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Sustainable healthy diets in China: a multidimensional framework and assessment

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In China, the urgent need to formulate food policies that address both nutritional health and climate challenges has become increasingly apparent. This study constructs a theoretical framework and a multi-objective programming model that takes into account income disparities, aiming to delineate a sustainable healthy diet for Chinese residents and pinpoint key areas for dietary transformation. Our findings reveal that a sustainable healthy diet in China should involve moderate adjustments to staple foods, such as reducing rice consumption in favor of alternatives like flour and other grains. The diet should emphasize low-fat consumption, increased intake of fruits and vegetables, and a balanced intake of animal products by reducing meat, poultry, eggs, and fish, while ensuring sufficient consumption of chicken, shrimp, and dairy products. Furthermore, it recommends reducing alcohol consumption and limiting high-calorie snacks like cakes. This proposed diets achieves multiple objectives: it can reduce greenhouse gas emissions from the food system by 12.8%, decrease food expenditure by 1.1%, and significantly improve dietary quality. However, the study also highlights a trade-off between consumer interests and environmental benefits across different income groups. For the low-income group, minimal dietary changes result in a 2.0% increase in food expenses and an 11.1% increase in greenhouse gas emissions. Conversely, while the diet may slightly misalign with the preferences of middle and high-income groups, these groups benefit from reductions in food expenses (ranging from 0.4 to 4.8%) and greenhouse gas emissions (ranging from 14.5 to 23.4%). Thus, initiating reforms from the consumer end of the food system and guiding dietary patterns towards a healthier and more sustainable pattern through targeted food policies could be a crucial strategy for addressing nutritional and environmental challenges. However, it is essential to balance environmental benefits with ensuring the welfare of different income groups within China's diverse economic landscape. This calls for differentiated policies to safeguard the wellbeing of the population.

KEYWORDS

sustainable healthy diets, food system, theoretical framework, greenhouse gas emissions (GHGs), different income groups, multi-objective programming model, food policy, China

1 Introduction

The food system, intricately linked to dietary preference of consumers, has increasingly intersected with both the climate-environment and nutrition-health systems in recent years. The second United Nations Sustainable Development Goal emphasizes the eradication of hunger, the achievement of food security and improved nutrition, and the promotion of sustainable agriculture. However, the environmental impacts of shifting diets and their consequent health repercussions are intensifying. On one hand, the growing preference for animal-based foods has led to a marked increase in greenhouse gas emissions from food systems, which now contribute to 30% of total emissions, with over 70% attributed to animal-based products (Castellanos-Gutiérrez et al., 2021; Conrad et al., 2023; Verly-Jr et al., 2022). On the other hand, despite significant advancements in food production and distribution that have reduced global hunger, increased life expectancy, and decreased poverty rates, these gains are being progressively undermined by the adverse effects of unhealthy dietary choices (Willett et al., 2019). Currently, over 3.1 billion individuals cannot afford a healthy diet, approximately 1.9 billion adults are overweight, 462 million remain underweight, and over 2 billion suffer from micronutrient deficiencies, with diabetes cases having doubled in the past three decades (Zhou et al., 2016).

Animal-based foods are an effective source of high-quality proteins, while grains in plant-based foods serve as the primary sources of carbohydrates and energy. Fruits and vegetables contribute essential dietary fiber and trace elements. A balanced and moderate intake of a diverse range of foods is key to maintaining good health (U.S. Department of Agriculture and U.S. Department of Health and Human Services, 2020; Chinese Nutrition Society, 2022). In China, the traditional diet, predominantly based on grains and vegetables, is gradually shifting towards a more Western-oriented consumption pattern, characterized by higher intakes of meat, eggs, and dairy (Yu, 2015; Zheng et al., 2019; Zhu et al., 2022). While this dietary transition has addressed basic nutritional needs, the current food consumption pattern remains imbalanced. Pork consumption is excessive, while the intake of beef, lamb, dairy products, and aquatic products, which are rich in high-quality proteins, remains insufficient. Additionally, the consumption of vegetables, fruits, and whole grains is insufficient. This dietary pattern has contributed to the rapid rise in overweight and obesity rates, as well as an increase in cardiovascular diseases in China. Furthermore, according to FAOSTAT, China has emerged as a major contributor to global greenhouse gas emissions from food systems. Concurrently, the Chinese government is committed to the Healthy China Strategy and has pledged to achieve peak carbon emissions by 2030 and carbon neutrality by 2060. Transforming the food system to promote healthier diets while reducing carbon emissions represents a crucial and comprehensive solution. Therefore, given the health and environmental challenges associated with food consumption, it is both necessary and urgent for Chinese residents to transition towards a more sustainable healthy diet (Cai et al., 2024; Sheng et al., 2021).

The Food and Agriculture Organization of the United Nations defines a sustainable healthy diet as one that satisfies four criteria: environmental sustainability, nutritional health, economical affordability, and cultural acceptability. Environmental sustainability primarily involves reducing diet-induced greenhouse gas emissions (Conrad et al., 2023; Springmann et al., 2018; Tilman and Clark, 2014), while nutritional health is concerned with ensuring adequate nutrient intake (Yue et al., 2022). Economical affordability and cultural acceptability focus on maintaining low food costs and respecting diverse dietary preferences across consumer groups (Larrea-Gallegos and Vázquez-Rowe, 2020; Rancilio et al., 2022; Springmann et al., 2021). A pivotal aspect of Chinese agricultural and food policy is addressing the challenges faced by low-income groups, taking into consideration the varied dietary habits among Chinese residents. As such, economical affordability and cultural acceptability are becoming increasingly significant in the governance of diets in China (Wen et al., 2024; Yin et al., 2021).

Achieving a sustainable healthy dietary transformation necessitates a tailored solution that considers the specific needs and circumstances of different income groups within China. The disparate impacts of such diets, which may inadvertently exacerbate inequalities, should not be overlooked, as different income nations contribute differently to nutrition status and carbon emissions, and the same is true within different income groups in the same country (Reynolds et al., 2019; Steenson and Buttriss, 2021). Most existing research on transitioning to low-carbon and healthy diets tends to overlook the nuances among internal groups, typically focusing on the general population (Castellanos-Gutiérrez et al., 2021; Horgan et al., 2016). There is a pronounced heterogeneity among Chinese residents in terms of food consumption, which is reflected in significant differences in dietary structure, nutritional status, diet affordability, and eating habits across income groups (Fan et al., 2021; Song et al., 2017; Zhu et al., 2021). This heterogeneity implies that the starting points, objectives, strategies, and constraints for transitioning towards a sustainable healthy diet vary among different income levels, leading to diverse optimized diet models suitable for various groups. Without addressing this income-related diversity, it is impractical to comprehensively explore the issue of sustainable healthy diets.

The existing literature on formulating sustainable healthy diets predominantly employs optimization programming models under nutritional intake constraints. These models typically aim to minimize either greenhouse gas emissions or alterations in existing diets to derive optimal dietary solutions. Such models conceptualize sustainable healthy diets as those which balance environmental impacts with nutritional adequacy, economic feasibility, and adherence to established consumption patterns. As evidenced in Table 1, through strategic dietary adjustments, reductions in greenhouse gas emissions from the food system range from 2.8 to 87%, while simultaneously ensuring nutritional health, economical affordability, and cultural acceptability. Macdiarmid et al. (2012) utilized a deterministic linear programming model to recalibrate a typical British diet within nutritional constraints, achieving a significant reduction in meat consumption by 60% and a 36% decrease in associated greenhouse gas emissions. However, this modified diet may not fully resonate with prevailing consumption preferences. In subsequent studies, Green et al. (2015), Milner et al. (2015), and Horgan et al. (2016) integrated consumer habits into their models by prioritizing minimal changes to existing diets. Their models also incorporated parameters such as the proportion of food expenditure and the price elasticity of food demand to more accurately reflect consumer dietary preferences. Further research has expanded to include the economic implications of adopting sustainable healthy diets, ensuring that such diets remain affordable for consumers. These considerations have been integrated into either the constraints or the optimization objectives of the models (Larrea-Gallegos and Vázquez-Rowe, 2020; Wilson et al., 2013). Recognizing the significant variation in food consumption patterns among different income groups, Reynolds et al. (2019) factored in the

TABLE 1 Literature on building sustainable healthy diets.

Authors	Country	Method	Objective	Nutritional constrains	Economical affordability	Cultural acceptability	GHGs changes
Macdiarmid et al. (2012)	UK	Linear Programming Model	Min GHGs	YES	YES	YES *	−36%
Wilson et al. (2013)	New Zealand	Linear Programming Model	Muti-objectives	YES	YES	YES *	−43 ~ 87%
Green et al. (2015)	UK	Nonlinear Programming Model	Min changes in diets	YES		YES #	−10% ~ 40%
Milner et al. (2015)	UK	Nonlinear Programming Model	Min changes in diets	YES		YES #	−17%
Horgan et al. (2016)	UK	Linear Programming Model	Min changes in diets	YES		YES *#	−15% ~ 27%
Song et al. (2017)	China	Linear Programming Model	Min GHGs	YES		YES *	−5% ~ 28%
Chalmers and Revoredo-Giha (2019)	Scotland	Nonlinear Programming Model	Min changes in diets	YES		YES #	−30% ~ 55%
Reynolds et al. (2019)	UK	Linear Programming Model	Min changes in diets	YES	YES	YES #	−34% ~ 57%
Larrea-Gallegos and Vázquez-Rowe (2020)	Peru	Linear Programming Model	Min GHGs	YES	YES	YES *	−2.8% ~ 5.8%
Yin et al. (2021)	China	Nonlinear Programming Model	Min changes in diets and GHGs	YES		YES	−19%

"Yes" indicates that the factor has been considered; "*" denotes that the indicator has been used as an objective in the programming model; "#" signifies that the indicator has been used as a constraint in the programming model; Source: The author has compiled this based on previous literature.

heterogeneity of these groups in their programming models, tailoring sustainable healthy diets that accommodate the specific dietary habits and economic capabilities of each group. Research focusing on China remains nascent and largely exploratory. Existing studies predominantly address the dual benefits of environmental and health impacts (He et al., 2019; He et al., 2018; Song et al., 2017), but often overlook factors such as cultural acceptability and the multifaceted nature of consumer decision-making, potentially undermining the practical adoption of new dietary practices. Yin et al. (2021) considered cultural acceptability but only on a general level, without addressing the variability among income groups or issues of economic affordability in China.

Given these gaps, this study is crucial as it analyses the concept of sustainable healthy diets among Chinese residents, considering the diversity of income groups. It establishes a conceptual framework and utilizes data from sources like the China Urban Household Survey to parameterize income-specific models. This research employs a multi-objective programming model to explore suitable dietary options for different income groups under various scenarios, assesses the outcomes, and verifies the robustness of the results. It concludes with a discussion and the formulation of pertinent policy recommendations. The innovative aspects of this study are twofold: first, it recognizes the heterogeneity among income groups in theoretical mechanisms, pathways, and goals of dietary transition in China and provides a China-specific plan for the formulation of food policies; second, develops a multi-objective programming model that simultaneously considers economic constraints, dietary preferences, nutritional needs, and environmental impacts. The study is structured into five main sections, starting with this introduction, followed by a detailed presentation of the conceptual framework and methodology, an analysis of the findings, and concluding with a discussion on the implications and policy recommendations.

2 Materials

2.1 Diets and food cost

The data on food consumption and expenditure utilized in this study are derived from the microdata of the Urban Household Income and Expenditure Survey conducted by the National Bureau of Statistics in China. This survey spans six provinces or autonomous regions, namely Guangdong, Sichuan, Jilin, Hebei, Henan, and Xinjiang. A significant strength of this dataset is its comprehensiveness, which surveyed households recorded their complete dietary consumption and expenditures daily throughout the year. This dataset encompasses detailed records of food expenditures and various family characteristic variables. Characterized by its large sample size and high quality, the data accurately reflect the Chinese diets and have been extensively used in empirical studies concerning food consumption in China (Han et al., 2019; Zheng and Henneberry, 2012; Zhu et al., 2022; Zhu et al., 2021).

The residents' diet categories in this study primarily include seven major food groups: cereals, oils and fats, meat and poultry, dairy and eggs, aquatic products, fruits and vegetables, and other foods. To paint a detailed picture of consumers' diets, these seven major food groups were further subdivided into 20 sub-categories (Table 2). To ensure data integrity and reduce the influence of extreme values, the approach adopted from Zheng and Henneberry (2012) was employed, wherein samples with food price and expenditure variables exceeding five standard deviations from the mean were excluded. This filtering process yielded a total of 6,535 samples suitable for analysis. Additionally, to explore diets across different income strata, households were categorized into low, middle, and high-income groups according to the income group division method of the National Bureau of Statistics in China. These groups represent the lowest 20%, middle 60%, and highest 20% of the total household income distribution, respectively. Furthermore, due to the lack of price data in this survey, a quality-adjusted price was used (Cox and Wohlgenant, 1986; Gao et al., 1995; Zheng and Henneberry, 2009; Zhu et al., 2021). First, the unit value for 20 food items was calculated by dividing food expenditure by the quantity consumed for each item. Next, based on these unit values without considering quality factors, the quality-adjusted price was estimated using hedonic price regression. These price variables are later used to calculate demand price elasticity parameters and dietary costs.

Table 2 presents a detailed breakdown of the current diets and food expenditures for the overall sample and across the three income groups. The data reveal notable disparities in both food consumption expenditures and dietary structures among the different income groups. The average *per capita* food expenditure for all samples stands at 8.73 yuan/day. Specifically, the expenditure for the low-income group is 6.61 yuan/day, while the expenditures for the middle and high-income groups are 8.98 yuan/day and 9.97 yuan/day, respectively. There is a prevalent trend towards higher consumption of plant-based products, such as cereals, fruits and vegetables, with comparatively lower consumption of animal-based products. Notably, the consumption of most food types tends to increase with income across the groups, with some exceptions such as wheat, edible animal oil, mutton, and alcohol, which are consumed more by the middle-income group than by the high-income group.

TABLE 2 Diets and food cost in different income groups.

	All	Low-income group	Middle-income group	High-income group
Sample size	6,535	1,307	3,921	1,307
Food expenditure (CNY/day/person)	8.73	6.61	8.98	9.97
Food consumption (grams/day/person)				
Cereals	**278.22**	**223.18**	**288.15**	**303.50**
Rice	131.75	100.70	133.11	158.71
Wheat	41.90	40.07	46.62	29.58
Other cereals	104.57	82.41	108.41	115.20
Edible oils	**33.43**	**27.69**	**34.78**	**35.09**
Vegetable oil	32.43	26.84	33.69	34.21
Animal oil	1.00	0.85	1.09	0.88
Meat and poultry	**109.69**	**76.08**	**108.96**	**145.48**
Pork	69.52	49.56	69.25	90.30
Beef	8.13	5.44	8.49	9.74
Mutton	4.18	3.17	4.66	3.74
Chicken	22.10	14.17	20.98	33.39
Duck	5.76	3.74	5.58	8.32
Eggs and milk	**89.94**	**67.48**	**94.27**	**99.40**
Eggs	34.63	27.29	36.34	36.84
Fresh milk	44.41	33.01	46.14	50.62
Yogurt	10.90	7.18	11.79	11.95
Aquatic products	**33.77**	**20.54**	**32.87**	**49.72**
Fish	30.64	18.69	29.69	45.44
Shrimp	3.14	1.84	3.18	4.29
Fruits and vegetables	**534.96**	**407.80**	**550.98**	**614.06**
Vegetables	383.38	300.11	396.05	428.63
Fruits	111.82	78.33	112.89	142.09
Melons	39.77	29.36	42.05	43.33
Other food groups	**38.42**	**29.82**	**40.57**	**40.54**
Alcohol	24.04	20.12	25.69	22.99
Confectionery	14.38	9.71	14.88	17.55

Source: Microdata from the Urban Household Sample Survey conducted by the NBSC.

2.2 Nutrition intake

In this study, nutrient analysis encompasses 19 distinct categories, including energy, protein, fat, carbohydrates, dietary fiber, cholesterol, and various vitamins and minerals (vitamin A, vitamin C, vitamin E, calcium, phosphorus, potassium, sodium, magnesium, iron, zinc, selenium, copper, and manganese). To integrate these nutrients into the multi-objective programming model, it is imperative to convert food consumption data into nutrient content. The conversion coefficients for each nutrient, along with the edible portion coefficients for each food, are derived from the *China Food Composition Tables* (National Institute for Nutrition and Health, 2021). Additionally, the nutrient intake guidelines, including recommended and maximum intake levels for each nutrient, are sourced from the *Chinese DRIs Tables (2013 Edition)* (Chinese Nutrition Society, 2014).

2.3 Greenhouse gas emissions from food system

A primary objective of this study is to construct a diet pattern that not only promotes health but also minimizes greenhouse gas (GHG) emissions from the food system. Accurate GHG emission conversion coefficients are essential for this purpose. This research utilizes the food system GHG emission coefficients reported by Song et al. (2017), which are based on a global life cycle assessment (LCA) method and drawn from an extensive database of 1,237 articles maintained by the Barilla Center for Food & Nutrition (BCFN). These coefficients encompass the entire supply chain from production to consumption, accounting for GHGs such as CO_2, N_2O, and CH_4 produced during agricultural activities, as well as CO_2 emissions from energy consumption in subsequent stages of the supply chain. An advantage of these coefficients is their incorporation of uncertainty measures, employing triangular probability distributions and Monte Carlo simulations to enhance the reliability of the GHG emissions assessment (Eggleston et al., 2006; Song et al., 2015). The specific parameters are detailed in Table 3. To validate the reliability of these GHG emission conversion coefficients, a sensitivity analysis is conducted as part of the robustness tests.

2.4 Food preference and elasticity

To accurately reflect consumers' dietary habits and preferences, this study incorporates demand price elasticity as a critical parameter in the diet programming model. This approach follows the methodologies established by Green et al. (2015) and Irz et al. (2015). Chalmers and Revoredo-Giha (2019) suggest that different socio-economic groups exhibit distinct demand price elasticities, necessitating tailored calculations to accurately mirror the food consumption preferences of these groups. Consequently, this study estimates demand price elasticities for low, middle, and high-income groups, integrating these parameters into the model to reflect the inertia in changing consumption habits. The economic model employed is comprehensive and robust, built upon the Stone index implicit Marshallian demand system (EASI) as proposed by Lewbel and Pendakur (2009), and uses a two-stage consistent estimation method by Shonkwiler and Yen (1999) to address the issue of zero consumption values. This model combines the strengths of widely utilized models such as Almost Ideal Demand System (AIDS) and Quadratic Almost Ideal Demand System (QUAIDS) and is capable of discerning complex impacts of income, price, and other variables on food consumption behavior (Zhen et al., 2014). The data employed for estimating demand price elasticity are consistent with the food consumption and expenditure data previously mentioned, ensuring coherence in matching parameters with dietary data. To address potential endogeneity concerns related to the association between expenditure share and expenditure, price, the Dubin-Wu–Hausman (DWH) method is used, and the Generalized Method of Moments (GMM) is applied for estimation (Zhu et al., 2022). Estimates of own-price elasticity of Marshallian demand are provided in Table 3.

3 Methods

3.1 Conceptual framework

The development of a sustainable healthy diet necessitates a holistic approach that bridges multiple systems. This approach is primarily focused on the food system, yet extends into socio-economic, nutrition-health, and climate-environment systems, integrating foundational theories from diverse disciplines. The overarching goal is to formulate diets that are not only aligned with established eating habits and cost-effective, but also confer benefits to

TABLE 3 Parameters of multi-objective programming model considering different income group.

Food items	GHG emission conversion coefficients	Own-price elasticity			
		Full sample	Low-income group	Middle-income group	High-income group
Rice	2.470	−1.005	−1.111	−0.996	−0.916
Wheat	0.970	−1.161	−1.172	−1.152	−1.187
Other cereals	0.788	−1.379	−1.525	−1.351	−1.348
Vegetable oil	2.820	−0.978	−1.058	−0.972	−0.894
Animal oil	2.820	−0.840	−0.909	−0.842	−0.706
Pork	4.220	−0.939	−0.953	−0.939	−0.921
Beef	21.300	−0.830	−0.794	−0.843	−0.819
Mutton	13.360	−0.791	−0.732	−0.816	−0.760
Chicken	3.920	−0.802	−0.840	−0.787	−0.807
Duck	3.920	−0.700	−0.873	−0.689	−0.563
Eggs	3.260	−0.761	−0.769	−0.764	−0.744
Fresh milk	1.450	−0.956	−0.977	−0.959	−0.927
Yogurt	1.550	−1.021	−1.024	−1.024	−1.015
Fish	4.840	−0.917	−0.919	−0.912	−0.928
Shrimp	3.000	−0.876	−0.897	−0.878	−0.840
Vegetables	0.870	−0.834	−0.907	−0.830	−0.767
Fruits	0.880	−0.860	−0.838	−0.860	−0.883
Melons	0.880	−1.054	−1.095	−1.048	−1.035
Alcohol	2.300	−0.993	−0.987	−0.995	−0.992
Confectionery	1.677	−0.686	−0.539	−0.691	−0.786

The greenhouse gas emission coefficients ζ_i for food are primarily derived from Song et al. (2017). Specifically: The coefficient for other grains is based on the average of corn, root crops, other cereals, and legumes. Data for other coefficients are sourced from the BCFN (The Barilla Center for Food & Nutrition) database. The coefficient for pastries is the average of biscuits, bread, and desserts. The Marshallian own-price elasticity of food demand is calculated by the authors.

both environmental and health outcomes. This conceptual framework is illustrated in Figure 1.

Initially, the food system is deeply intertwined with the socio-economic system. Grounded in consumer behavior theory and welfare economics, individuals aim to maximize their utility from food consumption or minimize the costs associated with their food purchases. Within the confines of their financial resources, individuals choose foods that reflect their dietary preferences, exemplifying the quintessential consumption behavior of a rational actor within society. As socio-economic conditions evolve, they prompt a diversification among consumer demographics, leading to varying income levels and consequently, distinct patterns of food consumption. Therefore, a sustainable healthy diet should aim to maximize economic welfare across these diverse income groups while accommodating their dietary preferences. This necessitates that the optimized diets should not significantly elevate the cost of food and should preserve consistency in the consumption of various food types. Our study aims to minimize both the economic costs and the alterations in food consumption patterns in the pursuit of optimized diets.

Moreover, the food system is closely linked to the nutrition-health system. The primary role of food is to supply the essential energy required for human survival and to support health through a diverse array of nutrients. Drawing on the theories of nutritional balance and dietary transition, it is crucial for individuals to consume a balanced mix of nutrients to foster healthy development, with nutritional health influenced by factors such as income, dietary preference and nutritional awareness (Popkin, 1993; Popkin, 2006). Consequently, a sustainable healthy diet should also strive to maximize health welfare for all income groups by ensuring nutrient intakes are within recommended levels. Thus, the optimized diets should offer a more balanced nutrient intake and significantly improve the overall dietary quality. In this study, adequate nutrient intake is incorporated as a constraint within our diet optimization model.

Finally, with the intensification of global climate change and shifts in diets, the food system's greenhouse gas emissions increasingly impact the climate-environment system. The entire life cycle of food, from production to consumption, generates greenhouse gases, contributing to global warming, glacier melt, sea-level rise, and various other environmental challenges (Garnett, 2011; Xiong et al., 2020). From the perspective of environmental economics, consumption behaviors that negatively affect the environment are economically inefficient and can result in significant negative externalities when environmental welfare losses are substantial, jeopardizing the welfare of both current and future generations. This is contrary to the theory of sustainable development, which advocates for a balance between economic growth and environmental preservation. Therefore, a sustainable healthy diet should also aim to maximize environmental welfare by reducing greenhouse gas emissions. According to environmental economic theory, internalizing these external costs into consumer food choices is a critical strategy for addressing these externalities. Consequently, our study incorporates the reduction of food system greenhouse gas emissions as a key optimization objective.

Building upon this conceptual framework, Figure 2 presents the technical roadmap for developing a sustainable healthy diet for Chinese residents. This roadmap includes four main components: (1) Data and parameter acquisition, involving the collection of data on food consumption, expenditures, nutrient and greenhouse gas

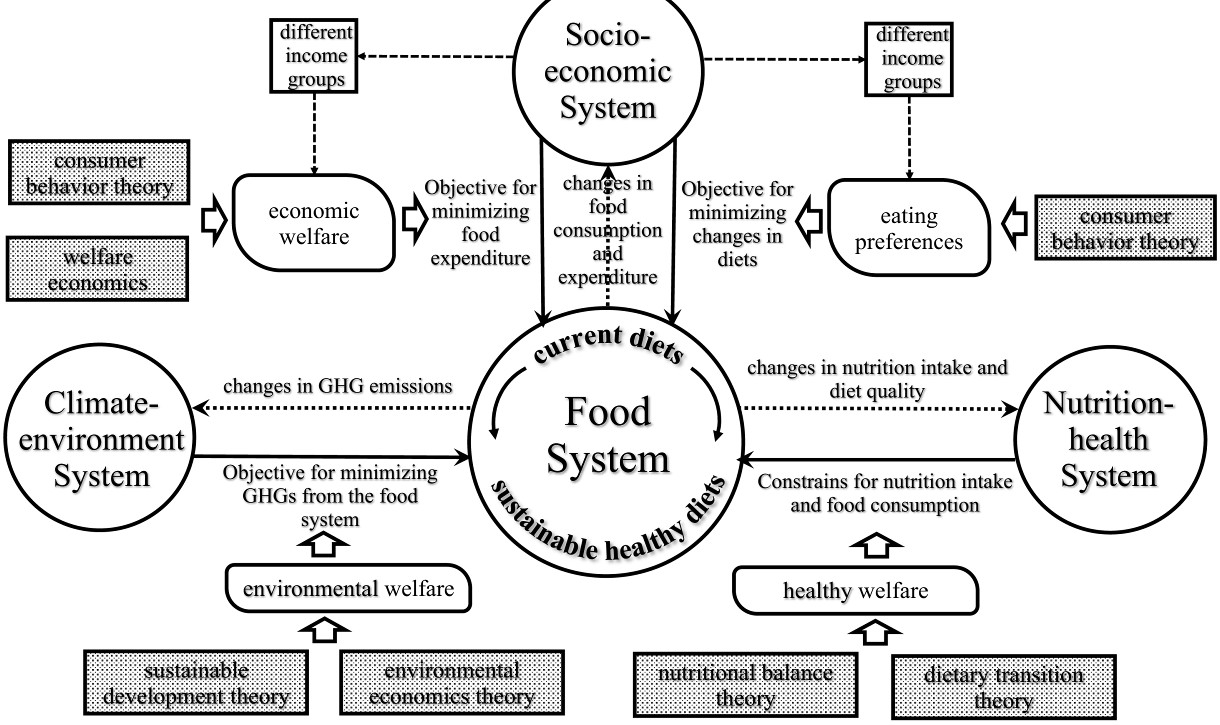

FIGURE 1
Conceptual framework for building sustainable healthy diets.

emission conversion coefficients, and food demand elasticity parameters to support the construction of the diet; (2) The establishment of a multi-objective programming model that recognizes income group disparities and includes three types of optimization objectives, alongside nutrient intake constraints, providing a methodological foundation for diet development; (3) The design of scenarios, which considers five different types of scenarios based on the optimization objectives and the programming model; (4) The evaluation of the resulting diets, assessing them from socio-economic, nutrition-health, and climate-environment perspectives, and confirming the robustness of the results through a sensitivity analysis of the parameters.

3.2 Multi-objective programming model considering income group differences

Prior studies on programming models for sustainable healthy diets typically employed single-objective linear or nonlinear frameworks, addressing diet optimization at a uniform group level(Chalmers and Revoredo-Giha, 2019; Green et al., 2015; Yin et al., 2021). However, significant disparities exist in dietary preferences across different income groups, and decision-making in this context is inherently multi-objective. Decisions are influenced by a range of considerations beyond merely reducing greenhouse gas emissions or minimizing deviations from existing dies. Economic considerations, such as the cost of food purchases, often play a critical role, and decision outcomes can be seen as an amalgamation of these varied factors. This study, therefore, proposes the development of a multi-objective programming model that explicitly incorporates income group differences. The core premise is that residents from diverse income brackets, constrained by specific limitations and guided by the relative significance of each objective, collaboratively determine the most suitable diet. In this study, we define three primary objectives: minimizing food expenditure, minimizing changes in diets, and reducing greenhouse gas emissions from the food system.

Multi-objective programming involves balancing and prioritizing multiple goals. On one hand, it is crucial to determine a target level for each objective, which represents the decision-makers' perception of acceptable values for each goal. In this model, the target values for food expenditure, changes in diets, and greenhouse gas emissions are derived from the results of single-objective optimizations that do not consider the other objectives. Consequently, achieving an optimal balance in the multi-objective model necessitates trade-offs, and the outcomes are likely to approach but not fully achieve the values determined by single-objective optimizations (Rardin, 2018). On the other hand, establishing a priority sequence for these objectives is essential. Drawing on Maslow's hierarchy of needs in psychology, which posits that human behavior is motivated by the fulfilment of hierarchical needs (Maslow, 1943), the prioritization in this model reflects different levels of consumer needs. At the most basic level, economical and sufficient food meets the fundamental physiological needs. Once these are met, the focus shifts to intermediate social needs, such as maintaining established dietary habits, which provide comfort beyond mere survival. At the highest level, minimizing greenhouse gas emissions reflects a need for self-actualization, where

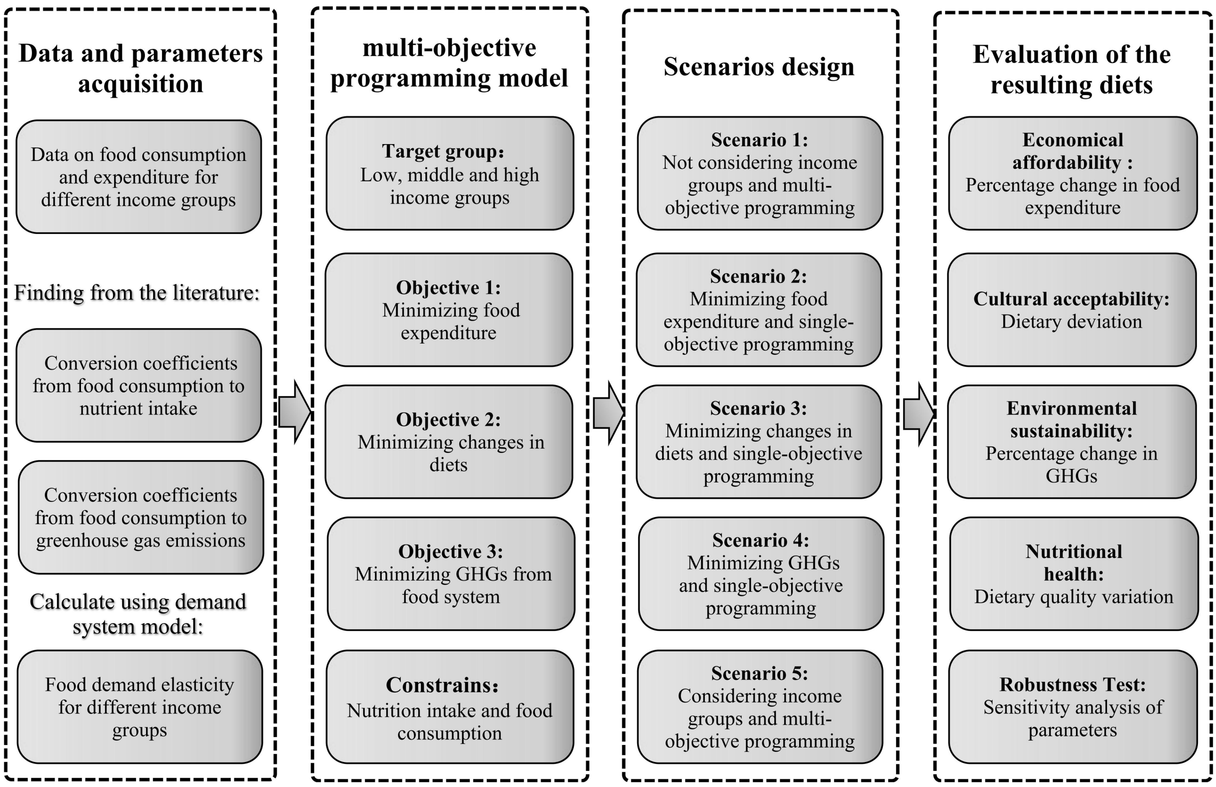

FIGURE 2
Technical roadmap for building sustainable healthy diets.

individuals express their environmental philosophy through their dietary choices. Thus, the prioritization of objectives in this study is structured as follows: first, minimize food expenditure; second, minimize changes in diets; and third, reduce greenhouse gas emissions from the food system.

Building upon the conceptual framework and pertinent theoretical underpinnings, this research delineates three distinct objective functions within its model:

1) Objective for minimizing food expenditure:

$$Minimize\ C = \sum_i p_i q_i \tag{1}$$

In Equation 1, C represents the total expenditure on food consumption as defined by this study; q_i denotes the consumption quantity of food i within the sustainable healthy diet, which is also the decision variable; p_i indicates the purchase price of food i.

2) Objective for minimizing changes in diets:

$$Minimize \Delta D = \sum_i \frac{w_i}{\varphi}\left(\frac{q_i - x_i}{x_i}\right)^2 \tag{2}$$

In Equation 2, ΔD measures the weighted sum of squares of deviations from the current diet to the target diet (changes in dietary structure). The larger the value of this indicator, the greater the deviation from the current diet, indicating a greater dissatisfaction with personal food preference. The weight is the ratio of the food expenditure share to the price elasticity of food demand, reflecting the difficulty for consumers to deviate from their eating habits. w_i represents the share of expenditure for food i in the total food expenditure, φ represents the absolute value of the Marshallian own-price elasticity of demand for food i, which is estimated based on the EASI model based on the estimating procedure from Zhu et al. (2022). x_i denotes the current consumption of food i.

3) Objective for minimizing greenhouse gas emissions from the food system:

$$Minimize\ G = \sum_i \zeta_i q_i \tag{3}$$

In Equation 3, G denotes the *per capita* greenhouse gas emissions from the food system, while ζ_i represents the greenhouse gas emissions conversion factor per unit of food i.

The model incorporates constraints predominantly focused on the dietary intake of various nutrients:

$$R_j \le \sum_{i=1}^{n} q_i \eta_{ij} r_i \le UL_j \tag{4}$$

In Equation 4, R_j represents the recommended intake of nutrient j, UL_j represents the maximum intake of nutrient j. η_{ij} indicates the content of nutrient j in food i, r_i represents the edible proportion of food i.

Additionally, the research introduces constraints on the consumption range for food items:

$$a_i \le q_i \le b_i \tag{5}$$

In Equation 5, a_i is the 20% quintile of the current consumption quantity of food i, and b_i is 180% of the current consumption quantity of food i. Considering the potential health hazards of excessive intake of certain foods, the constraints also stipulate that the consumption of alcoholic beverages and oils and fats should not increase. It should be noted that given the complexity of the optimization objectives and constraints, the multi-objective programming might not be able to find the optimal solution; thus, the constraints are set as soft constraints in this study, meaning that the nutritional constraints are met as much as possible. Therefore, the evaluation of the optimization results is conducted through the overall improvement of dietary quality (Vieux et al., 2013).

In refining the multi-objective programming model, this study integrates the methodological approach of Reynolds et al. (2019) to address the dietary preferences of different income groups. By calculating the diets specific to each income bracket and subsequently taking a weighted average based on the sample sizes of these groups, we derive a comprehensive, healthy, and sustainable diet that represents the general populace of Chinese residents.

3.3 Scenario design

To evaluate the efficacy of the multi-objective programming model that incorporates income group differences, as applied in this study, it is compared against the outcomes of a traditional single-objective programming model that overlooks such distinctions. To this end, five scenarios have been established (Table 4). Notably, scenario 5 (S5) implements the multi-objective programming model with consideration of income group differences. In contrast, scenario 1 (S1) operates without regard to income group disparities, employing a multi-objective programming model at an aggregate sample level. Additionally, scenario 2 (S2), scenario 3 (S3), and scenario 4 (S4) each utilize a single-objective programming model that acknowledges income group differences but focuses exclusively on distinct optimization objectives: minimizing food expenditure (S2), minimizing changes in diets (S3), and minimizing greenhouse gas emissions from the food system (S4), respectively. It is important to note that all five scenarios adhere to the same set of constraints, which ensure that the diets meet a basic level of balanced nutrient intake. This consistent constraint framework allows for an equitable comparison of the scenarios, highlighting the impact of integrating multiple objectives versus focusing on a single objective.

3.4 Evaluation of the resulting diets

In this study, the multi-objective programming model, which incorporates variations among income groups, along with the five designed scenarios, has facilitated the derivation of several sustainable healthy diets. It is imperative to conduct a comprehensive evaluation of these diets, focusing on several critical aspects: economical affordability, cultural acceptability, environmental sustainability, and nutritional health statuses. Furthermore, the robustness of these outcomes is rigorously assessed through sensitivity analysis of key parameters. This analysis explores how changes in these parameters might influence the stability and viability of the resulting diets, ensuring that the sustainable healthy dies are both practical and resilient under varying conditions.

The economical affordability is evaluated using the percentage change in food expenditure (changes in dietary costs), ΔC, as expressed in Equation 6:

$$\Delta C = \left(\sum_i p_i q_i - \sum_i p_i x_i \right) / \sum_i p_i x_i \times 100\% \qquad (6)$$

To assess the cultural acceptability, a weighted sum of squares of deviations from current diets to the target diet (changes in dietary structure), ΔD, is used, as shown in Equation 7. A smaller ΔD value indicates greater alignment with consumers' dietary habits:

$$\Delta D = \sum_i \frac{w_i}{\varphi} \left(\frac{q_i - x_i}{x_i} \right)^2 \qquad (7)$$

The environmental sustainability is measured by the percentage change in *per capita* greenhouse gas emissions from the food system (changes in dietary emissions), ΔG, as formulated in Equation 8:

$$\Delta G = \left(\sum_i \zeta_i q_i - \sum_i \zeta_i x_i \right) / \sum_i \zeta_i x_i \times 100\% \qquad (8)$$

The variables and parameters in Equations 6–8 maintain their meanings consistent with the previous sections.

Furthermore, the nutritional health status is assessed using indicators that reflect dietary quality. Based on the methods of Vieux et al. (2013) and Chalmers and Revoredo-Giha (2019), changes in nutrient intake due to dietary changes can be translated into dietary quality indicators, specifically the Mean Adequacy Ratio (*MAR*) and the Mean Excess Ratio (*MER*), to measure overall nutritional quality improvement.

The *MAR*, used to evaluate nutrient intakes below recommended levels, is defined as:

$$MAR = \frac{1}{m} \cdot \sum_{k=1}^{m} \frac{N_k}{RDA_k} \times 100 \qquad (9)$$

The *MER*, for assessing nutrient intakes above recommended levels, is:

$$MER = \frac{1}{n} \left(\sum_{k=1}^{n} \frac{N_k}{RDA_k} \times 100 \right) - 100 \qquad (10)$$

In Equations (9, 10), a higher *MAR* indicates better dietary quality; a lower *MER* suggests higher dietary quality. N_k denotes the average intake of nutrient k; RDA_k is the recommended intake quantity for nutrient k in the *Chinese Dietary Guidelines* during the *MAR* calculation, if N_k changes to N_k^*, exceeding the RDA_k, then N_k^* is set to RDA_k to ensure that high intake of one nutrient cannot compensate for other nutrients, making the *MAR* more rational. Similarly, for the *MER* calculation, if N_k changes to N_k^*, falling below the RDA_k, then N_k^* is set to RDA_k to ensure that low intake of one nutrient cannot offset deficiencies in other nutrients, making the *MER* more rational.

Lastly, the study conducts sensitivity analysis on the primary scenario outcomes by adjusting the greenhouse gas emission coefficient ζ_i and the price elasticity coefficient φ by a magnitude of ±10% to test the robustness of the results.

4 Results

4.1 Optimization results for the sustainable healthy diets

4.1.1 Overall analysis based on food categories and five scenarios

The analysis of overall trends in the diets reveals significant shifts from current consumption habits as evidenced in the five scenarios of sustainable healthy diets. Notably, there is an increase in the consumption of eggs and milk, fruits and vegetables, coupled with a reduction in the intake of edible oils, meat and poultry, as well as other food groups. Trends in cereal and aquatic products consumption were variable (Figure 3), aligning generally with findings from prior researches (Green et al., 2015; Reynolds et al., 2019; Song et al., 2017).

Detailed examination of Figure 3 indicates that among the categories where consumption has increased, fruits and vegetables show the most substantial rise in daily *per capita* consumption, varying from 108.6 to 255.0 grams. This increase is primarily attributed to their role in supplementing dietary fibers and other essential nutrients, their lower greenhouse gas emissions intensity, and their relatively affordable purchase costs. Eggs and milk consumption also show an increase, ranging from 9.4 to 36.5 grams, with milk specifically increasing from 31.3 to 63.8 grams. This rise is mainly due to the existing deficiency in calcium intake among Chinese residents, with milk serving as a key source of calcium.

TABLE 4 Scenarios design.

Scenarios	Objective			Consider income groups	Nutritional constrains	Objective procedure
	Minimize food expenditure	Minimize changes in diets	Minimize GHGs in food system			
S1	Yes	Yes	Yes	No	Yes	Multi
S2	Yes	No	No	Yes	Yes	Single
S3	No	Yes	No	Yes	Yes	Single
S4	No	No	Yes	Yes	Yes	Single
S5	Yes	Yes	Yes	Yes	Yes	Multi

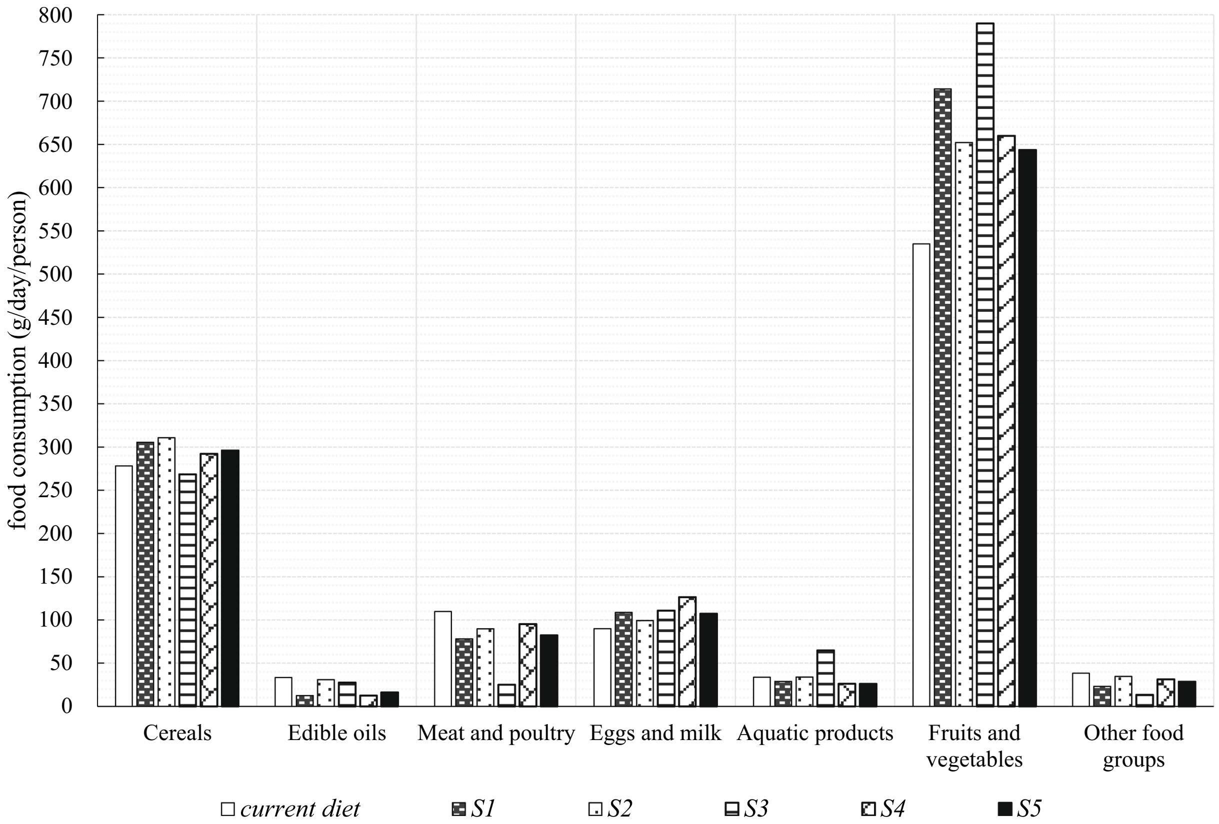

FIGURE 3
Results of sustainable healthy diets under five scenarios Notes: "current diet" indicates the diet before optimization in Table 2; "S1" is a multi-objective programing ignoring income group differences; "S2," "S3," and "S4" are single-objective programing considering income differences, with goals to minimize food expenditure, changes in diets, and GHGs from the food system, respectively; "S5" is a multi-objective programing with income differences considered. Source: Author's calculation based on programming models.

Conversely, in categories with reduced consumption, edible oils see a decrease ranging from 2.5 to 20.9 grams, primarily driven by efforts to control fat and cholesterol intake. Meat and poultry consumption decrease by approximately 14.4 to 84.7 grams. Despite being major protein sources, these food items are high in fats and have a considerably higher greenhouse gas emissions intensity compared to plant-based foods. Additionally, due to their higher costs, their consumption is reduced under scenarios optimizing for carbon emissions and expenditure reduction. Alcoholic beverages and confectionery show a reduction ranging from 3.7 to 25.0 grams, reflecting health concerns associated with excessive intake.

For the two categories with uncertain trends, cereal consumption shows variations from a decrease of 9.8 grams to an increase of 32.5 grams. The decrease is primarily observed in the cost minimization scenario (S3), which reflects a significant reduction in the consumption of more expensive cereal varieties. In contrast, other scenarios indicate an increase in cereal consumption. Aquatic product consumption fluctuates between a decrease of 7.7 grams and an increase of 30.9 grams, with the cost minimization scenario (S3) showing the largest increase due to a shift towards consuming lower-priced fish varieties. The diet change minimization scenario (S2) maintains current levels of aquatic product intake, while the other scenarios generally indicate a reduction in consumption.

4.1.2 In-depth analysis of scenario 5 considering multi-objectives and income group disparities

Under the overarching objectives of minimizing food expenditure, reducing variability in food consumption, and mitigating greenhouse gas emissions from the food system, while adhering to nutritional guidelines, the preferred sustainable healthy diets in S5 are illustrated by the dark columns in Figure 4.

Figure 4 highlights the cereal group as the primary energy source. Despite stable overall consumption, significant reallocations within this category are evident in the sustainable diet. Specifically, average rice consumption has decreased by 31.0 grams, whereas wheat and other cereals have increased by 29.2 grams and 19.6 grams, respectively. These adjustments primarily aim to minimize greenhouse gas emissions, as rice production and processing emit substantially more greenhouse gases—rice's carbon footprint is 2.5 and 3.1 times greater than that of wheat and other cereals, respectively. Additionally, the higher protein content in wheat has prompted a substitution, particularly critical for addressing protein deficiencies observed in lower and middle-income groups. In addition, edible oil has been considerably reduced. Vegetable oil and animal oil, the main sources of fats, have seen significant consumption cuts, especially among middle and high-income groups, who previously had excessive fat intake. Consequently, consumption of both oil types has decreased by 51 and 80%, respectively.

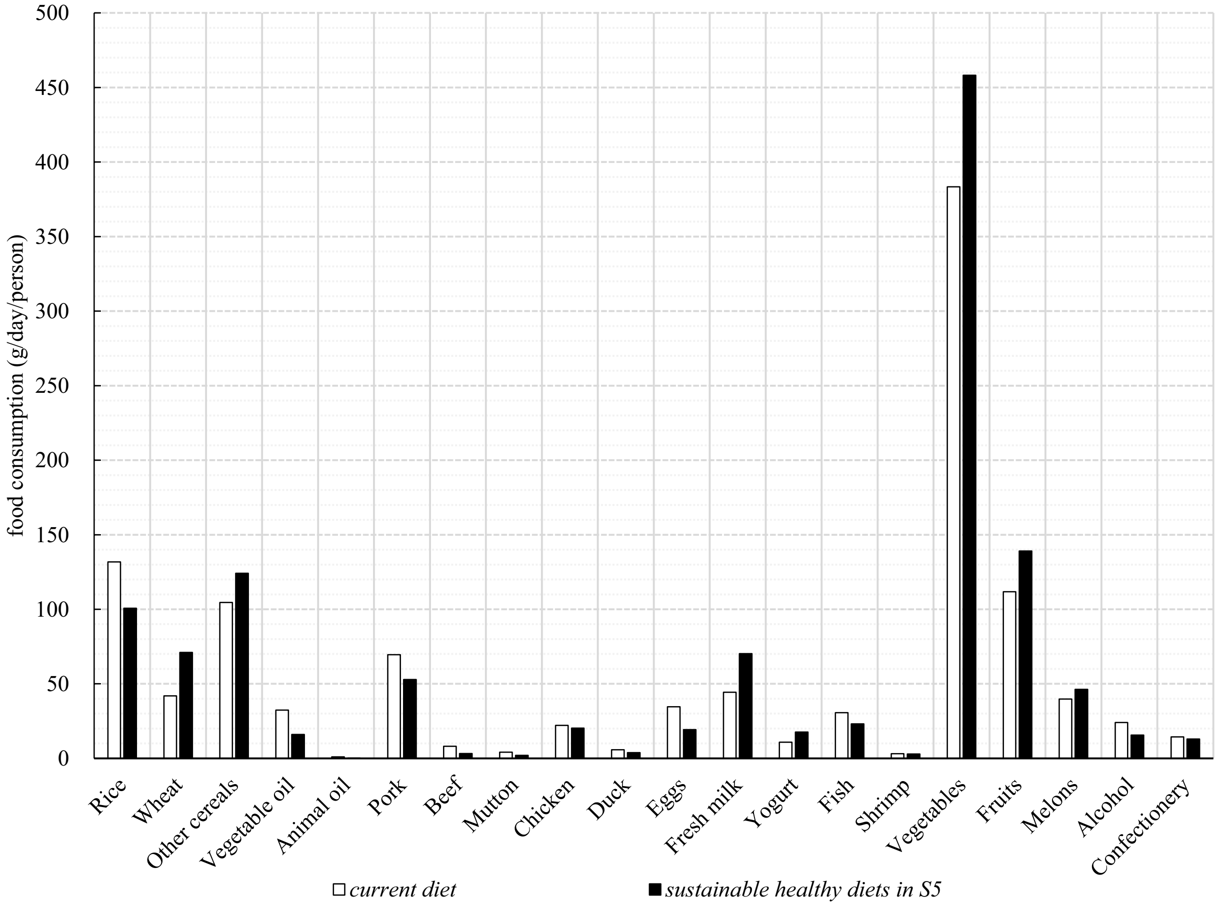

FIGURE 4
Results of sustainable healthy diets under Scenario 5 Notes: "current diet" indicates the diet before optimization in Table 2; "the sustainable healthy diet in S5" corresponds to the multi-objective programming results (S5) accounting for income group differences. Data Source: Author's calculation based on programming models.

Analysis also indicates a reduction in meat and poultry consumption within the sustainable healthy diet, closely linked to their high greenhouse gas emissions and elevated cost factors. Pork, predominantly consumed by Chinese, has seen the largest decrease of 16.7 grams. However, beef and mutton show the most significant percentage declines at 61 and 53% respectively, due to their exceptionally high greenhouse gas emissions. Chicken and duck consumption have decreased by 1.8 grams and 1.9 grams, respectively, with duck showing a notable percentage decrease of 33% due to its low baseline consumption, while chicken exhibits the smallest reduction at 8%, attributed to its lower cost and fat content, suggesting a preference to maintain some chicken consumption amidst overall meat reductions.

There is a marked increase in eggs and milk consumption in the diet, primarily driven by increases in milk and yogurt consumption, which have risen by 25.8 grams and 6.8 grams, equating to growth rates of 58 and 62%, respectively. This surge is necessitated by the high calcium content in milk, addressing the severe calcium deficiency among residents in China. Conversely, due to their high cholesterol content and excessive cholesterol intake among these residents, egg consumption has decreased by 15.3 grams, a 44% reduction. Aquatic product consumption has slightly declined. Fish and shrimp intake has been reduced by 7.5 grams and 0.2 grams, with decreases of 24 and 8%, respectively. The significant reduction in fish consumption is mainly attributed to its high greenhouse gas emission intensity, while the smaller decrease in shrimp is due to its higher calcium content, balancing the need to reduce emissions with increasing calcium intake.

Fruit and vegetable consumption has significantly increased, aligning with both domestic and international research that advocates for higher consumption in sustainable diets (Willett et al., 2019). This study observes increases in vegetable, fruit, and melon consumption by 74.8 grams, 27.3 grams, and 6.5 grams, respectively, with growth rates ranging from 16 to 24%. These foods are essential in diets low in dietary fiber and high in fat, offering not only fiber but also essential micronutrients like potassium, with the added benefits of low greenhouse gas emissions and reduced costs. Lastly, the sustainable healthy diet advocates for reducing the intake of alcoholic beverages and confectionery, which are high in alcohol and sugars, respectively. Under nutrient intake constraints and the goal of not increasing alcohol consumption, the intake of these items has decreased by 8.4 grams and 1.4 grams, respectively, with decreases of 35 and 10%.

TABLE 5 Evaluation of the resulting diets for different scenarios.

Evaluation indicators	Current diets	Scenarios				
		S1	*S2*	*S3*	*S4*	*S5*
ΔD	0.0	2013.6	1352.5	8209.8	7664.6	1524.9
ΔC	0.0	−6.5%	5.0%	−30.3%	3.1%	−1.1%
ΔG	0.0	−10.8%	−0.1%	−7.4%	−14.1%	−12.8%
MAR	78.6	88.4	87.0	86.5	88.1	84.4
MER	56.4	45.1	57.8	53.8	50.3	46.4

ΔD indicates the weighted sum of squares of deviations from the current diet to the target diet (changes in dietary structure); ΔC indicates the percentage change in food expenditure (changes in dietary costs); ΔG indicates the percentage change in per capita greenhouse gas emissions from the food system (changes in dietary emissions); a higher MAR indicates better dietary quality and a lower MER suggests higher dietary quality. Source: Author's calculation based on programming models.

TABLE 6 Evaluation of the resulting diets for different income groups.

Evaluation indicators	Low-income group		Middle-income group		High-income group	
	Current diet	Diet in S5	Current diet	Diet in S5	Current diet	Diet in S5
ΔD	0.0	1232.8	0.0	1658.9	0.0	1897.0
ΔC	0.0	2.0%	0.0	−0.4%	0.0	−4.8%
ΔG	0.0	11.1%	0.0	−14.5%	0.0	−23.4%
MAR	66.1	70.1	80.9	89.1	77.2	86.4
MER	30.0	36.4	61.1	51.3	60.5	38.6

ΔD indicates the weighted sum of squares of deviations from the current diet to the target diet (changes in dietary structure); ΔC indicates the percentage change in food expenditure (changes in dietary costs); ΔG indicates the percentage change in per capita greenhouse gas emissions from the food system (changes in dietary emissions); a higher MAR indicates better dietary quality and a lower MER suggests higher dietary quality. Source: Author's calculation based on programming models.

4.2 Evaluation results

This section evaluates the alignment of the sustainable healthy diet with the FAO's foundational principles, including environmental sustainability, nutritional health, economical affordability, and cultural acceptability. According to Equations 6–10, the evaluation results are summarized in Table 5. According to Table 5, the scenario focused on minimizing the deviations from current diet (S2) reported the lowest weighted sum of squared deviations, totaling only 1352.5. The multi-objective programming scenario that considers income group differences (S5) recorded a slight increase in the weighted sum of squared deviations to 1524.9, which remains substantially lower than those observed in the other scenarios. In terms of changes in food expenditure, the scenario aimed at minimizing these costs (S3) determined that the diet could reduce expenses by 30.3%. In contrast, the single-objective programming scenarios (S2 and S4) saw increases of 5.0 and 3.1% in food expenditure. The multi-objective programming scenario (S5), which incorporates income group differences, achieved a modest cost reduction of 1.1%, successfully meeting the essential goal of economical affordability. All scenarios effectively reduced greenhouse gas emissions from the food system, with reductions ranging from 0.1 to 14.1%. The scenario exclusively targeting the minimization of these emissions (S4) demonstrated the most significant reduction. The multi-objective scenario (S5) also showed a notable decrease in emissions by 12.8%, aligning with the 5 to 28% reduction range reported by Song et al. (2017). Regarding improvements in dietary quality under nutritional constraints, the diets across all scenarios significantly enhanced the existing diet, aligning it more closely with nutritional health standards. Initially, the diet's *MAR* and *MER* stood at 78.6 and 56.4, respectively. Post-scenario implementation, *MAR* values increased to between 84.4 and 88.4, while *MER* values decreased to between 45.1 and 57.8. Notably, the *MAR* and *MER* for the multi-objective scenario (S5) were 84.4 and 46.4, respectively, indicating substantial improvements in dietary quality.

The diets for different income groups, as calculated by the multi-objective programming model, are detailed in Table 6. For the low-income group, minimal changes in diets were required to achieve a sustainable healthy diet. However, this resulted in a 2.0% increase in food expenditure and an 11.1% increase in greenhouse gas emissions. The primary cause is the need to supplement protein and fats through animal products, escalating both costs and emissions. The improvements in *MAR* confirm effective nutrient enhancement. This suggests the necessity for income subsidies to mitigate the increased food costs when optimizing the diets for the low-income group. Conversely, the middle- and high-income groups experienced only minor changes in diets, yet saw reductions in food expenditure and greenhouse gas emissions ranging from 0.4 to 4.8% and 14.5 to 23.4%, respectively. The *MAR* and *MER* indicators also reflected an enhancement in diet quality, highlighting the significant role of dietary improvements in the high-income group in optimizing overall diets.

4.3 Robustness check

This section details the robustness check of the diets derived from the multi-objective programming scenario (S5), which incorporates variations by income group, using a sensitivity analysis of key parameters. This analysis involves four distinct outcomes, designated as *GHG_coef+*, *ELA*_coef+, *GHG_coef−*, and *ELA_coef−*. These

TABLE 7 Outcomes of diets change in sensitivity analysis.

Food items	Current diet	*S5*	*GHG_coef+*	*ELA_coef+*	*GHG_coef−*	*ELA _coef−*
Rice	131.7	100.7	101.6	100.9	101.7	100.6
Wheat	41.9	71.1	71.1	73.2	67.1	71.1
Other cereals	104.6	124.1	127.6	123.3	124.6	124.0
Vegetable oil	32.4	16.0	11.3	15.2	29.2	17.4
Animal oil	1.0	0.2	0.2	0.2	0.5	0.2
Pork	69.5	52.9	58.8	50.4	51.3	52.7
Beef	8.1	3.2	3.2	3.9	5.0	3.2
Mutton	4.2	2.0	1.9	2.5	3.7	2.2
Chicken	22.1	20.3	24.0	21.5	19.6	20.2
Duck	5.8	3.9	1.8	3.7	4.1	3.9
Eggs	34.6	19.3	17.8	17.8	17.1	19.1
Fresh milk	44.4	70.3	73.7	72.5	66.6	69.8
Yogurt	10.9	17.7	18.0	18.5	17.4	17.6
Fish	30.6	23.2	10.4	24.1	26.4	23.5
Shrimp	3.1	2.9	4.2	2.9	2.6	2.9
Vegetables	383.4	458.2	449.6	470.0	465.4	458.9
Fruits	111.8	139.1	163.7	143.1	136.4	138.8
Melons	39.8	46.3	21.7	46.2	49.0	46.6
Alcohol	24.0	15.6	8.5	15.4	22.5	16.3
Confectionery	14.4	13.0	16.6	12.1	12.1	12.9

Author's calculation based on programming models.

TABLE 8 Outcomes of evaluation change in sensitivity analysis.

Evaluation indicators	*S5*	Scenarios for robust check				
		Average	*GHG_coef+*	*ELA_coef+*	*GHG_coef−*	*ELA _coef−*
ΔD	1524.9	1617.2	2370.9	1829.0	1047.8	1221.0
ΔC	−1.10%	0.10%	−0.6%	−0.8%	2.6%	−0.7%
ΔG	−12.80%	−11.70%	−15.4%	−11.3%	−7.5%	−12.5%
MAR	84.4	84.9	84.9	85.6	84.7	84.4
MER	46.4	48.7	45.4	46.7	55.4	47.4

ΔD indicates the weighted sum of squares of deviations from the current diet to the target diet (changes in dietary structure); ΔC indicates the percentage change in food expenditure (changes in dietary costs); ΔG indicates the percentage change in per capita greenhouse gas emissions from the food system (changes in dietary emissions); a higher MAR indicates better dietary quality and a lower MER suggests higher dietary quality. Source: Author's calculation based on programming models.

outcomes capture the impact of changes in greenhouse gas emission coefficients (ζ_i) and the Marshallian own-price elasticities of food demand (φ). Specifically, these outcomes correspond to a 10% increase in the value of ζ_i (*GHG_coef+*), a 10% increase in the absolute value of φ(*ELA*_coef+), a 10% decrease in the value of ζ_i (*GHG_coef−*), and a 10% decrease in the absolute value of φ(*ELA_coef−*; Table 7).

The effects of these adjustments on the diets under scenarios *S5* and *R1* through *R4* are compiled in Table 8. Firstly, the weighted sum of squared deviations from current diets across the four robustness checking scenarios ranges between 1047.8 and 2370.9, with the S5 scenario yielding 1524.9, closely aligning with the mean value of 1617.2. This indicates that the S5 scenario reflects a typical outcome within the range of tested conditions. Secondly, the average change in food expenditure across the robustness checking scenarios is marginally positive at 0.10%. This result is influenced by an increase in food consumption expenditure in scenario *R3*, while the changes observed in the other three scenarios (*R1*, *R2*, and *R4*) are consistent in direction and magnitude with those of the *S5* scenario. Thirdly, all robustness checking scenarios demonstrate a reduction in greenhouse gas emissions from the food system, with decreases spanning from 7.5 to 15.4%. The average reduction across the scenarios is 11.70%, closely aligned with the 12.80% reduction observed in the *S5* scenario. This consistency underscores the reliability of the model's performance in terms of environmental sustainability. Lastly, the average values of the *MAR* and *MER* indicators across the robustness checking scenarios are 84.9 and 48.7, respectively. These figures exhibit minimal deviation from the values of 84.4 and 46.4 recorded for the *S5* scenario, indicating a stable improvement in diet quality across varying conditions. In summary, the results affirm that the diets formulated under the multi-objective programming scenario (*S5*), which takes into account income group differences, are robust and reliable. This reliability is demonstrated by the consistency of outcomes across a range of sensitivity analyses, reinforcing the dependability of the model in guiding dietary improvements that are both healthy and sustainable.

5 Conclusion and discussion

This study commenced by exploring the coupling relationships and theoretical foundations of food systems and their interconnected systems, constructing a conceptual framework to analyze sustainable healthy diets. Utilizing this framework, alongside collected data and parameters, a multi-objective programming model was developed to account for variations among income groups. Sustainable healthy diets for Chinese residents were determined under various simulated scenarios, followed by evaluations and robustness check. The key findings are summarized as follows:

Firstly, the recommended sustainable healthy diet for Chinese residents involves a significant modification of the staple food consumption structure—specifically, reducing rice consumption in favor of flour and other grains. It is advisable to adopt a diet low in fats, enhancing vegetable and fruit intake, and consuming animal products moderately. This includes a slight reduction in the consumption of meat, poultry, eggs, and aquatic products, while ensuring adequate intake of chicken and shrimp and notably increasing milk consumption. Additionally, it is suggested to decrease alcohol intake and limit consumption of snack foods like pastries. Secondly, the sustainable healthy diet derived from the multi-objective programming model, which incorporates income group differences, is capable of reducing food consumption expenditure by 1.1% with minimal changes in diets and it also decreases greenhouse gas emissions from the food system by 12.8%. This pattern significantly enhances diet quality, meeting the criteria for environmental sustainability, nutritional health, economical affordability, and cultural acceptability. Thirdly, differences in the optimized diets among various income groups were observed. All groups showed improved nutritional health after dietary optimization. The low-income group required the least change in diets but faced a 2.0% increase in food expenditure and an 11.1% increase in greenhouse gas emissions. Conversely, middle- and high-income groups, despite larger changes in diets, experienced reductions in both food expenditure and greenhouse gas emissions, ranging from 0.4 to 4.8% and 14.5 to 23.4%, respectively.

The findings underscore that guiding Chinese consumers towards adopting sustainable healthy diets can reduce food expenditure costs and effectively promote reductions in greenhouse gas emissions from the food system. This approach holds considerable potential for enhancing economic welfare, health welfare, and external environmental benefits. However, the reality presents challenges. With the steady increase in income and urbanization, especially in recent years, policies supporting low-income groups and those aimed at improving income distribution have significantly unleashed potential for increased food consumption. This shift has led to a dietary transition towards more animal products, which may pose ongoing challenges for nutrition, health, and climate impact in the near to medium term.

Setting dietary targets is crucial, but equally important is exploring pathways to achieve these sustainable healthy diets. From the consumption end of the food system, future research should focus on two main pathways: first, guiding the transformation of residents' diets through medium-to-long-term plans that promote nutritional health and environmental sustainability, and enhancing dietary education through new media and the internet. Second, it is vital to consider the heterogeneity among income groups when formulating food policies, setting differentiated policy targets, and implementing appropriate policy tools for different income groups. For low-income groups, providing sufficient income subsidies is crucial to enhance their purchasing power, while middle- and high-income groups should be primary targets for policy interventions due to their higher health and environmental awareness and the greater feasibility of improving their diets.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WZ: Conceptualization, Data curation, Funding acquisition, Validation, Visualization, Writing – original draft, Writing – review & editing. XH: Data curation, Methodology, Software, Supervision, Writing – review & editing. YL: Funding acquisition, Writing – review & editing. GL: Funding acquisition, Software, Writing – review & editing. JW: Formal analysis, Investigation, Project administration, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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