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Assessing food and nutrient security in Taiwan: Integrating sustainability and the planetary health diet

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A B S T R A C T

Objectives: Food and nutrient security are critical for population health and environmental sustainability. This study aimed to assess Taiwan's food and nutrient security and its alignment with the planetary health diet (PHD), integrating CO_2 impact analysis.
Methods: This study introduces the Food Security Index (FSI) and Nutrient Security Index (NSI) to assess Taiwan's food and nutrient security. It also examines adherence to the PHD and uses life cycle assessment to evaluate CO_2 emissions across regions/countries, offering a comprehensive view of environmental impacts. From 2017 to 2020, the Nutrition and Health Survey in Taiwan estimated the prevalence of undernourishment (PoU) for 12 120 participants using FAO methods. Additionally, the Food Insecurity Experience Scale (FIES) was calculated for 2879 participants in 2022–23 with FAO's RM.weights package. The FSI and NSI were derived from supply-to-needs (S-Nr) and intake-to-needs (I-Nr) ratios using NAHSIT and the food balance sheet (FBS). Moreover, PHD score (PHDS) was applied to assess PHD adherence and compare CO_2 emissions across 12 regions/countries using FBS.
Results: Taiwan with PoU below 2.5% (2017–20), FIES 1.1% (2022–23). FBS showed S-Nr 0.84 for vegetables, 0.77 for fruits, and 0.47 for dairy. I-Nr for calcium was 0.56, while NAHSIT S-Nr was 0.97 for cereals/roots, 0.36 for dairy, and 0.71 for vegetables/fruits, I-Nr 0.58 for fiber, 0.56 for calcium, and 0.49 for vitamin D. Taiwan achieved the highest PHDS (48.55%), while Brazil had the lowest (31.06%). A moderate negative correlation ($r = -0.413$) was found between PHDS and food-related CO_2 emissions.
Conclusion: Despite high food security, targeted policies are needed to address nutrient imbalances and promote sustainable diets.

Introduction

Food and nutrient security are critical societal concerns, directly influencing health, economic stability, and environmental sustainability. To address these challenges, the United Nations established the Sustainable Development Goals (SDGs), positioning food security (SDG 2) as a cornerstone for achieving zero hunger. However, achieving this goal demands more than an adequate food supply; it requires addressing imbalances in food and nutrient intake, adapting to environmental pressures, and ensuring equitable access to a sustainable diet [1]. Environmental sustainability (SDG 13) plays a key role in this effort, as reducing greenhouse gas emissions helps mitigate climate change while enhancing health and well-being (SDG 3) [2,3]. By investigating the effectiveness of sustainable dietary patterns, this study seeks to provide actionable insights that inform government policies aimed at achieving food security while reducing environmental impact.

Taiwan has achieved notable success in food security, as demonstrated by its low prevalence of undernourishment, substantially

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lower than in many other regions/countries. However, imbalances between food supply and nutrient intake requirements require further investigation. This study utilizes the Food Security Index (FSI) and Nutrient Security Index (NSI) to evaluate the adequacy of Taiwan's food system by integrating macro- and micro-level availability with age-specific nutrient needs [4,5]. By bridging the gap between broad food system assessments and individualized dietary insights, these indices address a critical need in global food policy. They evaluate how food supply aligns with nutritional needs and how dietary intake corresponds with both supply and requirements. The algorithm combines these factors into a unified framework, enabling effective evaluation, monitoring of Taiwan policy development.

Building on the principles of sustainable diets championed by the FAO and WHO, this study explores the sustainable healthy diets (SHDs) framework, which promotes health and well-being while minimizing environmental impact [6]. A key focus is the planetary health diet (PHD), a globally recognized dietary model that emphasizes plant-based foods to reduce carbon footprints and improve health outcomes [7,8]. This dietary model emphasizes increased consumption of plant-based foods and unsaturated fats while advocating for a reduction in the intake of poultry, seafood, red and processed meats, refined grains, starchy vegetables, and added sugars [9]. Despite the growing interest in the planetary health diet score (PHDS), a standardized methodology for assessing adherence to this diet remains a challenge. Meanwhile, integrating life cycle assessment (LCA) highlights the environmental consequences of food systems—particularly CO_2 emissions and the high resource demands of animal products [10]. Given that global food systems contribute an estimated 25–30% of total anthropogenic greenhouse gas emissions [11], linking these perspectives underscores how dietary shifts can concurrently promote public health and address urgent sustainability challenges.

This study is designed to assess the FSI and NSI in Taiwan, estimate the global warming potential of food consumption, and analyze adherence to the PHDS across 12 different regions/countries. While the PHDS has gained global recognition as a benchmark for sustainable diets, its correlation with CO_2 emissions remains underexplored. Using an integrated framework of supply, intake, nutrient needs, and environmental data, this study aims to inform policies that support both nutritional adequacy and sustainability. We hypothesize that greater adherence to the PHD is associated with lower diet-related CO_2 emissions, and that food and nutrient gaps persist in Taiwan despite high food security. To test this hypothesis, we combined national food balance sheets, dietary intake surveys, and LCA data to evaluate nutrient adequacy, food security, and associated CO_2 emissions across multiple populations.

Methods and materials

Study design and population

This study utilized data from two primary sources. The food balance sheet (FBS), provided by the Ministry of Agriculture, served as the first source. The second source, the Nutrition and Health Survey in Taiwan (NAHSIT) same data as this paper [12], was conducted using a stratified, multistage sampling design to ensure national representativeness. Participants were randomly selected from 20 counties and cities across Taiwan, with recruitment balanced across regions to prevent overrepresentation. The final NAHSIT dataset comprised 12 120 individuals for the years 2017 to 2020, ranging in age from 1 to over 70 y old. In addition, data from the Food Insecurity Experience Scale (FIES) for the years 2022 to 2023 were incorporated, involving 2879 participants from 16 to 98 y old.

Prevalence of undernourishment (PoU)

The PoU is estimated using FAO's statistical approach, which measures the proportion of the population with habitual dietary energy intake below the minimum dietary energy requirement (MDER). To assess energy needs across populations, FAO defines three key parameters: MDER**,** which represents the minimum energy intake necessary for maintaining health and activity; average dietary energy requirement (ADER)**,** which reflects normal population energy needs; and maximum dietary energy requirement (XDER)**,** which accounts for individuals with higher energy expenditures [13]. For PoU estimation, mean dietary energy intake, derived from survey data, is compared to MDER, with variability accounted for by the coefficient of variation (CVR). To improve accuracy, adjustments were applied for physical activity level (PAL) and additional energy demands during pregnancy and lactation, following FAO guidelines [14].

Food insecurity experience scale (FIES)

FIES data from 2022 to 2023 included 2879 participants (16–98 y). After excluding 33 incomplete responses, 2846 remained. FIES is a survey-based tool used to assess individuals' experiences with food insecurity over the past 12 mo through eight standardized questions that measure difficulties in accessing sufficient food due to financial constraints. Each response is recorded as either "Yes" (1 point) or "No" (0 points) to quantify the severity of food insecurity [15]. There are 2610 (91.7%) who answered "no" to all eight questions, while only 4 (0.1%) answered "yes" to all. Data analysis is conducted using FAO's official R.M weight package**,** which applies Rasch modeling**,** a statistical method based on item response theory (IRT) [16]**.** This process includes data preprocessing, checking response patterns, and running the IRT model to estimate the severity of each question and calculate scores for respondents, allowing classification into different levels of food insecurity. The FAO categorizes food insecurity into three severity levels**:** mild**,** moderate, and severe [17].

Food Security Index (FSI) and Nutrient Security Index (NSI)

The FSI and NSI were developed to evaluate food availability and dietary intake in relation to population needs. These indices are based on two key ratios: the supply-to-needs ratio (S-Nr) and the intake-to-needs ratio (I-Nr). The S-Nr is a macro-level indicator that measures food and nutrient availability by comparing national food supply data from the FBS to the recommended intake levels set by food guides (FGs) and dietary reference intakes (DRIs)**.** Food supply data are classified according to the FGs, which categorizes the population into nine age groups (1–3, 4–6, 7–12, 13–15, 16–18, 19–44, 45–64, 65–74, and over 75 y), whereas the DRI classification system defines ten age groups (1–3, 4–6, 7–9, 10–12, 13–15, 16–18, 19–30, 31–50, 51–70, and over 70 y). To estimate total national food and nutrient needs, the average per capita requirement for each age group was first calculated. These values were then multiplied by the corresponding population sizes and summed to yield national-level estimates. Meanwhile, the I-Nr serves as a micro-level indicator, assessing dietary intake at the individual level by comparing 24-h dietary recall from the NAHSIT with the same dietary standards used in the S-Nr calculations. Both ratios are expressed relative to dietary needs, where a value of 1.0 indicates adequacy, values above 1.0 suggest excess supply or intake, and values below 1.0 indicate insufficiency, highlighting gaps in food availability or dietary intake. By considering both food availability and consumption patterns, these indices ensure a thorough and actionable assessment of the nutritional landscape [4].

Calculation of the PHDS score

The planetary health diet score (PHDS) was calculated using food availability data from the FAO FBS, which reports annual per capita food supply in kilograms, rather than energy-based values such as kcal/d. As such, the PHDS derived from FBS reflects the availability of food groups relative to the gram-based targets set by the EAT-Lancet Commission, rather than actual intake or energy-adjusted consumption. Unlike studies that compute PHDS based on food frequency questionnaires (FFQs) and normalize intakes to 2500 kcal/d, our approach provides a macro-level assessment of food supply patterns and national alignment with dietary sustainability goals. Given that FBS data are gram-based and do not include energy-standardized intake information, the PHDS in this study was calculated directly from unadjusted food supply quantities. We acknowledge this methodological limitation and therefore applied a gram-based scoring algorithm to ensure consistency and maintain cross-country comparability across all datasets [18,19]. Although this method does not account for individual-level energy needs or bioavailability, it offers a comparable framework for evaluating dietary alignment across regions/countries using standardized food group targets. Thus, PHDS was computed by comparing unadjusted supply quantities to PHD gram-based targets for 14 food components as outlined by the EAT-Lancet Commission. The first category, adequacy components, includes vegetables, fruits, nuts, legumes, unsaturated fats, and fish. These components reflect foods that should be consumed in sufficient quantities to support health. The second category, moderation components, includes total grains, red meat, saturated fats, and added sugars, which should be consumed within limits. The final category, optimum components, comprises foods contributing to balanced nutrition, such as potatoes, dairy, poultry, and eggs. Each dietary component is scored on a scale from 0 (no adherence) to 10 (optimal adherence), with higher scores indicating closer alignment with the dietary recommendations. The total PHDS, which ranges from 0 to 140, is calculated by summing the individual scores of all 14 components [20]. This supply-based approach evaluates how well national food availability patterns align with the PHD's health and sustainability goals, offering a comprehensive, macro-level perspective. Detailed calculations are provided in Supplementary 1.

Calculation of CO_2 emissions for various food groups using LCA

This study examines the global warming potential (GWP) of food consumption across twelve regions/countries: Taiwan, Thailand, India, China, Japan, Korea, Vietnam, the United States, Germany, France, Brazil, and Chile. Data were obtained from the FBS in 2017, which provides detailed annual information on food production, supply, and consumption, focusing on the reported food quantities [21]. National food energy availability showed minimal variation between 2017 and 2020, making 2017 an appropriate representative year for CO_2 emission estimation. Foods were categorized into 10 primary groups using the FAO's standardized classification system: cereals; root vegetables; legumes, nuts, and seeds; oils; vegetables; fruits; meat; fish and seafood; animal products; sugar and confectionery. This classification ensures consistency and comparability across regions/countries. CO_2 emissions were estimated using the life cycle assessment methodology, covering the entire product lifecycle—from raw material extraction to consumption and waste management. The global warming potential per kilogram of each food group, as presented in Supplementary Table 2, was then calculated. By integrating these emissions data with country-specific food consumption patterns, the study provides insights into the environmental impact of dietary habits across the 12 regions/countries [22].

Statistical analyses

PoU was estimated using FAO's FBS and national dietary energy consumption patterns. Key parameters included the MDER, Average dietary energy consumption (DEC), and the CV to reflect inequality in energy access. Assuming a log-normal distribution, PoU was calculated as the proportion of the population consuming less than the MDER, using the FAO software and validated against national dietary survey data [23].

The FIES was analyzed in accordance with the FAO methodology using the Rasch model, implemented via the RM.weights in R. The raw scores of the eight dichotomous FIES items were fitted to a unidimensional Rasch model to estimate both item severity parameters and respondent ability. Model fit was assessed through infit and outfit statistics, with acceptable values ranging from 0.7 to 1.3, as recommended by FAO technical guidelines [24].

Descriptive statistics, including means and weighted estimates, were calculated to summarize food and nutrient intake patterns. The Pearson correlation coefficient (r) was used to assess the linear association between CO_2 emissions and the PHDS, with statistical significance evaluated at a two-sided P-value < 0.01. Microsoft Excel 2021 was used for data management, supplementary calculations, and graphical visualization, including trend analyses and the depiction of CO_2 and PHDS relationships. All continuous data are presented as mean $\pm$ SD unless otherwise specified. Only significant figures appropriate to each measurement are reported. Statistical analyses were performed using SPSS version 19.0 (IBM Corp., Armonk, NY, USA) [25], Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, USA), and R version 4.4.0 (R Foundation for Statistical Computing, Vienna, Austria) [26].

Results

Prevalence of undernourishment

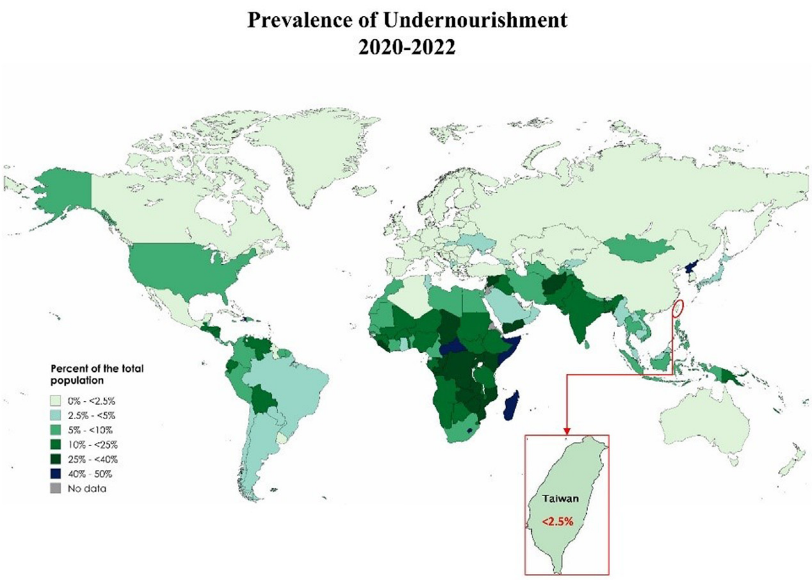
Figure 1 underscores Taiwan's classification as a high-income nation with a PoU below 2.5% from 2017 to 2020, reflecting a stable food security status. In contrast, developing countries such as Vietnam (6%), Thailand (6.5%), and India (13.1%) exhibit higher PoU rates, indicating persistent challenges in achieving adequate nutritional intake.

Food insecurity experience scale

Figure 2 illustrates food insecurity levels from 2020 to 2022. Among developed economies such as Taiwan (1.1%), Japan, and Korea, food insecurity remains under 10%. In contrast, many developing nations, particularly in parts of Africa, with rates exceeding 30%.

Food Security Index and Nutrient Security Index

Table 1, which focuses on the FSI based on the FBS, reveals disparities in the supply of key food groups—certain items are oversupplied while others face critical shortages. For instance, oil and nuts have an S-Nr of 2.76, followed by soy, meat, eggs, and fish at 1.31, and cereals and roots at 1.17, reflecting an unbalanced supply



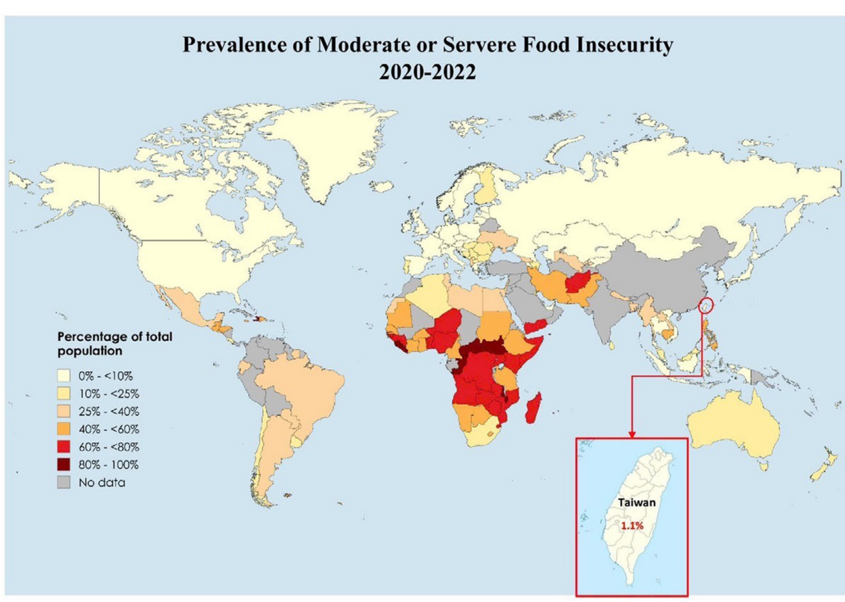
	Country	2020-2022 Undernourishment
1	Japan	<2.5%
2	Korea	<2.5%
3	Viet Nam	6.0%
4	Thailand	6.5%
5	India	13.1%
6	Myanmar	3.0%
7	Philippines	5.4%
8	Malaysia	4.4%
9	Indonesia	5.9%
10	Australia	<2.5%
11	New Zealand	<2.5%
12	Canada	<2.5%
13	USA	<2.5%
14	Mexico	3.4%
15	Brazil	<2.5%
16	Argentina	3.4%
17	Portugal	<2.5%
18	Spain	<2.5%
19	UK	<2.5%
20	Taiwan	<2.5%

Fig. 1. Comparison of the prevalence of undernourishment (PoU) (%) among different regions/countries (2020–2022).

relative to needs. In contrast, dairy, vegetables, and fruits show lower S-Nr values of 0.47, 0.84, and 0.77, respectively.

Table 2 builds on this analysis by presenting the NSI for Taiwan (2017–2020). The NSI calculated S-Nr of the food supply from the FBS relative to the DRIs and adjusted for population size and demographic distribution—identifies key nutrient deficiencies and oversupplies at a population level. Notably, the NSI values indicate a calcium deficiency (S-Nr = 0.56), a fat oversupply (S-Nr = 2.19), and a vitamin A excess (S-Nr = 17.23), among other nutrient imbalances.

Table 3 focuses on the FSI calculated from 24-h dietary records and the food guides, revealing significant trends across age and gender groups for various food categories. E.g., dairy intake is notably low among males, especially in the 45 to 64 and 65 to 74 age groups, with an FSI value of only 0.27, indicating a substantial consumption gap. Fruits and vegetables also show low intake across all age groups, averaging an FSI of 0.71; however, females consistently have higher fruit consumption, with the lowest intakes observed among high school-aged individuals (males at 0.18 and females at 0.25). Vegetable consumption is particularly low in the 1 to 3 age group, with FSI values of 0.23 for males and 0.27 for females. In contrast, cereals and roots maintain a relatively stable intake across all age groups, with an average FSI of 0.97. Finally, the intake of soy, fish, meat, and eggs reaches its peak with an FSI of 1.51 among males aged 19–44, reflecting increased consumption during their most active years, although this intake declines significantly in older age groups, with females consistently showing lower FSI values across the board.



	Country	2020-2022 Food Insecurity
1	Japan	4.4%
2	Korea	5.6%
3	Viet Nam	9.0%
4	Thailand	7.1%
5	India	NA
6	Myanmar	29.3%
7	Philippines	44.7%
8	Malaysia	16.0%
9	Indonesia	4.9%
10	Australia	11.4%
11	New Zealand	15.1%
12	Canada	7.7%
13	USA	7.8%
14	Mexico	27.6%
15	Brazil	32.8%
16	Argentina	36.9%
17	Portugal	12.4%
18	Spain	8.0%
19	UK	4.1%
20	Taiwan	1.1%

Fig. 2. Comparison of the food insecurity (FIES) (%) among different regions/countries (2020–2022).

Table 1
FSI (2017–2020) based on FBS and food guide

Category	FBS*	Food guide	S-Nr
Fruits	2	2.6	0.77
Vegetables	3.2	3.8	0.84
Cereals/roots	13.9	11.9	1.17
Soy, fish, eggs, and meat	7.2	5.5	1.31
Dairy products	0.7	1.5	0.47
Oil, nuts	14.1	5.1	2.76

The table presents the Food Security Index (FSI) for 2017–2020, which incorporates the supply-to-needs ratio (S-Nr). The S-Nr represents the ratio of food supply, derived from the FBS, to the recommended dietary intake (based on the Food Guides), while accounting for population. An S-Nr < 1 indicates insufficient supply, 1 indicates sufficient supply, and >1 indicates oversupply.
*FBS (Food Balance Sheet) classified according to the Taiwan Food Guides (2018).

Table 6 highlights significant trends in NSI across different age and gender groups, emphasizing that calcium, vitamin D, and fiber are the most deficient nutrients, with adolescents and the elderly being the most affected. Calcium intake is consistently inadequate across all age groups, with the lowest adherence observed during adolescence. For example, males and females ages 13 to 15 y have I-Nr values of 0.40 and 0.36, respectively, indicating a substantial deficiency. Similarly, vitamin D intake is critically low across all demographics, with a population average I-Nr of only 0.49, highlighting a significant dietary gap, particularly in older adults. Fiber intake is also insufficient across all groups, with the lowest adherence found in adolescents and the elderly. For instance, fiber I-Nr values are 0.38 for males and 0.37 for females ages 13 to 15 y, and 0.39 for males ages > 71 y. In addition to these deficiencies, magnesium intake decreases with age, with elderly males (> 71 y) showing the lowest adherence at an I-Nr of 0.76, slightly below the population average of 0.92.

Taiwan's plant health diet, introduced in 2022 as an update to the original six-category food guide, emphasizes a shift toward plant-based nutrition. This guideline prioritizes increased soybean consumption and plant-based proteins over traditional animal sources, leading to modifications in the "meat, beans, eggs, and fish" category to reduce meat reliance while promoting a healthier, more sustainable diet. Despite this, Table 5 shows that fish, meat, and eggs are significantly overconsumed with an average intake of 6.78 servings, far exceeding the suggested 2.0 servings, resulting in a high I-Nr of 3.39. Conversely, soybean products are underconsumed at 1.19 servings compared to the recommended 3.5 servings, with a low I-Nr of 0.34. Whole grains slightly exceed recommendations with an I-Nr of 1.05, while fat and oil intake is just above the suggested levels with an I-Nr of 1.09. Vegetables and fruits are under the recommended intake, with I-Nr of 0.80 and 0.76, respectively. The S-Nr reveals excess supply in fats and oils, S-Nr of 2.82, and deficits in soybean products, S-Nr of 0.40, highlighting areas for dietary improvement in line with the new guidelines.

Planetary Health Diet Score

Table 7 shows significant variations in PHD adherence across regions and countries based on FBS from 2017. Taiwan scored the highest (67.97 points, 48.55%), followed by Japan (63.33 points, 45.23%) and India (61.24 points, 43.74%). In contrast, Brazil recorded the lowest adherence (31.06%), along with Chile (31.51%) and the United States (32.58%). Among plant-based foods, Taiwan had the highest whole grain consumption (9.62 points), and potato intake was notably higher in Asian countries than in Western nations, reflecting regional dietary preferences. Vegetables and unsaturated fats achieved perfect scores (10 points) in most countries, aligning well with PHD recommendations. Fish consumption was also high, with Taiwan, Japan, Thailand, India, the United States, and France all scoring 10 points, highlighting its importance in both Eastern and Western diets. For animal-based foods, pork intake was minimal in most countries, with India showing almost no adherence due to cultural dietary restrictions. Egg consumption was highest in Vietnam and India. Milk intake showed marked regional variation, with Chile (9.79 points) and India (7.22 points) scoring highest, while most Asian countries had comparatively lower scores.

CO_2 emissions estimation using LCA

Figure 3 illustrates the global warming potential (GWP) of food consumption across 12 regions/countries, highlighting significant differences in CO_2 emissions per kilogram of food. Western countries, particularly the USA, Germany, and France, exhibit the highest emissions, primarily driven by high meat consumption, which is the largest contributor to GWP. South American countries, including Brazil and Chile, also demonstrate relatively high GWP levels, largely due to animal-based foods and oil consumption. In contrast, Asian countries - namely India, Vietnam, Thailand, and Japan—show much lower emissions, with India recording the lowest GWP, reflecting minimal reliance on meat and animal-derived foods Taiwan (1400 kg CO_2 emission/per capita/year) and South Korea exhibit moderate emissions, with a more balanced dietary profile including cereals, vegetables, fish, and animal products. China falls in the middle-to-high range due to substantial consumption of both cereals and animal-based foods. Overall, the results emphasize substantial regional differences in the environmental footprint of diets, with plant-based foods contributing less to GWP than meat and dairy. These findings highlight the importance of dietary transition toward sustainable, plant-forward patterns, particularly in high-emission countries—to reduce climate

Table 2
NSI (2017–2020) based on FBS and DRIs

Nutrients	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)	Calcium (mg)	Phosphorus (mg)	Iron (mg)	Vit A (i.u.)	Vit B_1 (mg)	Vit B_2 (mg)	Vit C (mg)	Niacin (mg)
FBS	2787	88	119	347	545	1137	12	92761	1.4	1.4	147	15
DRI	1938	62	54	278	979	785	12	538	1.0	1.1	95	15
S-Nr	1.44	1.42	2.19	1.25	0.56	1.45	1.03	17.23	1.36	1.23	1.54	1.02

DRI, dietary reference intakes; FBS, food balance sheet.
The table presents the Nutrient Security Index (NSI) for 2017–2020, which incorporates the supply-to-needs ratio (S-Nr) for key nutrients in Taiwan's general population. The S-Nr represents the ratio of nutrient supply, derived from the food balance sheet (FBS), to the recommended dietary intake (based on the dietary reference intakes, DRIs), adjusted for population size and demographic distribution.
An S-Nr < 1 indicates insufficient supply, 1 indicates sufficient supply, and >1 indicates oversupply.

Table 3
FSI (2017−2020) based on 24-h dietary records and food guide

I-Nr							
Age*	Gender	Cereals/ roots	Soy/fish/meat/eggs	Dairy	Oils nuts	Vegetables	Fruits
1−3	Male	0.96	1.03	1.07	0.60	0.23	0.50
	Female	0.86	0.90	1.07	0.58	0.27	0.50
4−6	Male	0.96	1.27	0.60	0.91	0.43	0.50
	Female	1.02	1.13	0.53	0.98	0.43	0.50
7−12	Male	1.09	1.30	0.40	0.90	0.48	0.33
	Female	0.98	1.14	0.33	0.96	0.43	0.42
13−15	Male	0.98	1.16	0.29	0.84	0.38	0.21
	Female	0.92	0.92	0.33	0.78	0.36	0.25
16−18	Male	0.96	1.20	0.34	0.85	0.36	0.18
	Female	0.89	1.20	0.40	0.96	0.43	0.25
19−44	Male	1.10	1.51	0.33	1.02	0.47	0.29
	Female	1.00	1.39	0.33	1.11	0.57	0.50
45−64	Male	1.07	1.39	0.27	0.87	0.64	0.61
	Female	0.90	1.28	0.33	1.07	0.89	0.95
65−74	Male	1.11	1.25	0.27	0.99	0.82	0.88
	Female	1.06	1.18	0.33	1.04	1.03	1.10
>75	Male	1.07	1.00	0.47	0.86	0.74	0.80
	Female	1.00	1.13	0.33	0.72	0.93	0.95
Weight average		**0.97**	**1.27**	**0.36**	**1.03**	**0.71**	**0.71**

The table presents the Food Security Index (FSI) for 2017−2020, which incorporates the supply-to-needs ratio (S-Nr) for different food categories, based on 24-h dietary records and recommended intake from the Taiwan Food Guides (2018). S-Nr represents the ratio of food supply to the recommended dietary intake, adjusted for population size and demographic distributions during this period.
*Age groups are classified according to the Taiwan Food Guides (2018).

impact while ensuring nutrition and food security. Detailed calculations are provided in Supplementary Table 3.

To further examine the dietary contribution to CO_2 emissions, Table 4 summarizes the estimated CO_2-equivalent emissions per kilogram for red meat (including bovine, mutton, and pig meat) and white meat (poultry) across 16 countries. These data provide more granular insights into the emission intensity of different protein sources and support targeted dietary transition recommendations. The results reveal that red meat consistently generates substantially higher CO_2 emissions than white meat in all countries evaluated. The red-to-white meat emission ratio varies widely, highlighting notable regional differences. For example, Nigeria (16.48), Korea (10.77), Germany (10.73), and France (10.02) exhibit the highest ratios, indicating that red meat in these countries produces approximately 9 −11 times more CO_2 emissions per kilogram than white meat. In contrast, countries like

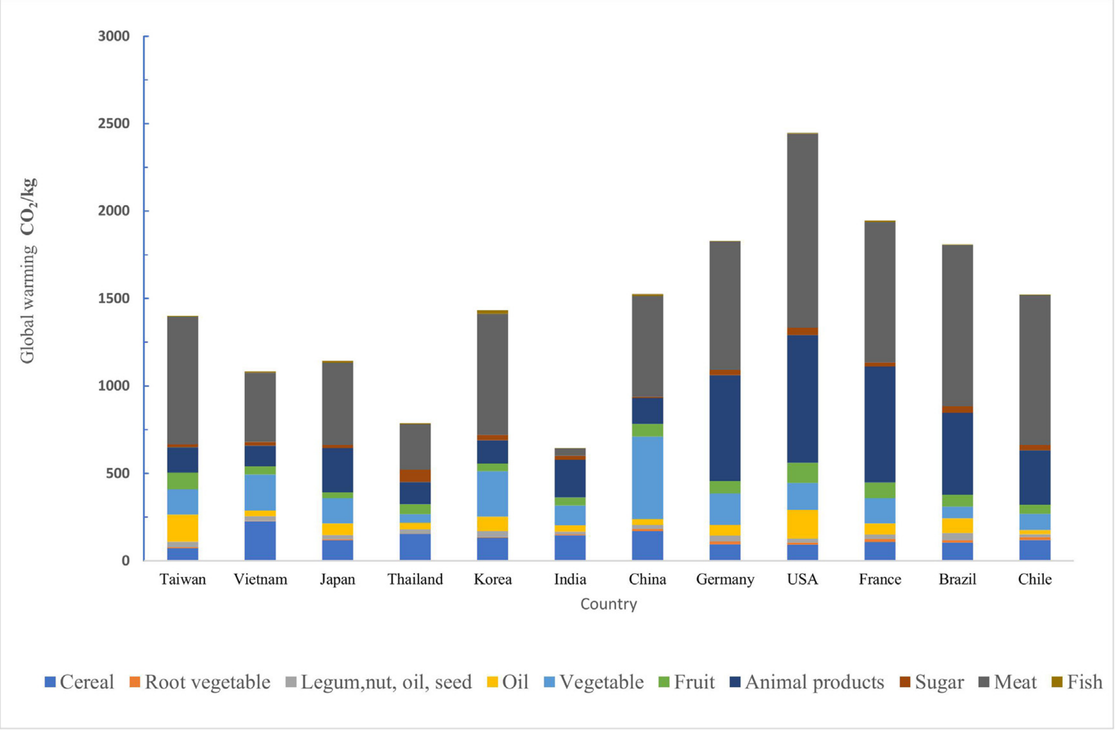


Fig. 3. Global warming potential (CO_2/kg) of food consumption across 12 regions/countries (2017) per capita, based on food balance sheet. Bars represent emissions by region/country, driven by dietary composition (see Supplementary Table 3).

Table 4
Estimated CO_2 emissions from red meat (bovine, mutton, pig) and white meat (poultry) consumption by country (2017) [55]

	Red meat kg CO_2-eq/kg	White meat kg CO_2-eq/kg	Ratio red/white
Taiwan	592.20	195.80	3.02
Japan	633.23	469.84	1.35
Korea	1153.81	107.11	10.77
Vietnam	202.37	56.25	3.60
Thailand	192.59	72.28	2.66
India	56.03	15.99	3.50
China	634.06	74.22	8.54
Germany	1103.93	102.93	10.73
France	1484.31	148.13	10.02
Brazil	1962.12	270.70	7.25
Chile	1498.60	228.39	6.56
America	2039.46	313.53	6.50

Estimates are derived from FBS (2017) and represent CO_2-eq emissions (kg CO_2-eq/kg meat) associated with red meat (bovine, mutton, pig) and white meat (poultry) consumption in 16 countries. Higher CO_2-eq values for red meat indicate a greater environmental impact compared with white meat, underscoring the potential climate benefits of shifting toward lower-emission protein sources.

Japan (1.35), Fiji (1.80) show very low ratios, reflecting either lower red meat emissions or relatively higher emissions from poultry. These emphasize the significantly greater climate impact of red meat and suggest that shifting from red to white meat could be a practical strategy for reducing dietary CO_2 emissions, particularly in high-ratio countries.

Figure 4A shows a scatterplot illustrating the relationship between CO_2 emissions per capita (kg/year) and PHDS per day across 12 countries or regions. The Pearson correlation coefficient is −0.413, and the P-value is 1.71×10^{-6}, indicating a statistically significant moderate negative correlation. This means that countries with higher PHDS adherence, such as Taiwan, Japan, and India, tend to have lower food-related CO_2 emissions, while countries with lower PHDS adherence, like the USA, Brazil, and Chile, tend to have higher emissions. The downward-sloping dotted line represents the trend that greater alignment with the PHD is associated with reduced environmental impact through lower CO_2 emissions from food systems. A noticeable regional clustering pattern is also observed, with Asian countries tending toward higher PHDS scores and lower emissions compared with European and American countries.

Figure 4B shows a scatterplot illustrating the relationship between CO_2 emissions per capita (kg/year) and PHDS per day across three aggregated regions: Asia, Europe, and the Americas. The Pearson correlation coefficient is −0.782, and the P-value is 0.025, indicating a statistically significant, strong negative correlation. This means that regions with higher PHDS adherence, such as Asia, tend to have lower food-related CO_2 emissions, while regions with lower PHDS adherence, such as the Americas, tend to have higher emissions. The downward-sloping dotted line represents the trend that greater alignment with the PHD is associated with reduced environmental impact through lower CO_2 emissions from food systems. These regional findings support the country-level results and suggest that broader dietary cultures, such as greater reliance on plant-based staples in Asia versus higher consumption of animal-sourced foods in Western regions, may shape the strength of the diet−environment relationship.

Discussion

Taiwan has achieved remarkable success in food security, as evidenced by its exceptionally low PoU (below 2.5%) and food insecurity rate (1.1%), significantly lower than in many other countries. However, this study highlights notable imbalances within Taiwan's FSI and NSI, particularly in the form of insufficient intake of essential micro-nutrients such as calcium and vitamin D, as well as a lack of dietary fiber, vegetables, and fruits. Additionally, cross-country comparisons reveal substantial variation in adherence to the PHD across regions and continents. Taiwan demonstrated one of the highest levels of adherence among the analyzed, which was

Table 5
NSI (2017−2020) based on 24h dietary record and DRIs

I-Nr																			
Age*	Gender	Energy	Protein	Fat	Carbo-hydrate	Calcium	Iron	Vit B_1	Vit B_2	Niacin	Vit C	Vit E	Vit B_6	Mg	Fiber	Vit A	Vit B_{12}	ZinC	Vit D
1−3	M	1.00	2.36	0.92	0.93	1.27	0.92	1.55	1.80	1.22	2.00	1.34	2.26	2.15	0.39	1.51	4.40	1.59	0.73
	F	0.93	2.23	0.87	0.85	1.29	0.93	1.47	1.80	1.12	2.07	1.37	2.13	2.00	0.39	1.61	3.30	1.38	0.70
4−6	M	1.00	2.27	1.31	0.90	0.85	1.07	1.32	1.3	1.15	1.83	1.23	2.33	1.68	0.44	1.50	3.97	1.89	0.53
	F	0.95	1.93	1.26	0.86	0.72	0.93	1.27	1.23	1.08	1.87	1.10	1.97	1.48	0.45	1.35	3.59	1.63	0.42
7−9	M	1.00	2.06	1.31	0.88	0.64	1.36	1.36	1.20	1.20	1.88	1.05	2.22	0.42	1.47	1.77	3.13	1.39	0.45
	F	0.93	1.68	1.21	0.84	0.53	1.11	1.28	1.13	1.13	1.54	0.91	1.73	1.20	0.44	1.47	3.06	1.15	0.37
10−12	M	0.99	1.63	1.31	0.88	0.54	0.95	1.41	1.11	1.20	1.52	0.88	1.41	1.10	0.43	1.34	2.87	1.25	0.44
	F	0.90	1.52	1.26	0.78	0.45	0.81	1.24	1.04	1.09	1.40	0.83	1.24	0.95	0.41	1.18	2.05	1.01	0.43
13−15	M	0.88	1.35	1.18	0.77	0.40	1.04	1.27	0.94	1.11	1.19	0.81	1.44	0.75	0.37	1.14	2.21	0.87	0.44
	F	0.79	1.14	1.04	0.71	0.36	0.77	1.04	0.86	0.95	0.95	0.61	1.13	0.63	0.38	1.06	2.01	0.79	0.4
16−18	M	0.84	1.29	1.18	0.71	0.44	0.98	1.17	0.86	1.13	1.18	0.77	1.33	0.68	0.36	0.89	2.19	0.86	0.48
	F	0.89	1.43	1.25	0.75	0.39	0.88	1.19	1.13	1.05	1.06	0.63	1.28	0.69	0.41	1.24	2.3	0.92	0.41
19−30	M	1.04	1.43	1.45	0.84	0.51	1.51	1.30	1.11	1.39	1.30	0.8	1.49	0.74	0.42	1.09	2.27	0.88	0.50
	F	1.05	1.35	1.50	0.87	0.48	0.87	1.41	1.29	1.17	1.11	0.68	1.09	0.74	0.52	1.31	2.61	0.94	0.42
31−50	M	1.13	1.49	1.50	0.94	0.56	1.80	1.39	1.19	1.44	1.48	0.88	1.60	0.83	0.52	1.23	2.44	0.95	0.59
	F	1.03	1.32	1.45	0.85	0.5	0.92	1.4	1.25	1.27	1.47	0.75	1.24	0.80	0.62	1.31	1.97	0.87	0.53
51−70	M	1.09	1.35	1.37	0.94	0.57	1.67	1.33	1.10	1.31	1.90	0.82	1.44	0.96	0.65	1.60	2.58	0.93	0.47
	F	1.00	1.21	1.27	0.90	0.56	1.42	1.35	1.23	1.18	1.87	0.75	1.21	0.97	0.81	1.90	1.70	0.88	0.42
>71	M	0.99	1.09	1.15	0.93	0.59	1.43	1.11	0.99	1.05	1.59	0.73	1.28	0.90	0.66	1.59	1.83	0.78	0.54
	F	0.98	1.03	1.17	0.92	0.53	1.23	1.26	1.1	0.91	1.52	0.63	1.01	0.87	0.74	1.92	1.59	0.84	0.39
Weight average		**1.03**	**1.39**	**1.36**	**0.89**	**0.56**	**1.32**	**1.34**	**1.18**	**1.24**	**1.56**	**0.80**	**1.39**	**0.92**	**0.58**	**1.44**	**2.29**	**0.95**	**0.49**

Values in bold represent weighted averages across all age and sex groups.
F, female, M, male; Mg, magnesium.
This table presents the Nutrient Security Index (NSI) for 2017−2020, which incorporates the intake-to-needs ratio (I-Nr). The I-Nr represents the ratio of nutrient intake, derived from 24-h dietary records, to the dietary reference intakes (DRIs), while accounting for population size and demographic distributions.
*Age groups are classified according to the Taiwan DRI (2011) to ensure comparability across subgroups.

Table 6
Comparison of Taiwan's plant health diet assessment using FBS and 24-h dietary records (2017–2020)

	Whole grains	Fish, meat, and eggs	Soybean products	Dairy products	Fats and oils	Vegetables	Fruits
Taiwan's plant health diet suggestion	**12.0**	**2.0**	**3.5**	**1.0**	**5.0**	**3.0**	**2.0**
Average servings by FBS	13.90	5.80	1.40	0.70	14.10	3.20	2.00
S-Nr	**1.16**	**2.90**	**0.40**	**0.70**	**2.82**	**1.07**	**1.00**
Average servings consumed by the population (19–70 y old)	12.66	6.78	1.19	0.46	5.44	2.40	1.53
I-Nr	**1.05**	**3.39**	**0.34**	**0.46**	**1.09**	**0.80**	**0.76**

Values in bold represent weighted averages across all age and sex groups.
I-Nr (Intake-to-need ratio) represents the ratio of actual dietary intake to the recommended servings based on the Taiwan's plant health diet. S-Nr (Supply-to-need ratio) indicates the ratio of food supply to recommended servings, accounting for population size.

Table 7
Comparative PHDS and adherence percentage across different regions/countries

PHDS	Taiwan	Japan	Korea	China	Thailand	Vietnam	India	USA	Brazil	Chile	Germany	France
Whole grains	9.62	3.00	0.93	0	0	0	0	6.22	4.88	2.80	6.32	4.07
Potato	9.0	6.79	7.57	0	3.94	6.64	4.51	0	0	0	0	0
Vegetables	10	10	10	10	3.45	10	8.15	10	4.83	6.68	10	10
Fruits	10	6.31	8.31	10	10	8.59	8.32	10	10	9.43	10	10
Soy foods	4.93	2.8	2.53	1.83	0.74	1.47	0.06	0.01	0	0.02	0.17	1.80
Added sugar	0	0	0	1.53	0	0	0	0	0	0	0	0
Nuts	0.74	1.74	4.28	1.69	0.43	2.27	0.76	1.80	0.58	0.58	8.95	4.13
Unsaturated fat	10	10	10	0	6.27	2.66	6.55	10	10	5.29	10	10
Eggs	0.70	0	0	0	0	5.92	6.44	0	0	0	0	0
Chicken	0	2.08	2.25	7.48	8.02	9.32	0.27	0	0	0	2.94	0
Pork	0	0	0	0	0	0	10	0	0	0	0	0
Fish	10	10	10	10	10	10	7.19	10	8.79	10	10	10
Milk	2.82	6.99	2.97	3.00	3.20	3.74	7.22	0	4.41	9.79	0.89	0
Saturated fat	0.90	3.60	0	0	1.98	0	1.78	0	0	0	0	0
Total	67.97	63.33	58.84	45.53	48.03	60.61	61.24	48.02	43.48	44.11	59.24	48.22
% adherence PHD	**48.55**	**45.23**	**34.89**	**32.52**	**34.31**	**43.29**	**43.74**	**32.85**	**31.06**	**31.51**	**42.31**	**34.44**

Values in bold represent weighted averages across all age and sex groups.
The data from FBS for the year 2017 according to the Planetary Health Dietary Scores (PHDS) from a previous study, which categorizes them into 14 food groups across 12 regions/countries. This evaluation assesses the consumption patterns of various food groups in relation to recommended guidelines for planetary health. Each food category can score up to 10 points, with a maximum possible total of 140 points, indicating the highest adherence to a Planetary Health Diet.

inversely associated with food-related carbon emissions, suggesting that stronger alignment with the PHD may contribute to lower environmental impact.

Although CO_2 emissions were estimated using the 2017 FBS, while the food security assessment covers the period from 2017 to 2020, this time discrepancy is unlikely to significantly affect the findings. To further verify its representativeness, we examined Taiwan's national food energy availability for the period 2017 to 2020, which showed minimal variation (2017: 2769 kcal/d; 2018: 2807 kcal/d; 2019: 2760 kcal/d; 2020: 2806 kcal/d). These stable values suggest that dietary patterns during this period were consistent, supporting the use of 2017 data as an appropriate reference year. A significant dairy deficiency, identified in the FSI, affects over 40% of Taiwan's population due to the absence of dairy in traditional diets, high lactose intolerance rates, relatively high costs, and limited regional availability [27]. Restricted grazing opportunities further hinder large-scale dairy farming, exacerbating the calcium deficiency observed in the NSI [28]. This deficiency is particularly pronounced among females, with adolescent girls ages 13 to 15 showing the lowest calcium intake, consistent with findings from China and Malaysia [29,30]. These deficiencies are especially concerning during adolescence, a critical period for bone growth and peak bone mass development, prevention of osteoporotic fractures later in life [31]. A study in Iran, using the transtheoretical model (TTM) in schools, successfully increased dairy consumption from 15% to 37% through educational sessions and

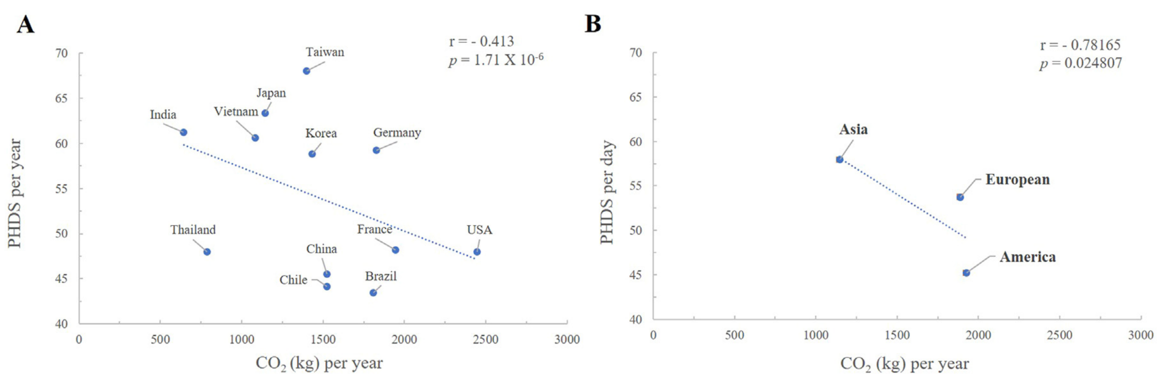


Fig. 4. Scatterplot showing the correlation between CO_2 emissions and planetary health diet score (PHDS) across 12 different regions/countries. A negative correlation (−0.413) suggests that higher PHDS adherence is associated with lower CO_2 emissions (P value < 0.01).

behavior-focused strategies [32]. Fortified plant-based milks (soymilk, oatmilk, and almond milk) provide lactose-free options and calcium and vitamin D sources, offering a culturally acceptable and physiologically suitable alternative to traditional dairy products [33,34].

The NSI's finding of a vitamin D deficiency may contribute to bone mineral density (BMD) loss, affecting nearly 50% of women and 25% of men over 50 in Taiwan [35]. This deficiency aligns with global challenges and highlights the need for targeted interventions. The observed association between higher EAT-Lancet diet adherence and increased risk of vitamin D and calcium inadequacy aligns with previous studies, highlighting nutritional limitations in plant-based dietary models [36]. In clinical settings, high-dose vitamin D_3 (e.g., 50 000 IU every 2 wk) has been shown to improve calcium absorption in postmenopausal women with low vitamin D levels [37]. Similarly, a Thai study found that daily supplementation with 1000 IU of vitamin D3 significantly raised 25-hydroxyvitamin D [25(OH)D] levels to 26.03 ng/mL, outperforming weekly doses of 20 000 IU of vitamin D2 [38]. Beyond supplementation, consuming UV light-treated Pleurotus citrinopileatus mushrooms, as demonstrated by Hsu et al. [39], significantly increased serum 25(OH)D levels, offering a natural dietary strategy. Functional foods such as vitamin-D-enriched mushrooms provide a sustainable solution, as evidenced by their ability to modulate metabolic pathways and support nutrient security [40]. Gender-specific approaches are also critical: boys may benefit from dietary measures to improve vitamin D status, while girls could leverage supplementation and hormonal contraceptives, which are associated with higher serum 25(OH)D levels, as noted by Öberg [41].

The FSI's low values for fruits and vegetables, particularly among men [42,43], reflect insufficient fiber intake, posing risks for chronic diseases such as cardiovascular disease, type 2 diabetes [44]. This deficiency is compounded by Taiwan's vulnerability to natural disasters, such as typhoons and earthquakes, which disrupt supply chains, damage crops, and impede transportation. To enhance food security and dietary diversity, urban agriculture initiatives in Japan, integrating professional and hobby farming, have contributed approximately 6.18% of vegetable needs and 2.86% of key nutritional requirements annually, offering a model for Taiwan [45]. Similarly, smart farming technologies in Europe have optimized food production in land-scarce regions, providing a sustainable approach to bolster Taiwan's FSI and NSI [46,47]. Implementing these innovations could strengthen supply chains, improve vegetable and fruit intake, and promote healthier dietary practices [48]. Moreover, increasing fiber intake by 5 to 10 g per day whole foods or supplements, has been shown to significantly improve blood pressure, cholesterol levels, and glycemic control [49].

This study finds that meat-heavy diets in Western countries like the United States are often tied to affluence and tradition [50,51], driving the highest CO_2 emissions among food groups, with animal agriculture accounting for 14.5% of global human-induced emissions [52]. In contrast, Asian countries have lower CO_2 emissions due to their dietary habits. The FAO predicts that global meat consumption will increase by over 70% by 2050 [53]. From 2000 to 2020, Taiwan's greenhouse gas (GHG) emissions rose, with CO_2 making up about 95% of these emissions [54]. Taiwan's shift toward plant-based diets backed by government guidelines could cut emissions while enhancing nutrient security. Poore et al. [55] highlighted the markedly higher emission intensity of red meat compared to white meat, particularly in countries with high red-to-white meat ratios, underscoring the need for targeted dietary recommendations to reduce red meat consumption as an effective climate mitigation strategy. Providing subcategory-specific emission data enables policymakers to design interventions focused on the most impactful protein sources [56]. Importantly, the large emission difference between red and white meat observed in this study indicates that substituting a portion of ruminant meat with poultry or fish could produce substantial emission reductions. Because ruminant emissions are driven by enteric fermentation and land-intensive feed requirements, this substitution offers a practical mitigation pathway that does not require major changes to total protein intake [57]. Such benefits are especially relevant for Western countries with high red-meat consumption, whereas Asian countries with lower ruminant intake and greater reliance on white meat and plant-based staples already reflect lower-emission dietary patterns [58].

Our findings, based on PHDS and CO_2 emissions, highlight distinct patterns in dietary quality and environmental impact across different countries. Countries like Taiwan and Japan, with greater availability of whole grains, potatoes, and vegetables, exhibit higher PHDS values, supporting previous research on the positive correlation between plant diversity and diet quality [59,60]. Furthermore, plant-based diets are associated with reduced risks of cardiovascular disease, obesity, and hypertension—conditions frequently encountered in clinical settings [61–63]. Supporting this shift, almond protein powder has been shown to improve nitrogen balance, delivering 30 g of plant protein daily, comparable to meat-based sources [64]. Plant-based protein options are especially valuable for renal patients [65], elderly individuals at risk of sarcopenia [66]. Taiwan achieved the highest PHDS among the 12 countries assessed, but exhibited nutrient intake patterns for vitamin D and calcium consistent with previous findings, underscoring persistent micro-nutrient challenges even in high-adherence populations [36]. In contrast, Western countries face challenges in adhering to the PHD, consistent with Costlow's observation that the limited availability of plant-based foods restricts dietary diversity and nutritional adequacy [67]. Cultural and regional factors further shape PHD adherence: India's minimal pork consumption, driven by religious and cultural preferences, aligns with the PHD's recommendation to reduce red meat intake [68], whereas pork-dominant cuisines may struggle with this shift. Higher PHDS adherence, as observed in Taiwan and Japan, correlates with lower CO_2 emissions, reinforcing prior studies linking plant-based diets to improved health and environmental sustainability [7,69]. While our results suggest a link between PHDS adherence and reduced CO_2 emissions, correlation does not imply causation. Emission reductions depend on multiple factors beyond diet, such as deforestation for soy and palm oil production, which can negate the benefits of plant-based diets, particularly in Southeast Asia, Africa, and Latin America [70]. When examined at the regional level (Asia, Europe, and the Americas), a strong negative correlation emerged between PHDS adherence and CO_2 emissions, with Asia showing both higher PHDS and lower emissions compared to the Americas. This suggests that broader regional dietary patterns mirror country-level trends, reinforcing the role of cultural norms and food systems in shaping both diet quality and environmental outcomes [71,72].

These regional differences likely reflect variations in food system structure and long-standing dietary cultures. Asian food systems are centered around staple crops, vegetables, legumes, and soy, and culinary practices emphasize plant-forward meals, contributing to higher PHDS adherence and lower CO_2 emissions. In contrast, Western regions rely heavily on livestock-based food systems and meat-centric diets, resulting in lower alignment with PHD recommendations and substantially higher emissions [73]. This suggests that the diet–environment relationship is shaped not only by nutrient composition but also by cultural norms and agricultural priorities, underscoring the need for sustainable diet strategies that account for regional food environments [74].

Additionally, the carbon intensity of energy sources used in farming, processing, and distribution significantly influences overall emissions [75]. To promote plant-based dietary patterns effectively, policymakers must consider cultural preferences, local food availability, and affordability, tailoring interventions to each country's context [76].

Our study's strength lies in its use of a nationally representative sample, allowing the findings to be generalized to Taiwan's entire population and other ethnic Chinese groups with similar dietary patterns. The FSI, NSI, and CO_2 emissions were calculated using standardized government data sources, including the FBS, DRIs, and FGs, ensuring reliability and consistency in the analysis. Integrating FBS data enables the comparison of PHD adherence across regions or countries spanning Asia, South America, North America, and Europe, providing a comprehensive view of global dietary patterns and facilitating the development of healthy, sustainable food systems tailored to each region's specific needs. This study pioneers the exploration of the correlation between CO_2 emissions and PHDS using FBS data, laying a valuable foundation for future research.

However, this study has several limitations that affect the breadth and depth of its findings. Notably, the government-reported FBS lacks data on key micro-nutrients such as vitamins B6, B12, D, E, zinc, and magnesium, preventing their inclusion in the NSI. In particular, the omission of vitamin B12 and zinc—critical for neurological and immune function [77] and often insufficient in plant-based diets—may lead to an underestimation of nutritional risks in sustainable dietary shifts. As populations shift toward lower-emission diets that reduce red meat and increase plant-based foods, these nutrients may become limiting; therefore, their exclusion could lead to an underestimation of nutritional vulnerabilities that commonly arise in plant-forward eating patterns [78]. This limitation reflects gaps in national-level data availability rather than methodological oversight. The analysis also does not account for changes in dietary patterns over time, restricting its ability to track long-term trends in food security and their environmental impacts. Additionally, while CO_2 emissions are considered a primary environmental factor, other key ecological aspects such as water usage, biodiversity loss, and land degradation were not assessed, resulting in an incomplete evaluation of the overall environmental impact of food consumption. Moreover, the PHDS was calculated using per capita food consumption data from the FAO FBS, but it does not provide individual-level energy intake information. As a result, the score could not be standardized by personal energy requirements, as in the original EAT−Lancet approach. This non−energy-standardized method may not fully capture dietary quality, particularly in populations with higher or lower caloric needs. While the use of FBS food consumption data ensures global coverage, low cost, public accessibility, and enables standardized cross-country comparisons, it reflects population-level availability for consumption rather than individual-level adherence to dietary recommendations.

Conclusion

In conclusion, while Taiwan maintains strong food security with low rates of undernourishment and food insecurity, imbalances in food and nutrient security persist. The supply and intake of dairy, fruits, and vegetables remain insufficient, along with inadequate calcium, vitamin D, and dietary fiber consumption, potentially impacting public health. To address these issues, targeted policies should promote nutritionally balanced and sustainable diets that not only meet the population's nutritional needs but also reduce environmental impacts.

Ethical approval

Ethical approval for this study was granted by the Institutional Review Board of Taipei Medical University, under the approval number N202405028, validated on May 17, 2024.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sing-Chung Li reports that financial support was provided by Taipei Medical University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Dang Hien Ngan Nguyen: Writing − original draft, Software, Methodology, Formal analysis. **Chiao-Ming Chen:** Methodology, Data curation. **Shih-Ping Lin:** Software. **Hong Nhung Lam:** Validation. **Chien-Tien Su:** Validation. **Kang Ernest Liu:** Validation. **Shu-Chen Lee:** Data curation. **Sing-Chung Li:** Writing − review & editing, Supervision, Project administration, Conceptualization.

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Supplementary materials

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