Environmental Impact Assessment Review 106 (2024) 107531

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Aligning health, environment, and cost aspects of diets: Identifying sustainable dietary patterns in China

Hongyi Cai [a,b,d,*], Elise F. Talsma [a], Zhiyao Chang [c,a,b], Xin Wen [c], Shenggen Fan [b,d], Pieter Van 't Veer [a], Sander Biesbroek [a]

[a] *Division of Human Nutrition and Health, Wageningen University & Research, Stippeneng 4, 6708, WE, Wageningen, the Netherlands*
[b] *Academy of Global Food Economics and Policy, China Agricultural University, Beijing, 100083, China*
[c] *College of Food Science and Nutritional Engineering, China Agricultural University, Beijing, 100083, China*
[d] *College of Economics and Management, China Agricultural University, Beijing 100083, China*

ARTICLE INFO

Keywords:
Sustainable diets
Dietary pattern
Reduced rank regression
Dietary quality
Dietary environmental impacts
Cost of diet

ABSTRACT

Considering the adverse effects of agricultural-food systems on both human health and the environment, this research aimed to identify sustainable diets, which are nutritious, culturally acceptable, affordable, and have low environmental impacts, based on self-reported diets in China. Dietary data was collected with a 3-day 24-h dietary recall and weight food record combined method among 10,324 subjects aged 18–64 year, who participated in the China Health Nutrition Survey 2011. Diet quality was assessed by the Chinese Healthy Eating Index 2016 (CHEI2016). Environmental impact was measured by greenhouse gas emissions (GHGE), total water use (TWU), and land use (LU), and diet costs were calculated using market prices of community surveys. Reduced rank regression derived dietary patterns with 34 food groups as predictor variables, and used CHEI2016 score, dietary greenhouse gas emissions (GHGE), total water use (TWU), land use (LU), and cost of the diet as response variables. Four dietary patterns were identified. Participants with the highest adherence (decile 10) to the "High animal-based food" pattern showed higher dietary GHGE (+57%), TWU (+51%), and LU (+54%) and dietary costs (+64%), compared to the average population's diets. The diet in decile 10 for the "High fruit, low ruminant meat" pattern displayed a 21% higher CHEI2016 score, and higher dietary environmental impact (GHGE +17%; TWU +22%; LU +19%) and dietary costs (+46%) than the average diets. Diets of participants who followed the "High fish, low beverages" pattern showed higher environmental impact (GHGE +39%; TWU +32%; LU +28%) and dietary costs (+19%), but the CHEI2016 score was similar (+0.1%). Finally, the "High wheat, low pork" pattern demonstrated lower environmental impacts (GHGE -17%, TWU -12%, LU -2%) and lower cost of the diet (−2%) but also lower CHEI2016 score (−1%) compared to average population. This study reveals the complex trade-offs between diet quality, environmental sustainability, and dietary costs of current dietary patterns. None of the four patterns achieved the desirable combination of high CHEI2016 scores, reduced environmental impact, and reduced dietary costs. The findings offer insights into sustainable diet choices within the current food system, suggesting dietary guidelines should consider environmental sustainability and cost-effectiveness.

1. Introduction

Adopting sustainable diets has the potential to achieve multiple benefits, including the reduction of environmental impacts of the food system, such as greenhouse gas emissions (GHGE) and land occupation, as well as increasing nutritional health, and the prevention of diet-related chronic diseases(Willett et al., 2019). Food production, processing, storage, and transportation are responsible for significant contributions to global land use (LU) (38%)(Abdella et al., 2021), total water use (TWU) (70%)(Gibin et al., 2022), and GHGE (19–29%)(Vermeulen et al., 2012). Unhealthy dietary patterns, characterized by high consumption of sugar, salt, and saturated fatty acids, have led to increasing obesity rates(Willett et al., 2021) and non-communicable diseases(Berthy et al., 2022). Given the interdependence between dietary patterns, nutritional health, and environmental impacts, the Food and Agriculture Organization (FAO) has recommended sustainable diets

* Corresponding author at: Division of Human Nutrition and Health, Wageningen University & Research, Stippeneng 4, 6708, WE, Wageningen, the Netherlands.
E-mail address: hongyi.cai@wur.nl (H. Cai).

https://doi.org/10.1016/j.eiar.2024.107531
Received 3 December 2023; Received in revised form 24 March 2024; Accepted 14 April 2024
Available online 30 April 2024

that are "nutritionally adequate, safe, healthy, culturally acceptable, and economically accessible, and that have low environmental impacts and contribute to food and nutrition security for present and future generations"(Burlingame and Dernini, 2010).

Along with the growing economy, the dietary patterns of Chinese residents have shifted from plant-based to mixed diets that include a larger proportion of animal-based foods(Fan, 2021). The nutritional quality of Chinese has been improving year by year, with a decreasing trend in stunted growth and malnutrition(Liu et al., 2021). From 2002 to 2012, the prevalence of malnutrition decreased from 15% to 11.4%(He et al., 2018). However, concurrently, the excessive intake of energy, added sugars, and fats increased along with the risk of health problems, including obesity, diabetes, and cardiovascular diseases(L. Huang et al., 2021a). By 2022, the percentage of overweight adults in China has risen to 50%, and obesity increased by 37% since 2012, reaching a prevalence of 16%(Chinese Nutrition Society, 2022). Moreover, the prevalence of type II diabetes had increased from <5% in 2000 to 11% in 2015(Wang et al., 2021). The GHGE of the food system in China has increased due to the rise in red meat consumption, the use of fertilizers, and food waste (Hu et al., 2020). In 2020, the food system in China emitted 1.9 billion tons of carbon dioxide equivalents, accounting for 14% of total national emissions(Tubiello et al., 2021), and 43% of Chinese water withdrawals for irrigation(Koncagül and Tran, 2022).

There has been a growing interest in diet modelling as an approach to identify healthy and environmentally sustainable dietary patterns. However, as such models have difficulty to incorporate the cultural dimensions of accessibility, acceptability and affordability, the optimized dietary patterns can be far from realistic(Biesbroek et al., 2023a). Moreover, many studies have been limited to GHGE as the environmental indicator(Strid et al., 2023), with little consideration to land use and water use(Ortenzi et al., 2023). Moreover, previous research largely focused on high-income countries (HIC), and there remains a lack of understanding the intricate trade-offs between dietary patterns and sustainable indicators in Low- and Middle-Income Countries (LMIC) (Rohr et al., 2021). In China, dietary patterns have previously been characterized using principal component analysis and factor analysis, subsequently linked to disease risk estimates and environmental impacts (T. Huang et al., 2021; Lu et al., 2016). These a posteriori analysis methods identify dietary pattern in the data but are not primarily aimed to derive patterns that have associations with environmental impact (Tapsell et al., 2016). In this study, our aim was to identify dietary patterns that not only promote health but also align with environmental sustainability goals, while taking into account the economic costs of diets in China. Furthermore, we explored the associations between sociodemographic characteristics and derived dietary patterns. Our study contributes to the literature in four main aspects: (1) Comprehensive consideration of the sustainability dimensions of diets by including diet quality, environmental impact, and economic costs-and analyzed the trade-offs and synergies among them. (2) We have considered not only GHG emissions but also the use of water and land. (3) Consideration of the acceptability of dietary patterns: The identified dietary patterns are based on real dietary data from Chinese residents, making them culturally realistic within the socio-cultural context of China. (4) Exploration of group heterogeneity: We quantified the associations between various population subgroups and dietary patterns, exploring the transition pathways towards sustainable diets for different population subgroups.

2. Methods and data

2.1. Study design and population

This study utilized cross-sectional data from the 2011 China Health and Nutrition Survey (CHNS), a longitudinal study conducted since 1989 in nine provinces across China, to investigate sustainable dietary patterns among Chinese adults(Popkin et al., 2010). The survey collected comprehensive data on socio-demographic, dietary, lifestyle, and health-related factors from a sample of individuals from urban and rural areas, providing a rich database for studying household situations in China. The study protocol was approved by the Institutional Review Boards of the University of North Carolina at Chapel Hill, the National Institute of Nutrition and Food Safety, and the China Center for Disease Control and Prevention, ensuring the ethical conduct of the research.

For this study, we included individuals aged between 18 and 64 years who participated in the 2011 CHNS with a least two days of dietary consumption data. We excluded participants who were either younger than 18 or older than 65 years of age, pregnant and breastfeeding women, those with a z-score above 5 or below −5 for energy intake. Following the application of these exclusionary criteria, the resulting sample size comprised 10,324 participants from the CHNS 2011.

2.2. Dietary assessment

To collect dietary consumption data, this study utilized a 3-day 24 h dietary recall and weight food record combined method. Participants were instructed to record all food and beverages consumed over three consecutive days, including two weekdays and one weekend day. Trained interviewers visited participants' homes to review the food record and gather additional information on portion sizes and cooking methods. The CHNS 2011 covered 1950 food items, which were coded according to the Chinese Food Composition Table (CFCT). All the food items were combined into 34 categories, namely Rice, Wheat, Corn, Other cereals, Tubers & starches, Soybean, Other legumes, Nuts & seeds, Fungi & algae, Light vegetables, Dark vegetables, Fruit, Pork, Beef, Lamb, Other meat, Chicken, Duck, Other poultry, Fish, Crab, Other aquatic products, Shrimp, Cheese, Milk, Yogurt, Other dairy, Eggs, Tea, Liquor & alcohol, Other beverages, Sweets, Fast foods, Animal oil, Vegetable oil, Condiment. The estimation of energy intake for the recorded food items was accomplished through the utilization of the CFCT. To mitigate variations attributable to age and gender, consumption values were standardized to g/2000 kcal. Furthermore, the proportion of animal-based foods (%) in the diet was calculated by dividing the consumption of animal-based foods (including meat, poultry, dairy, eggs, and aquatic products) in grams per 2000 kcal by the total food consumption in grams per 2000 kcal.

2.3. Sociodemographic variables

This study considered various sociodemographic variables, such as age, gender, height, weight, work-related physical activity, educational attainment, degree of urbanization, annual household income per capita, dietary knowledge, smoking status, proportion of animal-based foods in the diet, and geographic regions. Trained technicians utilized standardized methods to measure weight and height. Body Mass Index (BMI) was calculated by dividing weight (in kilograms) by the square of height (in meters). This Work-related physical activity was categorized as light (e.g., sedentary job, office work, lab technician), moderate (e.g., driver, electrician), and heavy (e.g., farmer, steel worker, lumber worker, mason). Educational level was classified into three groups: low (below primary school, including those who did not attend school), medium (secondary school, including middle and high school), and high (above high school, including undergraduate and graduate school). The place of residence was categorized as urban or rural areas, and is constructed from the original sampling-unit variables. Household income was determined by dividing the total annual household income by the number of household members and further categorized into low (0–7900 CNY), middle (7916–17,237 CNY), and high-income groups (17,272–300,000 CNY). Dietary knowledge was assessed based on respondents' awareness of the Chinese Dietary Guidelines, with a simple Yes/No question. Smoking status was divided into three groups: nonsmoker, current smoker, and ex-smoker.

2.4. Chinese health eating index

To evaluate the daily dietary quality of Chinese individuals, the Chinese Healthy Eating Index (CHEI) was used, which applies the updated Dietary Guidelines for Chinese 2016(Yuan et al., 2017). Dietary consumption recorded in the survey was averaged and then used to calculate the CHEI. The CHEI evaluates the overall adherence to the guidelines through the scoring of seventeen components. A higher total score, ranging from 0 to 100, indicates better adherence to Dietary Guidelines for Chinese recommendations. The CHEI2016 encompasses 12 food components evaluating adequacy (cereals, whole grains and mixed beans, tubers, total vegetables excluding dark vegetables, dark vegetables, fruits, dairy, soybeans, fish and seafood, poultry, eggs, and seeds and nuts) and 5 food components assessing limitation (red meat, edible oils, sodium, added sugar, and alcohol). The scoring system generally ranged from 0 to 5 for most food components, while fruit, cooking oil, and salt were rated on a scale from 0 to 10. The index used standardized portions (SP) to quantify dietary consumption, ensuring consistent across food groups in terms of energy content, and comparable levels of carbohydrates, and protein. The CHEI accounts for total energy intake, by quantifying the contribution of each of its components by the density method (as amounts per 1000 cal of intake), except for sugar (percentage of energy) and alcohol (absolute consumption). The recommended quantities for each component derived from different food groups are standardized and presented in SP/1000 kcal, while cooking oils are expressed in grams/1000 kcal. Detailed information on the CHEI's validity and reliability is provided in Supplementary Table 1.

2.5. Diet related environmental impacts

In this study, the environmental impact of food consumption was evaluated using the China Food Life Cycle Assessment Database (CFLCAD)(Cai et al., 2022), which integrates over 1000 literature-based LCAs from the Chinese context. The CFLCAD provides estimates of GHGE, TWU, and LU per kilogram of food for each food item. The cradle-to-table system boundary was considered, which encompasses storage, processing, packaging, transportation, and household stages of food preparation, while accounting for food losses throughout the supply chain. To calculate the environmental impacts of individual diets, each food item reported in the dietary recall (in grams) is multiplied by the corresponding environmental impact factors from the CFLCAD (Supplementary Table 5). When LCA data were not available, data from similar food groups were used as a proxy, with food codes from the CFCT used to reference the CFLCAD database. The total environmental impacts per day from the diet were determined by summing the dietary GHGE, TWU, and LU and expressed as density (per 2000 kcal) to account for variation in energy intake. The adjustment was made to enable unbiased comparisons between the environmental impacts of participants' diets. Food items within the CFLCAD were cross-referenced with entries contained in the Chinese Food Composition Tables (FCT). This matching process guarantees that outcomes derived from both the CHNS and CFLCAD are at the specific level of individual "food items."

2.6. The cost of diet

In the CHNS, the community food price data encompassed the prices of food items from various markets in the community, including state stores and free markets (food price unit: Chinese Yuan, CNY). It was found that free market prices were the most influential in shaping consumption decisions, and as such, these prices were utilized in the analysis. The food price database included 13 food categories, i.e., cereals and tubers, legumes, vegetables, fruit and nuts, meat, poultry, dairy, eggs, aquatic products, beverages and fast food, liquor and alcohol, fats and oils, and condiments such as vinegar and soy sauce. Within each food group, the lowest free market price was used as the default, given a number of different types of foods available. If free market prices were not available, the lowest retail prices were used as a substitute. To determine an individual's total dietary cost, the unit cost of each food item was calculated by dividing the price of each item by its unit (e.g., grams or liters), and this was then multiplied by the amount of each energy adjusted food item consumed by the individual to obtain the cost of each item. Finally, the costs of all energy adjusted foods consumed were combined to obtain the overall cost of an individual's diet (CNY/2000 kcal).

2.7. Statistical analysis

Utilizing data from the Chinese Health and Nutrition Survey, this study applied the reduced rank regression (RRR) method in the PROC PLS procedure in SAS 9.4 to establish dietary patterns. The RRR is a multivariate technique that maximizes the correlation of explanatory variables (e.g. food groups) with a set of predefined response variables, usually biomarkers linked to a disease outcome (Weikert and Schulze, 2016). The diet-related environmental impacts, including GHGE, TWU, and LU per 2000 kcal, the CHEI2016 score, and the cost of the diet per 2000 kcal, were selected as response variables. The RRR will identify an equivalent number of dietary patterns corresponding to the number of response variables. The factor loadings (FL) of all 34 food groups for each dietary pattern were obtained as the regression results. The FL exceeding 0.20 or below −0.20 indicate a relatively strong association between the corresponding food group and the response variable and were used to describe the pattern. Scores for each participant's adherence to each dietary pattern were calculated based on the factor loadings of the food groups. Participants' dietary pattern scores were divided into ten groups (decile 1 to decile 10), representing increasing adherence to that pattern in order (decile 1 indicating least adherence, decile 10 indicating most adherence). This study assessed the Pearson correlation coefficient (r) between dietary pattern scores and consumption of each food group and sustainability indicators, respectively. Kruskal–Wallis test were employed to determine the statistical significance of the differences in the sustainable indicators between decile 1 and decile 10 of dietary patterns. To investigate associations between socio-demographic characteristics and the derived dietary pattern, generalized linear models were applied to estimate the association of socio-demographic characteristics across dietary patterns with 95% CIs. The variables age, gender, BMI, physical activity, household income, educational level, residence location, dietary knowledge, smoking habits were added as covariates to the model. Data analysis was performed using SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA) and STATA 17.0 (Stata Corporation, College Station). A two-sided p value of < 0.05 was considered statistically significant.

3. Results

3.1. Population characteristics and food consumption

The study population included a total of 10,324 participants from the CHNS, with 52.6% being female (Table 1). The participants mean age was 45.7 years (standard deviation (SD): 11.9), and their men daily energy intake was 1970 kcal/day (SD: 680). The average body mass index (BMI) was 23.6 kg/m^2, with approximately 25% of the population being current smokers, and around one-fifth of participants having attained a university-level education or higher. Additionally, 60% of the participants reported a low level of physical activity. The proportion of animal-based foods in the diet of the population was 15.1%, and 28% of individuals reported familiarity with the Chinese Dietary Guidelines. The average score on the CHEI2011 was 51.9 (SD: 10.5), out of a maximum score of 100. In terms of dietary environmental impact, the average dietary GHGE were 2.9 CO_2-eq/2000 kcal (SD: 1.1), with a TWU of 3.7 m^3/2000 kcal (SD: 1.3) and LU of 3.3 m^2/2000 kcal (SD: 1.3). The average dietary cost was 11.9 CNY/2000 kcal (SD:4.9).

Table 1
Sociodemographic characteristics and food group consumption (g/2000 kcal) of participants in the China Health Nutrition Survey 2011 (n = 10,324), and diets in decile 1 and decile 10 of dietary pattern derived by the Reduced Rank Regression[1].

	Average population in CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Participants (n)	10,324	1033	1033	1033	1033	1033	1033	1033	1033
Gender (n, %)									
Male	4889, 47.4	504, 48.8	453, 43.9	515, 49.9	331, 32.0	558, 54.0	445, 43.1	503, 48.7	470, 45.5
Female	5435, 52.6	529, 51.2	580, 56.1	518, 50.1	702, 68.0	475, 46.0	588, 56.9	530, 51.3	563, 54.5
Age (mean years, ±SD)	45.7 ± 11.9	45.8 ± 12.0	44.5 ± 12.4	46.2 ± 11.7	44.7 ± 12.4	45.3 ± 12.5	46.1 ± 11.4	45.5 ± 11.8	45.1 ± 12.4
BMI (mean kg/m[2], ±SD)	23.6 ± 4.2	24.6 ± 4.7	23.5 ± 3.6	23.6 ± 4.0	24.1 ± 4.3	24.2 ± 4.0	23.7 ± 3.7	23.8 ± 4.4	24.5 ± 4.2
Income (median 1000 CNY, interquartile range)	12.1, 6.1–20.9	5.7, 2.2–11.7	13.7, 7.0–23.1	9.7, 5.1–16.3	18.4, 9.4–29.1	10.7, 5.0–21.0	12.0, 6.0–19.8	10.6, 5.6–18.0	7.4, 2.6–14.4
Dietary Energy intake (mean kcal/d, ±SD)	1970 ± 680	2074 ± 776	1568 ± 547	1920 ± 685	1760 ± 546	2098 ± 785	1539 ± 514	1871 ± 607	1866 ± 629
Degree of urbanization (n, %)									
Urban	4253, 41.2	220, 21.3	690, 66.8	353, 34.2	601, 58.2	382, 37.0	607, 58.8	395, 38.2	279, 27.0
Rural	6071, 58.8	813, 78.7	343, 33.2	680, 65.8	432, 41.8	651, 63.0	426, 41.2	638, 61.8	754, 73.0
Dietary knowledge[2] (n, %)									
No	7437, 72.0	862, 83.4	719, 69.6	824, 79.8	563, 54.5	717, 69.4	813, 78.7	806, 78.0	776, 75.1
Yes	2887, 28.0	171, 16.6	314, 30.4	209, 20.2	470, 45.5	316, 30.6	220, 21.3	227, 22.0	257, 24.9
Educational level (n, %)									
Primary school and below	3053, 29.6	415, 40.2	256, 24.8	410, 39.7	169, 16.4	313, 30.3	339, 32.8	392, 37.9	341, 33.0
Secondary school	5106, 49.5	529, 51.2	477, 46.2	496, 48.0	498, 48.2	495, 47.9	507, 49.1	488, 47.2	548, 53.0
High school and above	2165, 21.1	89, 8.6	300, 29.0	127, 12.3	366, 35.4	225, 21.8	187, 18.1	153, 14.8	144, 13.9
Activity level (n, %)									
Low	6096, 59.0	413, 71.1	666, 66.0	487, 47.1	759, 73.5	551, 53.3	606, 58.7	525, 50.8	483,46.8
Medium	1666, 16.1	168, 28.9	201, 19.9	220, 21.3	126, 12.2	178, 17.2	238, 23.0	221, 21.4	151, 14.6
High	2562, 24.8	452, 72.9	166, 15.7	326, 31.6	148, 14.3	304, 29.4	189, 18.3	287, 27.8	399, 38.6
Smoking status (n, %)									
Non-smoker	7190, 69.6	694, 68.9	732, 70.7	725, 70.2	834, 80.7	647, 62.6	737, 71.3	714, 69.1	728, 70.5
Current smoker	2792, 27.1	313, 31.1	266, 25.7	275, 26.6	163, 15.8	333, 32.2	265, 25.7	280, 27.1	271, 26.2
Ex-smoker	342, 3.3	26, 7.7	35, 3.3	33, 3.2	36, 3.5	53, 5.1	31, 3.0	39, 3.8	34, 3.3
Animal-based food(mean grams/ 2000 kcal, ±SD)									
Pork	79.4 ± 53.6	36.0 ± 23.3	111.0 ± 69.3	99.5 ± 57.2	60.2 ± 42.2	51.3 ± 39.9	113.1 ± 66.3	101.0 ± 57.2	36.4 ± 24.5
Beef	42.3 ± 35.4	29.9 ± 16.5	57.1 ± 42.0	43.9 ± 40.1	41.1 ± 32.3	44.4 ± 42.9	45.1 ± 32.0	35.9 ± 24.0	68.8 ± 66.4
Lamb	48.3 ± 39	26.0 ± 17.5	67.1 ± 40.9	45.1 ± 33.5	53.4 ± 35.3	54.4 ± 53.2	55.1 ± 30.0	42.7 ± 32.4	45.2 ± 48.2
Other meat (include donkey, horse)	50.7 ± 36.8	52.7 ± 54.6	49.0 ± 29.0	58.0 ± 17.3	41.8 ± 32.1	54.2 ± 49.6	53.0 ± 44.4	79.0 ± 25.5	59.3 ± 45.6
Chicken	44.8 ± 32.1	37.2 ± 22.6	53.9 ± 38.9	43.3 ± 30.4	49.4 ± 34.4	39.3 ± 32.2	55.5 ± 37.6	46.3 ± 29.6	42.6 ± 22.9
Duck	43 ± 32.5	35.1 ± 19.9	50.4 ± 37.6	41.7 ± 38.1	39.5 ± 21.6	36.4 ± 25.8	53.4 ± 39.9	46.6 ± 39.6	39.9 ± 24.4
Other poultry (include goose, turkey)	35.8 ± 30.8	87.0 ± 71.1	28.7 ± 19.0	27.9 ± 30.1	37.8 ± 24.6	24.2 ± 2.3	37.7 ± 28.3	22.0 ± 11.7	40.7 ± 0
Milk	168.3 ± 110.8	122.8 ± 60.9	241.3 ± 151.1	111.4 ± 48.1	202.5 ± 139.1	183.7 ± 151.6	162.2 ± 91.7	172.5 ± 101.7	166.6 ± 111.4
Other dairy (include milk powder, butter)	55.5 ± 63.8	118.4 ± 39.1	6.6 ± 0.4	28.6 ± 24.1	65.7 ± 62.0	79.7 ± 84.2	14.7 ± 11.6	21.9 ± 27.2	43.7 ± 37.0
Yogurt	117.1 ± 79.9	76.7 ± 40.3	161.0 ± 101.7	222.8 ± 122.9	151.2 ± 93.3	142.9 ± 84.1	130.6 ± 83.3	99.2 ± 55.9	155.2 ± 109.5
Cheese	33.7 ± 35.6	54.4 ± 9.1	0 ± 0	0 ± 0	91.2 ± 73.9	77.7 ± 65.8	0 ± 0	0 ± 0	32.8 ± 2.5
Eggs	45.9 ± 34.7	41.3 ± 30.6	58.9 ± 42.6	38.1 ± 29.9	62.6 ± 44.6	40.9 ± 29.5	58.5 ± 46.0	42.9 ± 33.7	52.7 ± 40.4
Fish	53.4 ± 40.6	32.3 ± 21.9	77.4 ± 53.3	52.4 ± 41.2	55.6 ± 38.8	39.7 ± 28.5	84.7 ± 55.2	53.0 ± 36.9	50.1 ± 39.2
Shrimp	32.1 ± 30.3	18.0 ± 16.8	44.6 ± 35.4	37.4 ± 36.5	30.1 ± 28.0	22.3 ± 22.3	46.1 ± 43.6	44.9 ± 42.2	17.8 ± 19.9
Crab	36.5 ± 25.7	31.2 ± 28.6	43.1 ± 32.3	28.8 ± 15.0	40.4 ± 31.8	46.3 ± 36.6	42.0 ± 29.6	34.4 ± 19.9	17.9 ± 15.3
Other fish (include Sea Cucumber & Cuttlefish)	27.4 ± 20.3	26.6 ± 11.0	25.7 ± 16.6	21.1 ± 22.1	32.6 ± 21.4	23.6 ± 13.0	22.7 ± 13.1	26.7 ± 16.6	30.3 ± 22.5
Plant-based foods (mean grams/ 2000 kcal, ±SD)									
Wheat	162.5 ± 127.9	369.0 ± 148.6	90.4 ± 59.6	109.1 ± 77.3	162.3 ± 103.2	217.9 ± 150.5	112.2 ± 81.9	95.9 ± 57.4	384.2 ± 149.0
Rice	270.4 ± 188.8	82.6 ± 77.1	458.0 ± 324.4	377.2 ± 212.6	197.6 ± 140.5	168.0 ± 133.5	451.1 ± 276.3	381.8 ± 217.2	97.9 ± 110.9
Other cereals (include Corn, Sorghum)	66.9 ± 75.6	81.6 ± 105.7	76.4 ± 72.4	46.9 ± 40.4	83.0 ± 99.5	75.7 ± 88.1	76.5 ± 66.8	48.8 ± 48.8	104.3 ± 119.6
Tubers & starches	73.3 ± 67.3	86.8 ± 85.3	70.2 ± 73.1	73.9 ± 66.8	78.7 ± 89.2	102.7 ± 99.9	61.4 ± 52.9	78.8 ± 71.9	92.1 ± 93.0
Other legumes (include cowpeas & mung beans)	37.4 ± 33.2	30.2 ± 26.6	26.5 ± 30.6	44.4 ± 36.1	35.6 ± 36.4	27.3 ± 30.6	39.8 ± 32.4	42.5 ± 35.9	30.2 ± 33.2
Soybean	85 ± 83.1	66.9 ± 61.5	113.0 ± 122.6	64.1 ± 55.3	125.7 ± 121.3	57.2 ± 50.2	143.1 ± 146.4	76.5 ± 72.4	100.2 ± 93.7
Vegetables	305 ± 164.8	201.3 ± 110.3	489.5 ± 231.1	321.3 ± 174.8	308.7 ± 169.0	172.5 ± 100.0	569.0 ± 208.7	351.9 ± 193.7	252.0 ± 144.8

(*continued on next page*)

Table 1 (*continued*)

	Average population in CHNS	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
		Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10	Decile 1	Decile 10
Fungi and algae	32.9 ± 29.1	26.2 ± 22.4	41.9 ± 42.7	27.6 ± 22.4	35.7 ± 31.0	26.8 ± 21.8	43.0 ± 45.1	31.2 ± 26.6	32.3 ± 30.8
Fruit	140.2 ± 110.8	78.1 ± 48.0	251.5 ± 172.5	65.3 ± 45.0	277.0 ± 142.9	193.7 ± 158.0	131.1 ± 95.2	117.1 ± 83.6	206.4 ± 174.7
Nut	26.9 ± 22.1	23.1 ± 20.9	24.8 ± 22.2	24.2 ± 16.6	29.6 ± 28.3	28.2 ± 26.1	28.4 ± 21.5	26.6 ± 17.7	27.5 ± 23.6
Beverages (mean grams/2000 kcal, ±SD)									
Tea	530.7 ± 636.4	8.5 ± 7.4	920.4 ± 882.5	325.3 ± 244.1	558.3 ± 413.7	786.3 ± 828.7	370.6 ± 190.7	607.6 ± 1033.6	584.0 ± 326.1
Liquor	109.1 ± 193.4	93.3 ± 74.7	200.3 ± 366.1	51.9 ± 105.4	209.8 ± 406.2	269.5 ± 324.2	31.2 ± 67.5	173.0 ± 297.1	66.2 ± 93.8
Other beverages (include soft drinks, fruit juice)	169.1 ± 294.2	87.4 ± 37.7	310.8 ± 555.4	154.2 ± 147.5	250.7 ± 534.8	310.2 ± 527.4	82.2 ± 70.4	156.6 ± 136.0	155.8 ± 181.7
Miscellaneous (mean grams/2000 kcal, ±SD)									
Fast foods	111 ±88.1	144.3 ±110.1	96.8 ±73.0	87.8 ±73.1	120.8 ±89.1	132.0 ±106.4	91.9 ±66.8	99.9 ±88.2	115.1 ±84.9
Sweets	7.4 ± 16.5	16.8 ± 54.1	7.4 ± 14.5	7.1 ± 21.4	6.1 ± 7.9	10.6 ± 34.8	7.9 ± 14.0	5.9 ± 6.9	5.9 ± 6.8
Animal oil	21 ± 17.6	40.7 ± 38.7	17.8 ± 14.3	22.4 ± 17.1	12.9 ± 9.8	24.5 ± 25.5	19.6 ± 14.5	21.0 ± 15.8	21.8 ± 8.8
Vegetable oil	33.1 ± 21.4	38.6 ± 27.6	27.3 ± 17.2	37.7 ± 23.3	28.0 ± 17.2	36.0 ± 27.8	32.6 ± 19.5	32.3 ± 19.4	30.7 ± 18.1
Condiment	30.5 ± 31	31.5 ± 31.2	34.4 ± 34.5	37.6 ± 44.1	30.6 ± 27.3	35.0 ± 38.6	31.7 ± 30.4	31.8 ± 35.5	30.9 ± 27.1
Proportion of animal-based foods (mean %, ±SD)	15.1 ± 9.8	6.4 ± 6.2	19.0 ± 11.3	14.8 ± 9.0	17.2 ± 11.1	12.0 ± 10.7	15.9 ± 9.0	15.7 ± 9.4	8.6 ± 8.6
GHGE (mean CO_2-eq/2000 kcal, ±SD)	2.9 ± 1.1	1.7 ± 0.5	4.5 ± 1.1	2.9 ± 1.1	3.4 ± 1.1	2.5 ± 1.1	3.9 ± 1.1	3.2 ± 1.1	2.4 ± 1.2
TWU (mean m^3/2000 kcal, ±SD)	3.7 ± 1.3	2.4 ± 0.7	5.6 ± 1.4	3.6 ± 1.3	4.6 ± 1.3	3.6 ± 1.4	4.9 ± 1.4	3.9 ± 1.4	3.3 ± 1.5
LU (mean m^2/2000 kcal, ±SD)	3.3 ± 1.3	2.2 ± 0.6	5.1 ± 1.4	3.2 ± 1.2	3.9 ± 1.4	3.3 ± 1.5	4.2 ± 1.3	3.4 ± 1.2	3.2 ± 2.1
CHEI2016 score (mean, ±SD)	51.9 ± 10.5	45.5 ± 8.9	57.8 ± 10.5	44.5 ± 7.9	63.1 ± 9.1	51.2 ± 11.4	51.9 ± 9.8	48.8 ± 9.4	51.3 ± 11.4
Cost of diets (mean CNY/2000 kcal, ±SD)	11.9 ± 4.9	7.2 ± 2.5	19.6 ± 6.1	10.4 ± 3.8	17.4 ± 6.1	13.6 ± 6.6	13.8 ± 4.1	12.1 ± 5.5	11.6 ± 6.9

[1] Continuous variables were expressed by means and SD (except income variable was expressed by median and interquartile range). Categorical variables were expressed by number and percentage).

[2] Dietary knowledge indicated whether participants were familiar with the Chinese dietary guidelines.

3.2. Dietary patterns derived by RRR

RRR initially identified five distinct dietary patterns (**Supplementary Table 2**), corresponding to the number of response variables examined. The "High animal-based food" dietary pattern accounted for 66.3% of the variance in dietary GHGE, TWU, LU, CHEI2016, and cost of the diet, as well as 4.6% of the variation in food consumption. The "High fruit, low ruminant meat" pattern emerged as an influential dietary pattern that explained 9.1% of the variation in both the dependent and predictor variables. The "High fish, low beverages" pattern accounted for 2.4% and 2.9% of the variance in the dependent and predictor variables, respectively. Similarly, the "High wheat, low pork" pattern" explained 3.5% of the variance in the dependent variables and 1.5% in the predictor variables. In contrast, the fifth dietary pattern demonstrated minimal impact on the dependent variables (<0.50%) and was not considered in further analysis.

The "High animal-based food" dietary pattern was characterized by high consumption of beef (factor loading (FL): 0.38), pork (FL: 0.37), fish (FL: 0.31), lamb (FL: 0.24), milk (FL: 0.22), and chicken (FL: 0.20), while displaying a low consumption of wheat (FL: −0.24) (Fig. 1). Within this group, the D10 of population exhibited a higher average consumption of animal-based foods, accounting for 19.0% of dietary consumption, with pork contributing 111.0 g. Conversely, the "High fruit, low ruminant meat" pattern had high consumption of fruit (FL: 0.55), eggs (FL: 0.28), nuts and seeds (FL: 0.26), and milk (FL: 0.23), alongside a low consumption of pork (FL: −0.25), beef (FL: −0.24), and rice (FL: −0.22). In this pattern, the proportion of animal-based foods in diet was approximately 17.2%. While their consumption of ruminant meat was low, they had a notable milk and egg consumption, averaging 202 g and 62.6 g compared to the average of 168.3 g and 45.9 g, respectively. Furthermore, the "High fish, low beverages" pattern were characterized by a high consumption of fish (FL: 0.33) and eggs (FL: 0.22), while exhibiting a low consumption of alcohol (FL: −0.43), fast foods (FL: −0.42), tea (FL: −0.33), and tubers (FL: −0.31). The proportion of animal-based foods in their diet accounted for approximately 15.9%, with pork consumption averaging 113.1 g. Additionally, their rice consumption was high, reaching 451.1 g, compared to the overall mean of 270.4 g. Lastly, the "High wheat, low pork" patterns displayed a higher consumption of beef (factor loading (FL): 0.57), wheat (FL: 0.22), fruit (FL: 0.19), and other cereals (FL: 0.19), and a low consumption of pork (FL: −0.48), rice (FL: −0.25), liquor and alcohol (FL: −0.19). Even though "beef" was the dominant factor, the beef consumption in the D10 diet increased from 35.9 g in D1 to 68.8 g in D10. In contrast, pork consumption decreased significantly from 101.0 g in D1 to 36.4 g in D10. Consequently, the proportion of animal-based food in this diet pattern was low at 8.6%.

3.3. Sustainability of the dietary patterns

Environmental impacts (GHGE, TWU, LU), diet quality (CHEI2016), and cost of the diet were positively correlated between the "High animal-based food" pattern and the "High fruit, low ruminant meat" pattern (Table 2). Specifically, the "High animal-based food" pattern displayed a strong positive association with dietary environmental impacts (r = 0.765 for GHGE, r = 0.715 for TWU, and r = 0.647 for LU). Particularly, the "High fruit, low ruminant meat" pattern demonstrated a strong positive association with CHEI2016 (r = 0.507), it also exhibited a positive correlation with the cost of the diet (r = 0.462). While the "High fish, low beverages" pattern was weakly positively associated with dietary costs (r = 0.021), and was negatively associated with CHEI2016 (r = −0.013) and strongly positively associated with dietary GHGE, TWU and LU. Lastly, the "High wheat, low pork" pattern exhibited a negative correlation with environmental impact indicators (GHGE, r = −0.156; TWU, r = −0.106; LU, r = −0.031) and cost of diet

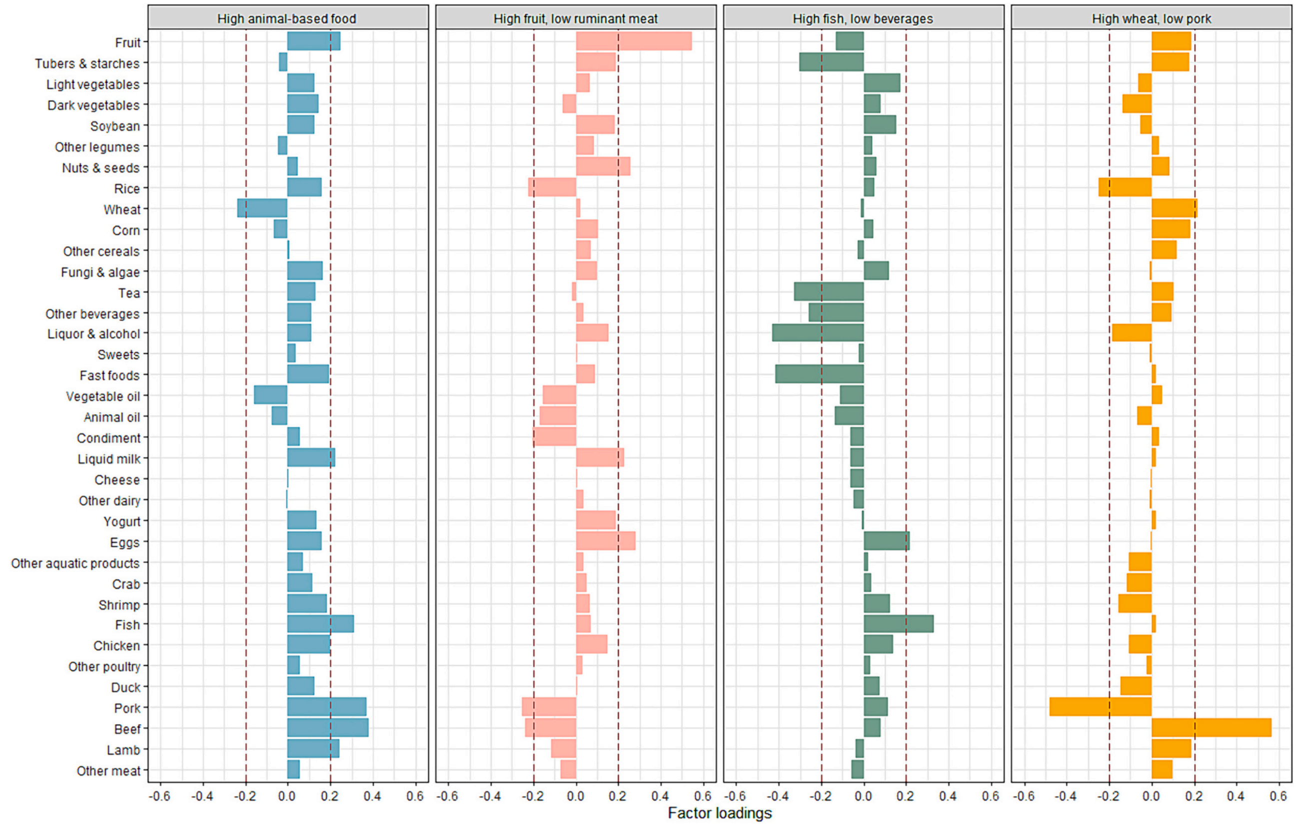

Fig. 1. Factor loadings of the food groups on dietary patterns derived by reduced rank regression explaining the variation in the sustainable indicators. Factor loadings >|0.20| were considered important contributors to a dietary pattern.

Table 2
Pearson correlation of sustainable indicators with dietary pattern derived by Reduced Rank Regression (extracted from n = 10,324)[1].

Pearson's correlation coefficient (r)	High animal-based food	High fruit, low ruminant meat	High fish, low beverages	High wheat, low pork
GHGE (kg CO_2-eq/2000 kcal)	0.765***	0.141***	0.404***	−0.156***
TWU (m^3/2000 kcal)	0.715***	0.226***	0.313***	−0.106***
LU (m^2/2000 kcal)	0.647***	0.164***	0.227***	−0.031*
CHEI2016 score	0.332**	0.507***	−0.013	0.072***
Cost of diet (CNY/2000 kcal)	0.724***	0.462***	0.021*	−0.057***

[1] Level of significance: *** <0.001, ** <0.01, * <0.05.

(r = −0.057), while exhibited a positive correlation with the CHEI2016 score (r = 0.072).

The mean energy-adjusted dietary GHGE were calculated to be 2.87 (SD: 1.09) kg CO_2-eq/2000 kcal, while the TWU was estimated at 3.75 (SD: 1.35) m^3/2000 kcal, and LU at 3.30 (SD: 1.32) m^2/2000 kcal. The mean CHEI2016 score was 51.9, and the mean cost of the diet amounted 11.92 (SD: 4.98) CNY/2000 kcal within the sample of CHNS 2011 participants (Table 1). Among the dietary patterns, the adherents in highest-scoring diet in decile 10 for the "High animal-based food" pattern demonstrated notable differences compared to the average population's diets (**Supplementary Fig. 1**). It exhibited a 11.4% higher CHEI2016 score, 56.9% higher dietary greenhouse gas emissions (GHGE), 50.9% higher total water use (TWU), 53.7% higher land use (LU), and a 64.5% higher cost of the diet (Fig. 2). Similarly, the diet in decile 10 for the "High fruit, low ruminant meat" pattern displayed a 21.4% higher CHEI2016 score than the average population's diets. Moreover, it had higher dietary environmental impacts (GHGE +16.8%; TWU +21.7%; LU +18.8%) and cost (+45.9%) compared to the average population. In contrast, the diet in decile 10 for the "High fish, low beverages" pattern exhibited higher dietary environmental impacts (GHGE +39.1% ; TWU +31.9% ; LU +28.4%)and cost (+16.2%) compared to the average population but had a slightly lower CHEI2016 score (+0.1%). Notably, the "High wheat, low pork" pattern in decile 10 demonstrated lower environmental impacts compared to other dietary patterns. Participants adhering to this pattern had the lowest cost of the diet. Increasing adherence to the "High wheat, low pork" pattern resulted in a 16.6% lower dietary GHGE, 12.5% lower dietary TWU, 2.1% lower dietary LU, and 2.3% lower cost of the diet compared to the average CHNS population's diets. Furthermore, diets in decile 10 of the pattern scores for the "High wheat, low pork" pattern had a 1.1% lower CHEI2016 score compared to the average population diets.

3.4. Characteristics of adherents of the dietary patterns

Distinct socio-demographic profiles emerge among adherents to different dietary patterns. Adherents to the "High animal-based food" pattern were characterized by higher education levels, greater income, lower physical activity, and urban residence (Table 3). Similarly, those following the "High fruit, low ruminant meat" pattern exhibited characteristics of being female, a significant proportion displaying knowledge about dietary guidelines, higher education levels, and residing in urban areas. In contrast, those following the "High fish, low beverages" pattern had less familiarity with healthy dietary guidelines and lower education level. Distinct from other patterns, the adherents to the "High wheat, low pork" pattern had higher education levels and activity levels. Remarkably, in all models, no significant association was observed between smoking status and dietary patterns.

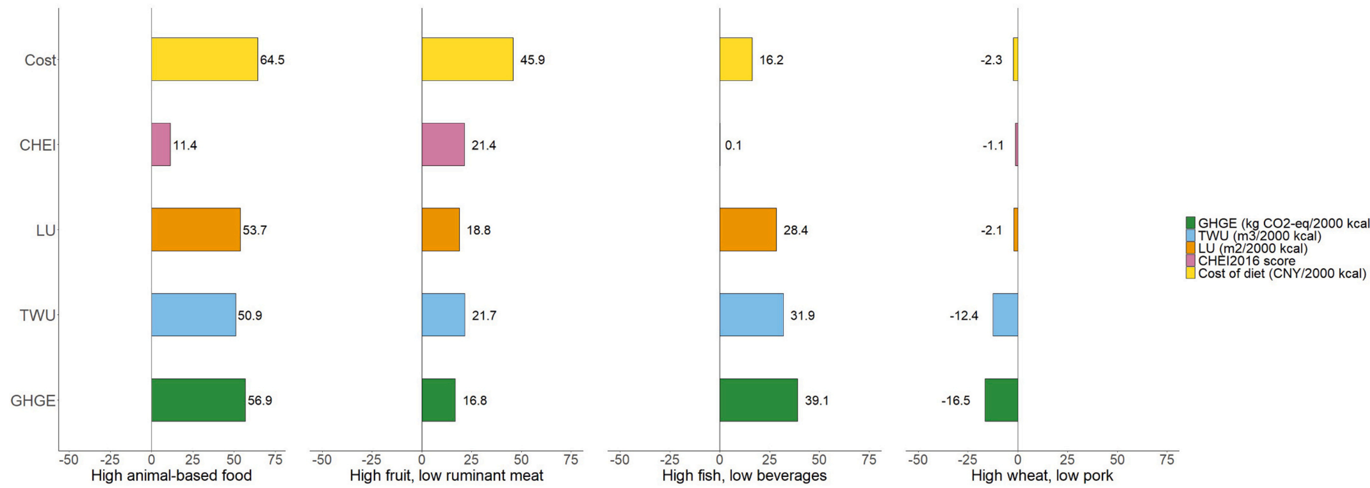

Fig. 2. Comparison of mean sustainability indicators for Decile 10 of adherence of the dietary patterns derived with Reduced Rank Regression with the average CHNS population.

Table 3
Associations between the socio-demographic characteristics of participant and the five derived dietary patterns in the 2011 CHNS. (n = 10,324)[1].

Participants (n)	High animal-based food		High fruit, low ruminant meat		High fish, low beverages		High wheat, low pork	
	Coefficient*	95% CI	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI
Gender (female vs male ref., category)	5.57*	(1.17, 9.98)	17.98***	(13.83, 22.14)	1.07	(−1.31, 3.46)	4.26***	(2.32, 6.21)
Age (per 10 years)	−3.42***	(−4.97, −1.86)	−0.69	(−2.17, 0.77)	0.68	(−0.16, 1.53)	−0.63	(−1.32, 0.05)
BMI (kg/m^2)	−1.44***	(−1.84, −1.05)	0.41*	(0.03, 0.78)	−0.36***	(−0.57, −0.14)	0.61***	(0.44, 0.79)
Household income (per 1000 CHY/year)	0.48***	(0.38, 0.58)	0.35***	(0.25, 0.44)	−0.08**	(−0.13, −0.03)	−0.08***	(−0.12, −0.03)
Degree of urbanization (rural vs urban area)	−39.84***	(−43.51, −36.17)	−14.12***	(−17.58, −10.65)	−7.24***	(−9.23, −5.26)	1.33	(−0.28, 2.95)
Dietary knowledge (Being aware of the dietary guidelines, vs not)	1.93	(−1.91, 5.78)	23.37***	(19.73, 27.01)	−6.88***	(−8.96, −4.81)	5.41***	(3.71, 7.11)
Educational level								
Secondary school, vs primary school or below	2.33	(−1.83, 6.51)	14.67***	(10.73, 18.61)	−2.23	(−4.48, 0.02)	3.05***	(1.21, 4.91)
High school and above, vs primary school or below	16.93***	(11.07, 22.79)	27.41***	(21.87, 32.94)	−7.56***	(−10.73, −4.39)	5.67***	(3.09, 8.26)
Activity level								
Medium, vs low	−1.97	(−5.12, 4.67)	−6.26**	(−10.89, −1.63)	3.19*	(0.53, 5.84)	−1.52	(−3.68, 0.64)
High, vs low	−17.89***	(−22.41, −13.37)	1.23	(−5.49, 3.03)	−3.87***	(−6.31, −1.43)	6.72***	(4.73, 8.72)
Smoking status								
Current smoker vs non-smoker	1.97	(−2.87, 6.82)	−4.61	(−9.19, −0.02)	−1.27	(−3.89, 1.35)	−0.35	(−2.49, 1.79)
Ex-smoker, vs non-smoker	7.84	(−1.81, 17.49)	12.81	(3.71, 21.93)	−2.73	(−7.95, 2.48)	1.77	(−2.48, 6.03)

[1] Level of significance: *** <0.001, ** <0.01, * <0.05.
* The coefficients in the model represent the absolute values of the dietary scores. The score averages 51.9 and ranges from 13.4 to 90.8.

4. Discussion

We derived four distinctive dietary patterns in the 2011 Chinese Health Nutrition Survey by using the hybrid RRR approach, namely the “High fruit, low ruminant meat,” “High animal-based food,” “High wheat, low pork,” and “High fish, low beverage”. These patterns were derived using the explained variance of diet quality, dietary environmental impacts, and dietary costs. Among them, the “High fruit, low ruminant meat” pattern exhibited the strongest correlation with diet quality (r = 0.507). However, it tended to be more costly (r = 0.462) while displaying a lesser connection to dietary environmental impacts, with modest correlations observed for GHGE (r = 0.141), TWU (r = 0.226), and LU (r = 0.164). Conversely, the “High animal-based food” pattern displayed a weaker association with diet quality (r = 0.332) and manifested high dietary environmental impacts, exhibiting substantial correlations with GHGE (r = 0.765), TWU (r = 0.715), and LU (r = 0.647). This pattern also ranked as the most expensive among the dietary patterns identified. The “High wheat, low pork” pattern emerged as a distinctive dietary choice, contributing positively to all outcome measures. It demonstrated a weak correlation with diet quality (r = 0.072) and displayed slightly lower dietary environmental impacts, indicated by negative correlations for GHGE (r = −0.156), TWU (r = −0.106), and LU (r = −0.031). Additionally, it incurred slightly lower dietary costs (r = −0.057). Meanwhile, the “High fish, low beverage” pattern was associated with a reduction in diet quality (r = −0.013), an increase in dietary costs (r = 0.021), and similarly elevated dietary environmental impacts, with positive correlations observed for GHGE (r = 0.404), TWU (r = 0.313), and LU (r = 0.227). In terms of the goals of reducing dietary environmental impacts and diet costs, the “High wheat, low pork” pattern emerges as the most environmentally sustainable and cost-effective choice of the current dietary patterns, although this pattern would not increase population health. Conversely, the “High animal-based food” pattern ranks as the most expensive with the highest environmental impacts.

Previous studies have extensively documented the significant contributions of animal-based foods to diet-related environmental impacts (Perignon et al., 2019; Seconda et al., 2021). Furthermore, some research has highlighted the potential cost benefits associated with reducing animal-based foods in the diet(Caillavet et al., 2016). However, the healthy and environmental sustainable EAT-Lancet diet was associated with increased cost(Hirvonen et al., 2020a). In line with our study, diets adhering to the “High animal-based food” pattern exhibited significantly higher levels of diet-related environmental impacts and dietary costs compared to the average population. Conversely, the derived “High wheat, low pork” pattern exhibits reduced dietary environmental impact and dietary costs compared to the average Chinese diets, primarily attributable to its limited incorporation of animal-based foods. However, it is essential to note that for dietary quality, the CHEI2016 score associated with the “High wheat, low pork” pattern slightly falls below the observed score in the average population (51.3 vs. 51.9 points) (**Supplementary Table 3**). This can be attributed to the fact that adherents of the “High wheat, low pork” pattern consumed less chicken and fish with elevated consumption of fruits and whole grains compared to the average population (**Supplementary Table 3**). Moreover, in the “High wheat, low pork” pattern, beef contributes a large part of the variation; adherents of this pattern replace pork with a small portion of beef. Despite the relatively increased beef consumption, the overall meat consumption in adherents of the “High wheat, low pork” pattern maintains a modest share at 8.6%, notably falling below the average population of 15.1%. Specifically, those with low adherence to the “High wheat, low pork” pattern showed a high pork consumption level of 101.0 g. Conversely, individuals with high adherence to the “High wheat, low pork” pattern exhibited a decrease in pork consumption to 36.4 g. Simultaneously, beef consumption experienced an increase from 35.9 g in the low adherents to 68.8 g in the high adherents (Table 1). Within the most adherents of the “High wheat, low pork” pattern, there exists a trade-off relationship between beef and pork consumption. Conversely, the proportion of animal-based food in the diet of decile 10 of the “High animal-based food” pattern was 19.0%, the highest among the four derived dietary patterns. Although increasing the consumption of beef is not recommended from the perspective of environmental or nutritional health (Hu et al., 2019), this association reflects the inverse association between beef and other types of animal protein sources in current Chinese diets.

When comparing the dietary patterns to those of other countries, several similarities and differences emerge. A study conducted in the Dutch EPIC-NL cohort applied the RRR approach with the DHD15-index of diet quality and diet-related GHGE as dependent variables and concluded that the “plant-based diet” exhibited greater health benefits and an inverse relation to GHGE (33). This is not consistent with the “High wheat, low pork” model derived in this study, which may be due to the different response variables used. Land use, water use, and affordability issues were not addressed in the Dutch cohort study. In an investigation conducted using data from the 2012–2016 Dutch National Food Consumption Survey(Heerschop et al., 2021), a dietary pattern characterized as ‘high dairy, low fruit juices’ was identified. This dietary pattern was found to be healthier while exhibiting higher dietary GHGE, aligning with the findings from our “High animal-based food” pattern. A recent systematic review emphasized that a shift towards reducing red meat and alcoholic beverage consumption, coupled with an increase in the consumption of fish, fruits, and vegetables, constitutes a pivotal factor for environmental enhancement, particularly in terms of reducing dietary GHGE and land use(Conrad et al., 2023). This is in line with the “High wheat, low pork” dietary pattern identified in our study. Another study conducted in five European countries applied energy-adjusted factor analysis to identify dietary clusters based on nutrient intake and GHGE as variables(Vieux et al., 2020). In line with our results, clusters with the lowest dietary GHGE had the poorest nutritional quality. In this study, the adherents of the “High wheat, low pork” pattern had the lowest diet cost among the different dietary patterns, but also no increase in dietary quality. A study assessing the affordability of healthy and sustainable diets across various income groups on a global scale revealed a notable increase in the cost associated with procuring a food basket that aligns with both health and sustainability objectives. These findings bear a resemblance to the outcomes observed in the “High fruit, low ruminant meat” dietary patterns identified in our current study(Bai et al., 2022).

The transition to healthy diets can lead to varying trade-offs and synergies with environmental impacts, depending on the proportion of animal-based foods in dietary patterns (Heck et al., 2018; Zhang and Chai, 2022). In low- and middle-income countries (LMIC), the EAT-Lancet diet may lead to a 25% to 75% rise of per capita water use (Tuninetti et al., 2022a), and a 3–8% increase of GHGE (Springmann et al., 2018a). This can be attributed to an increased consumption of vegetables, fruits, nuts, legumes, and various animal-based foods compared to current dietary patterns in LMIC. Conversely, high-income countries transitioning to the EAT-Lancet diet witness a decrease in per capita dietary GHGE by 40%–50% (Semba et al., 2020), TWU by 25%–50%(Tuninetti et al., 2022b), which can be attributed to the high consumption of resource-intensive meat products in typical diets in high-income countries(Springmann et al., 2018b).

4.1. Policy implications

This study applied dietary environmental impact, dietary health index, and dietary cost as the response variables, thereby the factor loadings reflect combinations of food groups and the trade-offs between them. None of the derived dietary patterns exhibited a combination of the highest CHEI2016 score, the lowest dietary environmental impacts, and reduced or similar cost of the diet. Although the “Low wheat, high pork” pattern has a low environmental impact and low cost, it is not an improvement in terms of dietary quality relative to the average current diet. Given that the dietary patterns are derived from the food consumption data of the Chinese population, it can be inferred that these patterns may be socially acceptable for a significant portion of the population. Consequently, this model offers insights into the pursuit of sustainable diets: the challenge of enhancing dietary quality while maintaining environmental and cost considerations at a minimum. In comparison to the EAT-Lancet Health Reference Diet, the “Low wheat, high pork” pattern shows deficiencies in vegetable and milk consumption, while the consumption of red meat and cereals needs to be further reduced. The results of this study indicate that young individuals, urban residents, and those engaged in low-intensity labor are more inclined to follow the “High animal-based food” pattern. Conversely, individuals with higher levels of education, rural residents, and those involved in labor-intensive work tend to adhere to the “High wheat, low pork” pattern. Education campaigns, especially those targeted at young people, can play a crucial role in promoting healthy and sustainable dietary pattern(Barone et al., 2019). These education campaigns may encourage the adoption of sustainable eating habits, such as increased consumption of fruits and vegetables and reduced food waste, from an early age (Biasini et al., 2021). Certainly, the reduction of meat consumption has been established as a pivotal factor in promoting both dietary sustainability and environmental well-being(Poore and Nemecek, 2018; Ritchie et al., 2018). Previous studies revealed that foods with similar nutritional profiles can exhibit substantial differences in GHGE(Clark et al., 2022). Individuals who habitually consume a significant proportion of animal-based foods, as indicated by their adherence to “High animal-based food” pattern, may derive benefits from incorporating plant-based alternatives, like legumes, nuts and seeds or food products with innovative protein sources as substitutes for meat products (Semba et al., 2021; Tidåker et al., 2021). Therefore, through the dietary choices mentioned above, individuals within the "High animal-based food" pattern can effectively mitigate dietary environmental impacts and lower dietary costs, facilitating a transition towards more sustainable diets. Similarly, consumers adhering to the "High wheat, low pork" pattern should choose foods with high nutritional quality, low environmental impacts, and lower cost, thereby improving diet quality and maintaining low dietary environmental impacts.

Our findings indicate that dietary patterns that adhere more closely to the Chinese Dietary Guidelines (higher CHEI scores) were associated with increased dietary costs. The dietary guidelines are typically designed with a primary focus on promoting health and may not inherently consider linkages to environmental sustainability and affordability(James-Martin et al., 2022). In a comprehensive review encompassing 83 countries' national food-based dietary guidelines (Gonzalez Fischer and Garnett, 2016), it was revealed that only four countries, namely Brazil, Sweden, Qatar, and Germany, had incorporated specific sustainability considerations into their guidelines, while affordability was not mentioned at all. Studies indicate that health-conscious and environmentally sustainable diets tend to be less affordable(Hirvonen et al., 2020a), a trend that is particularly pronounced in lower- to middle-income countries and among individuals from lower SES groups(Gupta et al., 2021). To mitigate the cost of diets, governmental efforts should prioritize agricultural policies and public food procurement strategies aimed at enhancing food productivity and diversity(Fan et al., 2021a). Concurrently, there is a need to improve market infrastructure and supply chains, facilitating the accessibility of a wide range of nutritious foods in the market(Fan et al., 2021b). This emphasis should particularly encompass fruits, vegetables, and legumes (Benton et al., 2021).

In addition, the government can provide agricultural subsidies for plant-based agricultural products such as vegetables and fruits to encourage sustainable dietary transitions transition(de Amorim et al., 2018). Furthermore, discouraging the consumption of foods with minimal nutritional value, such as sugar-sweetened beverages, cakes, and cookies – often associated with a higher environmental impacts(Biesbroek et al., 2023b) – can be achieved through appropriate policies and clear food labeling, aiding consumers in making informed choices. The interrelationships between diet quality, diet costs, and environmental impact also highlight the importance of their trade-offs and synergies when designing dietary guidelines that respect the planetary boundaries (Zhang et al., 2023). This requires an interdisciplinary and multi-stakeholder perspective to balance interests from politics, civil society, and the private sector(Reisch, 2021).

4.2. *Strengths and limitation*

The innovation of this study bridges this gap by applying the Reduced rank regression method, to identify dietary patterns that not only promote health but also align with environmental sustainability and reduced dietary costs. The conventional diet models often struggle to capture the realistic aspects of cultural considerations, making the optimized patterns less applicable. Moreover, this study is unique in its integration of diverse dimensions, moving beyond a singular focus on greenhouse gas emissions to include land use, water use and cost of diet. By applying RRR to the Chinese Health and Nutrition Survey, this study provides insights for decision-making by policymakers in low- and middle-income countries, where such methods have been less explored.

Nevertheless, several limitations need to be considered as well. Firstly, memory-based 24-h dietary recalls are susceptible to recall bias and underreporting (Liu et al., 2023), such day-patterns should be used less frequently in the population, which was accounted for by standardizing food consumption to 2000 kcal/day. Additionally, the response variables in this study were limited to encompass indicators of environmental impacts, dietary costs, and the CHEI2016. Future studies should strive to incorporate a broader range of response variables that capture the multifaceted dimensions of sustainability. Potential examples include measuring food availability in the food environment, pesticides and biodiversity, as well as evaluating the cultural acceptance of specific dietary practices in specific cultural contexts. While using the lowest free market price may not fully capture the typical economic impact of dietary patterns, focusing primarily on the most cost-effective options available(Hirvonen et al., 2020b), it's essential to acknowledge that employing the lowest cost estimate is a common practice in estimating the cost of healthy diets. However, its practicality may vary, as visiting numerous stores is often impractical. Despite its limitations, this approach is widely utilized in the field(Vandevijvere et al., 2021), and future research could improve accuracy by recording unit prices for each consumed food item during dietary surveys. In addition, a validated 2022 Chinese Healthy Diet Index is not available yet. However, both the 2016 and 2022 Chinese Dietary Guideline promote a higher consumption of dairy products while reducing recommendations for grains (Supplementary Table 6), with recommendations for other food groups remaining unchanged. It can be inferred that the more closely the 2022 Dietary Guideline are followed, the greater the environmental impact of the diet. Therefore, even if the 2022 Chinese Dietary Guideline was adopted, it would not alter the conclusion reached in this study that there is still a trade-off between dietary quality and environmental impacts. We understand the importance of incorporating the latest data to accurately capture the current dietary pattern in China. To assess individual-level regional variations, cultural practices, and dietary preferences, we used CHNS dietary data of 2011, as more recent CHNS data are not accessible through open access channels. Although major changes in the Chinese diet composition have occurred in the period 1960–2010, the consumption of the major food groups seem to have stabilized thereafter(L. Huang et al., 2021b). Despites differences in methodology of data collection, individual-level CHNS 2011 data and per capita data from the China National Bureau of Statistics 2013–2021, show that the dietary pattern of China remains predominantly plant-based (Supplementary Table 4). In the CHNS 2011, the consumption proportions of plant-based foods were 35.3% for cereals, 27.3% for vegetables, and 5.9% for fruits. According to the China National Bureau of Statistics data (2021), the consumption proportions were similar for cereals (35.0%) and vegetables (26.6%) while fruits were somewhat higher(14.7%). Consequently, the statistical data suggest that tome trends have stabilized and that dietary composition is largely similar according top per capita data. It is therefore unlikely that the use of CHNS 2011 data has significantly impact the generalizability of our conclusions regarding the associations between health and environmental sustainability in Chinese dietary pattern.

Moreover, we acknowledge that the CHNS is not a representative sample of the population of China. The CHNS areas cover 47% of China's population (according to the 2010 census), encompassing socio-economic diversity in rural regions, urban areas, and metropolitan areas, as well as variations in education and income. Therefore, the CHNS does represent the socio-economic diversity of China. Since the associations we studied rely on this socio-economic diversity rather than the representativeness of the CNHS, the lack of demographic representativeness does not impact our main results and conclusions. Additionally, in interpreting and applying CHNS data, it's crucial to remain aware of segments of China's population not represented, identifying areas requiring additional research and data collection for a more holistic understanding of the nation's dietary and health landscape.

5. Conclusion

In this study, reduced rank regression was applied to identify sustainable dietary patterns within the participants of the Chinese Health Nutrition Survey 2011. The study used a comprehensive array of indicators, including dietary quality, environmental impact, and affordability. Four dietary patterns were identified: "High animal-based food", "High fruit, low ruminant meat", "High fish, low beverages", and "High wheat, low pork". None exhibited the desired combination of increased CHEI2016 scores, reduced dietary environmental impact, and reduced dietary costs. These outcomes highlight trade-offs between these dimensions of the dietary pattern. Nevertheless, the "High wheat, low pork" diet exhibited noteworthy reductions in dietary greenhouse gas emissions by 21.7%, total water use by 16.5%, and land use by 10.4%. Additionally, this pattern demonstrated 13.4% lower costs while maintaining a similar CHEI2016 score. The "High wheat, low pork" pattern suggests the feasibility of adopting lower cost and environmentally sustainable diets without compromising current dietary quality. The observed associations between dietary patterns and sociodemographic factors underscore the need for targeted educational campaigns to promote sustainable and healthy eating habits, particularly among young individuals and urban populations. It is recommended that dietary guidelines include explicit recommendations regarding environmental sustainability and affordability.

Funding

This work was supported by China Scholarship Council (CSC) (grant number No. 201913043) and the National Natural Science Foundation of China (grant number No. 72061147002).

Authors' contributions

Concept and design: Pieter van 't Veer, Shenggen Fan, Elise F. Talsma, Sander Biesbroek. Acquisition, analysis, or interpretation of results: Pieter van 't Veer, Shenggen Fan, Elise F. Talsma, Sander Biesbroek, Hongyi Cai, Zhiyao Chang. Drafting the manuscript: Hongyi Cai. Revision of the manuscript for important intellectual content: Pieter van 't Veer, Shenggen Fan, Sander Biesbroek. Statistical analysis: Hongyi Cai, Zhiyao Chang. Administrative, technical, or material support: Pieter van 't Veer, Shenggen Fan, Sander Biesbroek, Elise F. Talsma, Xin Wen. Supervision: Pieter van 't Veer, Shenggen Fan, Sander Biesbroek, Elise F. Talsma, Xin Wen. All authors read and approved the final manuscript.

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Institute for Nutrition and Food Safety, China CDC (now renamed as National Institute for Nutrition and Health, China CDC).

Consent for publication

All the authors have reviewed and approved the manuscript for publication.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgements

We thank the College of Food Science and Nutritional Engineering (China Agricultural University), Academy of Global Food Economics and Policy (China Agricultural University) and College of Economics and Management (China Agricultural University) for their contribution to this study. We are grateful to all the participants in our study and all the staff working for the China Health and Nutrition Survey 2011 (CHNS2011).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107531.

References

Abdella, G.M., Kucukvar, M., Ismail, R., Abdelsalam, A.G., Onat, N.C., Dawoud, O., 2021. A mixed model-based Johnson's relative weights for eco-efficiency assessment: the case for global food consumption. Environ. Impact Assess. Rev. 89, 106588 https://doi.org/10.1016/j.eiar.2021.106588.

Bai, Y., Herforth, A., Masters, W.A., 2022. Global variation in the cost of a nutrient-adequate diet by population group: an observational study. Lancet Planet. Health 6, e19–e28. https://doi.org/10.1016/S2542-5196(21)00285-0.

Barone, B., Nogueira, R.M., Behrens, J.H., 2019. Sustainable diet from the urban Brazilian consumer perspective. Food Res. Int. 124, 206–212.

Benton, T.G., Beddington, J., Thomas, S.M., Flynn, D.J., Fan, S., Webb, P., 2021. A 'net zero' equivalent target is needed to transform food systems. Nat. Food. 2, 905–906. https://doi.org/10.1038/s43016-021-00434-2.

Berthy, F., Brunin, J., Allès, B., Fezeu, L.K., Touvier, M., Hercberg, S., Galan, P., Pointereau, P., Lairon, D., Baudry, J., Kesse-Guyot, E., 2022. Association between adherence to the EAT-lancet diet and risk of cancer and cardiovascular outcomes in the prospective NutriNet-Santé cohort. Am. J. Clin. Nutr. 116, 980–991. https://doi.org/10.1093/ajcn/nqac208.

Biasini, B., Rosi, A., Giopp, F., Turgut, R., Scazzina, F., Menozzi, D., 2021. Understanding, promoting and predicting sustainable diets: a systematic review. Trends Food Sci. Technol. 111, 191–207.

Biesbroek, S., Kok, F.J., Tufford, A.R., Bloem, M.W., Darmon, N., Drewnowski, A., Fan, S., Fanzo, J., Gordon, L.J., Hu, F.B., Lähteenmäki, L., Nnam, N., Ridoutt, B.G., Rivera, J., Swinburn, B., Veer, P. van't, 2023a. Toward healthy and sustainable diets for the 21st century: importance of sociocultural and economic considerations. Proc. Natl. Acad. Sci. 120, e2219272120 https://doi.org/10.1073/pnas.2219272120.

Biesbroek, S., Kok, F.J., Tufford, A.R., Bloem, M.W., Darmon, N., Drewnowski, A., Fan, S., Fanzo, J., Gordon, L.J., Hu, F.B., Lähteenmäki, L., Nnam, N., Ridoutt, B.G., Rivera, J., Swinburn, B., Veer, P. van't, 2023b. Toward healthy and sustainable diets for the 21st century: importance of sociocultural and economic considerations. Proc. Natl. Acad. Sci. 120, e2219272120 https://doi.org/10.1073/pnas.2219272120.

Burlingame, B., Dernini, S., 2010. Sustainable Diets and Biodiversity.

Cai, H., Biesbroek, S., Wen, X., Fan, S., van 't Veer, P., Talsma, E.F., 2022. Environmental footprints of Chinese foods and beverages: literature-based construction of a LCA database. Data Brief 42, 108244. https://doi.org/10.1016/j.dib.2022.108244.

Caillavet, F., Fadhuile, A., Nichèle, V., 2016. Taxing animal-based foods for sustainability: environmental, nutritional and social perspectives in France. Eur. Rev. Agric. Econ. 43, 537–560. https://doi.org/10.1093/erae/jbv041.

Chinese Nutrition Society, 2022. Dietary Guidelines for Chinese Resident.

Clark, M., Springmann, M., Rayner, M., Scarborough, P., Hill, J., Tilman, D., Macdiarmid, J.I., Fanzo, J., Bandy, L., Harrington, R.A., 2022. Estimating the environmental impacts of 57,000 food products. Proc. Natl. Acad. Sci. USA 119, e2120584119. https://doi.org/10.1073/pnas.2120584119.

Conrad, Z., Drewnowski, A., Belury, M.A., Love, D.C., 2023. Greenhouse gas emissions, cost, and diet quality of specific diet patterns in the United States. Am. J. Clin. Nutr. 117, 1186–1194. https://doi.org/10.1016/j.ajcnut.2023.04.018.

de Amorim, W.S., Valduga, I.B., Ribeiro, J.M.P., Guazzelli Williamson, V., Krauser, G.E., Magtoto, M.K., de Andrade Guerra, J.B.S.O., 2018. The nexus between water, energy, and food in the context of the global risks: an analysis of the interactions between food, water, and energy security. Environ. Impact Assess. Rev. 72, 1–11. https://doi.org/10.1016/j.eiar.2018.05.002.

Fan, S., 2021. Economics in food systems transformation. Nat. Food. 2, 218–219. https://doi.org/10.1038/s43016-021-00266-0.

Fan, S., Headey, D., Rue, C., Thomas, T., 2021a. Food Systems for Human and Planetary Health: economic perspectives and challenges. Ann. Rev. Resour. Econ. 13, 131–156. https://doi.org/10.1146/annurev-resource-101520-081337.

Fan, S., Teng, P., Chew, P., Smith, G., Copeland, L., 2021b. Food system resilience and COVID-19 – lessons from the Asian experience. Glob. Food Sec. 28, 100501 https://doi.org/10.1016/j.gfs.2021.100501.

Gibin, D., Simonetto, A., Zanini, B., Gilioli, G., 2022. A framework assessing the footprints of food consumption. An application on water footprint in Europe. Environ. Impact Assess. Rev. 93, 106735 https://doi.org/10.1016/j.eiar.2022.106735.

Gonzalez Fischer, C., Garnett, T., 2016. Plates, Pyramids, Planet: Developments in National Healthy and Sustainable Dietary Guidelines: A State of Play Assessment. FAO, Rome, Italy.

Gupta, S., Vemireddy, V., Singh, D.K., Pingali, P., 2021. Ground truthing the cost of achieving the EAT lancet recommended diets: evidence from rural India. Glob. Food Sec. 28, 100498 https://doi.org/10.1016/j.gfs.2021.100498.

He, P., Baiocchi, G., Hubacek, K., Feng, K., Yu, Y., 2018. The environmental impacts of rapidly changing diets and their nutritional quality in China. Nat. Sustain. 1, 122–127. https://doi.org/10.1038/s41893-018-0035-y.

Heck, V., Hoff, H., Wirsenius, S., Meyer, C., Kreft, H., 2018. Land use options for staying within the planetary boundaries – synergies and trade-offs between global and local sustainability goals. Glob. Environ. Chang. 49, 73–84. https://doi.org/10.1016/j.gloenvcha.2018.02.004.

Heerschop, S.N., Biesbroek, S., Temme, E.H.M., Ocké, M.C., 2021. Can healthy and sustainable dietary patterns that fit within current Dutch food habits be identified? Nutrients 13, 1176. https://doi.org/10.3390/nu13041176.
Hirvonen, K., Bai, Y., Headey, D., Masters, W.A., 2020a. Affordability of the EAT–lancet reference diet: a global analysis. Lancet Glob. Health 8, e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4.
Hirvonen, K., Bai, Y., Headey, D., Masters, W.A., 2020b. Affordability of the EAT–lancet reference diet: a global analysis. Lancet Glob. Health 8, e59–e66.
Hu, F.B., Otis, B.O., McCarthy, G., 2019. Can plant-based meat alternatives be part of a healthy and sustainable diet? JAMA 322, 1547–1548. https://doi.org/10.1001/jama.2019.13187.
Hu, Y., Su, M., Wang, Y., Cui, S., Meng, F., Yue, W., Liu, Y., Xu, C., Yang, Z., 2020. Food production in China requires intensified measures to be consistent with national and provincial environmental boundaries. Nat. Food. 1, 572–582. https://doi.org/10.1038/s43016-020-00143-2.
Huang, T., Ploner, A., Chang, E.T., Liu, Q., Cai, Y., Zhang, Z., Chen, G., Huang, Q., Xie, S., Cao, S., Jia, W., Zheng, Y., Liao, J., Chen, Y., Lin, L., Ernberg, I., Huang, G., Zeng, Yi, Zeng, Yixin, Adami, H.-O., Ye, W., 2021. Dietary patterns and risk of nasopharyngeal carcinoma: a population-based case-control study in southern China. Am. J. Clin. Nutr. 114, 462–471. https://doi.org/10.1093/ajcn/nqab114.
Huang, L., Wang, Z., Wang, H., Zhao, L., Jiang, H., Zhang, B., Ding, G., 2021a. Nutrition transition and related health challenges over decades in China. Eur. J. Clin. Nutr. 75, 247–252. https://doi.org/10.1038/s41430-020-0674-8.
Huang, L., Wang, Z., Wang, H., Zhao, L., Jiang, H., Zhang, B., Ding, G., 2021b. Nutrition transition and related health challenges over decades in China. Eur. J. Clin. Nutr. 75, 247–252. https://doi.org/10.1038/s41430-020-0674-8.
James-Martin, G., Baird, D.L., Hendrie, G.A., Bogard, J., Anastasiou, K., Brooker, P.G., Wiggins, B., Williams, G., Herrero, M., Lawrence, M., Lee, A.J., Riley, M.D., 2022. Environmental sustainability in national food-based dietary guidelines: a global review. Lancet Planet. Health 6, e977–e986. https://doi.org/10.1016/S2542-5196(22)00246-7.
Koncagül, E., Tran, M., 2022. The United Nations World Water Development Report 2022: Groundwater: Making the Invisible Visible; Facts and Figures.
Liu, A., Han, A., Chai, L., 2021. Assessing the nutrient adequacy in China's food supply from 1965 to 2018. Nutrients 13, 2734. https://doi.org/10.3390/nu13082734.
Liu, X.-T., Xiong, J.-Y., Xu, Y.-J., Zhao, L., Libuda, L., Cheng, G., 2023. Prospective association of family members' sugar-sweetened beverages intake with children's sugar-sweetened beverages consumption in China. Eur. J. Nutr. 62, 175–184. https://doi.org/10.1007/s00394-022-02971-3.
Lu, S., Huang, X., Yu, H., Yang, J., Han, R., Su, J., Du, W., Zhou, J., Yu, X., Wu, M., 2016. Dietary patterns and risk of breast cancer in Chinese women: a population-based case-control study. Lancet, Lancet-CAMS Health Summit. 2016 (388), S61. https://doi.org/10.1016/S0140-6736(16)31988-2.
Ortenzi, F., McAuliffe, G.A., Leroy, F., Nordhagen, S., van Vliet, S., del Prado, A., Beal, T., 2023. Can we estimate the impact of small targeted dietary changes on human health and environmental sustainability? Environ. Impact Assess. Rev. 102, 107222 https://doi.org/10.1016/j.eiar.2023.107222.
Perignon, Marlène, Sinfort, Carole, Ati, El, Jalila, Traissac, Pierre, Drogué, Sophie, Darmon, Nicole, Amiot, Amiot, M.J., Achir, N., Alouane, L., El Ati, J., Bellagha, S., Bosc, P.M., Broin, M., Darmon, N., Dhuique-Meyer, C., Dop, M.C., Drogué, S., Dury, S., Ferchoui, A., Gaillard, C., Ghrabi, Z., Jacquet, F., Kameli, Y., Kefi, F., Khamassi, F., Kesse-Guyot, E., Lairon, D., Martin-Prevel, Y., Méjean, C., Mouquet, C., Njoumi, S., Padilla, M., Perignon, M., Sinfort, C., Traissac, P., Verger, E. O., 2019. How to meet nutritional recommendations and reduce diet environmental impact in the Mediterranean region? An optimization study to identify more sustainable diets in Tunisia. Glob. Food Sec. 23, 227–235. https://doi.org/10.1016/j.gfs.2019.07.006.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.
Popkin, B.M., Du, S., Zhai, F., Zhang, B., 2010. Cohort profile: the China health and nutrition survey—monitoring and understanding socio-economic and health change in China, 1989–2011. Int. J. Epidemiol. 39, 1435–1440. https://doi.org/10.1093/ije/dyp322.
Reisch, L.A., 2021. Shaping healthy and sustainable food systems with behavioural food policy. Eur. Rev. Agric. Econ. 48, 665–693. https://doi.org/10.1093/erae/jbab024.
Ritchie, H., Reay, D.S., Higgins, P., 2018. The impact of global dietary guidelines on climate change. Glob. Environ. Chang. 49, 46–55. https://doi.org/10.1016/j.gloenvcha.2018.02.005.
Rohr, V., Blakley, J., Loring, P., 2021. A framework to assess food security in regional strategic environmental assessment. Environ. Impact Assess. Rev. 91, 106674 https://doi.org/10.1016/j.eiar.2021.106674.
Seconda, L., Fouillet, H., Huneau, J.-F., Pointereau, P., Baudry, J., Langevin, B., Lairon, D., Allès, B., Touvier, M., Hercberg, S., Mariotti, F., Kesse-Guyot, E., 2021. Conservative to disruptive diets for optimizing nutrition, environmental impacts and cost in French adults from the NutriNet-Santé cohort. Nat. Food. 2, 174–182. https://doi.org/10.1038/s43016-021-00227-7.
Semba, R.D., de Pee, S., Kim, B., McKenzie, S., Nachman, K., Bloem, M.W., 2020. Adoption of the 'planetary health diet' has different impacts on countries' greenhouse gas emissions. Nat. Food. 1, 481–484. https://doi.org/10.1038/s43016-020-0128-4.
Semba, R.D., Ramsing, R., Rahman, N., Kraemer, K., Bloem, M.W., 2021. Legumes as a sustainable source of protein in human diets. Glob. Food Sec. 28, 100520 https://doi.org/10.1016/j.gfs.2021.100520.
Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T.B., Rayner, M., Scarborough, P., 2018a. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet. Health 2, e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7.
Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T.B., Rayner, M., Scarborough, P., 2018b. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet. Health 2, e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7.
Strid, A., Johansson, I., Lindahl, B., Hallström, E., Winkvist, A., 2023. Toward a more climate-sustainable diet: possible deleterious impacts on health when diet quality is ignored. J. Nutr. 153, 242–252. https://doi.org/10.1016/j.tjnut.2022.10.004.
Tapsell, L.C., Neale, E.P., Satija, A., Hu, F.B., 2016. Foods, nutrients, and dietary patterns: interconnections and implications for dietary guidelines. Adv. Nutr. 7, 445–454. https://doi.org/10.3945/an.115.011718.
Tidåker, P., Karlsson Potter, H., Carlsson, G., Röös, E., 2021. Towards sustainable consumption of legumes: how origin, processing and transport affect the environmental impact of pulses. Sustain. Prod. Consump. 27, 496–508. https://doi.org/10.1016/j.spc.2021.01.017.
Tubiello, F.N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S.Y., Barros, J.D., Flammini, A., Mencos-Contreras, E., Souza, L., Quadrelli, R., Heiðarsdóttir, H.H., Benoit, P., Hayek, M., Sandalow, D., 2021. Greenhouse gas emissions from food systems: building the evidence base. Environ. Res. Lett. 16, 065007 https://doi.org/10.1088/1748-9326/ac018e.
Tuninetti, M., Ridolfi, L., Laio, F., 2022a. Compliance with EAT–lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population. Nat. Food. 3, 143–151. https://doi.org/10.1038/s43016-021-00452-0.
Tuninetti, M., Ridolfi, L., Laio, F., 2022b. Compliance with EAT–lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population. Nat. Food. 3, 143–151. https://doi.org/10.1038/s43016-021-00452-0.
Vandevijvere, S., Seck, M., Pedroni, C., De Ridder, K., Castetbon, K., 2021. Food cost and adherence to guidelines for healthy diets: evidence from Belgium. Eur. J. Clin. Nutr. 75, 1142–1151. https://doi.org/10.1038/s41430-020-00815-z.
Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.
Vieux, F., Privet, L., Soler, L.G., Irz, X., Ferrari, M., Sette, S., Raulio, S., Tapanainen, H., Hoffmann, R., Surry, Y., Pulkkinen, H., Darmon, N., 2020. More sustainable European diets based on self-selection do not require exclusion of entire categories of food. J. Clean. Prod. 248, 119298 https://doi.org/10.1016/j.jclepro.2019.119298.
Wang, Limin, Peng, W., Zhao, Z., Zhang, M., Shi, Z., Song, Z., Zhang, X., Li, C., Huang, Z., Sun, X., Wang, Linhong, Zhou, M., Wu, J., Wang, Y., 2021. Prevalence and treatment of diabetes in China, 2013-2018. JAMA 326, 2498–2506. https://doi.org/10.1001/jama.2021.22208.
Weikert, C., Schulze, M.B., 2016. Evaluating dietary patterns: the role of reduced rank regression. Curr. Opin. Clin. Nutr. Metab. Care 19, 341–346. https://doi.org/10.1097/MCO.0000000000000308.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W.D., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
Willett, W.C., Hu, F.B., Rimm, E.B., Stampfer, M.J., 2021. Building better guidelines for healthy and sustainable diets. Am. J. Clin. Nutr. 114, 401–404. https://doi.org/10.1093/ajcn/nqab079.
Yuan, Y.-Q., Li, F., Dong, R.-H., Chen, J.-S., He, G.-S., Li, S.-G., Chen, B., 2017. The development of a Chinese healthy eating index and its application in the general population. Nutrients 9, 977. https://doi.org/10.3390/nu9090977.
Zhang, J., Chai, L., 2022. Trade-off between human health and environmental health in global diets. Resour. Conserv. Recycl. 182, 106336 https://doi.org/10.1016/j.resconrec.2022.106336.
Zhang, M., Li, H., Chen, S., Liu, Y., Li, S., 2023. Interrogating greenhouse gas emissions of different dietary structures by using a new food equivalent incorporated in life cycle assessment method. Environ. Impact Assess. Rev. 103, 107212 https://doi.org/10.1016/j.eiar.2023.107212.