable from just 4 or 5 foods for approximately £2/wk (which was 5 times less than the average household food expenditure in 1987) in subpopulations with different physical activity levels (79); however, the minimal cost increased between 4-fold and 9-fold as soon as food-habit constraints were included in the models to improve acceptability (79). In France, the theoretical minimal cost for a nutritionally adequate diet considering food-habit constraints was estimated at €3.20/d for women and €3.40/d for men (i.e., close to the food budget of poor people in this country) (22). Without food-habit constraints, theoretical cost was as low as €1.50/d for men and women (22). Likewise, in Denmark, the minimal cost for a culturally acceptable food basket for a theoretical household increased almost linearly with an increase in food variety within each food group, so that minimal cost was ≥3 times cheaper without than with cultural acceptability considered (80).

A diet optimization software program called "Cost of the Diet" (CoD) was specifically developed to identify the "Minimum Cost Nutritious Diet" from a list of foods for a

typical household by minimizing cost while covering energy, nutrient requirements, and/or food-habit constraints (20, 21, 81–84). The methodology applied in the CoD can be seen as a population-based optimization, considering the household as a subgroup counting a specific number of individuals, more often representing a typical household in the studied country. When a comparison with household incomes shows that families/households cannot afford the Minimum Cost Nutritious Diet, the introduction of fortified products can be considered and evaluated through the impact on a household's budget (81). In Mozambique, iron, riboflavin, and pantothenic acid were identified as binding nutrients, meaning that fulfilling their RVs had a big impact on total diet cost (81). The study thus went on to assess the cost-effectiveness of 4 fortification vehicles (vegetable oil, sugar, wheat flour, and maize flour) and showed that the minimal cost obtained in the model without fortified products could be reduced up to 18% by introducing maize flour fortified with vitamin B-12, iron, zinc, and folic acid. Indeed, the cheapest fortified foods replaced some nutrient-dense but expensive foods such as small dried fish or beef liver, which were required when minimizing cost with local foods only (81). In Indonesia, the CoD tool was used to highlight regional differences in meeting nutritional requirements and to propose relevant food-fortification interventions (21). The CoD tool has been used in several countries for advocacy purposes: for example, to stress a situation of nutritional emergency in a Syrian refugee camp in Jordan (83) or to suggest interventions to improve access, availability, and demand for nutritious foods in 10 regions of Madagascar (84).

Designing low-cost and culturally acceptable nutritionally adequate diets

The previous sections support the evidence that it is necessary to simultaneously consider both diet cost and cultural acceptability when defining nutritionally adequate diets. Several diet optimization studies have attempted to find a tradeoff in the model parameters in order to design nutritionally adequate, culturally acceptable, and economically affordable diets.

The USDA has developed 4 food plans, which have been revised at regular intervals since 1971, for different food budgets and 15 age and sex groups (85). In the 2006 version (28, 86), each optimized food plan was a nutritionally adequate combination of 29 food groups (i.e., respecting the 1997–2005 RVs, 2005 Dietary Guidelines for Americans, and 2005 MyPyramid), respecting an upper bound on diet cost (no more than the previous version adjusted for inflation). Cultural acceptability was ensured by food-habit constraints and by minimizing the deviation of food groups from the average observed diet in the US population. On the basis of the optimized food plans obtained in the 2006–2007 revision, the total cost of each food plan is updated monthly and used to define the amount of institutional food aid (i.e., food allowances) in the United States. In low-income countries, FBRs for Indonesian children aged 9–11 mo costing <2500 Indonesian rupiahs (corresponding to the

mean daily food expenses for infants) were developed using Optifood (45) with an upper-bound constraint on diet cost and imposing food-habit constraints. Affordable and district-specific FBRs included recommendations on breastfeeding frequency as well as on the minimum number of servings per week of several foods, including fortified foods. Similarly, the cost and nutrient content of several sets of FBRs were compared among rural children from Malawi aged 9–10 mo (87) as well as in children from rural Kenya aged 6–23 mo (42) to finally select the simplest set of FBRs for each population that best ensured nutritional quality at low cost.

Nevertheless, designing a diet that is nutritionally adequate, culturally acceptable, and economically affordable is no easy task, often requiring tradeoffs between decreasing diet cost, reaching nutritional adequacy, and staying close to current food habits. To study these tradeoffs, various scenarios can be conducted to investigate the impact of progressively varying the set of constraints (i.e., progressively increasing the stringency of nutrient constraints introduced in the model, or imposing food-habit constraints with progressively less tolerance for any deviation from the observed diet) on dietary changes (22). The lowest-cost diets meeting 3 levels of nutritional requirements and 7 levels of food-habit constraints were developed for French adults (22), and the results showed that both types of constraints increased the minimal cost when they were more stringent (e.g., all RVs were obtained for as little as €1.50/d when consumption constraints were ignored, but the minimal cost doubled when the most stringent consumption constraints were imposed) (22). In another study, the total cost of diets for French women was gradually decreased by steps of €0.50 using population-based optimization until no solution was feasible (88). Nutritionally adequate optimized diets unconstrained by cost were €0.58/d per person more expensive than the average observed diet (€4.41/d per person) and required modest dietary changes. However, reaching nutritional adequacy at the lowest achievable cost (i.e. €3.18/d per person) required large deviations from the current food habits, relying on foods with good nutritional quality for their price but which could be rarely consumed by the population (89). Likewise, a study in the United States found that both nutrition and culture are costly demands (64). A recent study that used individual-based optimization among French adults showed that, even if reaching nutritional adequacy increased the diet cost by €0.22/d per person on average, the diet cost decreased for some individuals (90), which somewhat tones down the conclusions of the previous population-based optimization studies (22, 64, 88). In addition, modeling a nutritionally adequate and culturally acceptable diet at no extra cost was possible for all individuals in the study sample, even those who had the lowest observed diet cost (90).

Environmentally Friendly Diets

Research tackling the challenge of climate change has increasingly focused on the environmental impact of diets,

which has mainly been assessed with the use of dietary GHGEs (6, 7). However, a diet with reduced GHGEs is not necessarily a healthy diet (7, 91). A healthy and environmentally friendly diet may not be easy to attain, and not necessarily affordable or acceptable. Diet optimization has been used to specifically address the following questions:

- What would be the influence of reducing diet-related environmental impact on diet costs and nutritional quality?
- What is the minimum diet-related environmental impact reduction achievable while achieving nutritional adequacy?
- How can we find the best tradeoff between reducing environmental impact, reaching nutritional adequacy, and staying close to current food habits, ideally at no extra cost?

Impact of an environmental impact constraint on nutritional quality, diet cost, and cultural acceptability

There is still no consensus on the relation between the environmental impact and nutritional adequacy of diets. A systematic review, including both epidemiologic and modeling studies, on the association between GHGEs and diet nutritional quality (and other health indicators such as cancer prevalence) found that low-GHGE diets have a lower content in sodium and saturated fats but negative nutritional outcomes, such as a decrease in several key micronutrients and an increase in sugar content (7). In the United Kingdom, minimizing GHGEs without nutritional constraints except on energy led to a diet high in sugary foods and sweetened beverages and low in meat, fruit, and vegetables (92). To our knowledge, only one study has analyzed the impact of a progressive GHGE reduction on nutritional quality, diet cost, and cultural acceptability (26). Isoenergetic diets were modeled by minimizing departure from the average French diet under the impact of stepwise GHGE reductions (10% steps), but without nutritional constraints or with constraints on macronutrients only (26). Reducing GHGEs by 30% (or <30%) induced only minor food deviations (mainly a moderate decrease in meat) and therefore had only minor impacts on nutritional quality and diet cost. In contrast, forcing GHGEs to reduce by >30% significantly decreased nutritional quality (even with constraints on macronutrients), tended to decrease diet cost, and involved more food changes from the average observed diet. These results showed that, although environment and cost can be made easily compatible, it is not necessarily the case between environment and nutrition and between environment and cultural acceptability.

Food combinations for a nutritionally adequate diet at minimum environmental impact

With increasing recognition of our food system's environmental impact, there has been a surge in efforts to identify how far the environmental impact could be reduced while ensuring nutritional adequacy. Diet optimization identified the lowest-environmental-impact diets by minimizing one or more environmental metrics (26, 93–97), but this led to large deviations from current food habits.

In the United Kingdom, a maximal reduction of 90% of GHGEs (from the observed baseline in 1990) was reachable while meeting constraints on 12 nutrients without food-habit constraints, but only 7 food groups from a list of 82 were included in the modeled diet (94). Introducing constraints to account for food habits led to a healthy and environmentally friendly diet, with 52 food groups achieving a 36% GHGE reduction from baseline while diet cost decreased by 12% from the United Kingdom's average 2009 household spending on food (94, 96). In France, the greatest GHGE reductions achievable while attaining nutritional adequacy (i.e., >30 nutritional constraints) were 70% and 74% for women and men, respectively, but induced substantial changes from the average observed diet (e.g., large reduction in the meat, fish, and eggs group and a substantial reduction in the fruit and vegetables group) with a diet cost reduction (26). In Italy, working up from foods declared by students in a dietary record, optimized diets were designed by simultaneously minimizing diet cost and 3 environmental metrics (GHGEs, water use, and land use), while fulfilling constraints on 9 nutrients as well as a large set of food-habit constraints (e.g., maximal values on portion sizes, food-consumption frequencies, food-association constraints between complementary foods) (93). The optimized diet involved large changes liable to impair cultural acceptability, such as a complete removal of meat replaced by a high increase in fruit and vegetables, legumes, bread, and dairy. A modeling study on 5 European countries recently showed that achieving nutritional adequacy with maximal GHGE reductions (from 62% to 78% depending on country and sex) was theoretically possible but would require large departures from observed diets entailing changes in the quantity of ≥99% of food variables (97).

Designing sustainable diets

The previous sections outlined the challenge of combining dimensions of sustainability for a nutritionally adequate, culturally acceptable, economically affordable, and environmentally friendly diet. Among self-selected diets in a nationally representative survey in France, the positive deviance approach (i.e., the identification of uncommon but beneficial behaviors in a given population) was used to identify diets more sustainable than others (i.e., diets with both lower GHGEs and a higher nutritional quality) (98). Results showed that "more sustainable diets" were consumed by ∼20% of adults, and their GHGE values were ∼20% lower than the average value at no additional cost, but nutritional adequacy was not fully ensured. With observational data, it was not possible to establish whether greater GHGE reduction would be achievable while ensuring the other dimensions. As a multicriteria approach, diet optimization can combine several dimensions of diet sustainability without impairing any of them, provided they are included in the models.

A few studies have identified sustainable diets by imposing environmental, nutritional, and food-habit constraints while minimizing the departure from observed diets (25, 72, 99, 100). The environmental constraint is generally based on institutional goals for environmental impact reduction or on reduction from actual baseline environmental impact levels. For instance, among Dutch adults, a 50% reduction was imposed to hit the European goal of keeping global warming <2°C, along with a cost reduction of 50% from the average observed diet (100). In France, Spain, and Sweden, "LiveWell" diets were identified by reducing GHGEs by 25% from baseline while remaining acceptable for the population with no increase in cost (25). In another study in Dutch adults, the goal for the environmental impact reduction was derived from a first optimization that aimed to design a vegan diet complying with nutritional and food-habit constraints but no environmental constraints, and the resulting environmental impact level of this optimized vegan diet was taken as a goal to be reached in the next set of diets modeled (99). Regardless of the diet optimization model applied and local-country specificities (i.e., food habits and nutritional recommendations), a more sustainable diet required an increase in fruit and vegetables and legumes and a decrease in meat products. Note that a sustainable diet is not necessarily exclusively plant-based (25). For instance, in an individual-based optimization in the United Kingdom, meat intake had to increase for a small number of individuals to reduce GHGEs by 30% while attaining nutritional adequacy (72).

The environmental target imposed in the studies described above may not be the best tradeoff between all diet sustainability dimensions. The best threshold of environmental impact reduction compatible with other diet sustainability dimensions has been identified in models imposing stepwise reductions (until infeasibility) of diet environmental impact while staying as close as possible to the average observed diet and meeting nutrient recommendations (26, 97, 101–103). This approach is able to pinpoint the level of environmental impact reduction for which the optimized diet deviates too far from the observed diet. In France, GHGEs could be reduced by 30% at no extra cost while still fulfilling food-habit and nutritional constraints and without a major departure from the average observed diet (26). A similar threshold of environmental impact reduction (30%) was identified among Dutch adults by imposing a stepwise reduction of a global environmental metric taking into account GHGEs, fossil-energy use, and land occupation (101). However, diet cost was not considered (101). In the United Kingdom, GHGEs could be reduced progressively by ≤40% without any major changes in the average observed diet among both men and women. For example, at this threshold, the optimization mainly relied on "within food-group" substitutions (e.g., replacing red meat with the less impacting pork and chicken meats or by replacing cheese with milk) (102). In this study, the expenditure share and price elasticity of each food group were considered in the objective function as a proxy for

acceptable changes. The health impact of adopting the optimized UK diets with a progressive GHGE reduction was explored by using an epidemiologic model [IOMLIFET (104)] by assessing the changes in theoretical years of life loss between the observed and optimized diets (103). The more GHGEs were reduced, the more it would be beneficial for health (decrease in coronary heart disease, stroke, cancer, and type 2 diabetes). According to these simulations, it was estimated that dietary changes necessary at the threshold of a 40% GHGE reduction would save almost 7 million years of life over 30 y and increase life expectancy at birth by ∼8 mo (103).

Hence, with the current food production system (i.e., assuming no changes in the environmental impact and price of foods), nutritional, cultural, economic, and environmental dimensions seem compatible until a 30–40% reduction in the environmental impact of diets.

Discussion

Diet optimization has proven to be a unique and powerful tool for studying sustainable diets. This narrative review based on 67 publications shows how mathematical diet optimization has been used to examine the links between different dimensions of diet sustainability and to design tomorrow's nutritionally adequate, culturally acceptable, economically affordable, and environmentally friendly diets (Supplemental Tables 2 and 3). This review highlights the strengths of diet optimization as an approach to investigate the impact of varying 1 factor (e.g., diet cost, environmental impact) on outcomes of interest (e.g., food combinations, nutritional adequacy) and to qualify and quantify the dietary changes needed to achieve the best tradeoff between diet sustainability dimensions. Mathematical diet optimization has been applied in the field of public health nutrition in the past few decades, and the number of publications has increased since 2008 (Figure 2). Studies in the last few years have focused more specifically on the environmental dimension, because the nutritional and economic aspects of diet have been explored earlier (Figure 2, Supplemental Tables 1–3). This review shows how diet optimization can be applied for different subpopulations, on the basis of age and sex criteria, or on specific consumption patterns, or even at the individual level to account for individual food habits. Nevertheless, the difficulty when designing a sustainable diet revolves around the relevance of the model parameters (variables, objective function, constraints) and the quality of the input data.

The health dimension was almost always considered through nutritional constraints (Supplemental Table 2). However, careful analysis of published studies shows that using too few nutritional constraints can lead to deceptive conclusions or meaningless results. For example, certain studies, without clear justification, elected to omit some key nutrients (in particular, minerals and vitamins) essential to maintain good health (93, 102, 105), which may unintentionally deteriorate the content of those nutrients not taken into account in the models. Indeed, the failure to account
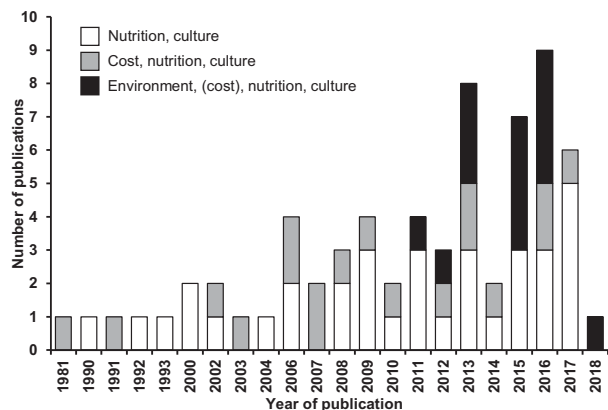
FIGURE 2 Number of selected publications using diet modeling in the field of nutrition, public health, and sustainable diets, stratified by sustainability dimensions taken into account. The figure includes, in total, the 67 studies reviewed in this article. Studies that present tools or methodologic concepts are not included. The cost was not always taken into account in studies considering the environmental impact.

for certain nutrients impairs nutritional adequacy, as shown in studies testing various sets of nutritional constraints (26, 59). Because fulfilling some RVs could be difficult and lead to infeasibility or unexpected results, some studies chose, with appropriate justification, to relax the constraints for some nutrients. For instance, the vitamin D level was imposed to be not lower than its observed intakes (36) or even removed (106) because vitamin D can be provided by supplements. In the several versions of USDA food plans (28, 86), no solution could be obtained with the dietary standards for vitamin E, potassium, and sodium. Therefore, for each age and sex group, these constraints were relaxed. However, when reaching an RV proves difficult, the issue may be the relevance of the recommended levels set for those difficult-to-fulfill constraints (65–67). When the RV for a beneficial nutrient is abnormally high, some foods containing traces of that nutrient may be introduced or increased by the model even though they are not the naturally abundant sources of this nutrient, leading to unusual food combinations. When fulfilling the set of RVs is too difficult, a goal-programming approach can be used to find the best achievable (or "near-optimal") diet, accepting that it is not fully nutritionally adequate (30). Indeed, when the food supply lacks nutrient-rich foods, it is preferable to maximize nutritional quality rather than trying to obtain diets that respect a set of hard nutritional constraints at the price of impracticability or even infeasibility. This is the method applied in the Optifood software program as described in Supplemental Methods 2 (35).

Further advances have been made to more accurately estimate the health dimension. Some studies have improved the assessment of nutritional adequacy by accounting for nutrient bioavailability (36, 39, 82) or exposure to food contaminants (106, 107). Accounting for nutrient bioavailability (i.e., efficiency of nutrient absorption and utilization

or retention by the body) is relevant because of its impact on the quality of nutrient intakes. Some nutrients (e.g., iron, zinc) have better bioavailability when derived from animal-based foods (108). Therefore, a shift toward more plant-based diets, as advocated to meet sustainability goals, may prove nutritionally inadequate due to the reduced bioavailability of some nutrients when provided by plant- instead of animal-based foods. For instance, among French adults, accounting for iron, zinc, protein, and provitamin A nutrient bioavailability induced changes in the foods selected by the optimization process, in particular within the meat category (36).

The cultural dimension needs to be considered to avoid unrealistic results. In all of the studies reviewed, the assumption for diet optimization models was that the closer the model is to the observed diet, the more acceptable the optimized diet would be. Staying closer to food habits has been achieved in more or less refined ways, by imposing food-habit constraints and/or by minimizing the deviation from an observed diet, working at either population, subpopulation, or individual levels.

Cultural acceptability has traditionally been taken into account by introducing food-habit constraints, imposing minimum and maximum quantities on foods or food groups, and/or setting complementarity relations between raw foods or ingredients (e.g., relation between bread and jam) (34). In the studies reviewed, food-habit constraints were mostly based on the distribution of food or food-group intakes in dietary surveys (24, 30, 45, 58), but could also be based on expertise and a priori choices (28, 95) (Supplemental Table 2). When one single metric is optimized (e.g., diet cost or GHGEs) (22, 78, 79, 93, 95, 109), the model very often leads to puzzling results. For instance, in Mozambique, nutritionally adequate diets at minimum cost were designed without food-habit constraints, leading to nondiversified low-cost diets mostly based on high amounts of very few nutrient-rich foods (110). Even food-habit constraints are not sufficient to ensure cultural acceptability of the modeled diets when cost or environmental impact is directly minimized. In a New Zealand study, arbitrary constraints were imposed on several foods to improve acceptability, but the lowest-GHGE diets were not very diversified and seemed to be mainly driven by the food-habit constraints (95). It is therefore key to avoid arbitrary constraints on food habits when modeling diets, and optimizing just one single diet characteristic is not recommended.

Deviating as little as possible from observed diets is assumed to be the best way to model acceptable diets, even though no one knows whether the minimum deviation achieved would be realistic and effective in terms of behavior change. Because there is no formal definition of minimal deviation from an existing diet, the objective function can be chosen in such a way as to favor specific types of behavior. Minimizing quadratic deviation from the observed intake would foster minimal variations on all foods and penalize large variations (28, 86), whereas expressing the deviation in percentage of the observed diet (39, 58, 73)

would induce larger variations on fewer foods. Because no form is better than the others, the choice must be made on the basis of a hypothesis of what the population of interest would find most acceptable. In an innovative individual-based optimization, cultural acceptability was considered with the use of a stepwise approach, making it increasing difficult to depart from the observed diet (72). The authors assumed that an individual would prefer to increase the amount of any food currently eaten before adding a new food or removing a food from the diet (72). Finally, to foster the communication of the results, the model and results should be adapted to the objectives. For instance, for public health purposes, it may be more appropriate to conduct diet optimization with a limited number of variables (i.e., food groups as decision variables) or to communicate the results at the food-group level only in order to develop more practical FBRs. Conversely, conducting diet optimization with individual foods as decision variables, or building FBRs on the basis of specific food items (and not food groups), allows more flexibility in the model but could lead to overspecific messages based on nutrient-rich foods identified as "key foods" but that may not widely consumed and not realistically promotable.

In all of the published studies, cultural acceptability remained difficult to evaluate because there are still no objective criteria to determine what is acceptable and what amount is considered a "small" or "large" dietary change. Another unresolved issue is whether it is acceptable to promote variation of many foods in small quantities, or large variations for a few foods. Therefore, to respect the cultural dimension of a sustainable diet, properly characterizing the population, subpopulation, or individual food habits is key, and all model parameters need to be carefully justified and adapted to the study objectives when designing the model and when interpreting the results.

Designing an affordable diet has long been a concern in diet optimization studies, whereas the environmental impact has been integrated in diet optimization models for <10 y. Both the economic and environmental dimensions have been taken into account by imposing a minimal or maximal constraint, by running a posteriori evaluation, or by being directly minimized. Only one study accounted for the economic dimension by adding the expenditure share and price elasticity of each food as weighting factors on each decision variable to favor certain foods over others, because it considered the price as a major driver of food choices (102). The difficulty when imposing a constraint on the metric studied (e.g., diet cost or GHGEs) was to objectively define the target value, which was usually set as not lower than in the observed diet (25) or based on expert opinion (28, 45, 72, 96, 99, 100). Nevertheless, the best way to find the best tradeoffs between decreasing the environmental impact of diet, decreasing diet cost, reaching nutritional adequacy, and staying close to current food habits is to apply diet optimization with a stepwise approach (26, 97, 101–103).

Among the 16 studies that aimed to identify a sustainable diet, only 9 included the economic dimension (25, 26, 93–96, 100, 102, 103) (Supplemental Table 3), but further research is needed to design a "fully" sustainable diet. With regard to the environmental dimension, its impact has mostly been assessed using GHGEs, yet there are many other important impacts, such as fossil energy, land occupation, or water use. The integration of co-production relations would also be beneficial to ensure coherence with the current food production system (36). For instance, it is questionable policy to encourage the consumption of low-fat milk while promoting a reduction in the consumption of cream, which is a by-product of the current dairy production system (92).

Whatever the dimensions of sustainability considered in a diet optimization model, input data must be carefully selected to accurately represent the population considered and the foods consumed and/or available in a given food system. Quantified food intakes are a prerequisite in any attempt to ensure cultural acceptability, whether by identifying the list of foods usually consumed in the population, taking into account food consumption distribution in the constraints, or deriving the average observed diet if the aim is to stay as close as possible to current food habits. Complete and accurate nutrient composition data, environmental food data, or cost data are crucial in all models to avoid boosting or deleting certain foods in the optimized diets due to possible over- or underestimated values. The main challenge for modeling sustainable diets now is probably to combine several databases containing metrics of each dimension of diet sustainability. A methodology was recently published that describes how to combine different data sources on food-consumption habits, nutrient composition, food prices, and environmental impact of foods (111).

Finally, the applicability of the results of a diet optimization study, which remain very theoretical, can also be improved, either upstream by adapting the parameters of the model (variables, objective function, constraints) or downstream by refining the expression of the results or adjusting them after testing their practicability in real life. For instance, food contents of the optimized diet are generally expressed in real numbers, in grams per day or per week, which are probably not meaningful for individuals when food changes amount to only a few grams. More pragmatic dietary changes could be obtained by conducting optimization with integer numbers (number of portion sizes), called "integer linear programming" (29), but the process is computationally intensive. In the Optifood software program, the decision-variable values, which are the number of portions for each food (expressed in real numbers), are expressed a posteriori in integer numbers of portions per week or per day, by rounding the optimized values (35). To improve practicability, further research could be done to conduct diet optimization by moments of consumption, to avoid, for instance, removing all foods consumed during breakfast without replacing them with other foods habitually consumed at this time of the day. Certain studies have imposed "association" constraints between foods, such as between bread and jam, but they remain limited and arbitrarily chosen (56, 79, 93). To take a step further, the outputs of the optimization should be

tested in real life among the population studied, with the objective of assessing the realism and feasibility of the dietary changes, to adjust them, or to review the model parameters. A few studies have checked a posteriori the acceptability, feasibility, or effectiveness of FBRs designed with the use of diet optimization (68, 112–114) via qualitative techniques such as the "Trial of Improved Practices," which consists of a series of visits with an interviewer to analyze participants' practices, discuss the challenges for applying new practices, and to readjust and test the guidelines in a trial experience (115, 116). This technique was applied in Myanmar (112) and Indonesia (68) to test the acceptability and feasibility of FBRs developed using Optifood. In Kenya, results of diet optimization were combined with a qualitative study (a focus ethnographic study) to identify the perception of cost, convenience, accessibility, and appropriateness of the foods included in the FBRs (113). These qualitative studies underline the added value of going beyond the theoretical solutions to identify barriers (e.g., financial, cultural, and accessibility constraints) and opportunities, such as providing advice on how to cook the promoted foods, informing on health benefits of consuming specific nutrient-dense foods, or developing the accessibility of promoted foods through agronomic interventions.

Conclusions

This review provides evidence that diet optimization is a powerful tool for identifying the best balance to combine all dimensions of diet sustainability and to promote the food choices needed to make the transition toward more sustainable diets. Mathematical diet optimization is increasingly used in the literature, but its great flexibility and power can actually become weaknesses if the models are not well designed and if there are too many arbitrary decisions on the model parameters (variables, constraints, objective function). Solid expertise is necessary at all stages, from model construction to correct interpretation and communication of results. Care should be taken to clearly and transparently describe the models, and provide justification of all choices. It would be beneficial, for designing tomorrow's sustainable diets, to integrate more relevant metrics that assess each aspect of a sustainable diet and to improve the real-world practicability of theoretical results.

Acknowledgments

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