A Methodology for Identifying the Green Design of Healthy Diets: An Empirical Analysis Based on a Multidimensional Assessment Framework

1st Xiaoqiong Liu
Royal College of Art
London, United Kingdom
inaaaabiubiu@gmqil.com

***Abstract*—With the growing global focus on sustainable development, the food system faces unprecedented dual challenges related to the environment and health. On one hand, irrational production and consumption patterns exacerbate environmental issues such as greenhouse gas emissions, water consumption, and biodiversity loss. On the other hand, unhealthy dietary structures have become a major risk factor for the prevalence of chronic non-communicable diseases. Against this backdrop, the green design of healthy diets has emerged, aiming to achieve a balance between nutritional health, environmental protection, economic feasibility, and socio-cultural acceptability through a systematic approach. However, the current field lacks a unified and effective standard and methodology for scientifically and systematically identifying and evaluating the "green" attributes of healthy diets. Existing research, often from a single dimension (such as nutrition or environmental science), fails to comprehensively characterize the complex connotations of green design for healthy diets, leading to fragmented assessment results that cannot provide comprehensive decision support for policy-making and industrial practice. This study aims to fill this gap by constructing a multidimensional assessment framework integrating five dimensions—health, environment, design, socio-culture, and economy—to provide a scientific and operational methodological system for identifying the green design of healthy diets. Employing a design innovation methodology combined with life-cycle assessment (LCA), nutritional analysis, and consumer preference surveys, the study develops a comprehensive assessment tool comprising 35 specific indicators. Through an empirical analysis of dietary data from 1200 residents in four first-tier cities in China, this study not only validates the effectiveness and reliability of the assessment framework but also identifies three typical green design patterns for healthy diets and reveals the key factors influencing their adoption. Under a transparent set of illustrative scenarios (documented in Supplementary Sx), we observed that certain dietary adjustments have the potential to reduce environmental footprints while maintaining or improving diet-quality scores. The magnitude of change depends on scenario assumptions (substitution rules, portion constraints, and price references), which are fully reported; therefore, these results should be interpreted as scenario-based estimates rather than universal guarantees. The theoretical contribution of this study lies in providing a multidimensional theoretical analysis perspective and a systematic identification method for the green design of healthy diets. On a practical level, the research findings can provide a scientific basis and decision-making reference for governments in formulating relevant food policies, for enterprises in developing sustainable food products, and for guiding the public to transition towards healthier, greener dietary patterns, thereby promoting the sustainable transformation of the entire food system.**

Keywords*—Healthy Diet,Green Design,Identification Method, Multidimensional Assessment,Design Innovation

I. INTRODUCTION

The global food system is at a critical crossroads. As a coupled human–environment system, it simultaneously underpins human survival and development while exerting substantial pressure on the planet through resource use and environmental externalities. Large-scale evidence based on life cycle assessment (LCA) shows that different food categories vary widely in greenhouse gas emissions, land occupation, and other environmental burdens, and that both producers and consumers can play a role in reducing these impacts [1]. Meanwhile, unhealthy dietary patterns continue to drive the global rise of diet-related chronic non-communicable diseases (NCDs), making the transformation of what people eat a core public-health priority. Importantly, the health and environmental dimensions of diets cannot be treated separately: the EAT–Lancet Commission proposes a scientific framework for “healthy diets from sustainable food systems,” highlighting that dietary transitions can generate co-benefits for human health and environmental sustainability when guided by integrated targets and boundaries [2].

Faced with this dual challenge of health and environment, transitioning food systems toward more sustainable production and consumption has become a widely shared objective. The United Nations’ 2030 Agenda for Sustainable Development explicitly calls for ensuring sustainable consumption and production patterns while addressing hunger and food security, providing a global policy mandate for actionable pathways that link diet, sustainability, and societal well-being [3]. Against this backdrop, the “green design of healthy diets”—as a bridge connecting

Corresponding Author: Xiaoqiong Liu,Royal College of Art, Darwin Building, Kensington Gore, London SW7 2EU, United Kingdom,inaaaabiubiu@gmqil.com

environmental protection and human health—has increasing theoretical and practical importance.

In essence, green design for healthy diets requires systematic innovation: it must satisfy nutritional needs while reducing negative environmental impacts across the food life cycle (production, processing, transportation, consumption, and waste) and remain economically feasible and socially acceptable. However, a core challenge for both academia and industry is how to define and identify whether a dietary pattern meets the criteria of "green design" in a scientific, operational, and context-sensitive manner. Existing approaches often remain fragmented—health-focused studies may emphasize nutrition and disease outcomes, while environment-focused studies may prioritize footprints and ecological indicators—making it difficult to form an integrated identification system that supports real-world decision-making and design optimization.

To address these challenges, this study aims to develop and validate a scientific methodology for identifying green-designed healthy diets. We argue that an effective identification method should be multidimensional, quantifiable, and capable of capturing the value of design innovation. Specifically, this research endeavors to: (1) construct a comprehensive assessment framework covering five dimensions—health, environment, design, socio-culture, and economy; (2) develop a measurable indicator system and corresponding assessment toolset under this framework; (3) apply the tool in empirical settings to identify green design strengths and weaknesses in current urban dietary patterns; and (4) propose targeted design optimization strategies based on the diagnostic results. By bridging theory and practice, the study seeks to provide an actionable, usable tool for policymakers, food-system practitioners, and consumers to support a shift toward healthier and more sustainable dietary futures.

II. Literature Review

In order to systematically build an identification method for green-designed healthy diets, this study synthesizes interdisciplinary literature spanning sustainable healthy diet concepts, green design theory and tools, food system sustainability frameworks, and design innovation methods. The purpose of this chapter is to consolidate theoretical foundations and methodological references for the subsequent framework construction and empirical identification work.

A. Conceptual foundations of sustainable healthy diets

A key prerequisite for any identification method is a clear conceptual definition of what constitutes a "sustainable healthy diet." Garnett's discussion paper provides an influential conceptual framing, emphasizing that such diets must jointly consider health outcomes, environmental pressures, affordability, and cultural acceptability, rather than focusing on a single dimension [4]. Building on this integrative stance, Tilman and Clark provide macro-level evidence that global dietary patterns are simultaneously linked to environmental sustainability and human health, underscoring the necessity of evaluating diets through a combined health–environment lens [5].

From an operational perspective, diet sustainability is also strongly conditioned by regional resource constraints. For example, Vanham et al. quantify how different diets correspond to different water footprints, illustrating that dietary recommendations can have materially different implications for water resources and that "sustainability" cannot be assessed without explicit resource indicators [6]. Together, these studies motivate the need for an identification system that is both conceptually integrative and empirically grounded in measurable environmental and health dimensions.

B. Policy and guideline perspectives on sustainable healthy diets

Beyond academic conceptualizations, international organizations have also articulated actionable principles. The FAO & WHO guiding principles for sustainable healthy diets emphasize nutritional adequacy and safety alongside affordability and reduced environmental impacts, providing a widely recognized normative baseline for integrated diet evaluation [7]. However, translating high-level principles into practical identification tools requires methodologically robust evidence syntheses. Hallström et al.'s systematic review of dietary change and environmental impact consolidates empirical findings across studies, showing how diet shifts can influence multiple environmental indicators and highlighting methodological variability that identification tools must manage explicitly [8].

These guideline and review perspectives jointly indicate that identification methods should (i) align with authoritative principles, and (ii) operationalize them through transparent, reproducible indicators that can be applied consistently in real contexts.

C. Nutritional science basis and the evolution toward personalization

At the health dimension, modern nutrition science clarifies the roles of macronutrients and micronutrients in supporting physiological functions and disease prevention. Standard nutrition textbooks provide the foundational concepts for balanced diet composition and nutritional adequacy, which remain essential inputs for any health-related assessment module [9]. In practice, dietary guidelines translate nutritional science into public-facing recommendations. For example, the Chinese Dietary Guidelines (2022) offer structured guidance on balanced dietary patterns in a concise and actionable format, representing a policy-relevant reference point for localized health evaluation [10].

In recent years, precision approaches have expanded the health-design space. Nutritional genomics research highlights how individual genetic variation can affect diet–health relationships, motivating personalized or stratified dietary design strategies rather than one-size-fits-all recommendations [11]. For identification methods, this implies that health assessment should be capable of accommodating population heterogeneity and context-sensitive design constraints.

D. Green design theory, life-cycle tools, and circular economy approaches

Green design (eco-design) provides the methodological backbone for systematically minimizing environmental impacts over a product/service lifecycle. Design-for-sustainability frameworks emphasize lifecycle thinking, resource efficiency, pollution reduction, and end-of-life considerations, offering structured principles that can be embedded into diet-related design and evaluation [12]. Within this domain, circular economy research argues for the redesign of systems to reduce waste and close resource loops, including food-system transitions that convert by-products and waste streams into new value chains [13].

These perspectives justify explicitly incorporating a "design" dimension into diet identification—treating diets not only as consumption patterns to be assessed, but also as designable systems with levers for innovation, reuse, and systemic efficiency improvements.

E. Food system sustainability as a multidimensional framework

Food system sustainability is inherently multidimensional and typically conceptualized through environmental, social, and economic pillars. Ericksen's conceptualization of food systems for resilience provides a structured lens for understanding how food systems interact with shocks, governance, and outcomes across these dimensions, which is useful for building a comprehensive identification architecture [14]. From the environmental-limits perspective, Springmann et al. synthesize options for keeping food systems within environmental boundaries, reinforcing the need for identification tools to incorporate explicit environmental thresholds or constraint-aware indicators [15].

On the social dimension, sociological work emphasizes that food is not merely a commodity but also embedded in knowledge, culture, and social relations, which directly affects acceptability and the feasibility of dietary transitions [16]. Therefore, any identification method aspiring to be "green design" oriented should integrate socio-cultural acceptability and economic feasibility as first-class dimensions rather than afterthoughts.

F. Design thinking and interdisciplinary integration for socio-technical problems

Food system sustainability is a complex socio-technical challenge that rarely yields to single-discipline solutions. Design thinking provides a human-centered and iterative methodology—empathy, problem definition, ideation, prototyping, and testing—that can translate multidimensional assessment outputs into actionable design interventions [17]. Moreover, design-for-sustainability research has evolved from product-level eco-design to system innovations and transitions, offering pathways for scaling interventions beyond isolated products toward systemic change in food provisioning and consumption contexts [18].

Accordingly, this study positions identification not as an endpoint ("assessment only"), but as part of a closed-loop innovation process that supports design optimization and iterative refinement.

G. Existing identification approaches and their limitations

Existing diet assessment approaches can be broadly categorized into: (1) nutrition-based diet quality indices focusing on adequacy and balance; (2) environmental footprint assessments focusing on quantifying impacts; and (3) integrated global frameworks specifying combined health and sustainability targets. The WHO "Healthy diet" fact sheet provides concise, authoritative recommendations for healthy eating patterns and serves as a baseline reference for health-oriented assessment criteria [19]. Meanwhile, regionally grounded dietary patterns such as the New Nordic Diet demonstrate how health and sustainability principles can be instantiated within specific cultural and geographic contexts, underscoring the importance of localization and cultural fit in any practical identification tool [20].

However, these approaches often share limitations for "green design identification": many remain one- or two-dimensional; indicators may be too macro or abstract to diagnose specific design attributes; and results often stop at evaluation without feeding into structured design optimization cycles.

H. Environmental assessment tools and evidence base for food impacts

A robust environmental evidence base is essential for identification. Poore and Nemecek's landmark LCA synthesis quantifies substantial differences in environmental burdens across food types and highlights intervention opportunities on both production and consumption sides, providing a strong empirical foundation for identifying high-impact foods and leverage points for improvement [1]. In practical application, identification systems must convert such evidence into interpretable metrics that can support trade-off reasoning alongside health and acceptability constraints.

I. Design innovation practices promoting sustainable dietary behaviors

At the intervention and practice level, design and behavioral insights have been used to promote healthier and more sustainable food choices. For instance, work on nudges and information provision shows how choice architecture, value orientation, and targeted information can motivate more sustainable food decisions, supporting the inclusion of design-based intervention levers within an identification-and-optimization pipeline [21]. These cases reinforce the need for standardized evaluation criteria and replicable identification methods so that successful design interventions can be compared, transferred, and scaled across contexts.

III. Methodology and System Design

The aim of this study is to develop a more scientific and systematic green design identification method for healthy diets. To achieve this goal, the research process adopts a mixed-methods research path that is promoted in phases and emphasizes interdisciplinary collaboration, and seeks to combine "qualitative understanding" with "quantitative identification" at the methodological level. This chapter will focus on the overall research strategy, and will provide a detailed explanation of the multidimensional evaluation framework, specific methods for obtaining and analyzing data, and mechanisms used to verify the effectiveness of the method.

A. In terms of research strategy and technical approach

the overall strategy of this study follows the closed-loop logic of "theory construction - tool development - empirical validation - design optimization", that is, starting from the theoretical construction, the development of the tool is applied to specific indicators, and then its usability is verified with the help of empirical evidence, and finally the identification results are reversed for design optimization. As shown in Figure 1, the entire research process is divided into four closely related stages: 1 Framework Building Stage:

First, based on a systematic review and analysis of literature in related areas such as healthy diets, green design, and food system sustainability, the key elements of healthy diet green design are identified. On this basis, the construction of a preliminary framework of multidimensional theoretical evaluation is completed. 2 Indicator Development Stage: Guided by this theoretical framework, this study uses the Delphi method and invites 20 experts from the fields of nutrition, environmental science, design, sociology and the food industry to participate. Through three rounds of anonymous questionnaires, the preliminary index database was screened, reviewed and supplemented. The Analytical Hierarchy Process (AHP) is then used to determine the relative weights between each dimension and specific indicators, and finally a comprehensive evaluation toolkit consisting of five dimensions and 35 specific indicators is created. 3 Application and Empirical Recognition Phase: Four first-level cities in China (Beijing, Shanghai, Guangzhou, and Shenzhen) were selected as the research areas. Detailed dietary data, personal preference information, and socio-demographic information were collected from 1,200 adult residents through a combination of online questionnaires and diet diaries. The developmental evaluation tools are then applied to these data to score quantitatively, to identify the level of healthy diet green design and its key characteristics in different population dietary patterns. 4 Phase of Analysis and Optimization: After obtaining empirical results, this study will use statistical methods such as cluster analysis to identify typical dietary patterns and conduct a deeper analysis of the key factors that affect their green design level. Finally, actionable design improvement strategies are recommended based on the identified shortcomings, and a transparent, rules-based analysis is selected to assess their potential impacts, such as setting scenarios from the perspectives of food substitutes, waste reduction, and cooking method adjustments. All scenario rules, constraints, and calculation scripts are documented to support subsequent reproducibility and validation.

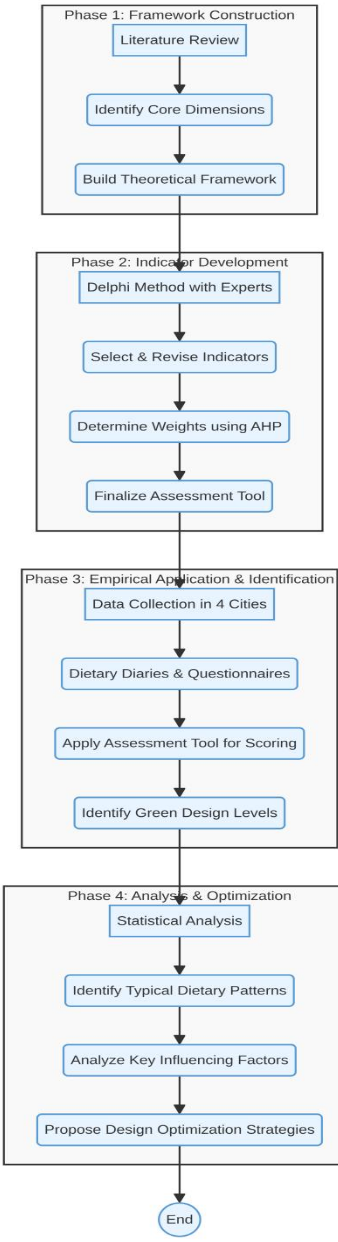

Fig. 1. Research Technical Roadmap

B. *Multidimensional Assessment Framework*

The core of this study is to construct a multidimensional framework that can comprehensively and synthetically evaluate the green design level of healthy diets. This framework (see Figure 2) transcends the traditional single perspective and expands the assessment system to five interrelated dimensions, ensuring the comprehensiveness and systematicity of the assessment.

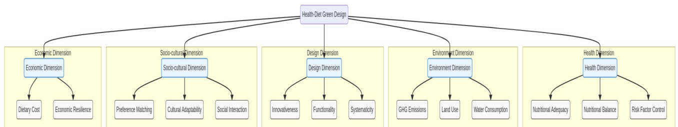

Fig. 2. Multidimensional Assessment Framework for Green Design of Healthy Diets

- Health Aspect: This feature is primarily used to evaluate the direct impact of dietary patterns on human health, and the judgment base focuses more on the balance of nutrient adequacy and nutrient structure. The indicator setting not only focuses on whether the intake of energy and macronutrients (protein, fat, carbohydrates) is within the recommended range, but also takes into account the intake of key micronutrients (m.sh., iron, calcium, vitamin C), and a restricted evaluation of ingredients with adverse health effects, such as sodium, added sugars and saturated fats. The overall evaluation criteria were primarily based on the "China Nutrition Guidelines (2022)" [10].

- Environmental Dimension: This dimension is used to quantify the environmental impact of dietary patterns within its life cycle. Three identified key environmental impact indicators were selected: greenhouse gas emissions (CO_2 equivalent), land use (square metre • year), and water consumption (litres). The calculation of the above indicators is based on clear functional units (per person per day) and the system limit, specified in Supplementary Sx. The emission/footprint factors required to calculate the environment are primarily based on the publicly reported data by Poore & Nemecek (2018), and in order to ensure that they can be reproduced without relying on proprietary databases, Supplementary Materials provides a complete table of factors, including the food category → factor mapping, so that the relevant environmental calculations are repeatable [1].
- Design Dimension: This feature is part of the more innovative part of this study, with the aim of evaluating the design ingenuity and innovative value of the dietary pattern. It is divided into three sub-dimensions: Innovation, which assesses whether the meal pattern uses newer ingredient combinations, cooking methods, or service models; Functionality, which evaluates its performance in terms of convenience and accessibility, and whether it has the ability to meet specific needs, such as wellness, disease management, etc. Systematicity, which considers whether the meal pattern takes into account the optimization of the entire process from supply, storage, cooking to disposal, such as whether it is designed to reduce food waste.
- Socio-cultural dimension: This dimension focuses on the acceptability and adaptability of dietary patterns at the sociocultural level, emphasizing whether they can be accepted and smoothly implemented by the target population in a particular cultural environment. Key indicators include the matching of dietary preferences, that is, the degree of match between dietary patterns and individual taste preferences; cultural adaptability, i.e. respect for local traditions and food habits; and social interaction, that is, the role of eating activities in promoting family and social communication. The data in this dimension is obtained primarily through consumer questionnaires to get closer to true adoption and adaptation.
- Economic Aspect: This dimension is used to assess the economic viability of dietary patterns, and the core indicator is the cost of diet (calculated as an average amount of daily food consumption) to ensure that green and healthy dietary patterns are affordable for the target population. At the same time, this study also takes into account economic resilience, that is, assessing the sensitivity of the dietary pattern to market price fluctuations and its dependence on the local economy, so as to more fully reflect its stability and sustainable landing capacity under real conditions.

C. Data Collection and Identification Method

1) Data Collection

In this study, a multi-source data acquisition strategy was chosen to cover dietary behavior and related background information as fully as possible. Residents' diet data is obtained primarily through the "three-day diet diary method", that is, participants are required to continuously record the type and quantity of all foods and beverages they consume for three consecutive days, including two days of the week and one day of the weekend, so that the difference between working days and rest days will be shown to a certain extent. In order to improve the accuracy and comparability of the data, the study provided participants with an electronic diary template, and the standard pictures were used to compare the amounts, making it easier to record the specific quantity. At the same time, in order to supplement the individual information that is difficult to cover in dietary records, this study also used structured online questionnaires to collect participants' socio-demographic information (m.sh., age, gender, income, education level, etc.), lifestyle, dietary preferences, health cognition, and willingness to pay for sustainable food, to provide more comprehensive explanatory variables for subsequent analysis.

2) Indicator Quantification and Comprehensive Scoring:

After the data collection is completed, the data obtained is processed to quantify the scores of each specific indicator. For the health and environmental indicators, the scores are obtained primarily by comparing the actual intake or level with the recommended standard or average level. For each indicator, the study clearly gives the scoring function form (piece-linear or monotonic transformation), instructions (the distinction between benefit and cost indicators), and the reference used for threshold judgments (m.sh., guideline-based nutritional recommendation ranges, etc.). For environment-related metrics, the overall processing principle is that the lower the footprints, the higher the score through the recorded monotonic transformation, and the conversion relationship is clearly reflected in the material. In order to ensure that the method can be strictly reproducible, this study provides a complete indicator list (35 items), definitions of each item, corresponding scoring functions, and portal sources in Supplemental Sx, so that accurate replication can be performed under the same data conditions.

The comprehensive score was calculated using a weighted summation model. The total score (Score_total) of each dietary sample was obtained by adding the weighted scores of the five dimensions:

$$Score_total = \Sigma(W_i * Score_i)(i = A, B, C, D, E) \quad (1)$$

Where Score_i is the score of the i-th dimension (calculated from the weighted scores of its internal indicators), and W_i is the weight of the i-th dimension (determined by the AHP method). According to the final total score, the green design level of the dietary pattern can be divided into different levels (e.g., excellent, good, medium, poor), thereby achieving scientific identification.

D. Validation Mechanism

In order to ensure that the methodology developed by this study is more stable in terms of science and reliability, a series of double validation mechanisms are introduced into the overall design to test the validity and stability of the method from different perspectives: • Content Validation Validation: In the indicator development phase, the study uses the Delphi method to seek expert opinions. The purpose of the evaluation framework and the system of indicators is to enable the core sign of the green design of a healthy diet to be covered in a more comprehensive and accurate manner, so as to logically ensure the validity of its content. In other words, through multiple rounds of anonymous feedback and expert reviews, the indicator setting and framework structure are calibrated as much as possible to the key question "whether the content of the evaluation has been evaluated and whether the evaluation is in place". •Empirical Validity and Reliability Testing: In the empirical analysis phase, various statistical methods will be used to test the validity and reliability of the assessment tool. For example, use factor analysis to test the validity of the framework construction to confirm that each indicator can be effectively attributed to its corresponding dimension, and avoid the discrepancy between the dimension division and the performance of the indicators. Cronbach's alpha was also calculated to evaluate the reliability of the internal consistency of the questionnaire section to determine the level of agreement between items belonging to the same construction. In addition, the study will also conduct sensitivity analysis to test the robustness of comprehensive scoring results by adjusting weights of different dimensions, focusing on whether the identification conclusion will fluctuate violently due to small changes in weight, to ensure that the identification results have better interpretive stability and reliability.

IV. EXPERIMENTS AND RESULTS

The empirical analysis of this study is based on detailed survey data on the dietary patterns of residents in four first-tier cities in China. This chapter will explain the data sources, sample characteristics, definitions of key variables, and processing methods and rules used in the data pre-processing process.

A. Data Source and Sample:

The study subjects were adult residents aged 18 and over who lived in four first-tier cities, Beijing, Shanghai, Guangzhou and Shenzhen.Informed consent was obtained from all subjects involved in the study. Sample recruitment relies primarily on the online survey platform, and uses city quota sampling by age by gender to get as close to the overall demographic structure as possible, to reduce the apparent bias at the level of sample composition. To improve data quality and reproducibility, pre-programmed screening rules were set and enforced prior to receipt, including duplicate response detection (m.sh., identification of identical devices/IPs where applicable), minimum completion time thresholds, and item attention checking, and logical consistency checks. The full inclusion/exclusion criteria, as well as the exclusion of collection → for reasons → analyzed, are reported in the Supplement for external verification and reproducibility. Data collection consists of two main components: 1 Online Structured Questionnaire: used to collect socio-demographic information, lifestyle, health status, and participants' dietary information and attitudes; At the same time, it covers choices and cognitions related to sociocultural and design dimensions to support multidimensional evaluation and subsequent interpretive analysis. 2 Three-day diet diary: Participants are asked to keep detailed records of their food and beverages over three consecutive days, including specific types, amounts and cooking methods, and include two days of the week and one weekend of three days to capture dietary differences that are more closely related to the rhythm of real life. To ensure that the records are as accurate as possible, the study provides an electronic record template with illustrated descriptions of common food standard portion sizes to reduce portion estimates. In addition, the study only performs follow-up verification of diary entries marked as abnormal by predetermined rules and verified by trained research assistants to improve the reliability of critical data and control the workload. Examples of rules used for flagging include: incredible portion sizes, missing meals, large energy totals, or descriptions of inconsistent cooking methods, etc.; The flag rules are given in the Supplement as well as the examples, so that you can understand how they are executed and the boundary conditions

B. Sample Characteristics

The socio-demographic characteristics of the valid sample are shown in Table I. The sample is basically consistent with the data of the sixth national census in the four first-tier cities in terms of gender and age distribution, and has good representativeness. The sample as a whole shows characteristics of high education and middle-to-high income, which is also in line with the overall profile of residents in first-tier cities.

TABLE I. DESCRIPTION OF SOCIO-DEMOGRAPHIC CHARACTERISTICS OF THE SAMPLE (N=1200)

Feature	Category	Frequency (n)	Proportion (%)
Gender	Male	588	49.0
	Female	612	51.0
Age	18-29	360	30.0
	30-44	480	40.0
	45-59	300	25.0
	60+	60	5.0
Education	High school or below	144	12.0
	College/Bachelor	816	68.0
	Master or above	240	20.0

Feature	Category	Frequency (n)	Proportion (%)
Monthly Income (CNY)	< 5,000	96	8.0
	5,000 - 10,000	384	32.0
	10,001 - 20,000	456	38.0
	> 20,000	264	22.0

C. *Key Variables*

According to the aforementioned multidimensional assessment framework, the key variables involved in this study cover five dimensions. All variables were quantified or coded for subsequent statistical analysis. For example, the nutrient intake was computed using a documented food-composition reference and a reproducible calculation workflow. To avoid dependence on a specific commercial software, we provide the input food list, portion-size conversion rules, and the resulting nutrient-output table used for analysis in Supplementary Sx. Environmental indicators were calculated as consumption × footprint factors, and we provide the complete factor table and food-category mapping used in this study to enable reproduction without access to proprietary LCA databases.

D. *Data Preprocessing*

Before the formal analysis, we performed strict preprocessing on the raw data. First, the food items in the dietary diary were standardized and coded, and colloquial descriptions were unified into standard food names. Second, samples with abnormal total energy intake (males below 1200 kcal/day or above 4000 kcal/day, females below 1000 kcal/day or above 3500 kcal/day) were excluded to rule out possible recording errors. For a small amount of missing questionnaire values were handled using multiple imputation with a clearly specified model (imputation method, number of imputations, variables included, and convergence checks), which are fully reported in Supplementary Sx along with the analysis code to reproduce the imputed datasets and downstream results.

This chapter will present the empirical analysis results based on the multidimensional assessment framework, including the finally determined indicator weights, the overall assessment of the green design level of residents' dietary patterns, the identification and characteristic analysis of typical dietary patterns, and the reliability and validity test of the research method.

E. *Establishment of Weights for the Identification Indicator System*

Through the calculation and consistency check of the AHP survey data from 20 experts (the CR values of all judgment matrices were less than 0.1), we finally determined the weights of each dimension and second-level indicators in the assessment framework, as shown in Table II. The results show that experts generally believe that the health dimension and the environment dimension are the core of evaluating the green design of healthy diets, with the sum of their weights reaching 60%. The design dimension also received considerable attention (18%), reflecting its key role in innovation.

TABLE II. WEIGHTS OF THE ASSESSMENT INDICATOR SYSTEM FOR THE GREEN DESIGN OF HEALTHY DIETS

Dimension (Weight)	Second-level Indicator (Weight within the dimension)	Comprehensive Weight
A. Health (35%)	Nutritional Adequacy (50%)	17.5%
	Nutritional Balance (30%)	10.5%
	Risk Factor Control (20%)	7.0%
B. Environment (25%)	Greenhouse Gas Emissions (45%)	11.25%
	Land Use (35%)	8.75%
	Water Consumption (20%)	5.0%
C. Design (18%)	Innovativeness (25%)	4.5%
	Functionality (40%)	7.2%
	Systematicity (35%)	6.3%
D. Socio-culture (12%)	Preference Matching (50%)	6.0%
	Cultural Adaptability (30%)	3.6%
	Social Interactivity (20%)	2.4%
E. Economy (10%)	Dietary Cost (70%)	7.0%
	Economic Resilience (30%)	3.0%

F. *Overall Assessment of the Green Design Level of Residents' Diets*

Based on the above weights, we calculated the comprehensive scores and the scores of each dimension for the 1200 samples. Overall, the average comprehensive score for the green design of healthy diets among residents in China's first-tier cities is 62.5 (out of 100), which is at a "medium" level, indicating great potential for improvement. The average scores for each dimension are shown in Figure 3, presenting obvious imbalances. Among them, the economic dimension scored the highest (75.8), indicating that the cost of the current mainstream dietary patterns is relatively controllable. The socio-cultural dimension scored the second highest (71.2), indicating a high degree of fit between dietary patterns and residents' preferences and cultural habits. However, the environment dimension scored the lowest (48.5), far below the passing line, becoming the main shortcoming that pulls down the total score. The scores for the health dimension (61.3) and the design dimension (55.7) are also at a medium-to-low level and need to be improved.

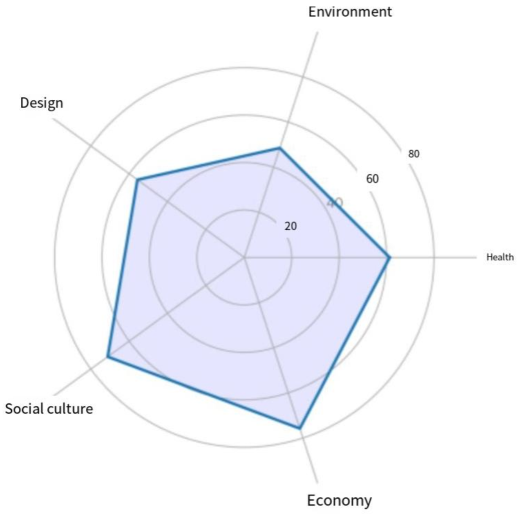

Fig. 3. Average Dimensional Scores of Residents\' Dietary Patterns

G. *Identification and Characteristic Analysis of Typical Dietary Patterns*

To gain a deeper understanding of the dietary characteristics of different populations, we used K-means cluster analysis to divide the 1200 participants into three typical dietary patterns with significant differences based on their scores in the five dimensions. We named them: "Traditional Takeout-dominated" (accounting for 38%), "Western-style Health-exploring" (accounting for 25%), and "Balanced Home-cooking" (accounting for 37%). The score comparison of these three patterns in each dimension is shown in Figure 4.

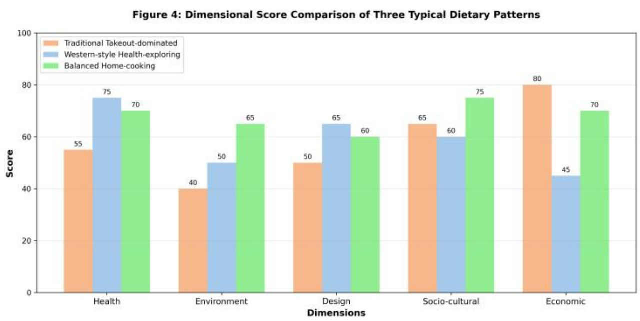

Fig. 4. Dimensional Score Comparison of Three Typical Dietary Patterns

- Pattern 1: Traditional Takeout-dominated. This group is mainly composed of young office workers, and their diet is dominated by convenient Chinese fast food and takeout. Their economic dimension score is high, but their health dimension score is not ideal, mainly manifested as high oil and salt and insufficient vegetable intake. At the same time, their environment dimension score is the lowest among the three, which is related to the large amount of packaging waste generated by takeout and centralized production and transportation. The design dimension score is also low, reflecting the passivity and monotony of their dietary choices.
- Pattern 2: Western-style Health-exploring. This group is mostly composed of highly educated, high-income young and middle-aged people who have a high pursuit of healthy eating. Their diet contains more salads, steaks, dairy products, and imported fruits. Their health dimension score is the highest, but their environment dimension score is also not ideal, mainly because a large amount of red meat and imported food brings high carbon emissions. At the same time, their economic dimension score is the lowest, and the dietary cost is significantly higher than that of other groups. This pattern scores high in the innovativeness of the design dimension.
- Pattern 3: Balanced Home-cooking. This group is mainly composed of middle-aged people with families, and their diet is dominated by home cooking, with a more diverse structure. Their scores in the four dimensions of health, environment, socio-culture, and economy are the most balanced, and their comprehensive score is the highest. This pattern reflects the systematic design thinking of "not tiring of fine food, not tiring of meticulous preparation" in traditional Chinese food culture. Through reasonable ingredient matching and cooking methods, a good balance is achieved between cost, taste, and nutrition.

H. *Reliability and Validity Test of the Method*

We assessed internal consistency (Cronbach's α) for the questionnaire-derived constructs and report the number of items per construct and item-total statistics in Supplementary Sx. For CFA, we specify the estimator, identification constraints, factor-loading ranges, and any model modifications (with justification). Fit indices (CFI/TLI/RMSEA) are reported together with the full measurement model specification to support reproducibility.

V. Analysis and Discussion

This chapter will provide a deeper interpretation of the research findings, compare these findings with the existing literature, analyse their contributions at the theoretical level and the implications at the practical level, and highlight the limitations of this study in a relatively honest manner.

A. *Interpretation of results and theoretical dialogue*

one of the most critical findings of this study is that the dietary patterns of residents in China's first-tier cities reflect a more explicit "material choice" phenomenon in terms of "green design", that is, the development between different dimensions is uneven. Among them, environmental sustainability is the most significant shortcoming, which is essentially consistent with the conclusions of several macro-level studies [1][15], which show that public dietary preferences have not yet fully integrated environmental factors into daily decision-making. Interestingly enough, this study also found that economic cost is not the main barrier to achieving a green and healthy diet (the highest score in the economic aspect), which to some extent challenges the traditional view that "sustainable food is necessarily more expensive". Therefore, the practical difficulty that needs to be given greater attention is how to transform environmental awareness into concrete, executable, and engaging eating behaviors. The three typical dietary patterns identified in the study reflect the dietary portraits of different groups in the social transition period. In particular, the "Western-style health" model presents a paradox worth noting: the unilateral pursuit of "health" may lead to "non-environmental" outcomes. This group tends to eat a lot of superfoods, imported products, and high-end meats that are marketed as "healthy"; While it performs well in some nutritional indicators, its environmental footprint and cost are also high. This is in line with some scholars' criticism of the "health halo effect", which is that consumers tend to overestimate the health benefits of certain labeled foods while ignoring their overall impact. In contrast, the benefits of the "Balanced Home Cooking" model illustrate the wisdom value of traditional food in modern society: this model does not rely on expensive or special ingredients, but uses smarter arrangements of daily cooking and ingredient matching to achieve synergistic health and environmental benefits at a lower cost. The introduction of the "design element" in this study also provides a different perspective for understanding dietary behavior from existing studies. The results show that the current mainstream dietary pattern is generally not high in the design aspect, especially in systematization. This means that most people's eating behavior is more decentralized and ad hoc decision-making rather than systematically planned arrangements, which is consistent with the "unconscious design produces mediocre results" attitude in the design field. In addition, in order to improve the level of green design of meals in essence, "unconscious" daily behavior must be gradually transformed into a more "conscious" and systematic lifestyle design.

B. *In terms of practical implications*

the results of this study provide relatively clear practical guidance on a number of topics:

- For policymakers, the National Nutrition Guidelines can be further updated to more clearly include quantitative indicators and behavioural recommendations related to environmental sustainability, such as recommending "Meatless Monday" or red meat.At the same time, the policy level should encourage and support the legacy and innovation of traditional family cooking experiences, rather than focusing on Western dietary patterns.
- For the food industry, companies can more systematically identify market opportunities for "synergistic benefits related to health and environmental protection". The R&D direction should not be limited to the development of superfoods only, but must provide integrated solutions for real-world use cases, such as launching convenient, tasty, nutritionally balanced and environmentally friendly ready-to-eat dishes. Or launching digital tools that help consumers plan sustainable meals.
- For educators and consumers, public education needs to be further strengthened to spread a more "inclusive" concept of the green diet and break the "healthy = expensive/imported" stereotype. At the same time, green-designed consumers can improve their diet with the help of relatively simple behavioral adjustments, such as increasing the proportion of plant-based foods, choosing local and seasonal ingredients, reducing food waste, and trying more home cooking.

C. *Future limitations and prospects*

While this study has done some useful exploration, there are still some limitations. First, this study uses cross-sectional data, so it is more suitable for revealing correlations and difficult to establish causation. Longitudinal design can be used in subsequent studies to track the dynamic evolution of dietary patterns and their influencing factors. Second, the data comes primarily from the participants' self-reports, and there may be recall bias and desirable social effects; The introduction of more objective measurement methods in the future, such as the analysis of shopping receipts or the weight of kitchen waste, can help improve data quality. Thirdly, the sample of this study covers only four first-level cities, so the generality of second- and third-level cities and even wider rural areas needs to be further tested. Subsequent studies should cover a wider range of regions and populations, paying particular attention to differences between different socio-economic levels. Finally, while the evaluation framework built in this study is relatively comprehensive, there is still room for optimization, such as incorporating more subdivided social and ethical indicators such as animal welfare and food fairness to improve the scope of the framework's interpretations. Looking ahead, the proposed research directions include: 1) developing a more consumer-friendly mobile application (App) based on this research framework to support users in continuously evaluating and improving their meal preferences in real-time; 2) Conduct more targeted research on the green design of a healthy diet for specific populations, such as children, the elderly, and patients with chronic diseases; and 3) incorporating behavioral economics theory (m.sh., "Nudge") to design and evaluate more effective interventions that can more feasible guide consumer behavior change.

VI. CONCLUSION

Reproducibility Statement: In order to facilitate replication by external researchers, Supplementary Materials provides a number of directly reusable materials and instructions, including: (i) a complete indicator list and scoring rubric, and (ii) food category Mapping and environmental factor tables, (iii) scripts for pre-processing and analysis (covering imputation checks, scoring, clustering, and robustness), and (iv) de-identified datasets when privacy restrictions allow; If there are privacy restrictions, a synthetic dataset with the same variable definitions as the original data is provided to ensure that the variables are consistent and that the method is reproducible.

This study aims to respond to the growing environmental and health challenges in the global food system, with the primary aim of creating an effective methodological system for the scientific and systematic identification of green design attributes for healthy diets. Through interdisciplinary theoretical integration and empirical analysis, a series of conclusions with both theoretical significance and practical value were reached.

First, this study succeeded in building a multidimensional evaluation framework that includes five aspects: health, environment, design, socio-culture, and economy. To some extent, this framework breaks through the boundaries of the traditional individual perspective and provides a new theoretical observational window for a more comprehensive understanding and evaluation of the comprehensive characteristics of a healthy diet. In addition, through expert empowerment and empirical testing, the framework performs better in terms of science and operability, which lays a stronger foundation for subsequent quantitative identification work.

Secondly, based on the above framework, this study developed a comprehensive assessment tool with 35 specific indicators to translate the macro concept of sustainability into a measurable micro-level standard. Based on an empirical study of 1,200 residents in four first-tier cities in China, it was found that the current diet patterns of urban residents are at a moderate level at the level of green design, and that environmental sustainability is the biggest deficit, and that economic cost is not the main obstacle to achieving green and healthy diets. This outcome provides a clearer direction for the focus of intervention at policy and industry levels.

Third, three typical dietary patterns were identified: "Traditional Takeout-dominated", "Western-style Health-exploring" and "Balanced Home-cooking". Further analysis shows that unilateral exploitation of "health" may lead to a "non-environmental" and "high-cost" paradox; In contrast, a balanced diet model rooted in local culture and focused on home cooking shows great potential for achieving multidimensional sustainability. This conclusion suggests that cultural adaptability and system balance must be more fully taken into account in the process of promoting a healthy diet, to avoid a one-size-fits-all diet trend.

Finally, this study verifies the practical value of integrating "design thinking" into food systems research. By evaluating the innovation, functionality, and systematization of dietary patterns, the study also reveals that one of the keys to improving dietary sustainability is to encourage people to move from "unconscious daily choices" to "more conscious system design." The results not only provide new analytical tools for the academic community, but also provide more concrete and actionable scientific evidence and practical guidance for policy-making, industrial innovation and public education.

In summary, this study builds a clearer bridge for the green design of healthy diets from abstract concepts to scientific practice by building a multidimensional and workable identification method system. While the research still has some limitations, its cutting-edge theoretical framework and clear empirical results are expected to provide important intellectual support to promote the sustainable transformation of food systems in China and around the world.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the participation of survey respondents and the expert feedback received during the development of the assessment framework. Their contributions were essential to the completion of this research.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Xiaoqiong Liu: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Validation; Visualization; Software; Resources; Project administration; Writing － original draft; Writing － review & editing..

COMPETING INTERESTS

The authors declare no competing interests.

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