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Adherence to the planetary health diet index and metabolic syndrome: cross-sectional results from the PERSIAN cohort study

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Abstract

Background/objectives The Planetary Health Diet Index (PHDI) was recently introduced to assess adherence to the EAT-Lance recommendations. In this study, we aimed to evaluate the relationship between PHDI and metabolic syndrome (MS).

Subjects/methods We used the data of 6465 participants from the PERSIAN cohort study at Mashhad University of Medical Sciences, Mashhad, Iran. Diet was assessed using a 130-item Food Frequency Questionnaire (FFQ). The PHDI comprises sixteen components and is scored between 0 and 150 points. We first assessed the validity and reliability of the PHDI for this population. We used regression logistic models to assess the relationships between PHDI and MS and its related indicators.

Results The average PHDI score was 52.3 ± 9. The Cronbach's alpha value was 0.53.

After controlling for age and sex, the PHDI was positively related to the Diet Quality Index-International (DQI-I) and was negatively related to carbon and water footprints ($p < 0.001$). PHDI quartile was negatively associated with MS, hypo-HDL cholesterolemia, and abdominal obesity after controlling for confounders ($P < 0.05$).

Conclusion The validity and reliability of the PHDI were found to be satisfactory for the Iranian population we studied. Our results showed that a higher PHDI was potentially related to a reduced likelihood of MS, hypo-HDL cholesterolemia, and abdominal obesity.

Keywords Sustainable diet, EAT-Lancet diet, Dietary pattern, Metabolic syndrome, Obesity

Introduction

Metabolic syndrome (MS) is a combination of risk factors such as hyperglycemia, dyslipidemia, hypertension, and abdominal fat accumulation [1]. According to the International Diabetes Federation (IDF) definition, a person has MS if he or she has a waist circumference (WC) above the ethnic threshold plus two or more of the following four factors: *1*) increased concentration of triglycerides (TGs) ≥ 150 mg/dl (1.7 mmol/l) or specific treatment for this lipid abnormality; *2*) reduced concentration of High-density lipoprotein cholesterol (HDL-c) < 40 mg/dl (1.03 mmol/l) in men and < 50 mg/dl (1.29 mmol/l) in women or specific treatment for this lipid abnormality; *3*) increased blood pressure: systolic blood pressure (SBP) ≥ 130 mmHg or diastolic blood pressure (DBP) ≥ 85 mmHg or treatment of previously diagnosed hypertension; and *4*) increased fasting blood glucose

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(FBG) concentration ≥ 100 mg/dl (5.6 mmol/l) or previously diagnosed type 2 diabetes melitus (T2DM) [2]. Patients with MS are at risk of chronic diseases such as T2DM, hypertension, cardiovascular disease, and cancer [3]. The global trend of MS has increased dramatically in recent years, reaching an alarming level [4]. According to estimates from the World Health Organization (WHO), the prevalence of MS ranges from 13.4% to 70.0% in different countries [5]. According to a meta-analysis by Kastorini C-M et al., the prevalence of MS was reported to be 34.6% and 36.9% in the Iranian population based on different definitions of MS [6]. According to the NCEP-ATPIII recommendations, therapeutic lifestyle modifications have a potential role in preventing and reducing the prevalence of MS [7]. Among the different factors associated with lifestyle, a healthy diet has potential effects on the management of MS [8].

As described in recent studies, a healthy diet must consider environmental factors in addition to disease outcomes [9]. A sustainable diet is defined as a diet with the least negative environmental effects and that improves society's health [10]. Sustainable diets protect biodiversity and ecosystems and are culturally acceptable, accessible, economically viable, nutritionally adequate, safe, and healthy while optimizing natural and human resources [11].

In early 2019, the EAT-Lancet Commission introduced a sustainable reference diet named the "Planetary Health Diet" [12]. This diet is based on the effects of food systems on the environment and human health; in summary, this diet recommends increasing the intake of plant-based foods and unsaturated fats and decreasing the consumption of poultry and seafood, red meat, processed meat, refined grains, starchy vegetables, and added sugar [12].

Recently, the Planetary Health Diet Index (PHDI), introduced by Cacau, L.T et al. [13], comprises 16 food items that evaluates adherence to the EAT-Lancet recommendations. This index is scored on a scale from 0 to 150, where a score of 150 signifies the highest level of dietary sustainability for an individual. The PHDI is associated with reduced greenhouse gas emissions (GHG) emissions and improved overall dietary quality.

Previous studies have examined the association between the PHDI and various obesity outcomes, cardiometabolic risk factors, and T2DM. Results indicate an inverse relationship between PHDI and certain indicators of MS. For instance, in the study by Cacau, L.T et al., a direct association was found between PHDI and lower WC, a key indicator of MS [14]. Additionally, in the other study of Cacau, L.T et al., PHDI was significantly related to lower blood pressure and higher levels of HDL-c, further supporting its connection to MS [15].

Several studies have also explored the relationship between the EAT-Lancet Planetary Health Diet and T2DM, confirming a potential link between adherence to EAT-Lancet recommendations and reduced risk of developing T2DM [16, 17].

However, to date, no comprehensive studies have assessed the association of PHDI with MS and its indicators.

In this study, our objective was to evaluate the relationship between the PHDI and MS, along with its specific indicators. To accomplish this aim, we undertook the task of validating the PHDI for the Iranian population using data from the extensive PERSIAN cohort.

Methods

Study design and population

This cross-sectional study used data from the PERSIAN cohort study (Prospective Epidemiological Research Studies in Iran). The main objective of this prospective study was to investigate and improve the health outcomes of the staff of Mashhad University of Medical Sciences. The PERSIAN Cohort will serve as a vital infrastructure for future implementation research, providing essential evidence to inform new healthcare policies aimed at improving the control, management, and prevention of non-communicable diseases (NCDs). The cohort was composed of 10,000 adults from 2017 to 2020 in Mashhad, Iran.

For the present study, data from 5206 participants (44.7% men) were included. The inclusion criteria were meeting the age criteria (30 – 70 years). They needed to be residents of Mashhad and hold Iranian citizenship. Participants with a daily energy intake of less than 800 kcal or more than 4200 kcal were not eligible to participate. Incomplete measurements of the subjects led to their exclusion from the study.

Sociodemographic and lifestyle characteristics and medical history were collected through interviews. Anthropometric measurements were performed by trained personnel. Written informed consent was obtained from all participants. More information about the PERSIAN cohort study is available elsewhere [13]. This study was approved by the Ethics Committee of the Mashhad University of Medical Sciences (Code of Ethics: IR.MUMS.MEDICAL.REC.1401.231). The study process is presented in Fig. 1.

Measurements

All measurements were obtained from the PERSIAN cohort study.

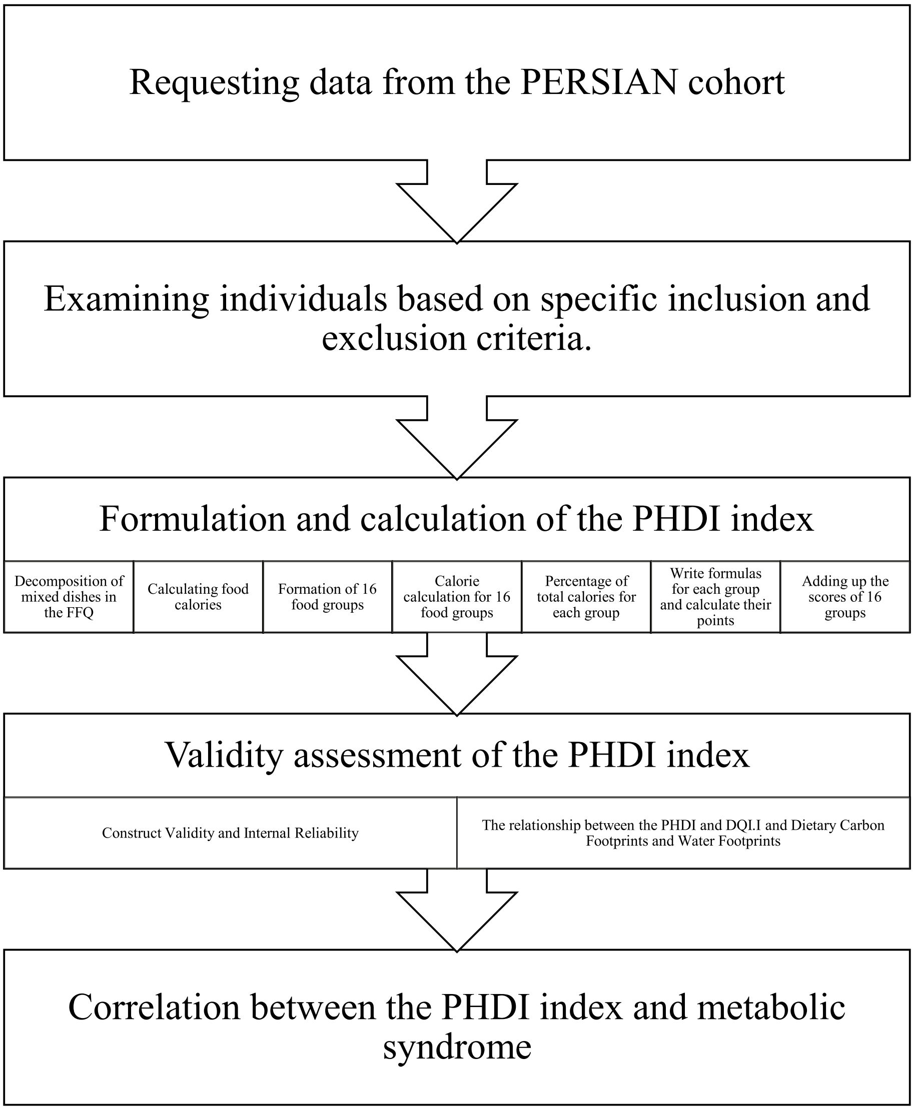

Fig. 1 The study flowchart. The flowchart shows the process of the study; PHDI Planetary Health Diet Index, FFQ food frequency questionnaire, DQI-I Diet Quality Index-International

Metabolic syndrome

MS was characterized as the presence of any three of five following criteria [18]: (1) WC ≥ 95 cm [19]; (2) FBG ≥ 100 mg/dl or drug therapy; (3) fasting TGs ≥ 150 mg/dl or drug therapy; (4) fasting HDL-c < 40 mg/dl for men and < 50 mg/dl for women or drug therapy; and (5) high blood pressure SBP ≥ 130 mmHg, DBP ≥ 85 mmHg, or antihypertensive drug treatment).

Anthropometric parameters and blood pressure

Weight was measured with a calibrated electronic scale (InBody 770, Cerritos, CA, USA) with minimum clothing. Participants were measured while wearing minimum clothing and without shoes. Height was measured using a stadiometer with an accuracy of 0.1 cm without shoes. Body mass index (BMI) was calculated by dividing body weight (kilograms) by height in meters squared. WC was measured with the participants in a standing position with flexible tape with an accuracy of 0.1 cm.

Blood pressure was measured by a trained nurse using a standard sphygmomanometer in a quiet room after 5–10 min of rest.

Biochemical assessments

All blood samples were collected after a 10–12-h overnight fast in potassium-EDTA vacuum tubes. FBG, total cholesterol, TG, HDL-c, and low-density lipoprotein cholesterol (LDL-c) were measured using standard laboratory procedures and analyzed using a standard analyzer.

Dietary assessment

A validated 130-item food frequency questionnaire (FFQ) was used to assess dietary intake [20]. Participants were asked to indicate how frequently they had consumed each food or drink in the past year. The frequency of intake for each item was reported as how many times a day, week, or month. The intake of energy, macronutrients, and micronutrients was measured by multiplying the frequency of each unit of food item by the energy and nutrient content of the determined portion size. An adopted version of Nutritionist IV software for Iranian foods (version 7.0; N-Squared Computing, Salem, OR, USA) was used in order to assess the nutrient and energy intakes [21]. To calculate the caloric intake of specific food groups for the calculation of the PHDI, all mixed dishes in the FFQ were decomposed into separate ingredients. There were only two mixed dishes in the FFQ questionnaire: Sholleh Mashhadi and pizza. We used the common recipes to calculate their ingredients.

Development of the PHDI

The PHDI is based on the "Planetary Health Diet" recommendations; this diet is set with energy intake (2500 Cal/day), with 23 different food groups [12]. To tailor these recommendations to accommodate various caloric needs, the ranges and midpoints suggested for each food group were calculated based on their energy contribution to a reference diet of 2500 kcal per day. The components, cutoffs and thresholds of the PHDI were defined based on these values, as described in Table 1.

The index includes sixteen components, with categories in four groups: (1) adequacy components; (2) optimum components; (3) ratio components; and (4) moderation components. Each component is scored between 0 and 5 or 10 points. Food groups classified as adequacy components were those where a zero intake (i.e., non-consumption) would be associated with lower dietary quality, whereas intakes at or above the reference levels would likely pose minimal risks to both human and planetary health. As a result, nuts, legumes, fruits, total vegetables, and whole grains were identified as adequacy components. Similarly, optimum components were chosen based on food groups where a certain minimum intake (represented by midpoint values) is preferable to non-consumption. However, as consumption nears or surpasses an upper limit—based on the maximum values set by the reference diet—it could negatively impact both sustainability and diet quality. Eggs, fish, seafood, potatoes, dairy, and unsaturated oils were categorized as optimum components.

In the PHDI, two ratio components reflect the proportion of dark green vegetables and red and orange vegetables relative to total vegetable intake. To prevent overemphasizing this dietary aspect, a maximum score of 5 points was assigned to each ratio component. Unlike adequacy components, moderation components were selected based on the assumption that lower intakes (approaching zero) would lead to higher diet quality and sustainability. Red meat, poultry and substitutes, animal fats, and added sugars were identified as moderation components in the PHDI. Detailed information about the PHDI and its scoring is found in the study by Cacau LT. et al. [13].

Assessment of demographic variables

Sociodemographic and lifestyle data were assessed using validated questionnaires as used for the PERSIAN cohort study.

Physical activity (PA) was measured by a validated 28-item Physical Activity Questionnaire designed by the PERSIAN Cohort. Physical activity level was evaluated based on self-reports of weekly activities using Metabolic Equivalent Rates (METs) of participants [22]. The MET of each activity was extracted using a compendium of physical activities.

Validity assessment

PHDI performance was assessed using a strategy to evaluate construct validity and reliability, as described by Reedy et al. [23], Additionally, we examined the relationships between the PHDI and overall dietary quality [24] and between the PHDI and carbon and water footprint estimations to assess the validity of the PHDI. To evaluate construct validity, linear regression was used to assess the relationships between total PHDI scores and selected nutrients.

In the third step, we used principal component analysis (PCA) to evaluate whether PHDI had more than one factor that explained the data variability. In this analysis, the correlation matrix was calculated using varimax rotation, and eigenvalues greater than one were only used to define the number of factors [25]. As an auxiliary method, we used the scree test to determine the degree of variation of each main component [26].

To evaluate internal reliability, Cronbach's alpha was calculated to measure the mean of the correlations between all possible combinations of the PHDI components [27]. Linear regression was used to examine the association of the PHDI score with overall dietary quality.

Overall dietary quality

We examined dietary quality by using the Diet Quality Index-International (DQI-I) [24]. The DQI-I includes

Table 1 PHDI components, standards for scoring (caloric densities), and corresponding point values (1)

Components	Score(points)1				
	0	5	10	5	0
Adequacy components					
Nuts and peanuts	0.0 |	⟷	| >=11.6		
Legumes ¢	0.0 |	⟷	| >=11.3		
Fruits	0.0 |	⟷	| >=5.0		
Vegetables	0.0 |	⟷	| >=3.1		
Whole cereals	0.0 |	⟷	| >=32.4		
Optimum components					
Eggs	0.0 |		| 0.8 |	⟷	| >=1.5
Fish and seafood	0.0 |		| 1.6 |	⟷	| >=5.7
Tubers and potatoes	0.0 |	⟷	| 1.6 |	⟷	| >=3.1
Dairy	0.0 |		| 6.1 |	⟷	| >=12.2
Vegetable oils °	0.0 |		| 16.5 |	⟷	| >=30.7
Ratio components					
DGV/total ratio ≠	0.0 | ⟷	| 29.5		29.5 | ⟷	| 100
ReV/total ratio ≡	0.0 | ⟷	| 38.5		38.5 | ⟷	| 100
Moderation components					
Red meat £	>=2.4|	⟷	| 0.0		
Chicken and substitutes	>=5.0|	⟷	| 0.0		
Animal fats ǂ	>=1.4|	⟷	| 0.0		
Added sugars	>=4.8|	⟷	| 0.0		

Table 1 (continued)

All values expressed as caloric densities from the reference diet proposed by EAT-Lancet Commission. The bars represent the limits. £ Red meat: beef, lamb, and pork. ¢ Legumes: beans and soy. § Dairy: excluding dairy fats. ° Unsaturated oils: including palm oil. ≠ DGV/total ratio: ratio between the energy intake of dark green vegetables (numerator) and the total of vegetables (denominator) multiplied by 10. ≡ ReV/total ratio: ratio between the energy intake of red and orange vegetables (numerator) and the total of vegetables (denominator) multiplied by 10. ╪ Animal fat: lard, tallow, and dairy fats. DGV/total ratio: dark green vegetables/total ratio. ReV/total ratio: red and orange vegetables/total ratio

four categories: 1) Variety: This category examines both overall variety and variety in different protein types to evaluate whether intake is obtained from different sources across and within food groups. 2) Adequacy: This item assesses the intake of nutrients that are critical for preventing malnutrition. 3) Moderation: This category evaluates food and nutrient intake related to chronic diseases. 4) Overall balance: This item evaluates the dietary balance in terms of the proportion of fatty acid composition and energy sources [24]. Detailed information about the DQI-I is explained in the study by Soowon Kim et al. [24].

Dietary carbon and water footprints

We used water and carbon footprints to consider the environmental aspects of diet. The carbon footprint is a measure of the total carbon dioxide produced by an activity or accumulated during the life cycle of a product [28]. The global database for carbon dioxide emissions of each food item from BCFNDOUBLEPYRAMIDDATABASE was used [29].

The water footprint is a measure of the total freshwater used for producing goods and services consumed by individuals or communities. The water footprint of each food must be multiplied by its amount to obtain the amount of water consumed for each food. The water footprint information was available for Iran [30, 31].

Statistical analysis

Categorical variables are described as numbers and percentages, and means ± SDs were calculated for continuous variables at baseline. Differences between quartiles of PHDI scores were examined with ANOVA and chi-square tests. Adjusted and unadjusted regression logistic models were used to evaluate the association of the PHDI with outcomes. Logistic regression models were adjusted for age and sex (Model 2) and more adjustments (education level, wealth score index, smoking status, sleep status, physical activity level, and energy intake) (Model 3).

The statistical analyses were performed using SPSS software version 26.0 (SPSS Inc., Chicago, IL, USA). P values < 0.05 were considered to indicate statistical significance.

Results

PHDI validation

The PHDI followed a normal distribution, and the mean score was 52.3 ± 9. Among the PHDI components, fruits (9.9 ± 0.5), vegetables (9.6 ± 1.2), tubers (5.3 ± 2.9), and whole cereals (4.4 ± 2.7) had the highest average scores. However, red meat (1.0 ± 2.2), added sugars (0.8 ± 1.9), and dark green vegetables (DGV) (0.5 ± 0.7) had lower mean scores (Table 2).

Construct validity and internal reliability

A higher PHDI was related to a lower intake of animal-based protein, total fat, some dietary fat sources (saturated and cholesterol), and some vitamins (A and B12) ($p < 0.001$). Furthermore, a higher PHDI was related to a greater intake of energy, total protein, carbohydrates, plant-based proteins, polyunsaturated fats, fibers, and micronutrients from fruits, vegetables, whole grains, and oilseeds ($p < 0.001$) (Table 3).

The Cronbach's alpha value was 0.53. Generally, the intercomponent correlations were low to moderate,

Table 2 Descriptive analysis of PHDI components

Components	Maximum points	Mean	SD	Median	IQR
Red meats	10	1.03	2.16	0.00	0.53
Nuts and peanuts	10	2.45	2.07	1.85	2.41
Legumes	10	2.95	2.06	2.39	2..37
Chicken and substitutes	10	1.68	2.18	0.29	3.19
Fish and seafood	10	2.93	2.54	2.14	3.28
Eggs	9.99	1.84	2.87	0.00	3.52
Fruits	10	9.92	0.55	10	0.00
Vegetables	10	9.58	1.16	10	0.00
DGV/total ratio	4.7	0.50	0.72	0.20	0.63
ReV/total ratio	5	2.89	0.99	2.86	1.35
Whole cereals	10	4.37	2.70	4.00	4.02
Tubers	10	5.28	2.88	5.67	4.64
Dairy	10	1.60	2.86	0.00	2.36
Unsaturated oils	9.86	2.48	1.74	2.10	2.14
Animal fats	10	1.87	3.17	0.00	3.00
Added sugars	10	0.81	1.93	0.00	0.00
Total score	0_150	52.26	8.94	51.48	12.31

Values are expressed as mean and SD, and median and IQR

SD Standard deviation, *IQR* Interquartile range, *DGV/total ratio* Dark green vegetable/total ratio, *ReV/total ratio* Red vegetable/total ratio

Table 3 Association between PHDI and nutrients

Nutrient	B[a]	95% CI		*p*-Value
Energy (kcal)	0.001	0.001	0.002	< 0.001
Protein (g)	0.032	0.023	0.040	< 0.001
Animal protein (g)	-0.005			< 0.001
Total fat (g)	-0.013	-0.020	-0.005	0.001
Cholesterol (mg)	-0.023	-0.024	-0.021	< 0.001
Saturated fat (g)	-0.159	-0.117	-0.141	< 0.001
Monounsaturated fat	-0.013	-0.034	0.009	0.244
Riboflavin (mg)	0.505	0.213	0.798	0.001
Niacin (mg)	0.174	0.148	0.201	< 0.001
Vitamin B5 (mg)	0.484	0.379	0.589	< 0.001
Pyridoxine (mcg)	0.026	-0.003	0.056	0.080
Vitamin B12 (mcg)	-0.127	-0.178	-0.075	< 0.001
Calcium (mg)	0.002	0.001	0.002	< 0.001
Sodium (mg)	0.00	0.00	0.00	< 0.001
Carbohydrate (g)	0.016	0.014	0.017	< 0.001
Vegetable protein (g)	0.011			< 0.001
Polyunsaturated fat	0.316	0.283	0.349	< 0.001
Fiber (g)	0.253	0.235	0.271	< 0.001
Vitamin A (RE)	-0.007			< 0.001
Vitamin E (mg)	0.447	0.399	0.495	< 0.001
Vitamin K (mg)	0.008	0.007	0.009	< 0.001
Vitamin C (mg)	0.011	0.009	0.013	< 0.001
Thiamine (mg)	4.034	3.674	4.395	< 0.001
Folate (mcg)	0.013	0.012	0.015	< 0.001
Iron (mg)	0.449	0.410	0.488	< 0.001
Phosphorus (mg)	0.003	0.002	0.003	< 0.001
Potassium (mg)	0.001	0.001	0.001	< 0.001
Zinc (mg)	0.164	0.104	0.224	< 0.001
Selenium (mcg)	0.021	0.015	0.026	< 0.001
Magnesium (mg)	0.019	0.017	0.020	< 0.001
Copper (mg)	3.666	3.333	4.000	< 0.001

CI Confidence interval

[a] Model adjusted for age and sex

ranging from 0.4 for chicken and substitutes and eggs to -0.3 for chicken and substitutes and fish/seafood.

Based on the PCA scree plot (Fig. 2), PHDI components were not responsible for dietary patterns covariation. Figure 2 shows the presence of five factors with an eigenvalue > 1, representing 50.5% of the total variance in the index, and this line is predicted to stagnate after the third factor.

The relationship between the PHDI and DQI.I and dietary carbon footprints and water footprints

The DQI.I the average was 56.9 ± 7. A higher PHDI score was associated with a higher DQI.I score after controlling for sex and age ($P < 0.001$). The carbon and water footprint average were 6043.4 ± 2297.3 and 15.7 ± 9.9, respectively; the PHDI was inversely related to the carbon and water footprint ($P < 0.001$) (Table 4).

General characteristics

Table 5 presents the demographic characteristics and socio-economic status of the studied population, comparing individuals with metabolic syndrome to those without. All variables showed a significant difference between the metabolic syndrome and healthy groups, except for the welfare index, which did not differ significantly.

Table 6 shows the baseline characteristics of the study population according to the PHDI quartiles. Generally, the average age, education level, HDL cholesterol, SBP, energy intake, weight, and WC varied significantly across PHDI quartiles. However, the average of the other variables did not significantly differ among the PHDI quartiles.

Logistic regression of the associations between PHDI and metabolic syndrome

Table 7 presents the ORs for MS and its indicators according to the PHDI quartiles.

The crude and adjusted models revealed that a higher PHDI quartile was associated with a lower prevalence of MS (P for model 1 = 0.04, model 2 = 0.013, and model 3 = 0.07) and hypo-HDL cholesterolemia (P for model 1 = 0.008, model 2 = 0.019, and model 3 = 0.015). Participants in the 4th PHDI quartile had a lower risk for MS and hypo-HDL cholesterolemia. There was a negative association between the PHDI quartile and WC after controlling for more cofounders (model 3) ($P = 0.041$). There was no significant association between other MS indicators, including hyperglycemia, high blood pressure, and hypertriglyceridemia, according to either the crude or adjusted models ($P < 0.05$).

Discussion

To the best of our knowledge, this study is among the first to evaluate the relationships between MS and its indicators and PHDI as an indicator of EAT-Lancet diet adherence. During the initial phase of this study, we first validated the PHDI for the Iranian population based on PERSIAN cohort data. As shown previously by Cacau T et al. [13], the validity and reliability of PHDI was satisfactory related to enhanced dietary quality, and lower water and carbon footprint, as higher PHDI score was associated with higher DQI.I score and lower carbon and water footprint ($P < 0.001$). these findings indicate that the index is qualitative and nutritionally adequate and has low environmental impact. A higher PHDI was related to a lower intake of animal-based protein, total fat, some dietary fat sources (saturated and cholesterol), and some

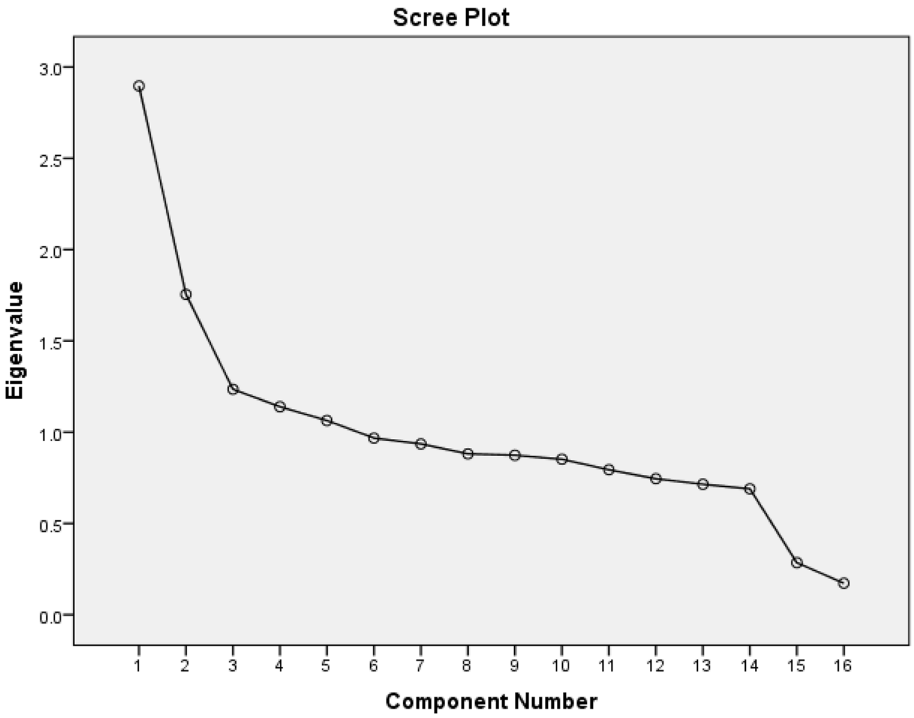

Fig. 2 Scree plot from principal components analysis (PCA) of Planetary Health Diet Index (PHDI). PERSIAN cohort study. The PCA used to evaluate whether PHDI had more than one factor that explained the data variability

Table 4 Association between PHDI and DQI.I score, carbon footprint and water footprint

Regression Models	Bivariate			
	B^a	95%CI		*p*-Value
		Lower	Upper	
DQI.I score	0.410	0.381	0.438	< 0.001
Carbon footprint	-0.121	-0.001	0.000	< 0.001
Water footprint	-0.055	-0.077	-0.034	< 0.001

DQI.I Diet Quality Index-International, *CI* Confidence interval

[a] Model adjusted for age and sex

vitamins (A and B12). Furthermore, a higher PHDI was related to a greater intake of energy, total protein, carbohydrates, plant-based proteins, polyunsaturated fats, fibers, and micronutrients from fruits, vegetables, whole grains, and oilseeds. The Cronbach's alpha found in this study was 0.53. According to some studies on different indexes of dietary evaluation, values from 0.22 to 0.68 are considered desirable [32]. Therefore, the Cronbach's alpha in this study can be considered desirable.

Similar to previous studies [15, 32], our evaluation showed that adherence to the EAT-Lancet diet was low, as the average PHDI score was 52.3 points out of a possible total of 150 points. However, those who strongly adhered to the EAT-Lancet recommendations had a lower risk of MS.

There is a scarcity of literature regarding the association between PHDI and health-related outcomes. Our findings showed that a higher PHDI score was related to a lower prevalence of MS among participants from the "PERSIAN cohort" study in Iran. A higher PHDI was also related to lower abdominal obesity and hypo-HDL cholesterolemia. However, no correlation was observed between this index and other MS indicators, including Hyperglycemia, High blood pressure, and Hypertriglyceridemia. While there has yet to be a comprehensive study examining the relationship between sustainability indices and MS, recent research has begun exploring the connection between a sustainable diet and various indicators of MS. These studies have utilized different metrics to assess the sustainability of diets.

In the study by Cacau LT et al., the relationship between the PHDI score and the obesity indicators was evaluated; similar to our findings, the results of this study revealed a negative association between the PHDI score and BMI and WC as an indicator of MS [14].

Knuppel et al. also reported a BMI reduction of 1.4 kg/m2 among individuals with an EAT-Lancet diet score of ≥ 12 points [33]. In another study by Shamah-Levy et al. [34] the associations between other indices according to the EAT-Lancet recommendations and obesity

Table 5 Baseline characteristics of study population comparing individuals with and without metabolic syndrome

Characteristics		Total ($N = 5206$)	With MS($N = 895$)	Without MS ($N = 4311$)	*p*-value[1]
Age (years), mean (SD)		45.57 (9.01)	48.52 (9.90)	44.96 (8.69)	< 0.001
Sex	Men, n (%)	2329 (44.7%)	438 (48.9%)	1891 (43.9%)	< 0.001
Education, n (%)	Diploma and less	1046 (20.1%)	242 (27.0%)	804 (16.7%)	< 0.001
	Bachelor	2658 (51.1%)	403 (45.0%)	2255 (52.3%)	
	Masters and PhD	1502 (28.9%)	250 (27.9%)	1252 (29.0%)	
Smoking status, n (%) Non-Smoker		4937(94.8%)	838 (93.6%)	4135 (95.9%)	< 0.001
Marital status, n (%)	Single	413 (7.9%)	36 (4.0%)	377 (8.7%)	< 0.001
	Married	4499 (86.4%)	795 (88.8%)	3704 (85.9%)	
	Divorced	294 (5.6%)	64 (7.2%)	230 (5.3%)	
BMI (Kg/m^2), mean (SD)		27.03 (4.05)	29.60 (3.98)	26.49 (3.86)	< 0.001
WC (cm), mean (SD)		96.40 (10.15)	102.83 (9.03)	95.06 (9.85)	< 0.001
WSI, mean (SD)		-0.07 (1.00)	-0.40 (1.03)	0.00 (0.98)	0.23
Physical activity (MET-h/week), mean (SD)		38.67 (5.52)	37.88 (5.74)	38.83 (5.46)	< 0.001
Muscle mass (%), mean (SD)		48.03 (10.18)	51.18 (11.30)	47.38 (9.81)	< 0.001
Fat mass (%), mean (SD)		24.88 (7.62)	29.22 (7.42)	23.98 (7.35)	< 0.001

BMI Body mass index, *WC* Waist circumference, *WSI* Wealth score index

[1] ANOVA or Pearson's Chi-square tests

were investigated; the results revealed that obesity was less prevalent in people with an index ≥ 9 points. As the indices investigated in two previous studies use a binary scoring system, they fail to quantitatively assess the extent of population adherence to the EAT-Lancet diet. Therefore, it is suggested that using a gradual scoring system would be more beneficial in the determination of population adherence [35, 36]. The PHDI is a gradual scoring system, allowing a greater distinction between the individual's levels of adherence, closer to a normal distribution, and more accurately related to the outcomes [37].

Apart from the studies mentioned earlier, in two other studies by Seconda et al., the association of the Sustainable Diet Index (SDI) with some health-related outcomes was examined [38], showing that individuals with lower SDI scores had an elevated risk of obesity and overweight status.

In regard other MS indicators, Cacau et al. showed that individuals with a higher PHDI (5th quartile of PHDI) displayed lower blood pressure [15]. Knuppel et al. [39] also reported a reduced blood pressure in patients with higher scores of EAT-Lancet diet score. This is noteworthy given that our study did not identify a significant correlation between blood pressure and the PHDI. The lack of a significant relationship between a sustainable diet and blood pressure in our study may be attributed to the inclusion of certain plant sources, such as nuts and seeds, in the Iranian diet, which are often processed with salt. This processing increases sodium intake, potentially leading to an unexpected rise in blood pressure, contrary to our initial expectations.

Knuppel et al. demonstrated that participants with higher EAT-Lancet diet scores had elevated HDL-c levels, which aligns with our findings. Their study also identified a link between higher EAT-Lancet diet scores and a lower risk of T2DM [39]. In contrast, we found no association between the PHDI and blood glucose levels. However, Cacau et al. showed no significant association between PHDI and HDL-c levels [15].

To date, no study has investigated the association between a sustainable diet and the risk of MS. However, there are studies evaluating the association of plant-based diets, such as the Mediterranean diet (MD) [40] and Dietary Approaches to Stop Hypertension (DASH) diet [41], with a reduced risk of MS. A systematic review and meta-analysis by Bakaloudi DR et al. [40] evaluated the relationship between MD and MS indicators. This study showed that greater adherence to MD has a positive effect on five components of MS, including blood pressure, WC, HDL-c, TG, and FBG.

In another study by Ghorabi S. et al. [41], the associations of adherence to the DASH diet with MS and its components were evaluated. Higher adherence to the DASH diet was related to a lower risk of MS and its indicators, such as hypo-HDL cholesterolemia, elevated blood pressure, and hypertriglyceridemia.

Therefore, a plant-based diet holds promise not only for health benefits, but also for sustainability, given its lower impact on GHG emissions [42]. By curbing the

Table 6 Baseline characteristics of study population according to PHDI quartiles

PHDI					
	1st	**2th**	**3th**	**4th**	***p*-value**[1]
Number	1616	1616	1616	1616	
Age, mean (SD)	44.0 (7.9)	44.3 (8.0)	45.3 (8.9)	47.1 (9.6)	< 0.001
Sex, n (%)					0.082
Men	757 (46.8)	710 (43.9)	737 (45.6)	689 (42.6)	
Women	859 (53.2)	906 (56.1)	879 (54.4)	927 (57.4)	
Wealth score index[2], (%)					0.297
Low	402 (33.1)	463 (34)	449 (31.8)	466 (31.6)	
Medium	392 (32.2)	474 (34.9)	495 (35)	494 (33.5)	
High	422 (34.7)	423 (31.1)	470 (33.2)	513 (34.8)	
Smoking, (%)					0.676
Current	74 (4.6)	76 (4.7)	74 (4.6)	63 (3.9)	
Never	1542 (95.4)	1540 (95.3)	1542 (95.4)	1553 (96.1)	
Physical activity, (%)					0.077
Low	492 (34.4)	482 (32)	491 (32)	543 (35)	
Medium	440 (30.7)	511 (33.9)	546 (35.6)	512 (33)	
Vigorous	500 (34.9)	514 (34.1)	498 (32.4)	496 (32)	
Sleep time, h	6.8 (1.6)	6.7 (1.4)	6.7 (1.3)	6.7 (1.3)	0.106
Education, (%)					0.003
Diploma and under diploma	307 (19)	305 (18.9)	323 (20)	373 (23.1)	
Bachelor and associated	889 (55)	862 (53.3)	853 (52.8)	778 (48.1)	
MSc and PhD	420 (26)	449 (27.8)	440 (27.2)	465 (28.8)	
PHDI total score, mean (SD)	41.5 (2.9)	48.6 (1.6)	54.5 (1.8)	64.2 (5.3)	< 0.001
BMI (Kg/m2), mean (SD)	26.8 (3.9)	26.9 (3.9)	26.8 (4.1)	27.1 (4.1)	0.209
SBP mmHg, mean (SD)	105.4 (14.8)	105.8 (15.3)	106 (15.1)	107.4 (16.3)	0.001
DBP mmHg, mean (SD)	68.2 (9.2)	68.8 (9.6)	68.5 (9.4)	68.9 (9.9)	0.207
Total cholesterol mg/d, mean (SD)	178.7 (36.5)	180.9 (36.1)	178.9 (36.6)	181.6 (37.8)	0.098
LDL-c mg/dl, mean (SD)	99.7 (30.3)	100 (30.1)	98.5 (30.9)	99.8 (31.8)	0.562
HDL-c mg/dl, mean (SD)	54.9 (12.8)	56.4 (13)	56.4 (13.2)	56.6 (12.8)	0.004
TG mg/dl, mean (SD)	122.1 (84.3)	123.2 (74)	121.6 (70.6)	126.9 (73)	0.226
Energy intake kcal/day, mean (SD)	2327.1 (642.4)	2410.8 (679)	2430.5 (675.9)	2451.1 (692.6)	< 0.001
Weight kg, mean (SD)	73.9 (13.6)	73.1 (13.3)	72.9 (13)	72.2 (13)	0.043
WC cm, mean (SD)	96.9 (9.8)	96.5 (10)	96.1 (9.9)	96.0 (10)	0.038
FBS mg/dl, mean (SD)	98 (25.1)	97.5 (24.4)	98.8 (26.7)	99.6 (25.9)	0.143

PHD Planetary Health Diet Index, *SD* standard deviation, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *LDL-c* low-density lipoprotein cholesterol, *HDL-c* high-density lipoprotein cholesterol, *TG* triglycerides, *BMI* body mass index, *WC* waist circumference, *FBS* fasting blood sugar

[1] ANOVA or Pearson's Chi-square tests

[2] Wealth score index: low (1st tertile), medium (2nd tertile), and high (3rd tertile)

consumption of meat and favoring plant foods such as legumes, fruits, and vegetables, sustainable diets encourage healthier eating patterns [43]. Likewise, a reduction in the consumption of ready-made and fast foods, along with a decrease in the consumption of sugar and fatty foods, can mitigate the risk of overweight and MS [44].

Our research has several strengths. One notable strength was that we used a validated index to evaluate adherence to the EAT-Lancet diet. This index encompasses all the food groups outlined in the EAT-Lancet diet and uses a suitable scoring system and calorie intake ratio for all food groups to assess adherence regardless of calorie intake [37]. In addition, in this study, we assessed the reliability and validity of the PHDI for the Iranian population. Another strength is that we utilized data from an established multicenter cohort study in Iran that adhered to rigorous procedures for gathering and handling data.

However, there are certain limitations worth mentioning. First, this is a cross-sectional study, allowing for the

Table 7 Logistic regression models of the association between the Planetary Health Diet Index and metabolic syndrome and its components

PHDI					
	1st	**2th**	**3th**	**4th**	**p-trend**[1]
	OR	**OR (95%CI)**	**OR (95%CI)**	**OR (95%CI)**	
Metabolic syndrome					
Model 1	1	0.85 (0.69- 1.04)	0.83 (0.67- 0.99)	0.79 (0.65- 0.97)	0.042
Model 2	1	0.84 (0.68- 1.04)	0.79 (0.64- 0.97)	0.76 (0.62- 0.94)	0.013
Model 3	1	0.82 (0.66- 1.01)	0.77 (0.63- 0.96)	0.74 (0.60- 0.92)	0.007
Abdominal obesity					
Model 1	1	0.98 (0.85- 1.12)	0.92 (0.80- 1.06)	1.10 (0.96- 1.27)	0.291
Model 2	1	0.89 (0.76- 1.04)	0.84 (0.71- 0.98)	0.92 (0.79- 1.09)	0.265
Model 3	1	0.95 (0.80- 1.13)	0.93 (0.78- 0.99)	0.89 (0.79- 0.98)	0.041
Hyperglycemia					
Model 1	1	0.92 (0.78- 1.09)	0.98 (0.83- 1.15)	1.06 (0.90- 1.25)	0.287
Model 2	1	0.93 (0.78- 1.10)	0.92 (0.78- 1.10)	0.93 (0.78- 1.10)	0.452
Model 3	1	0.92 (0.77- 1.09)	0.91 (0.77- 1.09)	0..91 (0.77- 1.08)	0.352
High blood pressure					
Model 1	1	1.26 (0.99- 1.62)	1.26 (0.99- 1.61)	1.28 (0.98- 1.161)	0.167
Model 2	1	1.32 (1.02- 1.70)	1.17 (0.90- 1.51)	1.26 (0.98- 1.62)	0.169
Model 3	1	1.20 (0.91- 1.60)	1.14 (0.86- 1.50)	1.17 (0.89- 1.53)	0.380
Hypo-HDL cholesterolemia					
Model 1	1	0.70 (0.58- 0.85)	0.75 (0.62- 0.91)	0.74 (0.61- 0.89)	0.008
Model 2	1	0.69 (0.57- 0.84)	0.76 (0.63- 0.92)	0.75 (0.62- 0.91)	0.019
Model 3	1	0.67 (0.55- 0.82)	0.75 (0.62- 0.91)	0.74 (0.61- 0.90)	0.015
Hypertriglyceridemia					
Model 1	1	1.01 (0.84- 1.20)	0.98 (0.82- 1.17)	1.08 (0.91- 1.29)	0.397
Model 2	1	1.02 (0.85- 1.3)	0.97 (0.80- 1.16)	1.07 (0.90- 1.28)	0.539
Model 3	1	1.01 (0.84- 1.21)	0.96 (0.80- 1.16)	1.07 (0.89- 1.28)	0.552

Model 1: unadjusted, Model 2: adjustment for age and sex, Model 3: model 2 plus additional adjustments for education level, wealth score index, smoking status, sleep time, and physical activity level, energy intake

P-trend modeling quintiles as an independent ordinal variable

Bold values mean statistical significance

PHDI Planetary Health Diet Index, *OR* Odd ratio, *CI* Confidence interval

assessment of associations but not causal relationships, so the results should be interpreted considering the study's framework. Additionally, food intake was assessed using the FFQ, which has some limitations, including a limited range of foods and the potential for bias due to inaccuracies in reporting dietary intake.

Conclusion

The validity and reliability of the PHDI were found to be satisfactory in relation to improved dietary quality and a lower water and carbon footprint for the Iranian population we studied. Our findings show that a higher PHDI score is associated with a reduced likelihood of MS. Additionally, a higher PHDI score was associated with lower hypo-HDL cholesterolemia and abdominal obesity. These findings indicate that adherence to the recommendations of the EAT-Lancet diet may be effective in preventing MS and obesity, which are important risk factors for noncommunicable chronic diseases. These results can help with food policy planning for recommending a sustainable healthy diet for society.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
SS and SRS designed the study. SS and SRS performed all the statistical analyses and wrote the first draft of the manuscript. ZD, KI, and FF contributed to draft editing and revisions. All the authors have read and approved the final manuscript**.**

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Data availability
The datasets collected and/or analyzed during the present study are not publicly accessible due to ethical concerns, but the corresponding author may provide datasets upon reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee of MUMS (Mashhad University of Medical Sciences), Mashhad, Iran. (Ethic Number: IR.MUMS.MEDICAL.REC.1401.231) and carried out based on the Declaration of Helsinki. Written informed consent was obtained from all subjects involved in this study. For illiterate subjects, informed consent was obtained from their legal guardian.

Consent for publication
This study was not applicable because no personal data were used.

Competing interests
The authors declare no competing interests.

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