frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 30 June 2025
DOI 10.3389/fsufs.2025.1629739

Check for updates

OPEN ACCESS

EDITED BY
Abhishek Das,
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India

REVIEWED BY
Xiaoyu Liu,
Hong Kong Polytechnic University, Hong Kong SAR, China
Patrick Elliott,
American College Dublin, Ireland

*CORRESPONDENCE
Raivo Vilu
raivo@tftak.eu

RECEIVED 16 May 2025
ACCEPTED 13 June 2025
PUBLISHED 30 June 2025

CITATION
Bashiri B, Kaleda A and Vilu R (2025) Sustainable diets, from design to implementation by multi-objective optimization-based methods and policy instruments.
Front. Sustain. Food Syst. 9:1629739.
doi: 10.3389/fsufs.2025.1629739

Sustainable diets, from design to implementation by multi-objective optimization-based methods and policy instruments

Bashiri Bashiri[1,2], Aleksei Kaleda[2] and Raivo Vilu[1,2]*

[1]Department of Chemistry and Biotechnology, Tallinn University of Technology, Tallinn, Estonia, [2]TFTAK AS, Tallinn, Estonia

The growing concerns over climate change, food security, and public health necessitate a transition toward sustainable diets. However, designing diets that are simultaneously healthy, environmentally friendly, culturally acceptable, and affordable presents significant challenges. This review explores the potential of multi-objective optimization (MOO) as a tool for sustainable diet design and a central element of implementation of optimized diets. MOO allows researchers to balance conflicting objectives, such as minimizing environmental impact while maintaining cultural acceptability and economic feasibility in design and implementation of healthy diets. The review highlights the limitations of traditional single-objective optimization and emphasizes the need for population-specific dietary recommendations using MOO. Furthermore, the paper identifies barriers to sustainable diet adoption and outlines policy solutions to facilitate dietary transitions. Finally, it underscores the need for the development and implementation of flexible national dietary guidelines to incorporate optimization methods for enhanced sustainability. By integrating mathematical modeling, behavioral insights, and policy interventions, this review outlines a holistic approach to development sustainable food systems capable for meeting efficiently global challenges.

KEYWORDS

diet, sustainability, multi-objective optimization, policy, regulations

1 The need for sustainable diet design

The global food systems contribute approximately 30% of anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021), 32% of global terrestrial acidification, and 78% of eutrophication (Poore and Nemecek, 2018), consumes about 70% of freshwater resources, and occupies over one-third of all potentially cultivable land (Foley et al., 2011). Simultaneously, diet-related health issues, including obesity, malnutrition, and non-communicable diseases, are becoming globally more prevalent (WHO European Office for the Prevention and Control of Noncommunicable Diseases, 2021; Al-Jawaldeh and Abbass, 2022; Ma et al., 2025; Pineda et al., 2024). Dietary patterns, particularly in high- and middle-income countries, contribute significantly to both chronic diseases and environmental degradation (Hundscheid et al., 2022; Clark et al., 2020). These challenges highlight the urgent need to transition toward more sustainable dietary patterns promoting human health and environmental well-being.

Research indicates that shifting to diets rich in plant-based foods and lower in animal-based products can significantly reduce the environmental footprint of food production while improving public health (Espinosa-Marrón et al., 2022). Such dietary changes lower greenhouse gas emissions and mitigate the hidden costs associated with diet-related health conditions (Lucas et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) has identified dietary change as a demand-side option with a large potential to mitigate emissions. Estimated annual GHG emissions reductions by 2050 associated with dietary shifts to low-meat, vegetarian, or vegan diets are in the range of 0.7–7.3, 4.3–6.4, and 7.8–8 $GtCO_2e$, respectively (Creutzig et al., 2021; Shukla et al., 2019), and thus can help achieve the targets of the Paris Agreement (Clark et al., 2020). Additionally, research carried out suggests that dietary modifications offer greater environmental benefits than improvements in agricultural production efficiency, emphasizing the critical role of consumption choices in reducing environmental impact (Poore and Nemecek, 2018; Garvey et al., 2021). Therefore, dietary shifts can play a crucial role in achieving the Sustainable Development Goals (SDGs), particularly those related to Zero Hunger, Good Health and Well-Being, and Responsible Consumption and Production (Chen et al., 2022).

Diet should be healthy and sustainable. The World Health Organization (WHO) together with the Food and Agricultural Organization of the United Nations (FAO) define sustainable healthy diets as '*dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable*' (WHO, 2025). Food production depends on the continued functioning of biophysical systems that regulate and maintain a stable Earth system. Within this context, diets are closely linked to both human health and environmental sustainability, and a shared framework enables the identification of diets that are simultaneously healthy and environmentally friendly (Willett et al., 2019). Although dietary shifts toward sustainable diets can reduce health risks and environmental impacts, reducing animal-based food consumption can lead to deficiencies in essential micronutrients (e.g., vitamin B12, selenium, calcium) if diets are not well planned (Beal et al., 2023).

Even the most scientifically sound and sustainable dietary recommendations may be met with resistance if they require significant departures from traditional eating patterns and habits (Van Dooren, 2024; Zhu et al., 2024). The cultural acceptability or 'consumer inconvenience' (as Nordman and coauthors refer to it (Nordman et al., 2024)) of the unusual, modified diet plays an important role in ensuring success of the diet optimization. To account for cultural acceptability, diet optimization models often limit the distance between the modeled diet and the observed diet (Heerschop et al., 2024; van Dooren, 2018). Cultural acceptability must be balanced with other complex responses, including sustainability, health, and affordability, ensuring that none of these criteria are neglected (Nordman et al., 2024; van Dooren, 2018). Designing diets that are in agreement with these complex and often conflicting criteria is not a simple task, as it requires careful consideration of balancing multiple factors simultaneously.

Despite growing recognition of the need for the development and implementation of sustainable diets, several important gaps persist. In the diet design phase, while many studies emphasize the environmental and health benefits of dietary shifts, there remains a lack of comprehensive frameworks that integrate multiple criteria into diet design. Existing research tends to focus predominantly on either health or environmental outcomes, without adequately addressing how to balance these dimensions in a practical and socially acceptable manner simultaneously (Fu et al., 2024). The authors of this review advocate for utilizing multi-objective optimization (MOO) to enable a holistic and carefully balanced approach to diet design (Bashiri et al., 2025; Bashiri et al., 2024) in the complex situation described.

In the adoption phase, cultural preferences and behavioral resistance are increasingly acknowledged as barriers to dietary change (Muñoz-Martínez et al., 2024). While a range of policy tools has been proposed to support the shift toward more sustainable diets (Ammann et al., 2023), there appears to be relatively limited exploration of approaches that link specific barriers with corresponding policy interventions. This gap is suggested by analyses showing that the implementation of food environment policies remains generally weak (Pineda et al., 2024).

In this article, we discuss diets from their design to their adoption. Section 2 provides an overview of the MOO method and its application in the context of sustainable diet design. Section 3 focuses on the social dimensions of dietary transition, examining the processes of social adoption and the barriers that hinder the shift toward new dietary patterns. It also discusses policy instruments that can help overcome these barriers. The authors argue that this work contributes to promoting a just and sustainable dietary transition for society.

2 Design of sustainable diets

2.1 Multi-objective optimization for the design of a sustainable diet

Mathematical optimization tools have been used in many studies to develop sustainable diets. Linear and non-linear single-objective optimization techniques have been used widely in diet-related studies to minimize the cost, minimize environmental footprints, or minimize the deviation from the reference diet. For more information, the reader is referred to a literature review about mathematical optimization for diet design (van Dooren, 2018; Gazan et al., 2018). Single-objective approaches often fail to capture the complex trade-offs required in sustainable diet planning. However, given the multidimensional nature of sustainability, MOO appears to be a suitable approach in these situations. This method allows us to carry out comprehensive analysis, enabling researchers to account for trade-offs between different dietary dimensions and develop balanced, sustainable dietary solutions. Table 1 summarizes an example of diet MOO problem solving, showing the mathematical formulation of the objective function and nutritional constraints.

The relationship between objectives in the MOO method can be represented by a hyperbolic Pareto front, which is calculated by varying weight coefficients. In a two-objective optimization, the trade-off between two objectives is visualized as a two-dimensional curve (Figure 1A), while for three objectives, presentation of the trade-off forms a surface (Figure 1B). These visualizations assist decision-makers in understanding the trade-offs and making informed choices. However, when MOO involves more than three objectives, visualizing the Pareto front becomes impractical, making decision-making excessively more complex (Bashiri et al., 2025). In this situation, multi-criteria decision-making (MCDM) methods could be used to reduce the number of

TABLE 1 Structure of a sample MOO model used for sustainable diet design.

$\min(w_1 f_1 + w_2 f_2 + w_3 f_3 + \ldots)$	Final objective function of the MOO model to be minimized. The function includes three terms as defined separately below, but more can be added. The relative importance of terms is adjusted using weight coefficients w_1, w_2, w_3 yielding the Pareto fronts as shown in Figure 1.
$f_1 = \sum_1^n \left(\frac{x_i^* - x_i}{x_i}\right)^2$	This term minimizes deviation from the current consumption pattern, ensuring that the new diet is culturally acceptable and easier to adopt. x_i^* is optimized consumption of food item *i*. x_i is current consumption of food item *i*, and n are the numbers of food items included in the model.
$f_2 = \sum_1^n x_i^* \times CF_i$	Minimizes the sum of carbon emissions associated with new diet. CF_i is carbon footprint per unit weight of food item
$f_3 = \sum_1^n x_i^* \times price_i$	Minimizes the sum of the prices of all selected food items. It ensures that the new diet remains affordable and economically accessible. $price_i$ is market price per unit weight of food item *i*
$N_{\min} \le \sum_1^n x_i^* \times a_i \le N_{\max}$	The objective function is subjected to several nutritional constraints. The constraints ensure that the optimal diet fulfills the nutritional recommendations. a_i is the amount of corresponding nutrition per unit weight of food product i. $N_{\min}$ and $N_{\max}$ are the lower bound and upper bound of the nutrition as per dietary recommendations.

This example model minimizes simultaneously three objective functions, which are incorporated as multiple terms into one equation: (1) deviation from the current dietary habits to maintain cultural acceptability, (2) total carbon footprint to reduce environmental impact, and (3) total diet cost to ensure affordability. These objectives are optimized under a set of nutritional constraints that ensure dietary adequacy.

objectives, making the decision-making process easier. All the solutions that are located on the Pareto front curve are optimal solutions. Changing the priority of one objective over the other objectives would give different optimal solutions. The selection of an optimal solution from the Pareto front can be based on the decision-makers' preferences or achieved using MCDM methods. In diet MOO problems, the challenge of balancing criteria (such as whether nutrition, health, or environmental impacts should be given greater weight) is particularly relevant. In this context, using the Pareto front allows for the analysis of different scenarios where various weights are assigned to each criterion, facilitating case-specific and transparent decision-making based on the presented trade-offs.

2.2 A scoping review on the multi-objective optimization application for the design of sustainable diets

Some studies have employed MOO to develop sustainable and nutritionally balanced diets, often aiming to minimize environmental impact, cost, and nutritional inadequacy while maintaining cultural acceptability. A pioneering study by Donati et al. (2016). in Italy demonstrated that a sustainable and nutritious diet can be healthier, more affordable, and environmentally friendlier than current consumption patterns. Similarly, Abejón et al. (2020). in Spain, showed that it is possible to reduce environmental impacts while ensuring affordability and nutritional adequacy. Muñoz-Martínez et al. (2023). optimized a sustainable and nutritionally balanced diet for Spain by minimizing costs and environmental impacts (specifically greenhouse gas emissions, land use, and blue-water consumption) while ensuring minimal deviation from existing dietary habits. Their findings suggested that fortified plant-based milk could offer additional environmental benefits. Such targeted strategies illustrate that novel food products could play a crucial role in enhancing the sustainability and acceptability of the designed diet. These studies emphasize the feasibility of achieving sustainability without increasing costs, underscoring the importance of promoting sustainable food choices.

Several researchers have explored the balance between environmental sustainability and dietary acceptability, noting the challenges posed by significant deviations from typical dietary habits. Mirzaie-Nodoushan et al. (2020). designed a model to reduce water footprint through a culturally acceptable dietary change, showing that reasonable reduction of red meat and vegetable oil intake could lower water usage by up to 16%. Yin et al, (2021). optimized diets to minimize carbon, water, and ecological footprints while ensuring cultural acceptability, recommending a 10% reduction in carbon footprint as the optimal balance between environmental, nutritional, and cultural acceptability goals. Fu et al. (2024). further demonstrated that integrating nutrition, environmental goals, and cultural preferences could reduce greenhouse gas emissions by over 60% compared to nutrition-focused diets alone. Nordman et al. (2024). found that reducing greenhouse gas emissions by more than 24–36% led to substantial deviations from conventional diets, impacting acceptability. Bashiri et al. (2024). observed similar trends in Estonia and proposed that incremental dietary changes could achieve environmental goals without compromising adherence to traditional eating patterns (Nordman et al., 2024).

Innovative approaches to optimizing diets through technology have also been investigated. Zhang et al. (2022). introduced a MOO-based food recommendation system in the UK, which integrated user preferences alongside nutritional and environmental factors, resulting in a more balanced recommendations compared to traditional preference-based methods.

Besides the conflicts between sustainability, affordability, and cultural acceptability, conflicts can also be inherent in the case of different environmental indicators. Comparison of footprints of different food products reveals that some are better in terms of one footprint, but worse in terms of another. For example, a food product with a low carbon footprint may require excessive land or water use. Focusing solely on one footprint (e.g., GHG) reduction can lead to unintended environmental consequences, such as increased water use or biodiversity loss (Ran et al., 2024). Poore and Nemecek (2018) pointed out the conflicts between the environmental footprints of food products. While the reduction of GHG emissions is important, it does not fully capture the environmental impact of food production. However, incorporating multiple indicators into dietary optimization increases complexity. Additionally, uncertainties in environmental footprint data (caused by variations in data sources, geographical differences, and farming practices) further complicate decision-making. Without a systematic approach to address these conflicts and uncertainties, dietary recommendations may be misleading or impractical. MOO has a capacity to address such conflicts.

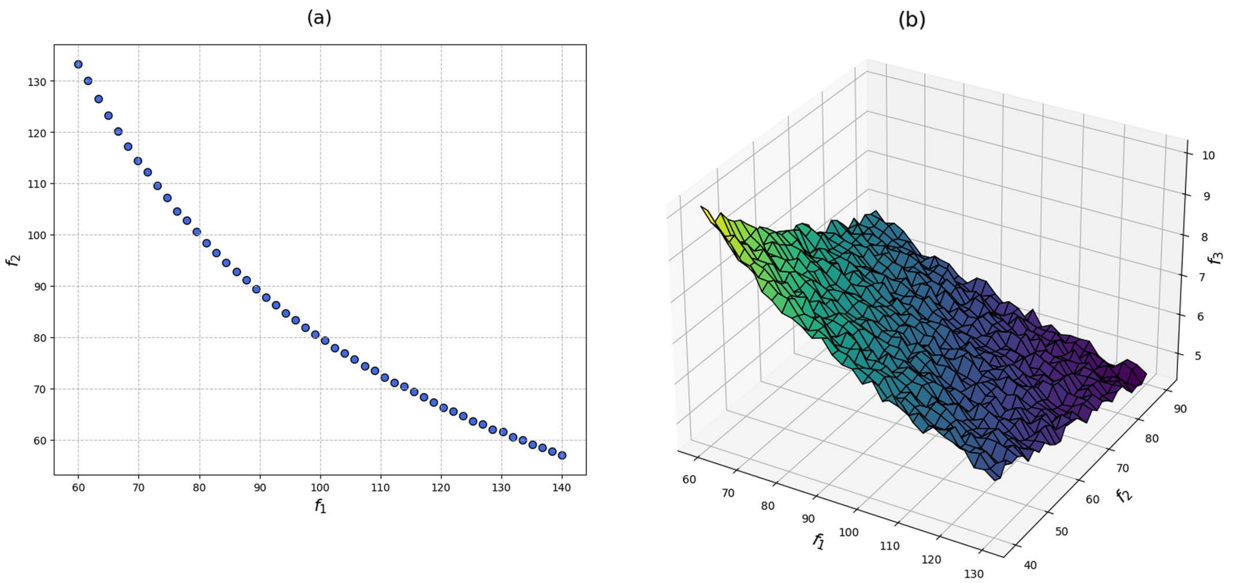

FIGURE 1
Illustration of Pareto front solutions in multi-objective optimization (MOO). **(A)** Two-objective Pareto front showing the trade-off between two competing objective functions f_1 and f_2. Each point on the curve represents a solution where improving one objective would worsen the other. **(B)** Three-objective Pareto front showing the trade-off between three objective functions f_1, f_2, and f_3 forming a surface.

To tackle the conflicts between environmental indicators, the authors of the present review developed a method that integrates MCDM with MOO to optimize diet sustainability (Bashiri et al., 2025). We applied the SURE MCDM (Hodgett and Siraj, 2019) method before performing MOO to aggregate multiple environmental footprints into a single score, simplifying the optimization process while still accounting for trade-offs. The application of this method on the Estonian diet demonstrated that using multiple environmental indicators instead of just one significantly altered the recommended dietary patterns. For instance, a previous study optimizing the Estonian diet based only on land footprint suggested increasing plant-based foods (Bashiri et al., 2024), whereas incorporating multiple footprints suggests decreasing the consumption of the same food groups due to the inherent conflicts between different environmental footprints (Bashiri et al., 2025). This approach is particularly important from a life cycle assessment (LCA) perspective. There are several impact categories that contribute to damage to human health, ecosystems, and resource availability. Therefore, efforts to optimize diets should aim to capture the full spectrum of system-level impacts, rather than focusing on a single indicator. Only by doing so can we begin to assess whether a dietary system is truly sustainable.

Together, these studies provide examples of the complex interplay between environmental sustainability, nutritional adequacy, cost-effectiveness, and cultural acceptability in diet optimization, and illustrate how MOO can support the exploration of trade-offs among competing objectives in a structured and transparent way. For instance, in a global diet optimization study using a single-objective approach, the results often suggest complete elimination of red meat from the optimal diets (Chaudhary and Krishna, 2019). While such diets remain nutritionally adequate and within planetary boundaries, their acceptability is uncertain (Chaudhary and Krishna, 2019). The examples analyzed also indicate that the results of each study are specific to the study region, reflecting the parameters and dimensions incorporated into the model. Cultural acceptability is assessed relative to a reference point, which varies from one region to another. Moreover, even within a single region, multiple dietary patterns exist, requiring individuals to be grouped based on their dietary habits. As a result, both cultural acceptability and sustainability outcomes can differ significantly across groups.

Also, the baseline data used to represent current diets plays a crucial role in shaping optimization outcomes. High-resolution dietary intake data (such as those obtained through food diaries or 24-h recalls) can provide a more accurate representation of actual consumption patterns, as opposed to Food Balance Sheet data, which has been used in previous studies using MOO (Bashiri et al., 2025; Bashiri et al., 2024; Mirzaie-Nodoushan et al., 2020). This is because Food Balance Sheet data overestimates population dietary intakes as it reflects country-level food availability and does not consider household-level food waste or measure actual individual-level consumption. This helps to explain why, in previous work, MOO-optimized dietary patterns can conflict with established sustainable diet principles (e.g., recommending reductions in legume and nut consumption) (Bashiri et al., 2025). Therefore, using more accurate dietary data would enhance the reliability and interpretability of the resulting optimized dietary patterns, thereby improving the potential of the model to inform truly balanced and sustainable dietary recommendations (Table 2).

2.3 Population-specific diet optimization

A key limitation in most dietary studies is the assumption that populations are homogeneous in their adherence to dietary patterns, whereas, in reality, individuals exhibit diverse eating behaviors. Consequently, while proposing a single optimized diet may be theoretically sound from a mathematical modeling perspective, its real-world implementation is likely to face significant challenges. A diet optimized for one demographic group may not be suitable for

TABLE 2 List of publications reviewed in this section.

Author (year)	Number of objectives	MOO solver method	Cultural acceptability included	Economic affordability included	Environmental indicators	Number of nutritional constraints	Scenario analysis
Mirzaie-Nodoushan et al. (2020)	2	Weighted sum method	Yes	No	Water footprint	15	Scenarios for increasing self-sufficiency in food production are investigated.
Bashiri et al. (2024)	2	Weighted sum method	Yes	No	Land footprint	19	Scenarios include reference diet, nationally recommended diet (NRD), and three optimized diets minimizing land footprint and deviation from the reference diet, while ensuring nutritional adequacy.
Nordman et al. (2024)	2	ε-constrained	Yes	No	Carbon footprint	32 (includes 6 limits on the consumption of food items)	Scenarios based on four dietary clusters with stepwise carbon footprint reduction targets
Fu et al. (2024)	2	Pareto method, distance-to-target	Yes	No	Carbon footprint	4	Three scenarios were considered: meeting nutritional needs; minimizing carbon footprint while ensuring nutrition; and balancing nutrition, low emissions, and cultural acceptability.
Abejón et al. (2020)	3	Distance-to-target	Yes	Yes	Carbon footprint	9	Six predefined diets were optimized
Donati et al. (2016)	4	Weighted sum method	No	Yes	Carbon footprint, Water consumption, ecological footprint	9	The lowest-cost diets, lowest-footprint diet, and diets combining both lowest cost and footprint were identified.
Yin et al. (2021)	4	ε-constrained	Yes	No	Carbon footprint, Water consumption, ecological footprint	24	Twelve optimized scenarios targeting stepwise and maximum reductions in water footprint, carbon footprint, and ecological footprint.
Zhang et al. (2022)	4	Pareto method	Yes	No	None	15	Four objectives have been investigated: user preferences, nutritional values, dietary diversity, and user diet patterns.
Muñoz-Martínez et al. (2023)	4	Distance-to-target	Yes	Yes	Carbon footprint, Water consumption, Land use	17	Two optimization scenarios were defined based on margin factors that control allowable deviations from the baseline diet.
Bashiri et al. (2025)	6	Weighted sum method, Pareto method, ε-constrained	Yes	No	Land use, GHG emissions, acidifying emissions, freshwater withdrawals, and eutrophying emissions	19	Scenarios include a bi-objective optimization using an aggregated score and dietary deviation, and a classical multi-objective optimization minimizing five separate environmental footprints alongside dietary deviation, all under nutritional constraints.

The table captures the technical characteristics of the multi-objective optimization (MOO) models in each study. All publications included are peer-reviewed articles indexed in the Web of Science and Scopus.

another due to differences in affordability, accessibility, and dietary norms (Brink et al., 2019; Irz et al., 2024). To develop effective and sustainable dietary strategies, it is essential to take account individual, cultural, and social differences in dietary acceptance and adherence.

Several studies have addressed these issues using traditional segmentation methods, e.g., based on age (Brink et al., 2019), gender (Brink et al., 2019; Irz et al., 2024), geographical location (Wang et al., 2024), education (Irz et al., 2024) and income level (Irz et al., 2024; Lauk et al., 2020; Reynolds et al., 2019). Although traditional population segmentation methods help to understand the difference in the eating patterns of people, they may not fully capture variations in behaviors and diet as observed by Van Dooren et al (van Dooren et al., 2018). because individuals within the same socio-demographic group can have vastly different food choices and motivations. To address the limitations of traditional segmentation methods, researchers have increasingly turned to data-driven methods such as clustering that can better capture the complexity of individual dietary behaviors.

Clustering is an unsupervised machine learning technique used to group unlabeled data based on underlying similarities, without prior knowledge of object relationships. It aims to uncover hidden patterns or natural groupings within datasets, ensuring that items within the same cluster are more like each other than those in different clusters (Oyewole and Thopil, 2023).

Clustering techniques, unlike traditional segmentation methods, segment individuals based on their eating habits. Clustering techniques reveal the hidden patterns in food consumption that cannot be readily recognized by socio-economic grouping. By identifying existing dietary intake patterns within a population, this approach paves the path for a better understanding of how different groups can achieve both nutritional adequacy and environmental sustainability. Clustering techniques could be used before MOO. Some researchers propose that integrating exploratory data-driven analysis with optimization can improve the development of population-specific diets (Nordman et al., 2024; Eustachio Colombo et al., 2023). Therefore, this approach supports the idea of population-specific diet optimization. This methodology has been applied in Sweden (Eustachio Colombo et al., 2023) and Denmark (Nordman et al., 2024). In Sweden, the study applied hierarchical clustering analysis and was able to identify three primary dietary groups. While in Denmark, by using the k-means clustering technique, researchers were able to categorize individuals into four dietary groups. In both studies the recognized dietary clusters were optimized.

In line with the argument presented in the current article, integrating clustering techniques with MOO rather than solely depending on single-objective optimization may offer a useful approach for identifying diets that are potentially more culturally acceptable and contextually appropriate.

3 Factors influencing the transition to a sustainable diet

When a sustainable diet is designed, it must be accepted and followed by people. Although the use of MOO in the design phase is considered to lead to a more balanced optimized solution in terms of sustainability and cultural acceptability, changes and departures from the reference diets are normally expected and observed. It is also normal that changes are met by resistance - adopting new diets often face different barriers in implementation. Muñoz-Martínez et al. (2024). examined a range of such barriers and categorized them into internal and external barriers (Table 3). According to Muñoz-Martínez et al. (2024), internal barriers stem from personal factors such as food literacy, attitudes, habits, and perceived behavioral control, all of which influence an individual's motivation and ability to adopt a sustainable diet. In contrast, external barriers to adopting new (more) sustainable diets arise from social norms, economic constraints, and policy restrictions. To effectively promote sustainable diets, policymakers must implement targeted interventions (systems of policy tools) that address the barriers and create an enabling food environment.

Mozaffarian et al. (2018). have published an extensive review of the policy tools for the adoption of a new diet. The following sections is an analysis of key barriers based on the study by Muñoz-Martínez et al. (2024). along with proposed policy solutions by Mozaffarian et al. (2018) to mitigate them as summarized in Table 3.

3.1 Internal barriers

As listed in Table 3, lack of food literacy is one of the primary internal barriers preventing individuals from adopting (more sustainable) new diets (Ares et al., 2024). Many people have limited knowledge of nutrition, sustainability, and ethical food choices, leading to misconceptions such as the belief that plant-based diets are nutritionally inadequate. In a pan-EU consumer survey majority of the participants agreed to the statement "I would not get energy or strength from these (plant-based) products" (Perez-Cueto et al., 2022). Additionally, insufficient cooking and meal-planning skills make it difficult for individuals to incorporate sustainable foods into their diets (Wu et al., 2024). Addressing this issue requires the integration of plant-based cooking courses into school curricula and community programs, which can enhance food literacy and empower individuals to prepare sustainable meals (Labbé et al., 2023). Governments should also revise national dietary guidelines to emphasize plant-based proteins and environmental sustainability, ensuring these recommendations are reflected in public health initiatives. The MOO method could support the design of more impactful national dietary guidelines. Although more and more countries are incorporating sustainability into their dietary guidelines, the extent to which environmental sustainability is addressed varies. In many cases, discussions are limited to broad explanations of what constitutes a sustainable diet (James-Martin et al., 2022). Implementation of standardized sustainability labels, such as carbon footprint indicators and organic certifications, can improve transparency and enable consumers to make informed choices (Fresacher and Johnson, 2023). A meta-analysis showed that food labeling could reduce energy intake by 6.6% and total fat intake by 10.6%, while increasing vegetable consumption by 13.5% (Shangguan et al., 2019). Also, it has been shown that there is a relationship between food literacy and the financial security of households. Financially secure households have better food literacy and are willing to pay more for healthy and sustainable foods (Nam and Suk, 2024).

Perceived behavioral control is another significant internal barrier. In the context of diet, it shows how much control a person feels they have when choosing healthy and sustainable food, even with financial, time, or accessibility challenges. Many individuals feel constrained by financial limitations, lack of time, and inadequate planning skills when considering sustainable diets. Meal planning tools developed using MOO can serve as tool to advance planning skills, offering individuals

TABLE 3 Internal and external barriers to dietary change and corresponding policy tools to address them.

Barrier type	Barrier	Policy solution
Internal	Lack of food literacy	Culinary education, updated dietary guidelines, and food labeling
	Perceived behavioral control	Financial incentives, supermarket layout changes, public procurement
	Emotions and cognitive dissonance	Awareness campaigns, appealing food descriptions
	Attitudes, beliefs, and convenience-driven habits	Market restrictions, meat reduction policies
	Habits and taste preferences	Gradual introduction, novel product innovation
External	Social norms and household composition	Public procurement rules, community initiatives
	Information and media influence	Stronger food labeling, media literacy programs
	Organoleptic factors	Improved food presentation
	Governance and policy	Advertising regulations, support for sustainable agriculture
	Cost and physical access	Food subsidies, infrastructure investment

the opportunity to design sustainable meals quickly. Helland and Nordbotten in their study (Hagen Helland et al., 2021) showed that individual's decision to change habits is a barrier against diet change. However, even those motivated to make dietary changes often struggle to find affordable and convenient sustainable food options. It has been also shown that as diets are becoming more diverse, a healthy and sustainable diet is becoming more unaffordable (Fanzo et al., 2022). This is because nutrient-rich foods tend to be more expensive because they require more effort and resources to cultivate, store, and transport compared to shelf-stable, low-cost products (Fanzo et al., 2022). To address this challenge, financial incentives (market-based incentives; Ammann et al., 2023) should be introduced to reduce the cost of plant-based proteins, fruits, and vegetables, making them more accessible, particularly to low-income segments of populations. Role of financial incentives on increase of the consumption of plant-based products and fruits have been previously confirmed in the United States Department of Agriculture (USDA) healthy incentives pilot program (Olsho et al., 2016). Results of another study showed that price reductions can lead to increases in purchases of fruit and vegetables (Huangfu et al., 2024). In addition to financial incentives, supermarket layouts should be adjusted to increase the visibility of sustainable foods by placing them at eye level and near checkout counters, thereby encouraging healthier purchases. Vogel et al. showed that healthier supermarket layouts can improve the nutrition profile of store sales and likely improve household purchasing and dietary quality (Vogel et al., 2021). Another effective policy measure is the introduction of default plant-based meal options in public institutions such as schools, hospitals, and workplaces, which can facilitate the transition to a sustainable diet without restricting individual choice. Such policies are referred to as public procurement that has been a successful strategy for achieving health and environmental objectives in the food sector (Smith et al., 2016). For example, the Estonian Ministry of Public Health has decided to place greater emphasis on vegetables and fruits in the school canteens to encourage healthier food consumption among Estonian children (ERR, 2025). Plant-based default menu options have proven effective, offering a simple yet impactful strategy to reduce the consumption of animal products at catered events (Boronowsky et al., 2022).

Emotional attachments to certain foods, particularly meat, create psychological resistance to dietary change. Many individuals value sustainability but continue to engage in unsustainable eating habits. Psychologists refer to such a condition as cognitive dissonance (Rothgerber, 2020). Additionally, distrust in food labels and skepticism toward novel foods further complicates consumer decision-making (Modlinska et al., 2020). Studies indicate that organizational trustworthiness and corporate social responsibility play a significant role in shaping consumers' willingness to purchase cultured meat as a novel food product (Lin-Hi et al., 2022). Public awareness campaigns like "Meatless Monday" (Ammann et al., 2023) can help normalize plant-based diets and positively frame sustainable eating. Research also suggests that renaming plant-based dishes using appealing and familiar language, such as "Slow-Roasted Tomato & Basil Flatbread" instead of "Vegan Flatbread" enhances consumer acceptance and reduces negative biases.

Attitudes, beliefs, and values also play a crucial role in food choices. Furthermore, convenience-driven habits can reinforce unsustainable food choices. Bogard et al. define convenience as a characteristic that minimizes the resources required by consumers (including time, physical effort, mental effort, and skills) across various stages of food-related activities, such as planning, acquisition, preparation, storage, transport, consumption, and cleanup (Bogard et al., 2024). In the context of the food environment, convenience has been described as the "time cost of obtaining, preparing, and consuming a food item." The time required to acquire food is closely associated with features of the food environment that influence physical accessibility. To address these barriers, governments and communities should regulate misleading advertisements that promote unhealthy and unsustainable food products, particularly those targeting children (Graff et al., 2017; Khan et al., 2024). Additionally, policies limiting red meat consumption in public institutions such as schools, hospitals, and government offices can help normalize plant-based diets and reduce overall demand for unsustainable products.

Dietary habits established during childhood often persist in adulthood (Winpenny et al., 2018), making shifting toward more sustainable eating patterns difficult. Furthermore, some consumers find plant-based foods less appealing in terms of taste, texture, and variety. The results of a study indicate that following a healthy dietary pattern is linked to a greater enjoyment of food. In other words, people who maintain a nutritious diet tend to find more pleasure in eating (Dubois et al., 2022). Therefore, plant-based food alternatives should be made more appealing to encourage healthier eating habits and enhance the enjoyment of food. Public institutions can facilitate the transition by gradually introducing blended meat-plant protein (meat hybrids) products (Profeta et al., 2021), which make dietary shifts more acceptable. Investing in research to improve the taste, texture, and sensory appeal of plant-based alternatives is also necessary to enhance consumer acceptance.

3.2 External barriers

Beyond internal barriers, external factors also significantly influence dietary choices (Table 3). Social norms and household composition shape eating habits, with cultural expectations, family dynamics, and peer influence playing a critical role (Higgs et al., 2019; Stok et al., 2016). In many societies, high meat consumption is linked to masculinity and social status (Camilleri et al., 2024; Vrijsen et al., 2025), making plant-based diets less acceptable. To change these norms, governments can require public institutions such as schools and hospitals to source sustainable food products, thereby normalizing plant-based diets and driving systemic change. Community-based initiatives that encourage families to transition toward sustainable eating habits together can also help reshape cultural norms (Metcalfe et al., 2022).

Information and media influence are also key external barriers. Misinformation, conflicting dietary advice, and aggressive marketing by the food industry create confusion and reduce trust in sustainability claims (Nugraha et al., 2024). To combat these challenges, governments must enforce stronger food labeling regulations to ensure that sustainability labels are transparent, science-based, and standardized, preventing greenwashing and enhancing consumer trust (Nugraha et al., 2024). There is evidence that media-based campaigns have successfully influenced dietary behaviors by promoting plant proteins and meat alternatives alongside traditional meat products (Consavage Stanley et al., 2024). Additionally, media literacy programs can educate the public on how to critically assess food-related media messages, helping consumers recognize and resist misleading advertisements (Guyader et al., 2017).

Organoleptic factors, including taste, texture, and appearance, often deter consumers from choosing plant-based alternatives, as they are unfamiliar with their sensory characteristics compared to conventional foods (Alcorta et al., 2021). To improve acceptance, retailers and restaurants should enhance the visual appeal and presentation of plant-based foods, making them more attractive to consumers (Farrar et al., 2024; Ruby et al., 2024).

Governance and policy frameworks also play a fundamental role in shaping food environments. Weak regulations allow misleading marketing practices, promote unsustainable agricultural systems, and create economic barriers to sustainable eating (Even et al., 2024). To address this, governments should implement stricter policies to regulate advertising and marketing, restricting deceptive sustainability claims and curbing the promotion of foods that contribute to poor dietary habits (Taillie et al., 2019). Additionally, financial support for local and sustainable agriculture is essential. Providing incentives for farmers who adopt sustainable practices will ensure a stable and affordable supply of environmentally friendly food options (Desalegn et al., 2024).

Cost and physical access further complicate the transition to sustainable diets (Bogard et al., 2024), as sustainable foods remain expensive and inaccessible, particularly in low-income areas. To make sustainable diets more accessible, subsidies should be provided to reduce the price of plant-based proteins, fruits, and vegetables. Investments in infrastructure, particularly in supply chains and distribution networks, will also ensure that sustainable foods are available in underserved regions.

3.3 Other barriers and implications for behavior change

Although the barriers discussed are primarily at the individual level, it is important to understand that factors extend to interpersonal and broader social levels. The DONE framework offers a comprehensive structure for analyzing the many factors that shape dietary behaviors, including food choices and eating patterns. It considers a wide range of determinants, from biological and psychological to social and environmental (Stok et al., 2017). The Behavior Change Wheel, on the other hand, provides a practical tool for identifying what needs to change for a specific behavior to occur. At its core is the COM-B model, which proposes that behavior (B) arises from the interaction of Capability (C), Opportunity (O), and Motivation (M). For example, improving dietary behavior may involve enhancing an individual's capability (e.g., cooking skills), increasing opportunity (e.g., access to healthy foods), and strengthening motivation (e.g., through social support or incentives). The Behavior Change Wheel connects these behavioral components to appropriate intervention strategies and policy measures, offering a systematic approach from behavioral diagnosis to implementation (Michie et al., 2011) that can be used by researchers and policymakers interested in dietary behavior change.

The barriers discussed in our review align closely with the key factors influencing sustainable (and unsustainable) dietary behaviors proposed by Elliott et al. (2024), demonstrating their possible relevance in influencing sustainable diet consumption. For example, the work by Elliott et al. highlights conscious habitual eating, self-regulation skills, and eating norms as key factors, which aligns with the inclusion of habits and taste preferences, perceived behavioral control, and social norms from Muñoz-Martínez et al. (2024). Similarly, the emphasis on product price and food accessibility in their findings reflects the cost and physical access barrier presented by Muñoz-Martínez et al. (2024). Furthermore, their discussion of the potential importance of food promotion corresponds with the broader examination of information and media influence on dietary behaviors by Muñoz-Martínez et al. (2024). Despite the general concordance between barriers discussed in our review and those proposed as high priority by Elliott et al., dietary behaviors can be influenced by a broader range of factors than those discussed in our review (Stok et al., 2017).

4 Integrating policy tools and the role of national recommendations in diet transition

A comprehensive approach that combines policy tools is necessary for maximum impact (Michie et al., 2011). Isolated interventions, such as labeling or taxation alone, may not lead to long-term behavioral shifts, but when combined with educational initiatives, economic incentives, and regulatory frameworks, they create an enabling environment for sustainable diets (Elliott et al., 2024).

The European Union's Farm-to-Fork Strategy exemplifies this multi-layered approach by integrating food labeling, fiscal policies, and procurement changes into a cohesive framework for sustainability (European Commission, 2025). Free school meal plans, educational initiatives from kindergarten, and taxation on less sustainable food have been emphasized by the Farm-to-Fork guidelines. These measures collectively aim to create a healthier, more sustainable food environment.

MOO can be effectively integrated with behavioral policy design frameworks, such as the Behavior Change Wheel, to assess trade-offs and identify optimal intervention combinations. To implement this approach, qualitative determinants (particularly behavioral factors) must first be translated into quantitative metrics. Methods, such as the Analytic Hierarchy Process (AHP) (Aliasgharzadeh et al., 2022), allow for the systematic weighting of these factors based on expert judgment or stakeholder input. In parallel, monetization techniques, including the assignment of economic values to health outcomes (e.g., avoided cost-of-illness) (Springmann et al., 2021) or environmental impacts, offer an additional means of quantification. Once quantified, these criteria can be incorporated into MOO models to generate policy portfolios that balance competing objectives (such as minimizing implementation costs or environmental impacts while maximizing health benefits or behavioral uptake) within predefined constraints.

Nationally Recommended Diets (NRDs) play a crucial role in guiding healthy eating habits, but they must become more sustainable and flexible to be followed by different socio-economic groups within society which could be achieved using MOO (Springmann et al., 2020). While studies indicate that NRDs are generally more sustainable than the average diet, there is still room for improvement (Bashiri et al., 2024). NRDs currently provide broad recommendations, but they should be more specific and actionable, enabling individuals to identify and choose sustainable foods specifically for the individuals more fully considering their individual peculiarities and preferences. Maillot et al. highlighted a critical limitation in many dietary guidelines: they assume that individuals who follow these recommendations receive all essential nutrients (van Dooren, 2018; Maillot et al., 2010). However, in practice, this is not always the case. Additionally, dietary guidelines should not be designed solely for the general population; they must be more individualized, better targeting different consumer groups, catering to people with specific health conditions and different age groups. As demonstrated by Eustachio Colombo et al. (2023) and Nordman et al. (2024) through clustering analysis, these objectives can be effectively achieved using MOO.

When applying MOO to design sustainable dietary guidelines, it is crucial to use baseline dietary data that reflects actual consumption patterns, as this strongly influences the feasibility of optimized diets. Model constraints should also align with recent national and international dietary updates, such as the Nordic Nutrition Recommendations (NNR2023) (Blomhoff et al., 2023; Lassen et al., 2020), which integrate sustainability with nutritional adequacy. Incorporating expert input, regional dietary norms, and culturally appropriate constraints can improve the relevance, acceptability, and policy coherence of MOO-generated diets.

Dietary guidelines have the potential to influence food choices at both the individual and societal levels. They can be promoted across the population through mass communication campaigns and supported by rigorous, transparent reviews of scientific evidence (Advisory Report, 2025). Additionally, they can directly shape government food service and assistance programs, providing a framework for healthier and more sustainable food policies. While these guidelines are considered a "soft" policy, they can also indirectly encourage industry reformulation efforts to align with healthier standards (Mozaffarian et al., 2018). However, the translation of these guidelines into concrete policies and regulations has been somewhat limited (Wood et al., 2023). NRDs should be updated more frequently and should form a system of recommendations supporting individual choices (Wood et al., 2023), health, and planetary boundaries (Rossi et al., 2023).

5 Conclusion

Sustainable diet transition is crucial for addressing both environmental and public health challenges. MOO can provide a robust framework for balancing nutritional adequacy, affordability, cultural acceptability, and environmental impact. Providing accurate dietary data to the MOO model is essential for generating reliable and meaningful results. However, effective dietary shifts require more than mathematical models. Successful implementation demands the integration of behavioral insights, consumer engagement, and supportive policy instruments to identify and overcome internal and external barriers to diet adoption. It is important to understand how these factors operate not only at the individual level but also across interpersonal and broader social contexts. Behavior change models can offer valuable insights to support this understanding. NRDs have a pivotal role in steering dietary behavior but must evolve to reflect sustainability considerations. They also need to be translated into concrete policies and regulations and should be updated regularly to remain relevant and effective. To make optimized diets work in real life, we need a well-coordinated approach that brings together different elements. This includes using scientific methods to design diets, giving people personalized advice, creating supportive policies, and involving the public. When these parts work together, it becomes easier for governments and other organizations to help people shift toward diets that are not only healthy and sustainable but also realistic and fair for everyone.

Author contributions

BB: Investigation, Software, Data curation, Methodology, Conceptualization, Resources, Writing – original draft, Writing – review & editing, Formal analysis. AK: Supervision, Writing – review & editing, Software, Investigation, Resources, Data curation, Validation, Methodology. RV: Writing – review & editing, Formal analysis, Funding acquisition, Supervision, Project administration, Conceptualization, Methodology, Resources, Investigation.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The authors would like to appreciate the constructive comments and input from the reviewers on an earlier version of this manuscript.

Conflict of interest

BB, AK, and RV were employed by company TFTAK AS.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abejón, R., Batlle-Bayer, L., Laso, J., Bala, A., Vazquez-Rowe, I., Larrea-Gallegos, G., et al. (2020). Multi-objective optimization of nutritional, environmental and economic aspects of diets applied to the Spanish context. *Foods* 9:1677. doi: 10.3390/FOODS9111677

Advisory Report. (2025). Available online at: https://odphp.health.gov/our-work/nutrition-physical-activity/dietary-guidelines/previous-dietary-guidelines/2015/advisory-report (Accessed February 18, 2025).

Alcorta, A., Porta, A., Tárrega, A., Alvarez, M. D., and Pilar Vaquero, M. (2021). Foods for plant-based diets: challenges and innovations. *Foods* 10:293. doi: 10.3390/FOODS10020293

Aliasgharzadeh, S., Ebrahimi-Mameghani, M., Mahdavi, R., Karimzadeh, H., Nikniaz, L., Tabrizi, J. S., et al. (2022). Prioritizing population-based nutrition-related interventions to prevent and control hypertension in Iran: a multi-criteria decision-making approach. *BMC Med. Res. Methodol.* 22, 1–24. doi: 10.1186/S12874-022-01761-Z

Al-Jawaldeh, A., and Abbass, M. M. S. (2022). Unhealthy dietary habits and obesity: the major risk factors beyond non-communicable diseases in the eastern Mediterranean region. *Front. Nutr.* 9:817808. doi: 10.3389/FNUT.2022.817808 /XML/NLM

Ammann, J., Arbenz, A., Mack, G., Nemecek, T., and El Benni, N. (2023). A review on policy instruments for sustainable food consumption. *Sustain. Prod. Consum.* 36, 338–353. doi: 10.1016/J.SPC.2023.01.012

Ares, G., De Rosso, S., Mueller, C., Philippe, K., Pickard, A., Nicklaus, S., et al. (2024). Development of food literacy in children and adolescents: implications for the design of strategies to promote healthier and more sustainable diets. *Nutr. Rev.* 82, 536–552. doi: 10.1093/NUTRIT/NUAD072

Bashiri, B., Kaleda, A., Gavrilova, O., and Vilu, R. (2024). A culturally acceptable shift in diet to reduce land footprint: an optimization study for Estonia. *Environ. Model. Assess.* 30, 1–15. doi: 10.1007/s10666-024-09996-4

Bashiri, B., Kaleda, A., and Vilu, R. (2025). Integrating multi-criteria decision-making with multi-objective optimization for sustainable diet design. *J. Clean. Prod.* 500:145233. doi: 10.1016/J.JCLEPRO.2025.145233

Beal, T., Gardner, C. D., Herrero, M., Iannotti, L. L., Merbold, L., Nordhagen, S., et al. (2023). Friend or foe? The role of animal-source foods in healthy and environmentally sustainable diets. *J. Nutr.* 153, 409–425. doi: 10.1016/J.TJNUT.2022.10.016

Blomhoff, R., Andersen, R., Arnesen, E. K., Christensen, J. J., Eneroth, H., Erkkola, M., et al. (2023). Nordic nutrition recommendations 2023.

Bogard, J. R., Downs, S., Casey, E., Farrell, P., Gupta, A., Miachon, L., et al. (2024). Convenience as a dimension of food environments: a systematic scoping review of its definition and measurement. *Appetite* 194:107198. doi: 10.1016/J.APPET.2023.107198

Boronowsky, R. D., Zhang, A. W., Stecher, C., Presley, K., Mathur, M. B., Cleveland, D. A., et al. (2022). Plant-based default nudges effectively increase the sustainability of catered meals on college campuses: three randomized controlled trials. *Front. Sustain. Food Syst.* 6:1001157. doi: 10.3389/FSUFS.2022.1001157

Brink, E., Van Rossum, C., Postma-Smeets, A., Stafleu, A., Wolvers, D., Van Dooren, C., et al. (2019). Development of healthy and sustainable food-based dietary guidelines for the Netherlands. *Public Health Nutr.* 22, 2419–2435. doi: 10.1017/S1368980019001435

Camilleri, L., Kirkovski, M., Scarfo, J., Jago, A., and Gill, P. R. (2024). Understanding the meat-masculinity link: traditional and non-traditional masculine norms predicting men's meat consumption. *Ecol. Food Nutr.* 63, 355–386. doi: 10.1080/03670244.2024.2361818

Chaudhary, A., and Krishna, V. (2019). Country-specific sustainable diets using optimization algorithm. *Environ. Sci. Technol.* 53, 7694–7703. doi: 10.1021/ACS.EST.8B06923

Chen, C., Chaudhary, A., and Mathys, A. (2022). Dietary change and global sustainable development goals. *Front. Sustain. Food Syst.* 6:261. doi: 10.3389/FSUFS.2022.771041

Clark, M., Macdiarmid, J., Jones, A. D., Ranganathan, J., Herrero, M., and Fanzo, J. (2020). The role of healthy diets in environmentally sustainable food systems. *Food Nutr. Bull.* 41, 31S–58S. doi: 10.1177/0379572120953734

Consavage Stanley, K., Leary, N., Holz, A., Hedrick, V. E., Serrano, E. L., and Kraak, V. I. (2024). Exploring the landscape of media campaigns that encourage or discourage sustainable diet transitions for Americans, 1917–2023: a systematic scoping review. *Sustainability* 16:4457. doi: 10.3390/SU16114457/S1

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., et al. (2021). Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* 12, 36–46. doi: 10.1038/s41558-021-01219-y

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Desalegn, G., Tangl, A., Fekete-Farkas, M., Gudisa, G., and Boros, A. (2024). Linking policies and regulations to sustainable finance for the promotion of urban agriculture: evidence from micro and small businesses. *Heliyon* 10:e31938. doi: 10.1016/J.HELIYON.2024.E31938

Donati, M., Menozzi, D., Zighetti, C., Rosi, A., Zinetti, A., and Scazzina, F. (2016). Towards a sustainable diet combining economic, environmental and nutritional objectives. *Appetite* 106, 48–57. doi: 10.1016/J.APPET.2016.02.151

Dubois, L., Bédard, B., Goulet, D., Prud'homme, D., Tremblay, R. E., and Boivin, M. (2022). Eating behaviors, dietary patterns and weight status in emerging adulthood and longitudinal associations with eating behaviors in early childhood. *Int. J. Behav. Nutr. Phys. Act.* 19, 1–11. doi: 10.1186/S12966-022-01376-Z/TABLES/6

Elliott, P. S., Devine, L. D., Gibney, E. R., and O'Sullivan, A. M. (2024). What factors influence sustainable and healthy diet consumption? A review and synthesis of literature within the university setting and beyond. *Nutr. Res.* 126, 23–45. doi: 10.1016/J.NUTRES.2024.03.004

ERR. Emphasis on fruit and vegetables in new school meals regulation | News | ERR (2025). Available online at: https://news.err.ee/1609689185/emphasis-on-fruit-and-vegetables-in-new-school-meals-regulation (Accessed May 14, 2025).

Espinosa-Marrón, A., Adams, K., Sinno, L., Cantu-Aldana, A., Tamez, M., Marrero, A., et al. (2022). Environmental impact of animal-based food production and the feasibility of a shift toward sustainable plant-based diets in the United States. *Front. Sustain.* 3:841106. doi: 10.3389/FRSUS.2022.841106

European Commission. (2025) Farm to fork strategy. Available online at: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en (Accessed February 18, 2025)

Eustachio Colombo, P., Elinder, L. S., Nykänen, E. P. A., Patterson, E., Lindroos, A. K., and Parlesak, A. (2023). Developing a novel optimisation approach for keeping heterogeneous diets healthy and within planetary boundaries for climate change. *Eur. J. Clin. Nutr.* 78, 193–201. doi: 10.1038/s41430-023-01368-7

Even, B., Thai, H. T. M., Pham, H. T. M., and Béné, C. (2024). Defining barriers to food systems sustainability: a novel conceptual framework. *Front. Sustain. Food Syst.* 8:1453999. doi: 10.3389/FSUFS.2024.1453999 PDF

Fanzo, J., Rudie, C., Sigman, I., Grinspoon, S., Benton, T. G., Brown, M. E., et al. (2022). Sustainable food systems and nutrition in the 21st century: a report from the 22nd annual Harvard nutrition obesity symposium. *Am. J. Clin. Nutr.* 115, 18–33. doi: 10.1093/AJCN/NQAB315

Farrar, S. T., Davis, T., and Papies, E. K. (2024). Increasing the appeal of plant-based foods through describing the consumption experience: a data-driven procedure. *Food Qual. Prefer.* 119:105212. doi: 10.1016/J.FOODQUAL.2024.105212

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., et al. (2011). Solutions for a cultivated planet. *Nature* 478, 337–342. doi: 10.1038/nature10452

Fresacher, M., and Johnson, M. K. P. (2023). Designing climate labels for green food choices. *J. Clean. Prod.* 430:139490. doi: 10.1016/J.JCLEPRO.2023.139490

Fu, H., Li, Y., Jiang, P., Zhou, S., and Liao, C. (2024). Transition towards sustainable diets: multi-objective optimization of dietary pattern in China. *Sustain. Prod. Consumpt.* 48, 14–28. doi: 10.1016/J.SPC.2024.04.029

Garvey, A., Norman, J. B., Owen, A., and Barrett, J. (2021). Towards net zero nutrition: the contribution of demand-side change to mitigating UK food emissions. *J. Clean. Prod.* 290:125672. doi: 10.1016/J.JCLEPRO.2020.125672

Gazan, R., Brouzes, C. M. C., Vieux, F., Maillot, M., Lluch, A., and Darmon, N. (2018). Mathematical optimization to explore tomorrow's sustainable diets: a narrative review. *Adv. Nutr.* 9, 602–616. doi: 10.1093/ADVANCES/NMY049

Graff, S., Kunkel, D., and Mermin, S. E. (2017). Government can regulate food advertising to children because cognitive research shows that it is inherently misleading. *Health Aff.* 31, 392–398. doi: 10.1377/HLTHAFF.2011.0609

Guyader, H., Ottosson, M., and Witell, L. (2017). You can't buy what you can't see: retailer practices to increase the green premium. *J. Retail. Consum. Serv.* 34, 319–325. doi: 10.1016/J.JRETCONSER.2016.07.008

Hagen Helland, M., Lise Nordbotten, G., Sala, A., and Tchounwou, P. B. (2021). Dietary changes, motivators, and barriers affecting diet and physical activity among overweight and obese: a mixed methods approach. *Int. J. Environ. Res. Public Health* 18:10582. doi: 10.3390/IJERPH182010582

Heerschop, S. N., Cardinaals, R. P. M., Biesbroek, S., Kanellopoulos, A., Geleijnse, J. M., Van 't Veer, P., et al. (2024). Designing sustainable healthy diets: analysis of two modelling approaches. *J. Clean. Prod.* 475:143619. doi: 10.1016/J.JCLEPRO.2024.143619

Higgs, S., Liu, J., Collins, E. I. M., and Thomas, J. M. (2019). Using social norms to encourage healthier eating. *Nutr. Bull.* 44, 43–52. doi: 10.1111/NBU.12371

Hodgett, R. E., and Siraj, S. (2019). SURE: a method for decision-making under uncertainty. *Expert Syst. Appl.* 115, 684–694. doi: 10.1016/J.ESWA.2018.08.048

Huangfu, P., Pearson, F., Abu-Hijleh, F. M., Wahlich, C., Willis, K., Awad, S. F., et al. (2024). Impact of price reductions, subsidies, or financial incentives on healthy food purchases and consumption: a systematic review and meta-analysis. *Lancet Planet. Health* 8, e197–e212. doi: 10.1016/S2542-5196(24)00004-4

Hundscheid, L., Wurzinger, M., Gühnemann, A., Melcher, A. H., and Stern, T. (2022). Rethinking meat consumption – how institutional shifts affect the sustainable protein transition. *Sustain. Prod. Consum.* 31, 301–312. doi: 10.1016/J.SPC.2022.02.016

Irz, X., Tapanainen, H., Saarinen, M., Salminen, J., Jaske, L. S., and Valsta, L. M. (2024). Reducing the carbon footprint of diets across socio-demographic groups in Finland: a mathematical optimisation study. *Public Health Nutr.* 27:e98. doi: 10.1017/S1368980024000508

James-Martin, G., Baird, D. L., Hendrie, G. A., Bogard, J., Anastasiou, K., Brooker, P. G., et al. (2022). Environmental sustainability in national food-based dietary guidelines: a global review. *Lancet Planet. Health* 6, e977–e986. doi: 10.1016/S2542-5196(22)00246-7

Khan, R., Suggs, L. S., Tanweer, A., and Bányai, G. (2024). Food advertisement and marketing policies aimed at reducing childhood obesity: a review of existing regulations in high-income countries. *Public Health Rev.* 45:1607103. doi: 10.3389/PHRS.2024.1607103

Labbé, C., Ward Chiasson, S., Dupuis, J. B., and Johnson, C. (2023). Effectiveness of a school-based culinary Programme on 9- and 10-year-old children's food literacy and vegetable, fruit, and breakfast consumption. *Nutrients* 15:1520. doi: 10.3390/NU15061520

Lassen, A. D., Christensen, L. M., and Trolle, E. (2020). Development of a Danish adapted healthy plant-based diet based on the EAT-lancet reference diet. *Nutrients* 12:738. doi: 10.3390/NU12030738

Lauk, J., Nurk, E., Robertson, A., and Parlesak, A. (2020). Culturally optimised nutritionally adequate food baskets for dietary guidelines for minimum wage Estonian families. *Nutrients* 12, 1–15. doi: 10.3390/NU12092613

Lin-Hi, N., Reimer, M., Schäfer, K., and Böttcher, J. (2022). Consumer acceptance of cultured meat: an empirical analysis of the role of organizational factors. *J. Bus. Econ.* 93, 707–746. doi: 10.1007/S11573-022-01127-3

Lucas, E., Guo, M., and Guillén-Gosálbez, G. (2023). Low-carbon diets can reduce global ecological and health costs. *Nat. Food.* 4, 394–406. doi: 10.1038/s43016-023-00749-2

Ma, H., Wang, M., Qin, C., Shi, Y., Mandizadza, O. O., Ni, H., et al. (2025). Trends in the burden of chronic diseases attributable to diet-related risk factors from 1990 to 2021 and the global projections through 2030: a population-based study. *Front. Nutr.* 12:1570321. doi: 10.3389/FNUT.2025.1570321

Maillot, M., Vieux, F., Amiot, M. J., and Darmon, N. (2010). Individual diet modeling translates nutrient recommendations into realistic and individual-specific food choices. *Am. J. Clin. Nutr.* 91, 421–430. doi: 10.3945/AJCN.2009.28426

Metcalfe, J. J., McCaffrey, J., Schumacher, M., Kownacki, C., and Prescott, M. P. (2022). Community-based nutrition education and hands-on cooking intervention increases farmers' market use and vegetable servings. *Public Health Nutr.* 25, 2601–2613. doi: 10.1017/S1368980022000660

Michie, S., van Stralen, M. M., and West, R. (2011). The behaviour change wheel: a new method for characterising and designing behaviour change interventions. *Implement. Sci.* 6, 1–12. doi: 10.1186/1748-5908-6-42/TABLES/3

Mirzaie-Nodoushan, F., Morid, S., and Dehghanisanij, H. (2020). Reducing water footprints through healthy and reasonable changes in diet and imported products. *Sustain. Prod. Consump.* 23, 30–41. doi: 10.1016/J.SPC.2020.04.002

Modlinska, K., Adamczyk, D., Goncikowska, K., Maison, D., and Pisula, W. (2020). The effect of labelling and visual properties on the acceptance of foods containing insects. *Nutrients* 12:2498. doi: 10.3390/NU12092498

Mozaffarian, D., Angell, S. Y., Lang, T., and Rivera, J. A. (2018). Role of government policy in nutrition—barriers to and opportunities for healthier eating. *BMJ* 361:k2426. doi: 10.1136/BMJ.K2426

Muñoz-Martínez, J., Cussó-Parcerisas, I., and Carrillo-Álvarez, E. (2024). Exploring the barriers and facilitators for following a sustainable diet: a holistic and contextual scoping review. *Sustain. Prod. Consum.* 46, 476–490. doi: 10.1016/J.SPC.2024.03.002

Muñoz-Martínez, J., Elías, R. A., Batlle-Bayer, L., Cussó-Parcerisas, I., and Carrillo-Álvarez, E. (2023). Optimizing sustainable, affordable and healthy diets and estimating the impact of plant-based substitutes to milk and meat: a case study in Spain. *J. Clean. Prod.* 424:138775. doi: 10.1016/J.JCLEPRO.2023.138775

Nam, S. J., and Suk, J. (2024). Influence of health food literacy on willingness to pay for healthier foods: focus on food insecurity. *Int. J. Equity Health* 23, 1–11. doi: 10.1186/S12939-024-02135-1

Nordman, M., Stockmarr, A., Lassen, A. D., and Trolle, E. (2024). Low-carbon diets across diverse dietary patterns: addressing population heterogeneity under constrained optimization. *Sci. Total Environ.* 953:176155. doi: 10.1016/J.SCITOTENV.2024.176155

Nugraha, W. S., Szakos, D., Süth, M., and Kasza, G. (2024). Greenwashing in the food industry: a systematic review exploring the current situation and possible countermeasures. *Clean. Respons. Consumpt.* 15:100227. doi: 10.1016/J.CLRC.2024.100227

Olsho, L. E. W., Klerman, J. A., Wilde, P. E., and Bartlett, S. (2016). Financial incentives increase fruit and vegetable intake among supplemental nutrition assistance program participants: a randomized controlled trial of the USDA healthy incentives pilot. *Am. J. Clin. Nutr.* 104, 423–435. doi: 10.3945/AJCN.115.129320

Oyewole, G. J., and Thopil, G. A. (2023). Data clustering: application and trends. *Artif. Intell. Rev.* 56, 6439–6475. doi: 10.1007/S10462-022-10325-Y

Perez-Cueto, F. J. A., Rini, L., Faber, I., Rasmussen, M. A., Bechtold, K. B., Schouteten, J. J., et al. (2022). How barriers towards plant-based food consumption differ according to dietary lifestyle: findings from a consumer survey in 10 EU countries. *Int. J. Gastron. Food Sci.* 29:100587. doi: 10.1016/J.IJGFS.2022.100587

Pineda, E., Atanasova, P., Wellappuli, N. T., Kusuma, D., Herath, H., Segal, A. B., et al. (2024). Policy implementation and recommended actions to create healthy food environments using the healthy food environment policy index (food-EPI): a comparative analysis in South Asia. *Lancet Regional Health* 26. doi: 10.1016/j.lansea.2024.100428

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science* 360, 987–992. doi: 10.1126/SCIENCE.AAQ0216

Profeta, A., Baune, M. C., Smetana, S., Broucke, K., Van Royen, G., Weiss, J., et al. (2021). Consumer preferences for meat blended with plant proteins – empirical findings from Belgium. *Future Foods* 4:100088. doi: 10.1016/J.FUFO.2021.100088

Ran, Y., Cederberg, C., Jonell, M., Bergman, K., De Boer, I. J. M., Einarsson, R., et al. (2024). Environmental assessment of diets: overview and guidance on indicator choice. *Lancet Planet. Health* 8, e172–e187. doi: 10.1016/S2542-5196(24)00006-8

Reynolds, C. J., Horgan, G. W., Whybrow, S., and Macdiarmid, J. I. (2019). Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr.* 22, 1503–1517. doi: 10.1017/S1368980018003774

Rossi, L., Ferrari, M., and Ghiselli, A. (2023). The alignment of recommendations of dietary guidelines with sustainability aspects: lessons learned from Italy's example and proposals for future development. *Nutrients* 15:542. doi: 10.3390/NU15030542

Rothgerber, H. (2020). Meat-related cognitive dissonance: a conceptual framework for understanding how meat eaters reduce negative arousal from eating animals. *Appetite* 146:104511. doi: 10.1016/J.APPET.2019.104511

Ruby, M. B., Graça, J., and Olli, E. (2024). Vegetarian, vegan, or plant-based? Comparing how different labels influence consumer evaluations of plant-based foods. *Appetite* 197:107288. doi: 10.1016/J.APPET.2024.107288

Shangguan, S., Afshin, A., Shulkin, M., Ma, W., Marsden, D., Smith, J., et al. (2019). A meta-analysis of food labeling effects on consumer diet behaviors and industry practices. *Am. J. Prev. Med.* 56, 300–314. doi: 10.1016/J.AMEPRE.2018.09.024

Shukla, P. R., Skeg, J., Buendia, E. C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., et al. (2019) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Available online at: https://philpapers.org/rec/SHUCCA-2

Smith, J., Andersson, G., Gourlay, R., Karner, S., Mikkelsen, B. E., Sonnino, R., et al. (2016). Balancing competing policy demands: the case of sustainable public sector food procurement. *J. Clean. Prod.* 112, 249–256. doi: 10.1016/J.JCLEPRO.2015.07.065

Springmann, M., Clark, M. A., Rayner, M., Scarborough, P., and Webb, P. (2021). The global and regional costs of healthy and sustainable dietary patterns: a modelling study. *Lancet Planet Health* 5, e797–e807. doi: 10.1016/S2542-5196(21)00251-5

Springmann, M., Spajic, L., Clark, M. A., Poore, J., Herforth, A., Webb, P., et al. (2020). The healthiness and sustainability of national and global food based dietary guidelines: modelling study. *BMJ* 370:m2322. doi: 10.1136/BMJ.M2322

Stok, F. M., de Vet, E., de Ridder, D. T. D., and de Wit, J. B. F. (2016). The potential of peer social norms to shape food intake in adolescents and young adults: a systematic review of effects and moderators. *Health Psychol. Rev.* 10, 326–340. doi: 10.1080/17437199.2016.1155161

Stok, F. M., Hoffmann, S., Volkert, D., Boeing, H., Ensenauer, R., Stelmach-Mardas, M., et al. (2017). The DONE framework: creation, evaluation, and updating of an interdisciplinary, dynamic framework 2.0 of determinants of nutrition and eating. *PLoS One* 12:e0171077. doi: 10.1371/JOURNAL.PONE.0171077

Taillie, L. S., Busey, E., Stoltze, F. M., and Dillman Carpentier, F. R. (2019). Governmental policies to reduce unhealthy food marketing to children. *Nutr. Rev.* 77, 787–816. doi: 10.1093/NUTRIT/NUZ021

van Dooren, C. (2018). A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally. *Front. Nutr.* 5:48. doi: 10.3389/FNUT.2018.00048

Van Dooren, C. (2024). Planet-based diets: improving environmental sustainability of healthy diets. *Proc. Nutr. Soc.* 83, 210–216. doi: 10.1017/S0029665123003737

van Dooren, C., Keuchenius, C., de Vries, J. H. M., Boer, J., and Aiking, H. (2018). Unsustainable dietary habits of specific subgroups require dedicated transition strategies: evidence from the Netherlands. *Food Policy* 79, 44–57. doi: 10.1016/J.FOODPOL.2018.05.002

Vogel, C., Crozier, S., Penn-Newman, D., Ball, K., Moon, G., Lord, J., et al. (2021). Altering product placement to create a healthier layout in supermarkets: outcomes on store sales, customer purchasing, and diet in a prospective matched controlled cluster study. *PLoS Med.* 18:e1003729. doi: 10.1371/JOURNAL.PMED.1003729

Vrijsen, E., Van Bauwel, S., Dhoest, A., and De Backer, C. (2025). Sizzling steaks and manly molds: exploring the meanings of meat and masculinities in young men's lives. *Appetite* 204:107754. doi: 10.1016/J.APPET.2024.107754

Wang, R., Xiong, F., Cheng, G., Wang, H., and Liu, G. (2024). Province-specific sustainable diets in China considering nutrition, environment, affordability, and acceptability. *J. Clean. Prod.* 468:143141. doi: 10.1016/J.JCLEPRO.2024.143141

WHO. Sustainable healthy diets: guiding principles. (2025). Available online at: https://www.who.int/publications/i/item/9789241516648 (Accessed May 26, 2025).

WHO European Office for the Prevention and Control of Noncommunicable Diseases (2021). Plant-based diets and their impact on health, sustainability and the environment: A review of the evidence: WHO European Office for the Prevention and Control of Noncommunicable Diseases. Copenhagen: WHO Regional Office for Europe.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Winpenny, E. M., van Sluijs, E. M. F., White, M., Klepp, K. I., Wold, B., and Lien, N. (2018). Changes in diet through adolescence and early adulthood: longitudinal trajectories and association with key life transitions. *Int. J. Behav. Nutr. Phys. Act.* 15:86. doi: 10.1186/S12966-018-0719-8/TABLES/2

Wood, A., Moberg, E., Curi-Quinto, K., Van Rysselberge, P., and Röös, E. (2023). From "good for people" to "good for people and planet" – placing health and environment on equal footing when developing food-based dietary guidelines. *Food Policy* 117:102444. doi: 10.1016/J.FOODPOL.2023.102444

Wu, Y., Kurisu, K., and Fukushi, K. (2024). What should be understood to promote environmentally sustainable diets? *Sustain. Prod. Consum.* 51, 484–497. doi: 10.1016/J.SPC.2024.10.001

Yin, J., Zhang, X., Huang, W., Liu, L., Zhang, Y., Yang, D., et al. (2021). The potential benefits of dietary shift in China: synergies among acceptability, health, and environmental sustainability. *Sci. Total Environ.* 779:146497. doi: 10.1016/J.SCITOTENV.2021.146497

Zhang, J., Li, M., Liu, W., Lauria, S., and Liu, X. (2022). Many-objective optimization meets recommendation systems: a food recommendation scenario. *Neurocomputing* 503, 109–117. doi: 10.1016/J.NEUCOM.2022.06.081

Zhu, W., Han, X., Liu, Y., Li, G., and Wen, J. (2024). Sustainable healthy diets in China: a multidimensional framework and assessment. *Front. Sustain. Food Syst.* 8:1464965. doi: 10.3389/FSUFS.2024.1464965 /BIBTEX