Original Article

DOI: 10.5582/bst.2026.01030

Dietary patterns and metabolic syndrome in a population living at a high altitude and consuming a halal diet: A cross-sectional study combining Dietary Approaches to Stop Hypertension (DASH) principles and locally derived patterns

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SUMMARY: Metabolic syndrome (MetS), characterized by the clustering of metabolic risk factors, substantially increases the risk of cardiovascular disease and type 2 diabetes. Although dietary patterns (DPs) are known to influence MetS, evidence remains limited regarding the applicability of established dietary principles in populations living at a high altitude in an environment with a halal diet. This study examined the associations between both a priori and locally derived DPs and MetS and its components, with particular emphasis on low high-density lipoprotein cholesterol (HDL-C). A cross-sectional analysis was performed among 1,133 adults ages 18–80 using data from an ongoing pilot cohort study (2024–2025). DPs were identified using a modified Dietary Approaches to Stop Hypertension (DASH) score and factor analysis. Associations with MetS and its components were assessed using inverse probability of exposure-weighted logistic regression. Subgroup and interaction analyses evaluated effect modification, and mediation analysis examined the mediating role of being overweight. The prevalence of MetS was 54.81%. Three major DPs were identified: the Sugary Drinks and Fast-Food Pattern, the Halal Protein-Rich Pattern, and the Traditional Grain and Tonic Pattern. The DASH score was moderately correlated with the Halal Protein-Rich Pattern (Spearman's $r = 0.37$). Participants in the highest tertile of the Halal Protein-Rich Pattern had a significantly lower risk of MetS compared to those in the lowest tertile (OR = 0.64, 95% CI: 0.45–0.92; p for trend < 0.05), as well as a 35% lower risk of low HDL-C. In contrast, higher adherence to the Sugary Drinks and Fast-Food Pattern was associated with an increased risk of low HDL-C. Similar protective associations were observed for higher DASH scores. Subgroup analyses showed that the Halal Protein-Rich Pattern was inversely associated with MetS among overweight participants (OR = 0.80, 95% CI: 0.66–0.96). Mediation analysis indicated that being overweight mediated 19.84% of the association between the Halal Protein-Rich Pattern and MetS. In conclusion, in a high-altitude environment with a halal diet, both DASH and a culturally adapted Halal Protein-Rich Pattern were inversely associated with MetS and low HDL-C in particular. DASH offers an evidence-based guideline, while the Halal Protein-Rich Pattern reflects a culturally appropriate and locally practical diet. Longitudinal studies are warranted to confirm these findings.

Keywords: metabolic syndrome (MetS), populations living at a high altitude, dietary pattern, cross-sectional study

1. Introduction

Metabolic syndrome (MetS), defined as the clustering of abdominal obesity, dyslipidemia, hypertension, and impaired glucose regulation, is a major risk factor for type 2 diabetes, cardiovascular disease, and premature mortality (*1,2*). Over the past two decades, the global burden of MetS has continued to rise. A comprehensive analysis of data from 2000 to 2023 shows that the prevalence of MetS increased from 14.7% to 31.0% among women and from 9.0% to 25.7% among men. By 2023, approximately 1.54 billion adults worldwide were estimated to have MetS, including 846 million women and 692 million men (*3*). These metabolic abnormalities substantially elevate the risk of type 2 diabetes and cardiovascular disease (*4,5*), positioning MetS as a major and growing public health challenge globally. Based on surveillance data from 2015 to 2017 covering 31 Chinese provinces and individuals age 20 and older, the burden of metabolic abnormalities associated with MetS remains substantial and increases significantly with age. The standardized prevalence was 39.0% among individuals ages 45–59, 43.9% among those ages 60–74, and 44.2% among those age 75 and older. Among obese individuals, the prevalence can be as high as 70% (*6*). Given the aging population and rising obesity rates in China (*7,8*), these findings emphasize that MetS prevention and control efforts should particularly focus on older populations and those who are overweight or obese. Among Asian populations, low high-density lipoprotein cholesterol (HDL-C) is a common dyslipidemic phenotype and is associated with cardiometabolic risk (*9,10*). In underdeveloped and rural areas of China, low HDL-C is a substantial contributor to dyslipidemia and remains prevalent (*11-13*), underscoring the practical significance of jointly investigating MetS and low HDL-C in populations of interest.

The unique characteristics of high-altitude environments result in more complex patterns of MetS prevalence. Several studies at high altitudes suggested that the prevalence of MetS may be lower than in some low-altitude areas (*14-16*), but variations in lifestyle, socioeconomic status, and diagnostic criteria across regions can lead to significant fluctuations in results (with prevalence ranging from 6.2% to 32.8%) (*17-19*). In the high-altitude regions of Qinghai Province (1900–3710 meters), the prevalence of MetS, as measured by the guidelines of the Chinese Diabetes Society, was 21.1% (*20*). Qinghai Province is part of the Qinghai–Tibet Plateau and is a region settled by multiple ethnic groups. In addition to Han and Tibetan populations, long-established ethnic minorities such as Hui, Salar, and Tu also reside in Qinghai (*21*).

The prevalence of MetS varies significantly between different ethnic groups (*22-25*). Several studies have shown that the prevalence of MetS in the Hui population is higher compared to other ethnic groups, such as the Han (*17,26,27*). In a nationwide cross-sectional survey, the prevalence of MetS was 22.82% in the Hui population, 19.80% in the Han population, and 6.17% in the Tibetan population (*17*). However, the prevalence of MetS in areas with plateaus, including those inhabited by the Hui, Salar, and Han populations consuming halal food, remains unclear due to considerable variation in results, and this needs to be clarified through empirical research rather than relying on past experience.

In global chronic disease prevention, diet is widely recognized as one of the most critical modifiable factors, and international guidelines are increasingly shifting toward optimizing overall dietary patterns (DPs) with a food-based emphasis (*28,29*). The updated 2025-2030 Dietary Guidelines for Americans notably reinforce an "Eat real food" orientation, prioritizing whole and minimally processed foods while reducing the intake of highly processed foods and added sugars to enhance real-world feasibility (*30*). Compared to individual nutrients, DPs provide a more stable reflection of food combinations and real-life eating behaviors (*1,31-33*). International guidelines and authoritative institutions emphasize the importance of healthy diets in cardiovascular metabolic risk management, including dietary frameworks such as the Dietary Approaches to Stop Hypertension (DASH) (*34,35*). However, the evidence supporting DASH primarily originates from Western dietary contexts, where the foundational food composition, nutrient ratios, and cooking methods differ significantly from those in the Northwestern plateau regions of China. Directly extrapolating this framework to populations living at a high altitude and consuming a halal diet may overlook the multidimensional influences of ethnic culture, environmental adaptation, and metabolic exposure.

The aim of this study was to explore the relationship between DPs and MetS and its components in the context of a halal dietary culture on the Qinghai Plateau. Although research on the influence of different dietary cultures on MetS is available, studies on the metabolic burden and protective effects of halal DPs in high-altitude areas remain scarce. This study's aim was to assess the impact of DPs on MetS and key components, such as low HDL-C, in the context of a halal diet in plateau regions by combining a priori DP (DASH) with a posteriori DP (principal component analysis, PCA), providing a theoretical basis for future dietary interventions in high-altitude regions.

2. Materials and Methods

2.1. Study population

This study was a cross-sectional analysis of an ongoing pilot cohort study of natural populations on the Qinghai-Tibet Plateau (2024-0204-SFC-0019). Multistage, stratified, cluster-randomized sampling was used to select participants in a halal dietary culture in eastern Qinghai Province between August 2024 and July 2025, yielding a total of 1,307 individuals. Inclusion criteria were residents ages 18–80 who had lived in plateau regions for at least 12 months (*36,37*). Exclusion criteria were pregnant or breastfeeding women, individuals with severe mental or cognitive impairments, and individuals unable to complete the survey due to illness. Demographic, socioeconomic, dietary, medication, and lifestyle information were collected through standardized face-to-face interviews. In the absence of reliable prior estimates of MetS prevalence in specific populations in this region, the minimum required sample size was calculated using a single-sample proportion formula. Based on previous research indicating a prevalence of MetS of 21.10% among populations in high-altitude areas of Qinghai Province (*20*), with a *p*-value of 0.05, a 95% confidence level (Z = 1.96), and an allowable error of d = 0.05, the minimum sample size was determined to be approximately 256 individuals. Considering the potential design effect and non-response rate associated with multistage cluster sampling, a design effect of 2.0 was applied, and a non-response rate of 20% was assumed. This resulted in a target minimum sample size of 640 individuals. Individuals from ethnic groups with small sample sizes, including the Tu (n = 20), Mongolians (n = 8), and Tibetans (n = 9), were excluded. In addition, 137 participants were excluded due to missing key variables or extreme values. Ultimately, 1,133 adults were included in the final analysis. All investigators received standardized training before the formal survey, and written informed consent was obtained from all participants before data collection. The study was approved by the Medical Ethics Committee of the School of Medicine, Qinghai University (Approval No. 2023-027).

2.2. Dietary assessment

Dietary intake was assessed using a semi-quantitative food frequency questionnaire (FFQ). This questionnaire asked about the usual frequency of consumption and portion size of 47 food items over the past year. This list of foods was developed based on local dietary habits, as determined by market surveys, and was then reviewed by nutrition experts. The dietary questionnaire used in this cohort study was adapted from the survey tool used in the Chronic Diseases and Their Risk Factors Surveillance among Adult Residents at Disease Surveillance Sites in Qinghai Province study (*38*). To ensure the questionnaire was suitable for this research context, its reliability and validity were assessed. Cronbach's alpha was 0.768, indicating acceptable internal consistency (*39*). The Kaiser–Meyer–Olkin (KMO) value was 0.752, and Bartlett's test of sphericity yielded a significant result ($p < 0.001$), confirming that the data are suitable for factor analysis.

For each food category, participants reported intake (converted to average grams per meal using standard portion templates) and consumption frequency (ranging from multiple times daily to several times monthly). Beverage and salt-related exposure independently impact metabolic outcomes but is often overlooked in conventional food group aggregations, participants were asked separately about tea and sugar-sweetened beverage consumption. In addition, the data were supplemented with information on high-salt foods and primary sources of salt, such as pickled foods, to better characterize local DPs and modifiable exposure. To accommodate cultural and religious sensitivities among the primary population, the questionnaire did not include questions about individual smoking and drinking habits. However, given the significant health implications of environmental exposure, a question on passive smoking was retained. Using the aforementioned FFQ, total daily energy intake was estimated based on the Chinese Food Exchange List and the 2018 Chinese Food Composition Table (*40,41*) (Supplementary Table S1, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*).

2.3. Assessment of DPs

To better ascertain the dietary characteristics of the study population, all participants were scored for adherence to specific DPs, including the predefined DASH diet and three posterior DPs derived from baseline cohort data. Adherence to the DASH diet was evaluated using a modified DASH score, in which low-fat and fat-free dairy products were substituted with full-fat dairy products because of their very low consumption in the study population (*42,43*). Processed soy products, such as bean flour dough, are excluded from the DASH diet, which emphasizes low-sodium intake and unprocessed legumes and nuts (*44*). In addition, nuts were excluded due to their extremely limited consumption and lack of a distinct food group in the FFQ. For each food component of the DASH diet, food groups were classified into quintiles, and participants were assigned scores from 1 to 5 based on their intake rank. The total score was then calculated by summing the individual component scores (*45*) (Supplementary Table S2, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*).

A posteriori DPs were identified *via* factor analysis of each variable's correlation matrix, using PCA with maximum variance rotation. The KMO sampling adequacy measure (KMO = 0.762) and Bartlett's sphericity test ($p < 0.001$) indicated that the data were suitable for factor analysis. To determine the number of factors to retain, a comprehensive approach was adopted, considering eigenvalues, scree plots, and interpretability (Supplementary Figure S1, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). Food groups contributing significantly to specific DPs were identified by selecting factor loadings greater than 0.30 (*18*) for the three rotated factors. The final three DPs were identified, accounting for 21.64% of the total cumulative variance. Subsequently, DP scores (factor scores) were calculated, and each pattern was divided into three tertile groups (T1–T3). T1 represents the low-score group, while T2 and T3 represent the medium and high-score groups, respectively.

2.4. Outcome variable

Participants were diagnosed with MetS if they met at least three of the following five criteria (*46*): *i*) Elevated waist circumference (WC): WC ≥ 90 cm in men or ≥ 80 cm in women; *ii*) elevated blood pressure (BP): systolic BP ≥ 130 mmHg or diastolic BP ≥ 85 mmHg, or self-reported hypertension; *iii*) Reduced HDL-C: HDL-C

< 1.03 mmol/L in men or < 1.30 mmol/L in women, or receiving lipid-lowering treatment; *iv*) elevated triglycerides (TG): TG ≥ 1.7 mmol/L, or on medication for elevated TG; and *v*) Impaired fasting glucose (IFG): IFG ≥ 5.6 mmol/L, or self-reported diabetes.

2.5. Covariates

In this study, covariates were selected using the directed acyclic graph (*47*) method within a causal inference framework (Supplementary Figure S2, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). Potential confounding factors that could affect the association between DPs and MetS were identified. Crude was an unadjusted model. Model 1 was adjusted for age and sex. Model 2 was further adjusted for level of education, ethnicity, physical activity, passive smoking, household income, family history of diabetes, family history of hypertension, and marital status.

2.6. Statistical analysis

Continuous variables are expressed as the mean ± SD and were compared using the Student's *t*-test. Categorical variables are expressed as frequencies (percentages) and were compared using the χ^2 test or Fisher's exact test. DPs were identified using PCA, and food items with factor loadings ≥ 0.30 were considered meaningful contributors. Factor scores were used to categorize DPs into tertiles of low (T1), medium (T2), and high (T3), with the lowest tertile serving as the reference group.

Marginal structural models, which combined logistic regression with the inverse probability of exposure weighting (IPEW), were used to estimate associations between the four DP score tertiles and MetS, as well as its components separately. The lowest tertile of the DP score served as the reference group. To determine the preferred weighting method, six weighting methods were used in the primary analysis, with the tertiles of DP scores serving as the dependent variable and confounders identified by DAGs serving as the independent variables. The balance of confounders across different exposure groups was then assessed. In the final model, entropy balancing weighting due to the optimal balance of confounders (Supplementary Figure S3, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*) was used. The results of the effect were expressed as odds ratios (ORs) and 95% confidence intervals (CIs).

Stratified analyses by predefined subgroups (including sex, age, ethnicity, level of education, employment status, income, and BMI) are also presented for MetS and its components. In addition, logistic regression was used to explore the associations between each food group in the FFQ and MetS, as well as its components. Then, to further illustrate the associations between DPs and MetS and low HDL-C, the mediating effects of overweight status, the neutrophil-to-lymphocyte ratio (NLR), and the systemic immune-inflammation index (SII) were explored. All statistical analyses were performed using R version 4.5.1 and Stata version 18.

3. Results

3.1. Characteristics of DPs

The DASH score ranged from 10 to 34. Participants were categorized into tertiles (T1–T3) of DASH adherence (Supplementary Table S3, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). Compared to participants in the lowest tertiles (T1), those in the highest tertiles (T3) reported higher intakes of fruits, vegetables, whole grains, and legumes/nuts, and low intakes of sodium, red/processed meat, and sugar-sweetened beverages.

Using factor analysis, three distinct DPs were identified (Table 1, Supplementary Figure S1, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). The Sugary Drinks and Fast-Food Pattern was characterized by frequent consumption of barbecued foods, instant rice noodles, functional beverages, carbonated beverages, instant noodles, other sugary beverages, pure fruit juices, processed meats, fried foods, sugar-sweetened tea beverages, and desserts. The Halal Protein-Rich Pattern was characterized by a high consumption of mushrooms, dried bean curd sticks, tofu, edible fungi, algae, chicken, cow and sheep milk, yogurt, fresh fruit, bean flour dough, corn, mutton, animal offal, dried vegetables, and millet. The Traditional Grain and Tonic Pattern was characterized by frequent consumption of wolfberries, red dates, eight treasure tea, beef, vermicelli, dried fruits, potatoes, and sweet potatoes, as well as fried flour-based foods.

3.2. Baseline characteristics according to the lowest and highest tertiles of the various dietary scores

This study enrolled 1,133 participants in 2025. The mean age was 54.58 ± 12.11 years. The prevalence of MetS was 54.81% (56.73% in males and 53.23% in females). Among overweight individuals, the prevalence of MetS was 55.49%, and the prevalence of low HDL-C was 51.10%. The study population predominantly consisted of Hui (45.45%) and Salar (43.78%) participants, with Han participants accounting for 10.77%. Compared to participants without MetS, those with MetS were significantly older, had a greater WC, and higher BMI, had a lower level of education and lower levels of physical activity (Supplementary Table S3, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*; $p < 0.05$).

Table 1. Dietary patterns identified by principal component analysis in an environment with halal food in Qinghai

Variable	Sugary Drinks and Fast-Food Pattern	Halal Protein-Rich Pattern	Traditional Grain and Tonic Pattern
	Factor1	Factor2	Factor3
Barbecued Foods	0.6206	0.0434	0.2133
Instant Rice Noodles	0.6165	-0.008	-0.015
Functional Beverages	0.6124	0.1553	-0.0429
Carbonated Beverages	0.6053	0.0562	0.0395
Instant Noodles	0.5969	0.0117	0.0542
Other Sugary Beverages	0.5765	0.1218	0.0033
Pure Fruit Juice	0.5751	0.1979	-0.0382
Processed Meat	0.5636	0.1098	-0.0634
Fried Food	0.5273	-0.0276	0.3017
Sugar-sweetened Tea Beverages	0.5067	0.2454	-0.0504
Desserts	0.4433	0.1087	0.1078
Mushrooms	0.1159	0.5547	0.0431
Dried Bean Curd Sticks	0.1773	0.5418	0.1513
Fresh Tofu	0.057	0.5278	0.146
Edible Fungi	0.0928	0.5199	0.0677
Algae	0.2021	0.4689	-0.0565
Chicken	0.0913	0.4516	0.2225
Cow and Sheep Milk	0.0828	0.4308	0.1183
Yogurt	0.231	0.4279	0.2563
Fresh Fruits	0.0872	0.4119	0.3245
Bean Flour Dough	0.1278	0.3719	0.0536
Corn	0.0026	0.3588	0.0068
Mutton	0.1023	0.3522	0.303
Animal Offal	0.0477	0.3423	0.023
Dried Vegetables	0.2263	0.3297	0.0329
Millet	0	0.3224	-0.0664
Wolfberries	-0.0297	0.1384	0.7082
Red Dates	-0.0152	0.0921	0.7074
Eight Treasure Tea	0.2477	-0.0747	0.5269
Beef	0.0295	0.1705	0.4519
Vermicelli	0.1288	0.1331	0.4009
Dried Fruits	0.1575	0.2262	0.355
Potatoes And Sweet Potatoes	0.0125	-0.0553	0.3155
Fried Flour-Based Foods	0.2692	-0.0629	0.3011
Variances explained (%)	7.57%	7.07%	7.01%
Cumulative variance explained (%)	7.57%	14.64%	21.64%

Method of extraction: Principal component analysis with varimax rotation. Tables in bold indicate absolute factor loadings are higher than 0.30 and considered to belong to the corresponding dimension in the column. Red: positive scores; blue: negative scores; darker colors indicate higher DP scores.

Demographic and lifestyle characteristics of 1,133 participants are shown based on tertiles of four DP scores (Table 2). Participants in the T3 for the Sugary Drinks and Fast-Food Pattern were the youngest (51.81 ± 12.82 years), had a median household income between 10,000–50,000 CNY, a higher level of education, and more moderate-to-vigorous physical activity. Compared to participants in T1, those in T3 of the Halal Protein-Rich Pattern were younger, had a lower level of education, engaged more frequently in moderate-to-vigorous physical activity, and were more likely to be exposed to passive smoking. Participants in the high-scoring Traditional Grain and Tonic Pattern (T3) reported higher exposure to passive smoking, included

Table 2. Demographic and lifestyle characteristics of participants by tertiles of major dietary patterns scores in Qinghai (n = 1133)

		Sugary Drink and Fast-Food Pattern				Halal Protein-Rich Pattern			
	All (n = 1,133)	T1 (n = 397)	T2 (n = 373)	T3 (n = 363)	p	T1 (n = 377)	T2 (n = 378)	T3 (n = 378)	p
Sex, n (%)									
Male	513 (45.28%)	172 (43.32%)	148 (39.68%)	193 (53.17%)	< 0.001	168 (44.56%)	163 (43.12%)	182 (48.15%)	0.237
Female	620 (54.72%)	225 (56.68%)	225 (60.32%)	170 (46.83%)		209 (55.44%)	215 (56.88%)	196 (51.85%)	
Age, years	54.58 ± 12.11	56.43 ± 10.64	56.74 ± 10.97	50.34 ± 13.59	< 0.001	56.05 ± 11.32	55.06 ± 11.71	52.65 ± 13.02	0.001
Weight, kg	68.98 ± 12.11	68.84 ± 12.17	67.70 ± 12.17	70.53 ± 11.86	0.044	68.06 ± 12.12	68.81 ± 12.09	70.31 ± 12.06	0.139
BMI, kg/m^2	26.44 ± 3.12	26.52 ± 3.35	26.35 ± 2.98	26.44 ± 3.00	0.753	26.46 ± 3.16	26.45 ± 3.04	26.41 ± 3.17	0.966
Waist, cm	93.44 ± 8.51	93.86 ± 8.13	93.66 ± 8.12	92.74 ± 9.26	0.184	93.08 ± 8.53	93.62 ± 9.13	93.62 ± 7.84	0.601
SBP, mmHg	132.82 ± 35.09	132.25 ± 18.60	136.46 ± 54.83	129.71 ± 18.95	0.033	136.27 ± 54.61	132.17 ± 19.54	130.02 ± 17.92	0.056
DBP, mmHg	81.19 ± 11.59	81.70 ± 11.63	81.27 ± 10.68	80.55 ± 12.41	0.420	81.31 ± 11.20	80.75 ± 11.78	81.52 ± 11.78	0.646
HDL, mmol/L	1.16 ± 0.22	1.19 ± 0.23	1.16 ± 0.21	1.13 ± 0.23	0.009	1.13 ± 0.22	1.17 ± 0.23	1.18 ± 0.22	0.002
LDL, mmol/L	3.31 ± 0.78	3.35 ± 0.74	3.30 ± 0.82	3.28 ± 0.79	0.641	3.28 ± 0.81	3.36 ± 0.79	3.30 ± 0.73	0.527
GLU, mmol/L	5.15 ± 2.00	5.39 ± 2.45	5.03 ± 1.70	5.02 ± 1.70	0.030	4.92 ± 1.83	5.11 ± 2.09	5.44 ± 2.04	0.001
TG, mmol/L	1.78 ± 1.17	1.80 ± 1.34	1.71 ± 0.87	1.84 ± 1.24	0.224	1.86 ± 1.23	1.75 ± 1.02	1.74 ± 1.24	0.339
CH, mmol/L	4.83 ± 0.76	4.87 ± 0.74	4.84 ± 0.78	4.77 ± 0.76	0.149	4.79 ± 0.81	4.87 ± 0.77	4.82 ± 0.69	0.381
SII	396.35 ± 189.68	382.76 ± 164.88	403.31 ± 216.94	404.05 ± 184.64	0.167	373.04 ± 193.13	412.42 ± 208.69	403.52 ± 162.56	0.015
NLR	2.07 ± 0.88	2.06 ± 0.83	2.13 ± 1.06	2.02 ± 0.71	0.229	2.01 ± 0.91	2.10 ± 0.92	2.10 ± 0.80	0.279
Passive smoking, n (%)	143 (12.62%)	44 (11.08%)	54 (14.48%)	45 (12.40%)	0.362	57 (15.12%)	51 (13.49%)	35 (9.26%)	0.044
Income (ten thousand/year), n (%)					0.097				0.413
≤1	382 (33.72%)	139 (35.01%)	135 (36.19%)	108 (29.75%)		137 (36.34%)	126 (33.33%)	119 (31.48%)	
1-5	568 (50.13%)	194 (48.87%)	190 (50.94%)	184 (50.69%)		182 (48.28%)	197 (52.12%)	189 (50.00%)	
≥5	183 (16.15%)	64 (16.12%)	48 (12.87%)	71 (19.56%)		58 (15.38%)	55 (14.55%)	70 (18.52%)	
Ethnicity, n (%)					0.001				< 0.001
Hui	515 (45.45%)	160 (40.30%)	186 (49.87%)	169 (46.56%)		268 (71.09%)	166 (43.92%)	81 (21.43%)	
Salar	496 (43.78%)	197 (49.62%)	135 (36.19%)	164 (45.18%)		70 (18.57%)	163 (43.12%)	263 (69.58%)	
Han	122 (10.77%)	40 (10.08%)	52 (13.94%)	30 (8.26%)		39 (10.34%)	49 (12.96%)	34 (8.99%)	
Job, n (%)					< 0.001				< 0.001
Agri-forestry worker	901 (79.52%)	319 (80.35%)	325 (87.13%)	257 (70.80%)		325 (86.21%)	311 (82.28%)	265 (70.11%)	
Public employee	121 (10.68%)	30 (7.56%)	21 (5.63%)	70 (19.28%)		29 (7.69%)	34 (8.99%)	58 (15.34%)	
Other	111 (9.80%)	48 (12.09%)	27 (7.24%)	36 (9.92%)		23 (6.10%)	33 (8.73%)	55 (14.55%)	
Level of education, n (%)					< 0.001				< 0.001
Below primary school	664 (65.68%)	263 (73.67%)	235 (73.21%)	166 (49.85%)		248 (73.37%)	211 (64.13%)	205 (59.59%)	
Primary school	188 (18.60%)	54 (15.13%)	50 (15.58%)	84 (25.23%)		41 (12.13%)	77 (23.40%)	70 (20.35%)	
Junior high school and above	159 (15.73%)	40 (11.20%)	36 (11.21%)	83 (24.92%)		49 (14.50%)	41 (12.46%)	69 (20.06%)	

DP scores were stratified into equal tertiles, T1-T3, representing the lowest to highest tertiles of dietary pattern scores. *Abbreviations*: MetS, metabolic syndrome; WC, waist circumference; BP, blood pressure; HDL-C, high-density lipoprotein cholesterol; TAG, triacylglycerol; SII, systemic immune-inflammation index; NLR, neutrophil-to-lymphocyte ratio; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; GLU, fasting plasma glucose; TG, triglycerides; CH, total cholesterol; IFG, impaired fasting glucose.

Table 2. Demographic and lifestyle characteristics of participants by tertiles of major dietary patterns scores in Qinghai (n = 1133) (continued)

		Sugary Drink and Fast-Food Pattern				Halal Protein-Rich Pattern			
	All (n = 1,133)	T1 (n = 397)	T2 (n = 373)	T3 (n = 363)	p	T1 (n = 377)	T2 (n = 378)	T3 (n = 378)	p
Marital , n (%)					0.344				0.452
Married	1005 (88.70%)	354 (89.17%)	336 (90.08%)	315 (86.78%)		337 (89.39%)	339 (89.68%)	329 (87.04%)	
Unmarried/widowed/divorced/separated	128 (11.30%)	43 (10.83%)	37 (9.92%)	48 (13.22%)		40 (10.61%)	39 (10.32%)	49 (12.96%)	
Physical activity , n (%)					0.111				< 0.001
Light	935 (82.52%)	324 (81.61%)	320 (85.79%)	291 (80.17%)		336 (89.12%)	308 (81.48%)	291 (76.98%)	
Moderate/Heavy	198 (17.48%)	73 (18.39%)	53 (14.21%)	72 (19.83%)		41 (10.88%)	70 (18.52%)	87 (23.02%)	
Mets	621 (54.81%)	222 (55.92%)	219 (58.71%)	180 (49.59%)	0.039	225 (59.68%)	206 (54.50%)	190 (50.26%)	0.034
Hypertension	510 (45.01%)	186 (46.85%)	183 (49.06%)	141 (38.84%)	0.014	176 (46.68%)	176 (46.56%)	158 (41.80%)	0.306
Central obesity	931 (82.17%)	332 (83.63%)	321 (86.06%)	278 (76.58%)	0.002	307 (81.43%)	311 (82.28%)	313 (82.80%)	0.884
Obesity	274 (24.18%)	100 (25.19%)	83 (22.25%)	91 (25.07%)	0.568	96 (25.46%)	97 (25.66%)	81 (21.43%)	0.308
Elevated BP	702 (61.96%)	254 (63.98%)	245 (65.68%)	203 (55.92%)	0.014	246 (65.25%)	239 (63.23%)	217 (57.41%)	0.070
Elevated WC	993 (87.64%)	354 (89.17%)	340 (91.15%)	299 (82.37%)	0.001	328 (87.00%)	329 (87.04%)	336 (88.89%)	0.666
IFG	260 (22.95%)	114 (28.72%)	77 (20.64%)	69 (19.01%)	0.003	66 (17.51%)	86 (22.75%)	108 (28.57%)	0.001
Low HDL-C	579 (51.10%)	184 (46.35%)	197 (52.82%)	198 (54.55%)	0.056	223 (59.15%)	191 (50.53%)	165 (43.65%)	< 0.001
Elevated TAG	468 (41.31%)	163 (41.06%)	154 (41.29%)	151 (41.60%)	0.989	177 (46.95%)	153 (40.48%)	138 (36.51%)	0.013

DP scores were stratified into equal tertiles, T1-T3, representing the lowest to highest tertiles of dietary pattern scores. *Abbreviations*: MetS, metabolic syndrome; WC, waist circumference; BP, blood pressure; HDL-C, high-density lipoprotein cholesterol; TAG, triacylglycerol; SII, systemic immune-inflammation index; NLR, neutrophil-to-lymphocyte ratio; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; GLU, fasting plasma glucose; TG, triglycerides; CH, total cholesterol; IFG, impaired fasting glucose.

Table 2. Demographic and lifestyle characteristics of participants by tertiles of major dietary patterns scores in Qinghai (n = 1133) (continued)

	Traditional Grain and Tonic Pattern				DASH			
	T1 (n = 340)	T2 (n = 391)	T3 (n = 402)	p	T1 (n = 397)	T2 (n = 412)	T3 (n = 324)	p
Sex, n (%)								
Male	148 (43.53%)	163 (41.69%)	202 (50.25%)	0.044	195 (49.12%)	182 (44.17%)	136 (41.98%)	0.136
Female	192 (56.47%)	228 (58.31%)	200 (49.75%)		202 (50.88%)	230 (55.83%)	188 (58.02%)	
Age, years	56.64 ± 12.43	54.00 ± 12.71	53.42 ± 11.01	0.001	53.70 ± 12.43	55.08 ± 11.33	55.04 ± 12.65	0.204
Weight, kg	66.50 ± 12.09	69.67 ± 11.87	70.06 ± 12.15	0.005	70.38 ± 12.29	68.56 ± 12.52	67.66 ± 11.29	0.040
BMI, kg/m^2	26.15 ± 3.00	26.70 ± 3.02	26.44 ± 3.29	0.045	26.79 ± 3.20	26.30 ± 3.15	26.20 ± 2.95	0.021
Waist, cm	93.53 ± 7.97	93.89 ± 8.16	92.92 ± 9.26	0.291	93.60 ± 9.33	93.24 ± 8.08	93.49 ± 8.01	0.827
SBP, mmHg	135.95 ± 56.96	132.34 ± 18.94	130.63 ± 19.26	0.168	133.81 ± 20.10	133.36 ± 51.76	130.91 ± 20.14	0.150
DBP, mmHg	80.93 ± 10.36	81.86 ± 11.97	80.76 ± 12.17	0.377	81.68 ± 12.43	80.47 ± 10.38	81.50 ± 11.95	0.254
HDL, mmol/L	1.17 ± 0.22	1.16 ± 0.22	1.16 ± 0.23	0.763	1.11 ± 0.22	1.19 ± 0.22	1.19 ± 0.21	< 0.001
LDL, mmol/L	3.35 ± 0.79	3.28 ± 0.78	3.32 ± 0.78	0.634	3.28 ± 0.78	3.31 ± 0.76	3.35 ± 0.81	0.667
GLU, mmol/L	5.37 ± 2.24	5.04 ± 1.69	5.09 ± 2.05	0.075	5.01 ± 1.81	4.88 ± 1.38	5.68 ± 2.68	< 0.001
TG, mmol/L	1.78 ± 0.92	1.76 ± 1.37	1.81 ± 1.14	0.824	1.88 ± 1.27	1.66 ± 0.78	1.83 ± 1.42	0.008
CH, mmol/L	4.87 ± 0.71	4.80 ± 0.76	4.82 ± 0.80	0.325	4.76 ± 0.78	4.85 ± 0.70	4.89 ± 0.80	0.076
SII	406.74 ± 180.98	394.89 ± 207.71	388.97 ± 178.23	0.401	378.07 ± 161.67	401.88 ± 208.59	411.70 ± 194.92	0.029
NLR	2.11 ± 0.83	2.08 ± 1.05	2.02 ± 0.71	0.261	2.05 ± 0.79	2.05 ± 0.88	2.13 ± 0.97	0.435
Passive smoking, n (%)	33 (9.71%)	51 (13.04%)	59 (14.68%)	0.121	49 (12.34%)	81 (19.66%)	13 (4.01%)	< 0.001
Income (ten thousand/year), n (%)				0.038				0.464
≤1	129 (37.94%)	131 (33.50%)	122 (30.35%)		127 (31.99%)	134 (32.52%)	121 (37.35%)	
1-5	163 (47.94%)	184 (47.06%)	221 (54.98%)		199 (50.13%)	214 (51.94%)	155 (47.84%)	
≥5	48 (14.12%)	76 (19.44%)	59 (14.68%)		71 (17.88%)	64 (15.53%)	48 (14.81%)	
Ethnicity, n (%)				< 0.001				< 0.001
Hui	126 (37.06%)	172 (43.99%)	217 (53.98%)		265 (66.75%)	152 (36.89%)	98 (30.25%)	
Salar	161 (47.35%)	176 (45.01%)	159 (39.55%)		122 (30.73%)	152 (36.89%)	222 (68.52%)	
Han	53 (15.59%)	43 (11.00%)	26 (6.47%)		10 (2.52%)	108 (26.21%)	4 (1.23%)	
Job, n (%)				0.009				0.011
Agri-forestry worker	269 (79.12%)	301 (76.98%)	331 (82.34%)		318 (80.10%)	335 (81.31%)	248 (76.54%)	
Public employee	29 (8.53%)	44 (11.25%)	48 (11.94%)		51 (12.85%)	40 (9.71%)	30 (9.26%)	
Other	42 (12.35%)	46 (11.76%)	23 (5.72%)		28 (7.05%)	37 (8.98%)	46 (14.20%)	
Level of education, n (%)				0.001				0.788
Below primary school	213 (74.22%)	226 (64.94%)	225 (59.84%)		250 (64.60%)	202 (66.45%)	212 (66.25%)	
Primary school	48 (16.72%)	60 (17.24%)	80 (21.28%)		69 (17.83%)	57 (18.75%)	62 (19.38%)	
Junior high school and above	26 (9.06%)	62 (17.82%)	71 (18.88%)		68 (17.57%)	45 (14.80%)	46 (14.37%)	

DP scores were stratified into equal tertiles, T1-T3, representing the lowest to highest tertiles of dietary pattern scores. *Abbreviations*: MetS, metabolic syndrome; WC, waist circumference; BP, blood pressure; HDL-C, high-density lipoprotein cholesterol; TAG, triacylglycerol; SII, systemic immune-inflammation index; NLR, neutrophil-to-lymphocyte ratio; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; GLU, fasting plasma glucose; TG, triglycerides; CH, total cholesterol; IFG, impaired fasting glucose.

Table 2. Demographic and lifestyle characteristics of participants by tertiles of major dietary patterns scores in Qinghai (n = 1133) (continued)

	Traditional Grain and Tonic Pattern				DASH			
	T1 (n = 340)	T2 (n = 391)	T3 (n = 402)	p	T1 (n = 397)	T2 (n = 412)	T3 (n = 324)	p
Marital , n (%)				0.010				0.792
Married	289 (85.00%)	346 (88.49%)	370 (92.04%)		349 (87.91%)	366 (88.83%)	290 (89.51%)	
Unmarried/widowed/divorced/separated	51 (15.00%)	45 (11.51%)	32 (7.96%)		48 (12.09%)	46 (11.17%)	34 (10.49%)	
Physical activity , n (%)				0.290				0.045
Light	288 (84.71%)	324 (82.86%)	323 (80.35%)		335 (84.38%)	347 (84.22%)	253 (78.09%)	
Moderate/Heavy	52 (15.29%)	67 (17.14%)	79 (19.65%)		62 (15.62%)	65 (15.78%)	71 (21.91%)	
Mets	195 (57.35%)	215 (54.99%)	211 (52.49%)	0.413	249 (62.72%)	200 (48.54%)	172 (53.09%)	< 0.001
Hypertension	162 (47.65%)	184 (47.06%)	164 (40.80%)	0.105	187 (47.10%)	177 (42.96%)	146 (45.06%)	0.496
Central obesity	287 (84.41%)	331 (84.65%)	313 (77.86%)	0.019	316 (79.60%)	344 (83.50%)	271 (83.64%)	0.251
Obesity	68 (20.00%)	104 (26.60%)	102 (25.37%)	0.091	119 (29.97%)	84 (20.39%)	71 (21.91%)	0.003
Elevated BP	224 (65.88%)	247 (63.17%)	231 (57.46%)	0.052	258 (64.99%)	252 (61.17%)	192 (59.26%)	0.265
Elevated WC	301 (88.53%)	349 (89.26%)	343 (85.32%)	0.203	339 (85.39%)	365 (88.59%)	289 (89.20%)	0.232
IFG	77 (22.65%)	90 (23.02%)	93 (23.13%)	0.987	81 (20.40%)	78 (18.93%)	101 (31.17%)	< 0.001
Low HDL-C	172 (50.59%)	209 (53.45%)	198 (49.25%)	0.484	239 (60.20%)	193 (46.84%)	147 (45.37%)	< 0.001
Elevated TAG	146 (42.94%)	149 (38.11%)	173 (43.03%)	0.284	190 (47.86%)	151 (36.65%)	127 (39.20%)	0.004

DP scores were stratified into equal tertiles, T1-T3, representing the lowest to highest tertiles of dietary pattern scores. *Abbreviations*: MetS, metabolic syndrome; WC, waist circumference; BP, blood pressure; HDL-C, high-density lipoprotein cholesterol; TAG, triacylglycerol; SII, systemic immune-inflammation index; NLR, neutrophil-to-lymphocyte ratio; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; GLU, fasting plasma glucose; TG, triglycerides; CH, total cholesterol; IFG, impaired fasting glucose.

more members of the Hui group, and were younger. The DASH high-scoring group (T3) had a higher proportion of members of the Salar group, a relatively lower BMI, engaged in moderate to vigorous physical activity, and were exposed to passive smoking at a lower frequency.

3.3. Association between DP tertiles and MetS and its components

Figure 1 shows the associations between tertiles of the DASH and Halal Protein-Rich Pattern scores and MetS and some of its components. After sequential adjustment for covariates from the crude Model to Model 2, higher scores on the Halal Protein-Rich Pattern were associated with a lower risk of MetS [Model 2 OR (95% CI): 0.74 (0.52–1.05) for T2 and 0.64 (0.45–0.92) for T3 *vs.* T1; p for trend < 0.05]. For low HDL-C, higher scores for the Sugary Drinks and Fast-Food Pattern were associated with increased disease risk [Model 2 OR (95% CI): 1.69 (1.20–2.39) for T2 and 1.75 (1.22–2.49) for T3; p for trend < 0.05]. In contrast, the Halal Protein-Rich Pattern was inversely associated with low HDL-C [Model 2 OR (95% CI): 0.52 (0.37–0.75) for T2 and 0.35 (0.24–0.51) for T3; p for trend < 0.05]. For elevated TG, higher Halal Protein-Rich Pattern scores were also associated with reduced disease risk [Model 2 OR (95% CI): 0.66 (0.47–0.94) for T2 and 0.49 (0.34–0.70) for T3, respectively; p for trend < 0.05]. However, for IFG, a higher score on the Sugary Drinks and Fast-Food Pattern was inversely associated with IFG in Model 2 [OR (95% CI): 0.63 (0.43–0.94) for T2 and 0.58 (0.38–0.87) for T3, respectively; p for trend < 0.05]. Conversely, higher Halal Protein-Rich Pattern scores were associated with increased risk of IFG, with OR (95% CI) values of 1.00, 1.59 (1.03–2.45), and 2.37 (1.55–3.62), respectively. Similarly, the DASH score displayed associations with these outcomes that were similar to those displayed by the Halal Protein-Rich Pattern.

In addition, the associations between individual food items and MetS, as well as HDL-C, are shown in Supplementary Table S4 (*https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288)*. Chicken, fresh fruits, mutton, and bean flour dough were positively associated with the Halal Protein-Rich Pattern, which remained significantly associated with a reduced risk of low HDL-C after FDR correction.

3.4. Subgroup analysis

For simplicity, we report only the associations of two DPs (DASH and the Halal Protein-Rich Pattern) with MetS and low HDL-C (Figure 2). In individuals with a Halal Protein-Rich Pattern, a significant association with MetS was observed in the overweight subgroup. Among overweight participants, a higher Halal Protein-Rich Pattern score was associated with a lower risk of MetS (OR = 0.80, 95% CI: 0.66–0.96), but there was no significant interaction between overweight and non-overweight groups. In contrast, a significant interaction by sex was observed for the Halal Protein-Rich Pattern (p for interaction = 0.024) (Figure 2A). Among individuals with a higher DASH score, the risk of MetS decreased significantly in females (OR = 0.93, 95% CI: 0.88–0.98) and in the Salar subgroup (OR = 0.89, 95% CI: 0.88–0.98). A significant interaction between ethnicity and the DASH score was observed (p for interaction = 0.004), suggesting heterogeneity of the association across ethnic groups (Figure 2A). There were no significant differences across the remaining subgroups, and no additional interaction effects were detected. Among individuals consuming the Halal Protein-Rich Pattern, a significantly reduced risk of low HDL-C was observed in participants > the age of 60 (OR = 0.38, 95% CI: 0.24–0.57), with a significant interaction by age group (p for interaction < 0.001). In addition, participants engaged in agriculture, forestry, animal husbandry, and fisheries exhibited a significantly lower risk of low HDL-C (OR = 0.61, 95% CI: 0.50–0.74), with a significant interaction across occupational groups (p for interaction = 0.044) (Figure 2B). In contrast, there were no significant interaction effects between the DASH score and the risk of low HDL-C for any subgroup. Overall, the Halal Protein-Rich Pattern was associated with a reduced risk of low HDL-C in individuals > the age of 60 (Figure 2B).

The Halal Protein-Rich Pattern was associated with an increased risk of elevated WC and elevated IFG among participants with a primary school education or below (Supplementary Table S5, Table S6, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). A significant interaction between DASH score and elevated BP was observed across age groups (Supplementary Table S7, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). However, the Halal Protein-Rich Pattern was associated with a reduced risk of elevated TG among participants with primary school education or below (Supplementary Table S8, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). In the remaining subgroups, the Halal Protein-Rich Pattern did not interact with DASH in terms of elevated BP, elevated TG, or IFG (Supplementary Tables S5-S8, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*).

3.5. Mediation analysis

To further elucidate whether being overweight mediates the associations between the Halal Protein-Rich Pattern and MetS as well as low HDL-C, a mediation analysis was performed with being overweight specified as the mediator. The same mediation analysis was performed for DASH. After adjusting for confounding factors, the total effect of the Halal Protein-Rich Pattern on

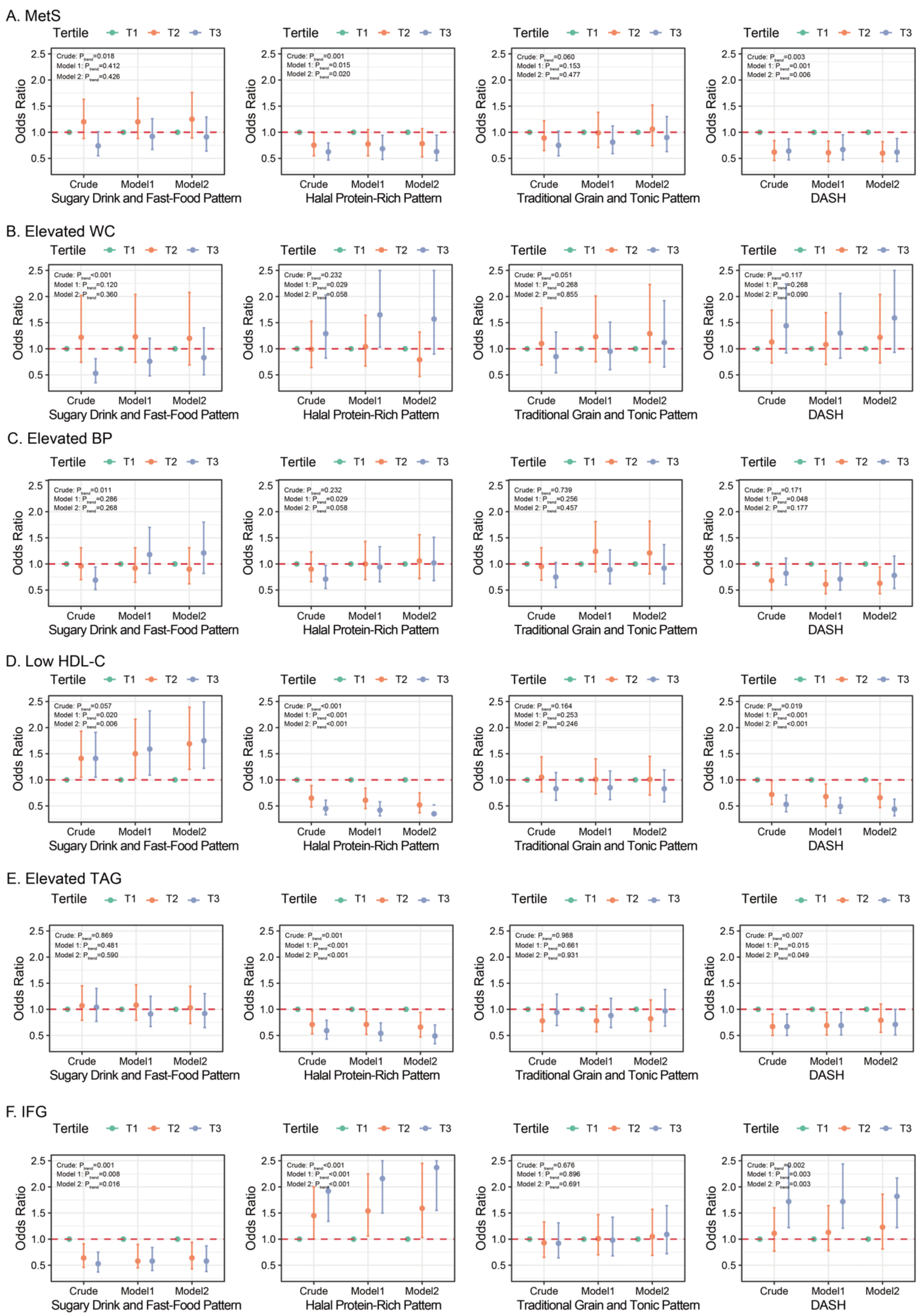

Figure 1. Associations between tertiles of three dietary pattern scores and DASH with Mets and its components in Qinghai. Crude was an unadjusted model. Model 1 was adjusted for age and sex. Model 2 was further adjusted for level of education, physical activity, passive smoking, household income, family history of diabetes, family history of hypertension, and marital status. Total energy intake was an additional adjustment variable in Model 2 for the DASH dietary pattern (not included in Model 2 of the other three DPs). DP scores were stratified into equal tertiles (T1-T3, representing the lowest to highest tertiles of DP scores, with T1 in green, T2 in orange, and T3 in blue). The filled dots represent adjusted odds ratios, and the vertical lines represent 95% confidence intervals. *Abbreviations*: DASH, Dietary Approaches to Stop Hypertension; DP, dietary pattern; MetS, metabolic syndrome; WC, waist circumference; BP, blood pressure; HDL-C, high-density lipoprotein cholesterol; TAG, triacylglycerol; IFG, impaired fasting glucose.

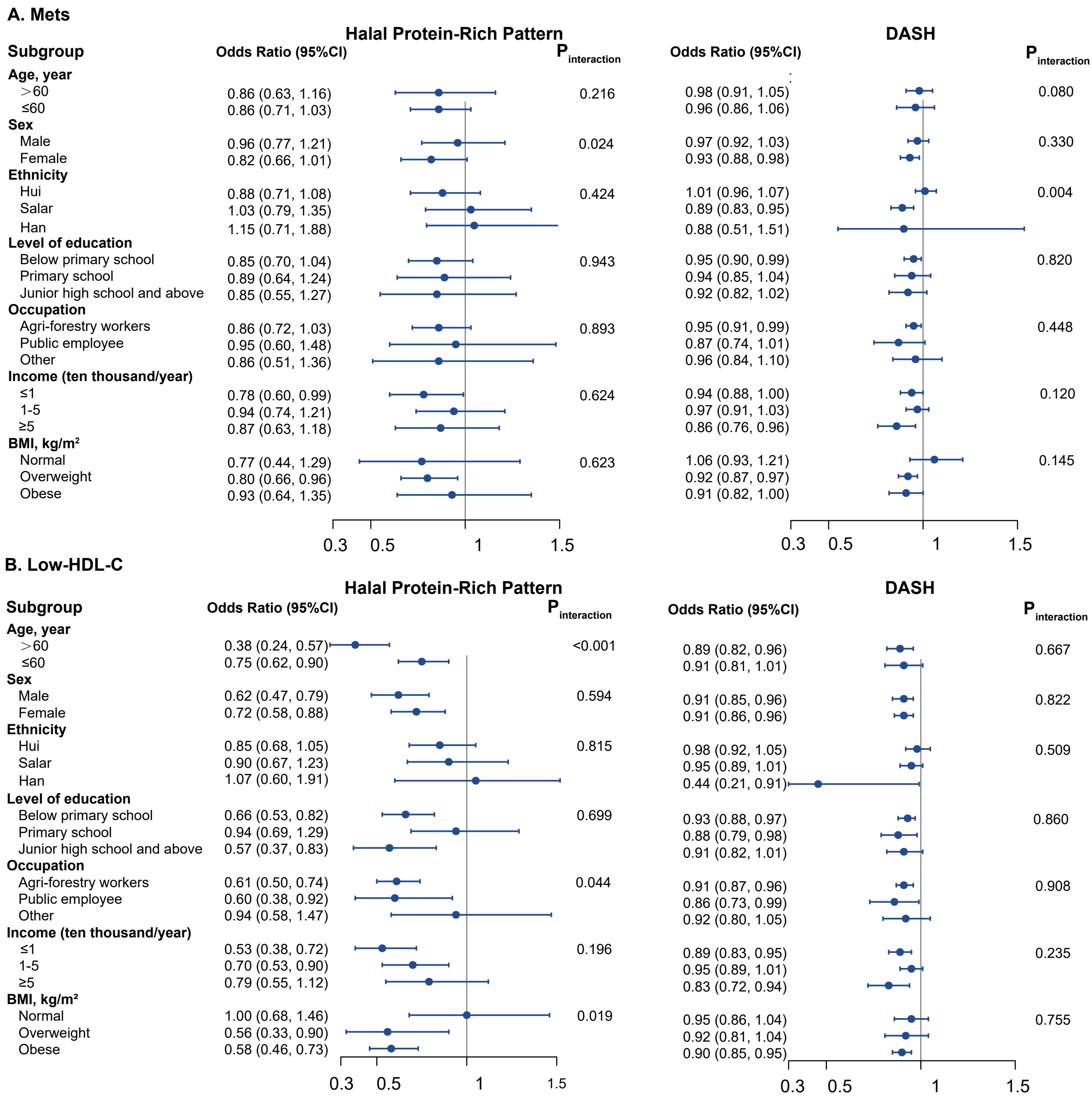

Figure 2. Stratified analysis of estimated associations between various dietary patterns and MetS risks and low HDL-C. Crude was an unadjusted model. Model 1 was adjusted for age and sex. Model 2 was further adjusted for level of education, physical activity, passive smoking, household income, family history of diabetes, family history of hypertension, and marital status. Total energy intake was an additional adjustment variable in Model 2 for the DASH DP (not included in Model 2 of the other three DPs). P-interaction was determined to examine the interaction among different subgroups. The filled blue dots represent adjusted odds ratios, and the blue lines represent 95% confidence intervals. Abbreviations: DASH, Dietary Approaches to Stop Hypertension; DP, dietary pattern; MetS, metabolic syndrome; HDL-C, high-density lipoprotein cholesterol.

MetS displayed a marginally protective association (OR = 0.87, p = 0.084). After additionally accounting for being overweight, the direct effect was significant (OR = 0.81, p = 0.015). The indirect effect, *via* being overweight, was β = 0.012 (p = 0.020), corresponding to 19.84% of the total effect mediated (Figure 3A). DASH displayed no significant overall effect on MetS (p > 0.05); nevertheless, the direct effect was significant after accounting for being overweight (OR = 0.94, p = 0.016). The indirect effect *via* being overweight was β = 0.002 (p = 0.040), accounting for 9.44% of the mediating proportion (Figure 3C).

Similarly, both DPs displayed protective associations with a low HDL-C outcome. The association with the Halal Protein-Rich Pattern remained robust after accounting for being overweight, with a strong direct effect (OR = 0.58, p < 0.001) and only a modest change from the total effect (OR = 0.68); the mediation effect accounted for 4.18% (Figure 3B). For DASH, the direct effect of being overweight was OR = 0.91 (p < 0.001), whereas the indirect effect *via* being overweight was not significant (Figure 3D). To further

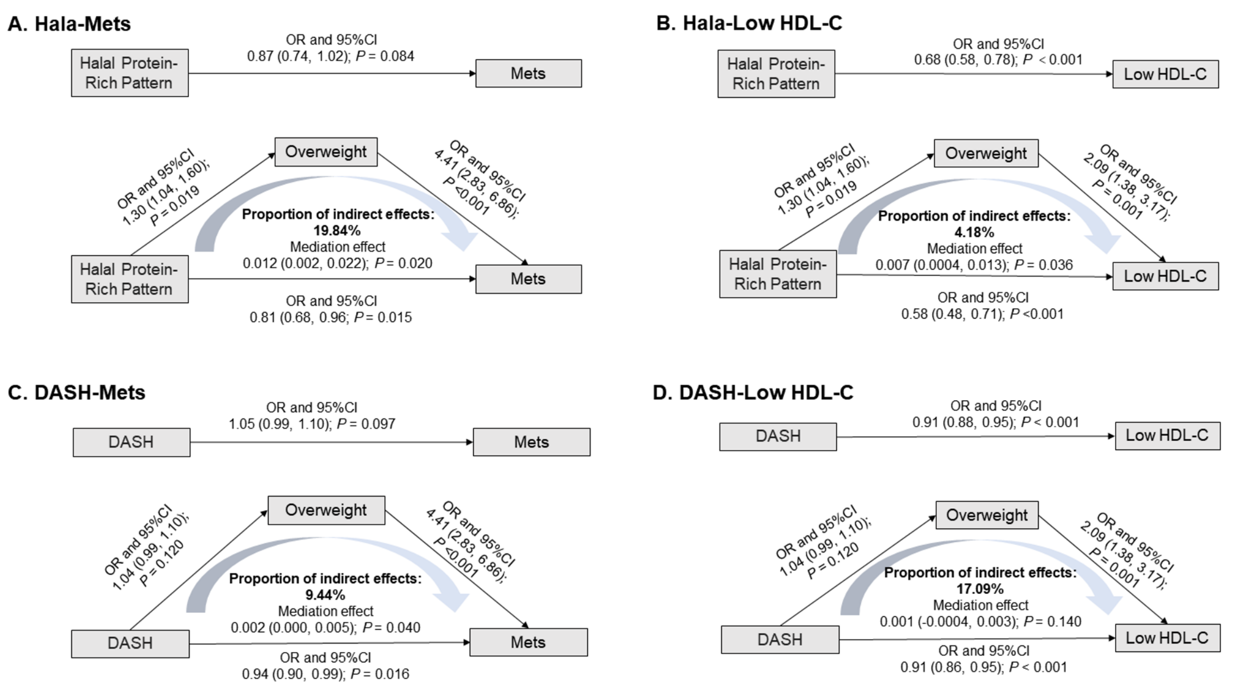

Figure 3. Mediation analysis of the associations between dietary patterns and Mets and its components mediated by being overweight. Abbreviations: DASH, Dietary Approaches to Stop Hypertension; MetS, metabolic syndrome; HDL-C, high-density lipoprotein cholesterol.

assess whether inflammatory pathways mediate the associations between DASH and the Halal Protein-Rich Pattern and MetS and low HDL-C, mediation analyses were performed using the SII and NLR as mediators. Neither SII nor NLR displayed significant indirect effects (Supplementary Figures S4 and S5, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*; $p > 0.05$).

4. Discussion

4.1. The key drivers: Older age and central obesity

The overall prevalence of MetS in this study was 54.81%, which is higher than that reported in some previous studies of plateau-dwelling populations. This elevated prevalence is likely driven primarily by an older age (54.58 ± 12.11) and the high burden of central obesity (82.17%) in the study population. Previous evidence consistently indicates that the prevalence of MetS increases markedly with age, reaching over 58% among individuals ≥ the age of 60 (*48,49*), suggesting that age may partly increase the overall estimate. Central obesity is recognized as one of the core pathogenic factors for MetS. Evidence from diverse populations consistently indicates that the prevalence of MetS among individuals with central obesity is generally high (> 60%) (*50,51*), with rates reaching up to 78.5% among men (*52*), based on estimates derived from published data.

In addition, shifts in lifestyle patterns may also be contributing to the growing burden of disease. As urbanization has accelerated in recent years, mounting evidence from northwestern and plateau regions has indicated am increased clustering of metabolic abnormalities and cardiovascular risk factors. For instance, a 2025 survey conducted in rural northwestern China reported a MetS prevalence of 53.6% among women ≥the age of 50 (*53*). Among Tibetan adults living at a high altitude, the prevalence of hypertension has been reported to exceed 60%, with the clustering of two or more cardiovascular risk factors approaching 50% (*54*). Long-term outcomes also suggest an increasing burden in plateau regions. In Qinghai, the age-standardized diabetes mortality increased from 1.74/100,000 (1975) to 20.44/100,000 (2020) (≈10-fold) (*55*). Using the same standardization approach, the National Mortality Surveillance System estimate was 13.62/100,000 in 2020 (*56*). Overall, plateau regions may experience a chronic disease burden comparable to that in low-altitude areas when unfavorable age and lifestyle factors accumulate, with more rapid increases in some indicators.

4.2. DASH principles and the Halal Protein-Rich Pattern in practice

This study identified four DPs, among which both DASH and the Halal Protein-Rich Pattern displayed a consistent protective association with MetS, with a correlation of approximately 0.37 (Figure 4A) that suggested a moderate association. Components shared between the two patterns mainly include vegetables, fruits, whole grains, and dairy products (Figure 4B).

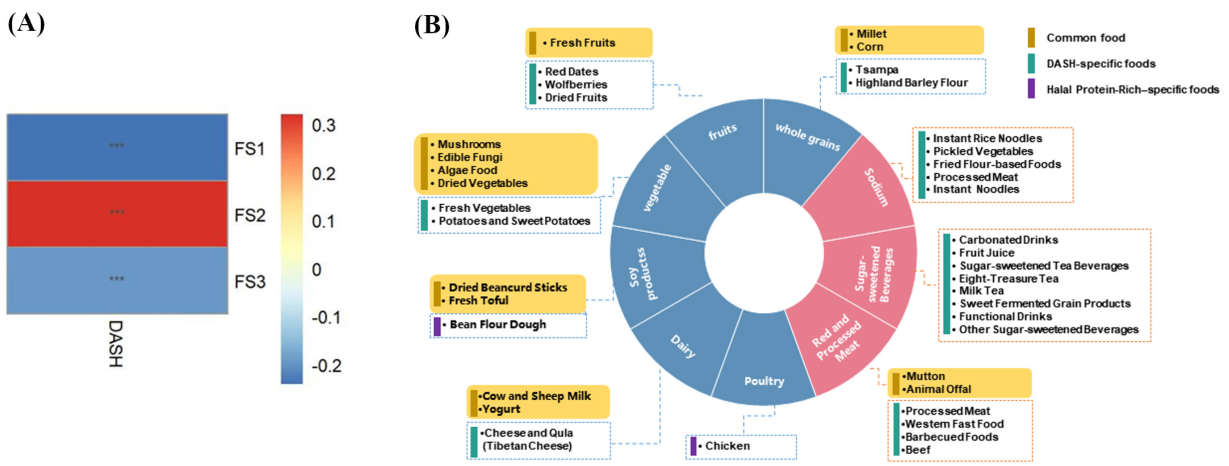

Figure 4 Correlations between PCA-derived dietary patterns and the DASH diet, and shared and unique food components of the Halal Protein-Rich Pattern and DASH. (A) Heatmap showing Spearman rank correlation coefficients between the DASH dietary score and three dietary patterns identified by principal component analysis (PCA). FS1: Sugary Drink and Fast-Food Pattern, FS2: Halal Protein-Rich Pattern, and FS3: Traditional Grain and Tonic Pattern. Correlation coefficients for FS1, FS2, and FS3 were −0.28086, 0.37391, and −0.18196, respectively, with P values < 0.001 for all. **(B)** Food composition of the Halal Protein-Rich dietary pattern in relation to the DASH diet. Portions of the circle in blue represent food groups recommended for higher intake in the DASH diet, while portions of the circle in red indicate food groups recommended for moderate intake. Foods are further classified by color: yellow indicates foods common to both dietary patterns, green indicates DASH-specific foods, and purple indicates Halal Protein-Rich Patterns-specific foods.

The DASH diet emphasizes a high intake of vegetables and fruits, fiber-rich staple foods, and limited red meat, all of which have been shown by multiple studies to be beneficial for cardiometabolic health. These findings are consistent with research results from populations in the US, Europe, and Asia *(57–59*). Unlike the beans recommended in the traditional DASH diet, a wide variety of soy products are a key component of traditional diets in East Asian countries, including China, South Korea, and Japan. In Chinese adult populations, higher soy product intake is associated with a lower prevalence of MetS and better metabolic components (*60*). Intervention evidence from systematic reviews and meta-analyses also suggests that soy product consumption helps improve lipid and glucose metabolism markers (*61*). In the Halal Protein-Rich Pattern, the bean flour dough (a local specialty) is typically made by mixing pea flour with refined wheat flour. In China, where dietary energy intake has long been predominantly derived from carbohydrate-rich staple grains (*62*), this food meets the local carbohydrate needs while aligning as closely as possible with the DASH principles. In traditional Chinese dairy consumption, whole milk and whole-fat yogurt are more common, with a higher proportion than low-fat dairy products. While earlier guidelines recommended reducing saturated fat intake, the latest US dietary guidelines have affirmed the nutritional value of whole-fat dairy products (*30*). Studies show that dairy consumption, and especially whole-fat dairy, is also associated with a reduced risk of MetS (*63-65*). The matrix of dairy products may have a combined effect on lipid metabolism, energy metabolism, and insulin sensitivity, which cannot be simply equated with saturated fat intake (*66-68*). High dietary salt intake is recognized as a key risk factor for hypertension. There is consistent evidence demonstrating its clear association with elevated BP (*69,70*). Reducing salt intake effectively lowers BP and reduces the risk of cardiovascular disease (*71,72*). Among the plateau population in this study, sodium intake was significantly higher than the daily intake recommended by China's Dietary Reference Intakes. However, there was no significant correlation between salt intake and BP or the components of MetS. This finding is consistent with the recent report by Xiao *et al*. (*73*), which indicated that in high-altitude areas of Tibet where there is a higher intake of fats and sodium, this pattern of higher intake did not directly translate into a higher burden of hypertension. Whether this phenomenon is directly related to altitude itself warrants further investigation.

Overall, these findings suggest that the Halal Protein-Rich Pattern largely incorporates DASH-consistent healthy food components within the local halal diet, supporting its potential cultural adaptability and practical feasibility for MetS prevention at high altitudes.

4.3. Diet improves low HDL-C

Low HDL-C is one of the most common types of dyslipidemia in Asian populations (*74-77*). In the current study, a high prevalence of low HDL-C (53.8%) was observed. This is consistent with previous studies of rural populations in Northwestern China, where the prevalence of low HDL-C was 55–68% (*78*).

Current lipid management strategies focus more on reducing LDL-C to lower cardiovascular risk, and simply increasing HDL-C through medication may not necessarily lead to improved cardiovascular outcomes (*79,80*). Therefore, management of low HDL-C is focused more on lifestyle changes and optimization of overall diet composition. In the current study, both DASH and the Halal Protein-Rich Pattern were associated with a reduced risk of low HDL-C. However, the protective association for low HDL-C was not observed with equal strength across all populations. Stratified and interaction analyses revealed that the protective effect of the Halal Protein-Rich Pattern was more pronounced in subgroups with greater metabolic vulnerability. The association was stronger in the population ≥ the age of 60 compared to the population <the age of 60. In addition, the effect was more significant in overweight/obese individuals. Aging and obesity are often accompanied by chronic low-grade inflammation, immune activation in adipose tissue, and exacerbated insulin resistance (*81,82*). Insulin resistance is commonly associated with a characteristic lipid profile of high TG and low HDL cholesterol (*83,84*). Given these circumstances, more beneficial DPs are more likely to demonstrate significant marginal benefits in these populations. In a further exploration of the analysis of individual foods, several items that were positively associated with the Halal Protein-Rich Pattern (such as chicken, fresh fruits, and bean flour dough) remained significantly associated with a reduced risk of low HDL-C after FDR correction. This provides compositional-level support for the effect of the Halal Protein-Rich Pattern on low HDL-C.

4.4. Dietary changes trump weight loss

Being overweight is not only a risk factor for MetS but also potentially serves as a mediating pathway through which diet influences MetS, by affecting fat accumulation, insulin sensitivity, and inflammation (*85,86*). The current study found that being overweight mediates only a small portion (less than 20%) of the association between DPs and MetS, with most of the risk still attributed to the direct effects of the DPs. For low HDL-C, both DASH and the Halal Protein-Rich Pattern maintained significant protective associations even after adjusting for BMI, with a minor mediating effect. These findings are consistent with existing research and further support the direct regulatory role of diet quality in lipoprotein metabolism (*87*). The above results suggest that the effect of dietary composition on metabolic health may extend beyond the energy balance. For example, the Sugary Drinks and Fast-Food Pattern, characterized by a high consumption of barbecued foods, instant noodles, and carbonated beverages, is negatively correlated with HDL-C levels. This is consistent with mechanisms described in the literature, in which high-sugar, high-fat diets exacerbate oxidative stress and inflammation, thereby disrupting lipid metabolism (*88,89*). In addition, the population in the current study was relatively older on average (54.58 years), and with aging, there is often a decrease in muscle mass and an increase in fat proportion, leading to changes in body composition. BMI has limitations in accurately reflecting true obesity and related metabolic risks in these populations (*90*). This further supports the notion that focusing solely on weight loss or BMI reduction may be insufficient for preventing and controlling MetS.

4.5. Potential inflammatory mechanisms linking DPs to MetS

Several dietary interventions and reviews have indicated that healthy diets can reduce chronic low-grade inflammation, thereby influencing MetS (*31,91,92*). In the current study, inflammation markers (SII and NLR) were not significantly associated with MetS or its components, but this does not negate the role of inflammation. Both SII and NLR are composite indices derived from peripheral blood cell counts and are susceptible to influence by acute infections, hematological conditions, and other systemic factors, which may limit their specificity in capturing diet-related chronic metabolic inflammation. Therefore, in this study population, the associations between DPs and metabolic outcomes may not be fully reflected by these blood count-based inflammatory indicators. In addition, DPs can directly modulate the composition and function of the gut microbiota, which may play an important role in the dietary regulation of MetS (*93,94*). Importantly, metabolic and inflammatory processes relevant to MetS may also be shaped by the unique hypoxic and climatic conditions at high altitudes, which are discussed in the following section.

4.6. Impact of high altitudes on metabolism

Regions at high altitudes exhibit a complex environmental profile characterized by a low atmospheric pressure, a low oxygen partial pressure, low temperatures, and a low humidity. Prolonged exposure to this hypoxic and hypobaric environment triggers compensatory adaptations across multiple physiological systems, including key pathways such as glucose and lipid metabolism, the regulation of oxidative stress, and the control of inflammation.

In terms of glucose metabolism, central obesity is a significant risk factor for type 2 diabetes due to its effect on insulin resistance (*95*). According to ADA criteria, diabetes has an overall prevalence of approximately 12.8% among Chinese adults, reaching 21.1% in the 50–59 age group (*96*). In representative samples from multiple provinces, the prevalence of diabetes among centrally obese individuals was around 15–16% (*97*). In contrast, the overall prevalence of diabetes in this study population was 12.89%, and 13.96% among participants with central obesity (Supplementary Tables S3, *https://www.biosciencetrends.com/action/getSupplementalData.php?ID=288*). This population was older on average and had a high prevalence of central obesity (>80%), and yet the prevalence of diabetes remained lower than national estimates reported for comparable age groups and obesity status. This discrepancy may be related to metabolic adaptations developed through long-term exposure to hypoxic conditions among populations living at a high altitude. Previous studies have shown that, compared to populations living at lower altitudes, those living at higher altitudes generally have lower fasting blood glucose levels and improved glucose tolerance (*98,99*). Animal experiments have shown that simulated high-altitude hypoxia can enhance the mitochondrial function of skeletal muscles and improve insulin sensitivity by activating the AMPK pathway (*100*). Mechanistically, exposure to hypoxic conditions at high altitudes can induce hypoxia-inducible factors and related molecular pathways that promote anaerobic glycolytic glucose metabolism, enabling more efficient glucose utilization and, to some extent, reducing the risk of type 2 diabetes (*101*). In addition, the cold and low humidity in regions at high altitudes have also been associated with a risk of type 2 diabetes. One study reported that for every 1°C increase in ambient temperature, the age-adjusted incidence of diabetes increases by 0.0314% (*102*), and another reported that each 1% increase in relative humidity is associated with a 12% higher likelihood of diabetes (*103*).

The effects of high-altitude hypoxia on lipid metabolism are inconclusive. Some studies suggest that higher altitudes are associated with a lower BMI, smaller WC, and reduced serum TG and low-density lipoprotein cholesterol (LDL-C) levels (*104-106*). A study of the Jiarong Tibetan population in Western Sichuan found that the contribution of dietary fat to energy increased to over 50% at higher altitudes. However, residents consuming these high-fat, high-energy diets did not have significantly elevated total cholesterol levels. In fact, LDL-C displayed a negative correlation with fat intake (*107*). At the same time, studies have also identified abnormalities in the lipid profiles of populations living at high altitudes. For example, some studies have reported elevated levels of total cholesterol and LDL-C among Tibetan residents who primarily consume high-fat diets. Conversely, hypertriglyceridemia is more prevalent among Han residents, whose staple diet consists mainly of carbohydrates, in plateau regions (*108*). Therefore, the effects of high-altitude hypoxia on lipid metabolism do not follow a uniform pattern and may be influenced by energy expenditure levels and dietary composition, resulting in heterogeneous lipid metabolic profiles across different populations.

In addition to glucose and lipid metabolism, oxidative stress and inflammatory responses also undergo complex changes at high altitudes. Hypoxia is widely recognized as an important trigger of oxidative stress, and acute exposure is often accompanied by transient elevations in circulating inflammatory mediators (*109,110*). However, with prolonged exposure at moderate altitudes, the body gradually makes adaptive adjustments, such as increased adiponectin levels and decreased leptin levels (*111*), indicating adaptive regulation that favors metabolic homeostasis under chronic hypoxic conditions (*112,113*). As adipose tissue is prone to chronic, low-grade inflammation induced by local hypoxia, the lean body phenotype commonly observed in populations living at high altitudes may alleviate the inflammatory burden associated with obesity to some extent.

4.7. Dietary recommendations for populations living at a high altitude

Evidence suggests that adults living in pastoral regions at high altitudes typically have energy and protein intakes close to the levels recommended by the Chinese Dietary Reference Intakes, while consuming excessive fat and sodium and not consuming sufficient vitamin C and other micronutrients (*73*). From a public health perspective, the value of this study lies not only in identifying DPs, but also in proposing a transferable framework for translating evidence-based DASH principles into locally feasible dietary strategies for high altitudes.

Specifically, maintaining traditional carbohydrate-based staple foods while prioritizing whole grains and legume-based products (*e.g.*, bean flour dough, highland barley products, and tsampa) may improve dietary fiber and plant protein intake and align with the metabolic preference for glucose utilization under chronic hypoxic conditions. Previous studies have indicated that oxygen-limited environments are associated with reduced reliance on lipid oxidation and increased glucose utilization (*99,114,115*). Therefore, carbohydrate-based DPs may be more consistent with metabolic adaptations.

For individuals with low HDL-C, dietary recommendations should emphasize optimization of fat quality rather than indiscriminate fat restriction. In pastoral regions with large ethnic populations, this may involve retaining ruminant meat and dairy products as key protein sources while reducing the intake of highly processed high-fat meats and increasing the consumption of plant-based fat sources rich in unsaturated fatty acids, such as legumes and nuts. Vitamin C insufficiency also warrants attention. Although traditional dried vegetables provide dietary fiber and minerals, vitamin C is highly susceptible to loss during drying and storage. Without substantially altering traditional DPs, increasing intake of storable fresh vegetables (*e.g.*, cabbage, Chinese cabbage, and radish) and seasonal fruits, alongside improved cooking practices, may help address this gap.

Finally, given the widespread excess sodium intake in these regions relative to the Chinese Dietary Reference Intakes, culturally acceptable sodium reduction strategies, such as limiting preserved foods, reducing salt and salty condiments, and increasing potassium-rich vegetables (particularly potatoes, a staple crop in northwestern China) and fruits, may contribute to the gradual attainment of an appropriate sodium intake in populations living at a high altitude.

4.8. Strengths and limitations

This study is the first to assess DPs in a population living at a high altitude and consuming a halal diet in Qinghai Province, combining a priori DASH DP with posteriori factor analysis to provide a more comprehensive evaluation. The consistency between the two approaches further supports the positive impact of DPs on metabolic health. Factor analysis also identified culturally specific healthy DPs, providing contextually relevant evidence for precision nutrition interventions in plateau regions with large ethnic populations, with strong practical and regional significance. From a global public health perspective on populations living at high altitudes, this study provides a significant reference. At least 5.7% of the global population is estimated to reside in regions at high altitudes. In China, plateau areas account for approximately 16.7% of the national land area and are inhabited by nearly 60 million people (*116,117*). These populations face environmental challenges such as chronic hypoxia, cold temperatures, and limited dietary diversity, resulting in unique metabolic adaptations. In this context, this study has analyzed characteristics of metabolic adaptation and DPs, proposing an approach to improving metabolism by optimizing dietary composition and fat quality in low-oxygen environments. This provides a referential framework for developing evidence-based dietary intervention strategies that are tailored to different high-altitude regions while respecting local diets.

This study had several limitations. First, the cross-sectional design prevented the identification of causal relationships between DPs and MetS components. Reverse causation cannot be excluded, particularly for IFG, as individuals with abnormal glucose levels may have already adopted healthier dietary behaviors before the dietary assessment, potentially resulting in an apparent inverse association. In other words, people who have already been diagnosed with metabolic abnormalities might alter their diets, which could affect the results of this study and give the appearance that healthier DPs are associated with better outcomes. Given that this study is part of an ongoing study of a natural population cohort living at a high altitude, the next step will be to perform a longitudinal analysis based on follow-up data. To address the potential reverse causality in the results related to IFG in this study, the cohort follow-up will exclude individuals with known metabolic abnormalities at the baseline to enhance causal inference. Second, there may be recall bias in the food frequency survey, as individuals may struggle to accurately recall or report their dietary intake. Due to some participants' low levels of literacy and language differences, the use of simple tools and translation assistance was the only feasible way to collect dietary information. DP analysis captures only part of changes in food consumption and may not fully represent diet quality (*118*).

Third, due to the influence of a halal diet and religious factors, information on smoking and drinking among individuals was not collected, which may lead to residual confounding. However, exposure to passive smoking was included as a covariate in this study to partially control for tobacco-related effects. In addition, the drinking behavior of the study population is culturally restricted, and its potential impact as a major confounding factor on the relationship between DPs and MetS is relatively limited. Fourth, in China, the estimation of salt intake may be biased by the common practice of mixed dishes and shared meals, potentially leading to inaccuracies in the salt intake estimates in this study. Lastly, future longitudinal studies should prioritize stable inflammatory markers such as CRP and IL-6, along with gut microbiome analysis, to provide a more comprehensive assessment of the diet's impact on low-grade inflammation and MetS, thereby improving mechanistic understanding and comparability. Given the environmental characteristics of chronic hypoxia in regions at high altitudes, subsequent analyses will incorporate an altitude gradient.

5. Conclusion

In conclusion, this study has demonstrated that evidence-based dietary guidelines can be effectively translated into culturally appropriate DPs at high altitudes where a halal diet is consumed. The DASH diet provides a robust scientific foundation, while the Halal Protein-Rich Pattern illustrates its practical and culturally relevant application. These findings support the use of localized DPs as feasible strategies for nutritional intervention. Moreover, for middle-aged and older adults, optimizing dietary composition and nutrient density should be a key focus of future nutritional strategies.

Funding: This work was supported by a grant from the Qinghai Provincial Department of Science and Technology (Grant No. 2024-0204-SFC-0019).

Conflict of Interest: The authors have no conflicts of interest to disclose.

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Received December 11, 2025; Revised February 2, 2026; Accepted February 18, 2026.

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Released online in J-STAGE as advance publication February 25, 2026.