

Menopausal status modulates the association between dietary patterns and bone injury: A cross-sectional analysis from the Chinese Multi-ethnic Cohort (CMEC)

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Abstract

Background Dietary nutrition is a key modifiable factor for bone health. However, the relationship between diet and bone health among women of different menopausal status in Southwest China remains unclear. This study aimed to evaluate their dietary quality and explore the association between dietary patterns and bone impairment risk.

Methods This study included 36,298 eligible women from the Chinese Multi-ethnic Cohort (CMEC), who were divided into three groups based on menopausal status: premenopausal, perimenopausal, and postmenopausal, to assess bone impairment in each group. The Entropy-Weight TOPSIS method was employed to compare differences in dietary quality across the three groups, providing staged dietary guidance. Additionally, the DASH dietary pattern was adjusted, and posteriori dietary patterns were constructed to systematically analyze their associations with bone health in the overall population and across different subgroups, aiming to comprehensively reveal the potential benefits of dietary patterns for skeletal health.

Results This study found that the overall dietary quality among women in southwestern China is generally poor, with compliance rates for recommended intake levels of all food categories below 50%. Postmenopausal women face the highest risk of bone impairment (48.3%) and also have the lowest dietary quality. Furthermore, the impact of dietary patterns on bone health shows significant dependence on menopausal status. The DASH-adjusted red meat pattern demonstrated a protective effect ($OR = 0.987$, 95% $CI: 0.975-1.000$), with animal-based foods likely serving as its core driving component, while Dietary Pattern 2 was identified as a risk factor ($OR = 1.049$, 95% $CI: 1.013-1.086$).

Conclusion This study found that the locally adapted "DASH-adjusted red meat pattern" aligns better with the needs for bone health in Southwest China, offering more significant benefits for postmenopausal women. Dietary strategies should be tailored to regional and population-specific contexts rather than rigidly following a single model.

1. Introduction

Bone health is a key factor for the human body to maintain normal life, and Bone Mineral Density (BMD) is an important indicator for evaluating bone strength, which is susceptible to physiological or pathological factors, leading to bone damage. Among them, Osteoporosis (OP) is the most common bone disease, a systemic bone disease characterized by decreased bone strength and changes in bone microstructure, which is more common in postmenopausal women and the elderly^[1]. Osteopenia refers to BMD at the critical value between normal and OP^[2]. Nowadays, the global aging problem is becoming increasingly prominent, which makes countries face an increased risk of bone damage^[3], further increasing the probability of fractures and bringing a serious disease burden to the population and society^[1]. As found in Yeon-HB et al.'s analysis of the 10-year fracture risk in Korean women aged 66 and above, the prevalence rates of osteopenia and OP in 271,197 women at baseline were 44.0% and 35.2% respectively, while the 10-year cumulative incidence rates of their fragility fractures were as high as 37.5% and 44.3%^[4]. It is also worth noting that multiple studies have shown that this severe public health problem has significant gender differences and increases with age. Men mostly stay in the stage of osteopenia, while the risk of women suffering from OP is 2.34 times that of men^[3], and this difference is particularly prominent in the Chinese population^[2]. The underlying mechanism may be due to the accelerated bone resorption caused by the sharp decline in estrogen levels in women after menopause, which in turn leads to rapid loss of bone mass^[5]. Although bone health is jointly affected by innate age, genetics, acquired environment, lifestyle and nutritional status^[1, 6], bone mass accumulation is a lifelong process. The increased risk of bone damage may be determined by the peak bone mass in adulthood and the subsequent rate of bone loss^[7].

Therefore, it is advocated that dietary management should be implemented throughout women's entire life cycle to prevent bone damage and reduce the risk of fractures. The scientific basis for this lies in the complex effects of various nutrients and other factors contained in the diet on bones^[6, 8, 9]; among them, calcium and vitamin D are regarded as essential

foundations for maintaining bone metabolic homeostasis, while the balanced intake of protein, unsaturated fatty acids, and trace elements is also crucial^[8, 10]. However, in view of the interactions between nutrients, the research focus on bone health has shifted from single nutrients to nutrient-integrated dietary patterns such as the DASH and Mediterranean diets^[11, 12].

At present, women in China, especially those in the underdeveloped southwest regions, still generally face problems of malnutrition and lack of nutrition knowledge^[13, 14]. However, there is still a relative lack of research on the association between dietary patterns and bone health in this population, especially among women with different menopausal statuses. Therefore, based on the China Multi-Ethnic Cohort (CMEC), also known as the Southwest Cohort^[15], this study comprehensively evaluated the dietary quality and dietary pattern characteristics of women with different menopausal statuses by comprehensively using multiple methods such as Dietary Pagoda Scoring, the Entropy-Weighted TOPSIS method, and principal component analysis. It also deeply explored the association between these factors and the risk of bone damage, aiming to provide more targeted and precise nutritional prevention strategies for women in different physiological stages.

2. Materials and methods

2.1 Study population

This study is based on the CMEC, a project under the National Key Research and Development Program of China. This cohort includes 99,556 respondents from five provinces/municipalities: Sichuan, Chongqing, Yunnan, Guizhou, and Tibet. Baseline survey data were collected through face-to-face interviews using electronic questionnaires, covering the following aspects: ☐ Demographic and socioeconomic status (basic information, ethnicity, education level, occupation, household income, etc.); ☐ Smoking history, alcohol consumption history, tea drinking history, and consumption history of other beverages; ☐ Food frequency questionnaire; ☐ Physical activity status; ☐ Life events, social support, and psychological status; ☐ Female reproductive and childbearing history (for female respondents only). In addition, physical examinations and relevant laboratory tests were conducted, and the Body Mass Index (BMI) of the respondents was calculated based on the physical examination data.

Calculation Method of BMI:

$$\text{BMI} = \text{weight (kg)} / [\text{height (m)}]^2$$

Women aged 18–79 from the cohort who completed dual-energy X-ray bone density testing and provided complete survey information were selected. The following individuals were excluded: ☐ those with diseases related to bone metabolism or calcium metabolism (diabetes, ovarian or uterine resection, chronic liver disease, malignant tumors); ☐ those with diseases related to absorption disorders (peptic ulcer, gastroenteritis, gallstones/cholecystitis). Ultimately, a total of 36,298 women were included as study subjects. Figure 1 shows details of the inclusions and exclusions in this study. Based on the *Guidelines for Menopause Management and Menopausal Hormone Therapy in China (2023 Edition)*^[16], individuals with inconsistent menstrual status and age were reclassified. The study subjects were then divided into three groups according to standard criteria: premenopausal, perimenopausal, and postmenopausal.

2.2 Criteria for evaluating bone damage

An ultrasonic bone densitometer was used to measure parameters related to bone quality, such as ultrasound speed, frequency attenuation, and bone index, by transmitting ultrasound waves through water or a coupling medium into the calcaneus. These parameters were used to calculate the T-score, a value reflecting human bone quality, which is applied in diagnosing osteoporosis and predicting fracture risk. Specifically, a T-score above – 1 standard deviation (SD) was classified as normal bone quality, and a T-score of -1 SD or below was classified as bone damage.

2.3 Food frequency method

In the baseline survey, researchers used a quantitative Food Frequency Questionnaire (FFQ) — a method that estimates the frequency of food consumption by respondents over a specified period in the form of a questionnaire. For each food category, participants were required to report the intake amount (average grams per meal based on standard portion models) and frequency (four frequency categories) ranging from several times a day to several times a year, recording their consumption frequency over the past 12 months. In addition, we also focused on detailed inquiries about alcohol, tea, sugar-sweetened beverages (SSBs), cooking oil, and salt.

2.4 Dietary pattern

2.4.1 A priori dietary pattern

To better capture the dietary characteristics of our study population, we scored all participants based on their adherence to a specific dietary pattern. We adopted the most widely used a priori dietary pattern—the DASH diet^[17]. Given the extremely low consumption of skimmed and low-fat dairy products in the study population, a modified DASH scoring system was used to reflect adherence to the DASH-style diet, replacing skimmed and low-fat dairy products with full-fat dairy products^[18]. Additionally, since only 6% of the population regularly consumed sugar-sweetened beverages, we excluded sugar-sweetened beverages from the food component.

Positive scoring was applied to the dietary intake of five components: vegetables, fruits, full-fat dairy products, whole grains, and nuts/legumes. In contrast, reverse scoring was applied to the intake of two components: sodium and red/processed meat. The modified DASH score for each group of participants was then calculated by summing the scores of these seven dietary components, with a total score ranging from 7 to 28.

To better align with the research context and explore the role of specific food components, we made further adaptive adjustments based on the modified DASH pattern to construct the "DASH-adjusted red meat pattern". This pattern modifies the original DASH scoring criteria for red meat by assigning positive scores to moderate intake of red meat and its products, while maintaining the scoring standards for other food components consistent with the classic DASH pattern. This adjustment aims to explore the association between red meat intake levels aligned with local dietary habits and bone health within the DASH dietary framework.

The lowest fifth of dietary scores was used as the reference group, and the quintiles of the dietary pattern were modeled as a categorical variable with five levels. To facilitate the interpretation of the impact of the overall dietary pattern, we conducted a single-component analysis. For the DASH-adjusted red meat pattern, the correlation between each dietary component and bone damage was evaluated by excluding one food component from the highest quintile (specific details and calculation methods are provided in Supplement 1).

2.4.2 A posteriori dietary pattern

A posteriori dietary patterns were extracted from the dietary data collected in this study using exploratory factor analysis to reflect the actual dietary structure of the population. The original food categories in the CMEC cohort dietary survey included 13 types: tubers, red and processed meats, poultry, fish/seafood, eggs, fresh vegetables, soy products, pickled vegetables, fresh fruits, dairy products, rice, wheat products, and coarse grains. In addition, alcohol, oil, salt, and tea were also recorded. These 17 food categories were included as variables in the factor analysis. The initial factor loading matrix was obtained through principal component analysis, and factors were derived after varimax rotation. By comprehensively considering eigenvalues, variance explanation, scree plots, and interpretability, the dietary patterns preferred by female groups with different menstrual statuses were identified. Ultimately, three main dietary patterns were determined (for details, see Supplement 2). The modeling was also based on quintiles.

2.5 Statistical analysis

Data were statistically analyzed using SPSS 20.0 combined with Excel software. Normally distributed measurement data were described as mean $\pm$ standard deviation ($\bar{X} \pm SD$), while skewed distribution data were described as median (M) and interquartile range (P_{25} , P_{75}). Categorical data were expressed as frequencies and percentages. The Kolmogorov-Smirnov test was used to test for normality, and Levene's test was used for homogeneity of variance testing. Data comparisons were conducted using the t -test, chi-square test, one-way analysis of variance (ANOVA) for comparing means among multiple samples, or the Kruskal-Wallis H test from non-parametric tests were applied. For statistically significant differences, pairwise comparisons were conducted using the LSD-test or Wilcoxon rank-sum test. Multivariate logistic analysis was used to estimate influencing factors for bone impairment, the impact of different dietary component intakes on bone health, and the association between various dietary patterns and bone impairment. Variable assignments are detailed in Supplement 3.

2.6 Entropy-Weighted TOPSIS Analysis

We used Excel to perform the entropy-weighted TOPSIS method to analyze the compliance rates of each dietary component among the three groups. Finally, based on the "Chinese Food Guide Pagoda (2022)" from the *Dietary Guidelines for Chinese Residents (2022)*^[19], nine dimensional indicators were selected: cereals (X1), tubers (X2), vegetables (X3), fruits (X4), animal-derived foods (X5), soybeans and nuts (X6), milk and dairy products (X7), oil (X8), and salt (X9). The weights of each dietary component were calculated using the entropy weight method, and then the TOPSIS evaluation method was applied to compare the comprehensive score indices of the three groups.

3. Results

3.1 Demographic characteristics

This study included a total of 36,298 women, with a median age of 49 (42, 56) years. Among them, there were 18,309 premenopausal women (50.4%) with a median age of 42 (36, 46) years; 2,497 perimenopausal women (6.9%) with a median age of 49 (47, 52) years; and 15,492 postmenopausal women (42.7%) with a median age of 59 (54, 66) years. Most of the participants resided in the Yunnan-Guizhou Plateau, accounting for 50.9%; the proportion of Han ethnicity was relatively high (54.5%); and the number of participants with middle-level income was the largest (50.4%). Other lifestyle characteristics are detailed in Table 1.

The analysis results showed that postmenopausal women had higher proportions of "almost never/never" drinking alcohol (77.2%) and not drinking tea (81.0%). Additionally, the usage rate of calcium tablets among postmenopausal women (18.6%) was higher than that in the premenopausal group (10.7%), while the proportion of those with a history of contraceptive use (8.5%) was significantly lower.

We noticed that the detection rate of bone damage increased significantly with the progression of menstrual status. The detection rates in the premenopausal, perimenopausal, and postmenopausal groups were 16.6%, 17.9%, and 48.3%, respectively. Moreover, the distribution differences of the surveyed factors among groups with different menstrual statuses were all statistically significant ($P < 0.05$).

Table 1
Demographic characteristics of different menstrual status groups (N = 36,298)

Variables	Overall (N = 36,298)	Premenopause (N = 18,309)	Perimenopause (N = 2,497)	Postmenopause (N = 15,492)	Statistical values <i>H/χ²</i>	<i>P</i>
Age M(<i>P</i> ₂₅ , <i>P</i> ₇₅)	49(42, 56)	42(36, 46)	49(47, 52)	59(54, 66)	25,656.88 ^a	<0.001 ^b
Region N(%)					622.32	<0.001 ^b
Yunnan-Guizhou Plateau	18,465(50.9)	8,258(45.1)	1,295(51.9)	8,912(57.5)		
Sichuan Basin	16,443(45.3)	9,095(49.7)	1,160(46.5)	6,188(39.9)		
Qinghai-Tibet Plateau	1,390(3.8)	956(5.2)	42(1.7)	392(2.5)		
Ethnicity N(%)					74.78	<0.001 ^b
Han	19,765(54.5)	10,322(56.4)	1,413(56.6)	8,030(51.8)		
Ethnic minorities	16,533(45.5)	7,987(43.6)	1,084(43.4)	7,462(48.2)		
Annual family income N(%)					1,271.42	<0.001 ^b
0~	13,632(37.6)	5,462(29.8)	911(36.5)	7,259(46.9)		
20000~	18,306(50.4)	9,925(54.2)	1,322(52.9)	7,059(45.6)		
100000~	4,360(12.0)	2,922(16.0)	264(10.6)	1,174(7.6)		
Occupation N(%)					2,160.82	<0.001 ^b
Workers and peasants	15,459(42.6)	6,912(37.8)	1,153(46.2)	7,394(47.7)		
Non-workers and non-peasants	16,882(46.5)	10,373(56.7)	1,117(44.7)	5,392(34.8)		
Retired/unemployed	3,957(10.9)	1,024(5.6)	227(9.1)	2,706(17.5)		
Marital status N(%)					2,535.62	<0.001 ^b
Married/cohabiting	31,894(87.9)	16,999(92.8)	2,303(92.2)	12,592(81.3)		
Separated/divorced	1,392(3.8)	804(4.4)	104(4.2)	484(3.1)		
Widowed	2,702(7.4)	251(1.4)	84(3.4)	2,367(15.3)		
Unmarried	310(0.9)	255(1.4)	6(0.2)	49(0.3)		
Note: ^a <i>t</i> -test; ^b The difference is statistically significant.						

Table 1. (Continued)						
Variables	Overall (N = 36,298)	Premenopause (N = 18,309)	Perimenopause (N = 2,497)	Postmenopause (N = 15,492)	Statistical values <i>H/χ²</i>	<i>P</i>
Educational attainment N(%)					3,859.24	<0.001 ^b
Primary school or below	20,469(56.4)	7,688(42.0)	1,488(59.6)	11,293(72.9)		
Junior high school or senior high school	12,009(33.1)	7,408(40.5)	824(33.0)	3,777(24.4)		
College degree or above	3,820(10.5)	3,213(17.5)	185(7.4)	422(2.7)		
Smoking status N(%)					39.92	<0.001 ^b
Non-smoker	35,828(98.7)	18,004(98.3)	2,476(99.2)	15,348(99.1)		
Smoker	470(1.3)	305(1.7)	21(0.8)	144(0.9)		
Drinking status N(%)					704.62	<0.001 ^b
Almost never/never	25,828(71.2)	12,123(66.2)	1,740(69.7)	11,965(77.2)		
Occasionally	8,801(24.2)	5,457(29.8)	638(25.6)	2,706(17.5)		
Frequently	1,669(4.6)	729(4.0)	119(4.8)	821(5.3)		
Bone quality status N(%)					4,182.28	<0.001 ^b
Normal	25,318(69.8)	15,261(83.4)	2,050(82.1)	8,007(51.7)		
Damaged	10,980(30.2)	3,048(16.6)	447(17.9)	7,485(48.3)		
Tea drinking status N(%)					62.44	<0.001 ^b
Yes	7,555(20.8)	4,112(22.5)	503(20.1)	2,940(19.0)		
No	28,743(79.2)	14,197(77.5)	1,994(79.9)	12,552(81.0)		
Vitamin D usage status N(%)					17.68	<0.001 ^b
Yes	768(2.1)	445(2.4)	44(1.8)	279(1.8)		
No	35,530(97.9)	17,864(97.6)	2,453(98.2)	15,213(98.2)		
Note: ^a <i>t</i> -test; ^b The difference is statistically significant.						

Table 1.						
(Continued)						
Variables	Overall (N = 36,298)	Premenopause (N = 18,309)	Perimenopause (N = 2,497)	Postmenopause (N = 15,492)	Statistical values H/χ^2	P
Calcium supplement usage status N(%)					423.63	<0.001^b
Yes	5,217(14.4)	1,959(10.7)	382(15.3)	2,876(18.6)		
No	31,081(85.6)	16,350(89.3)	2,115(84.7)	12,616(81.4)		
Whether (one) has taken contraceptive pills N(%)					1,312.69	<0.001^b
Yes	5,865(16.2)	4,208(23.0)	341(13.7)	1,316(8.5)		
No	30,433(83.8)	14,101(77.0)	2,156(86.3)	14,176(91.5)		
BMI status M(P25, P75)	23.56 (21.42, 25.90)	23.39 (21.34, 25.62)	23.99 (21.95, 26.29)	23.70 (21.41, 26.14)	105.79 ^a	<0.001^b
Physical activity level M(P25, P75)	23.63 (13.30, 38.40)	25.80 (15.80, 39.67)	26.74 (14.79, 40.16)	20.26 (10.08, 36.34)	712.74 ^a	<0.001 ^b
Note: ^a t-test; ^b The difference is statistically significant.						

3.2 Bone health status of the population

Through univariate analysis, we identified variables with statistical significance in association with bone damage (such as region, ethnicity, occupation, marital status, education, alcohol consumption, etc.) and included them as confounding factors in the model for adjustment. Details are provided in Supplement 4.

Multivariate logistic regression analysis was conducted to assess the association between different menstrual statuses and bone health outcomes. The results showed that, compared to premenopausal women, perimenopausal women did not exhibit an increased risk of bone impairment, with an *OR* (95% CI) of 0.75 (0.67, 0.84). In contrast, postmenopausal women had a significantly elevated risk of bone impairment, with an *OR* (95% CI) of 1.74 (1.60, 1.89). See Table 2 for details.

Table 2
Multivariate logistic regression analysis of factors affecting bone quality status

Characteristics	OR(95%CI)	Wald	P
Menopausal Status		271.70	< 0.001 ^a
Premenopause	1.00		
Perimenopause	0.75(0.67, 0.84)		
Postmenopause	1.74(1.60, 1.89)		
Note: ^a The difference is statistically significant.			

3.3 Evaluation of population dietary quality

Based on the evaluation criteria of the *Chinese Food Guide Pagoda (2022)*^[19], the cumulative compliance rate of the study participants with the Recommended Nutrient Intake (RNI) for all food categories was 0%. Dietary intake generally failed to meet the recommended standards. To conduct a comprehensive evaluation, this study employed the entropy-weighted TOPSIS method to determine the weight of each food category within the comprehensive evaluation system (see Figure S2 and Table S3 in Supplement 5 for details). The RNI adequacy rates for all dietary categories in the overall population and across different menopausal status groups were below 50%. The adequacy rates for each dietary component are detailed in Fig. 2.

To further explore the characteristics of dietary structures among women of different menopausal statuses, this study analyzed the adequacy of intake and the correlations in adequacy rates across nine major food categories. The results, shown in Fig. 3 and Table S4 in Supplement 5, revealed that premenopausal women had the highest adequacy rates in cereals, animal-based foods, and salt, with food weights of 15.499%, 8.125%, and 14.942%, respectively, indicating their substantial contribution to the overall bone health evaluation. Perimenopausal women performed relatively well in the intake of vegetables, fruits, and dairy products. Although dairy products had the highest weight (20.902%), highlighting the critical role of adequate dairy intake in maintaining bone health in women, the adequacy rate for dairy was as low as 0.5%, preventing this effect from being fully realized. Postmenopausal women had a slightly higher adequacy rate in tuber intake compared to other groups. However, their intake of protein-rich foods such as dairy products, soybeans, and nuts was insufficient, reflecting a distinct trend toward simplified and fragmented dietary patterns.

Therefore, by integrating food weights, the comprehensive score indices for the three groups, ranked from highest to lowest, were as follows: premenopausal, perimenopausal, and postmenopausal. Specific numerical results are provided in Table S5 of Supplement 5.

Figure 2. Comparison Line Chart of Achievement Rates for Each Dietary Component. Premenopausal women have optimal solutions in Oil, Salt, Cereals, Fruits, Animal Foods, and Soybeans; Perimenopausal women have optimal solutions in Fruits, Vegetables, Milk and Dairy Products; Postmenopausal women have optimal solutions in Tubers.

3.4 Dietary Patterns

Ultimately, we extracted three a posteriori dietary patterns. The weights of food components in different dietary patterns are detailed in Figure S3 of Supplement 6. ANOVA or *t*-tests were used to compare differences in the mean dietary pattern scores among populations with different characteristics. Here, we only present the differences between different menstrual statuses and bone health statuses; details on other characteristics are provided in Table S6 of Supplement 6. The results revealed that menopausal status was significantly associated with scores for all dietary patterns ($P < 0.001$). Adherence to both the DASH dietary pattern and the DASH-adjusted red meat pattern showed a declining trend with the progression of

menopausal status. Premenopausal women had the highest scores (17.714 ± 3.515 ; 18.111 ± 3.616), while postmenopausal women had the lowest (16.821 ± 3.590 ; 16.951 ± 3.671). Meanwhile, the scores of the DASH pattern and DASH-adjusted red meat pattern in the population with normal bone health were significantly higher than those in the population with bone damage. Statistically significant differences were also observed between groups for posteriori Dietary Pattern 2 and Dietary Pattern 3 ($P < 0.05$), as detailed in Table 3. This suggests that dietary structure characteristics are closely related to both menopausal status and bone health.

Logistic regression analysis was conducted to estimate the association between dietary patterns and bone damage after adjusting for confounding factors. The results of quintiles (Q1-Q5) for different dietary patterns are detailed in Tables S7-S11 of Supplement 8. After full adjustment for confounders (Model 3), the DASH-adjusted red meat pattern demonstrated a stable protective effect ($OR = 0.990$, 95% CI : $0.981-0.999$, $P = 0.035$), indicating significant protective effects in both the basic model and Model 3 (Model 1 $OR = 0.983$, $P < 0.001$; Model 3 $OR = 0.991$, $P = 0.025$). Details are shown in Table 4.

Further comparison of the distribution of the DASH dietary pattern and the DASH adjusted red meat pattern across the total population, different menstrual status subgroups, and subgroups with/without bone damage, Fig. 4 shows that the adherence scores of the normal bone mass group to both the standard DASH pattern and the DASH-adjusted red meat pattern were significantly higher than those of the abnormal bone mass group ($P < 0.05$). The significant association of the DASH adjusted red meat pattern further indicates that after adaptive optimization of the classic DASH pattern, its protective association with bone health remains robust. Additionally, the pie chart highlights that the adequacy rate for animal-based food intake was only 26.9%. The bar chart displays the distribution of daily red meat intake among women, with the x-axis representing daily intake and the y-axis representing the corresponding number of individuals. Therefore, we consider that the contextually adapted DASH-adjusted red meat pattern may be more suitable for the local situation and used this as a basis for further investigation.

Table 3
Dietary pattern scores among populations with different characteristics

Characteristics	DASH dietary pattern	DASH-adjusted red meat pattern	Dietary pattern 1	Dietary pattern 2	Dietary pattern 3
Menopausal Status					
Premenopause	17.714 ± 3.515	18.111 ± 3.616	-0.025(-0.833, 0.989)	-0.284(-0.773, 0.472)	-0.306(-0.968, 0.558)
Perimenopause	17.201 ± 3.603 ^a	17.509 ± 3.625 ^a	-0.188(-0.976, 0.770) ^a	-0.344(-0.818, 0.340) ^a	-0.092(-0.765, 0.774) ^a
Postmenopause	16.821 ± 3.590 ^{a,b}	16.951 ± 3.671 ^{a,b}	-0.426(-1.170, 0.509) ^{a,b}	-0.332(-0.883, 0.431) ^{a,b}	0.025(-0.664, 0.871) ^{a,b}
<i>F/H</i>	266.469	426.369	762.996	60.879	567.477
<i>P</i>	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Bone quality status					
Normal	17.354 ± 3.565	17.657 ± 3.664	-0.203(-0.986, 0.796)	-0.322(-0.826, 0.435)	-0.137(-0.840, 0.756)
Damaged	17.167 ± 3.608	17.385 ± 3.719	-0.226(-1.021, 0.747)	-0.279(-0.804, 0.467)	-0.171(-0.833, 0.651)
<i>t/Z</i>	4.584	6.477	-1.936	-2.874	-3.452
<i>P</i>	< 0.001	< 0.001	0.053	0.004	< 0.001
Note: ^a Indicates that the mean score is significantly different from that of the first group; ^b Indicates that the mean score is significantly different from that of the second group.					

Table 4
Logistic regression analysis of dietary pattern scores and bone quality status

Dietary pattern	Model 1		Model 2		Model 3	
	OR(95%CI)	P	OR(95%CI)	P	OR(95%CI)	P
DASH dietary pattern	0.983(0.974, 0.992)	< 0.001 ^a	0.990(0.982, 0.999)	0.030 ^a	0.991(0.982, 1.000)	0.025 ^a
DASH-adjusted red meat pattern	0.989(0.980, 0.998)	0.020 ^a	0.991(0.982, 1.000)	0.055	0.990(0.981, 0.999)	0.035 ^a
Dietary pattern 1	1.078(1.053, 1.104)	< 0.001 ^a	1.034(1.009, 1.061)	0.009 ^a	1.026(1.000, 1.052)	0.053
Dietary pattern 2	1.019(0.998, 1.040)	0.084	1.013(0.989, 1.037)	0.305	1.039(1.013, 1.066)	0.003 ^a
Dietary pattern 3	0.905(0.886, 0.925)	< 0.001 ^a	1.003(0.979, 1.028)	0.786	1.004(0.980, 1.029)	0.734
Note: ^a The difference is statistically significant;						
Model 1: Age + menopausal status + BMI + activity equivalent + other dietary patterns (excluding DASH-adjusted red meat pattern);						
Model 2: Model 1 + ethnicity + region + marital status + education level + occupation + annual household income;						

Model 3: Model 2 + alcohol consumption + tea consumption + contraceptive use + calcium intake.

3.5 Diet and Bone Health in Women of Different Menopausal Statuses

Further analysis revealed that regarding the modifying effect of menopausal status on the association between dietary patterns and bone health (details in Table 5), only the DASH-adjusted red meat pattern and Dietary Pattern 2 showed an interaction between premenopausal and postmenopausal women. Additionally, the differences in scores of these two patterns between premenopausal and postmenopausal women were the most contrasting (see Table S6 in Supplement 6 for details). Specifically, within the DASH-adjusted red meat pattern, scores were significantly higher in the normal bone mass group compared to the impaired group, suggesting a protective effect. Although the absolute difference in Dietary Pattern 2 between the two groups was small, the inter-group comparison was statistically significant ($P = 0.004$), suggesting that it might be a risky dietary pattern. Therefore, we conducted subsequent stratified analyses on the bone health status of these two patterns across different menopausal statuses.

To maximally control for potential confounding factors and provide the most conservative effect estimates, this study primarily presents the results from the fully adjusted Model 3. The results from the unadjusted and partially adjusted models (Model 1 and Model 2) are available in Supplementary Materials Supplement 7, Tables S12-13.

The results showed that among premenopausal women, no significant association was observed between the DASH-adjusted red meat pattern ($OR = 1.000$, 95% CI: 0.985–1.014) or Dietary Pattern 2 ($OR = 1.023$, 95% CI: 0.983–1.064) and bone health risk (all $P > 0.05$). However, among postmenopausal women, the DASH-adjusted red meat pattern exhibited a clear protective effect: for each 1-unit increase in its score, the risk of bone damage decreased by 1.3% ($OR = 0.987$, 95% CI: 0.975–1.000, $P = 0.044$). Although the risk in the highest quintile score group was only 17.5% lower than that in the lowest group ($OR = 0.825$, 95% CI: 0.709–0.960, $P = 0.013$), a trend of protective effect was observed from Q1 to Q5 ($P = 0.028$). In contrast, Dietary Pattern 2 showed a significant risk effect: for each 1-unit increase in its score, the risk increased by 4.9% ($OR = 1.049$, 95% CI: 1.013–1.086, $P = 0.008$), and the risk in the highest group was 29.4% higher than that in the reference

group ($OR = 1.294$, 95% CI : 1.141–1.468, $P < 0.001$), with a trend of risk effect ($P < 0.001$). See Table 6 for details. These findings suggest that the impact of dietary patterns on bone health is dependent on menopausal status, and their protective or risky effects are only significantly evident in postmenopausal women.

Table 5
Modifying effect of menopausal status on the association between dietary patterns and bone quality

Dietary pattern	Menopausal Status VS Premenopause	OR (95%CI)	P
DASH dietary pattern	Perimenopause	0.997(0.968, 1.026)	0.840
	Postmenopause	0.990(0.979, 1.000)	0.062
DASH-adjusted red meat pattern	Perimenopause	0.985(0.957, 1.014)	0.301
	Postmenopause	0.982(0.972, 0.993)	<0.001 ^a
Dietary pattern 1	Perimenopause	0.971(0.896, 1.053)	0.477
	Postmenopause	0.988(0.958, 1.019)	0.433
Dietary pattern 2	Perimenopause	1.086(0.994, 1.186)	0.067
	Postmenopause	1.031(1.000, 1.063)	0.047*
Dietary pattern 3	Perimenopause	1.005(0.923, 1.094)	0.911
	Postmenopause	1.019(0.989, 1.050)	0.207
Note: ^a The difference is statistically significant.			

Table 6
Logistic regression analysis of dietary pattern scores and bone health status in premenopausal and postmenopausal women

Dietary pattern	Premenopause		Postmenopause	
	OR(95% CI)	P	OR(95% CI)	P
DASH-adjusted red meat pattern	1.000(0.985, 1.014)	0.963	0.987(0.975, 1.000)	0.044 ^a
Quintile		0.376		0.007 ^a
Q1	1.000		1.000	
Q2	1.036(0.887, 1.209)	0.657	1.029(0.937, 1.129)	0.549
Q3	1.013(0.862, 1.189)	0.178	1.016(0.909, 1.135)	0.785
Q4	1.092(0.926, 1.288)	0.607	0.883(0.776, 1.005)	0.060
Q5	0.959(0.805, 1.144)	0.645	0.825(0.709, 0.960)	0.013 ^a
$P_{\text{for trend}}$		0.665		0.007 ^a
Note: ^a The difference is statistically significant.				

Table 6
(Continued)

Dietary pattern	Premenopause		Postmenopause	
	OR(95% CI)	P	OR(95% CI)	P
Dietary pattern 2	1.023(0.983, 1.064)	0.267	1.049(1.013, 1.086)	0.008 ^a
Quintile		0.298		< 0.001 ^a
Q1	1.000		1.000	
Q2	1.134(0.990, 1.298)	0.062	1.117(1.002, 1.244)	0.045 ^a
Q3	1.134(0.989, 1.301)	0.071	1.227(1.097, 1.372)	< 0.001 ^a
Q4	1.110(0.963, 1.279)	0.150	1.171(1.044, 1.314)	0.007 ^a
Q5	1.050(0.898, 1.227)	0.544	1.294(1.141, 1.468)	< 0.001 ^a
<i>P</i> _{for trend}		0.764		< 0.001 ^a
Note: ^a The difference is statistically significant.				

3.6 Contribution Analysis of Food Components in Each Dietary Pattern

To further elucidate the relative contribution of various food components to the bone health benefits observed in the DASH adjusted red meat pattern, single-component analysis was conducted. The results (see Table S14 in Supplement 8 for the total population and Table 7 for the postmenopausal subgroup) indicated significant differences in the contribution of different food components within this pattern to bone health, with these contributions being population-specific.

In the total population, although only dairy and its products (32.48%, $P = 0.046$) and red/processed meat (13.68%, $P = 0.045$) showed statistically significant beneficial apparent effects, the potential higher beneficial contributions from whole grains, fruits, vegetables, and low salt intake should still be noted.

Compared to the results in the total population, postmenopausal women showed opposite differences in bone health contributions for two dietary components: vegetables (-5.71%, $P = 0.006$) and fruits (-1.14%, $P = 0.005$). This may be related to an imbalanced plant-based dietary structure characterized by high fruit/vegetable intake accompanied by low animal-based food intake. Soybean intake might partially compensate for the protein supply issue (see Fig. 1), further suggesting the potential importance of dairy products (32.48%, $P = 0.046$) and red/processed meat (30.29%, $P = 0.088$) in supplementing protein for bone health. It is worth mentioning that when the "low sodium" characteristic (5.71%, $P = 0.013$) was removed, and the new Q5 group included some individuals with "high sodium" intake, the observed weakening of the bone protective effect still underscores the established importance of low sodium intake.

These findings preliminarily identify the component heterogeneity underlying the protective effect of the DASH adjusted red meat pattern: cereals, fruits/vegetables, animal-based foods, and low salt remain the foundation of the protective effect for the entire population. However, for postmenopausal women with insufficient red meat intake, adopting a balanced dietary pattern that encourages moderate red meat intake while ensuring adequate dairy products, whole grains, and low sodium is an effective dietary strategy for protecting bone health. The study results provide direct evidence for developing precise dietary intervention strategies tailored to different populations.

Table 7
Sensitivity analysis of the contribution of each component in the DASH-adjusted red meat pattern among postmenopausal women

Dietary score	OR (95% CI)	P	Reduction in apparent effect (%) ^b
DASH overall	0.825(0.709, 0.960)	0.013 ^a	0.00
DASH minus whole grain	0.833(0.721, 0.962)	0.013 ^a	4.57
DASH minus fruit	0.823(0.720, 0.942)	0.005 ^a	-1.14
DASH minus vegetables	0.815(0.705, 0.943)	0.006 ^a	-5.71
DASH minus legumes	0.825(0.714, 0.953)	0.009 ^a	0
DASH minus red & processed meats	0.878(0.757, 1.020)	0.088	30.29
DASH minus dairy products	0.901(0.804, 1.009)	0.072	43.43
DASH minus Low-salt group	0.835(0.725, 0.962)	0.013 ^a	5.71

Note: ^a The difference is statistically significant.

4. Discussion

This study analyzed the dietary patterns and their relationship with bone health among women of different menopausal statuses in the CMEC, aiming to explore specific dietary intervention strategies for different female populations in southwestern China. The study revealed that the median age of perimenopausal women in the five southwestern provinces was 49 (47, 52) years, consistent with the finding in the *Guidelines for Menopause Management and Menopausal Hormone Therapy in China (2023)* that 90% of Chinese women experience menopause between the ages of 45 and 55^[16]. Furthermore, the sharp decline in estrogen levels during menopausal transition is one of the most significant risk factors for female bone health^[1–3, 5]. This aligns with our results, which showed a much higher detection rate of impaired bone mass in postmenopausal women (48.3%) compared to premenopausal women (16.6%), and multivariate analysis indicated a significantly increased risk ($OR = 1.74$). These findings are also consistent with results from multiple studies in other countries^[20–23].

Similar to our results, studies by Zhong Huaichang, Zhang Lin, and others also found a higher prevalence of impaired bone mass among older, postmenopausal, unmarried women and those with lower BMI, while higher BMI, higher education level, and estrogen therapy^[24] were negatively correlated with impaired bone mass. Analysis of factors influencing abnormal bone mass in the Tibetan region of China also indicated a higher incidence of impaired bone mass among postmenopausal Tibetan women^[25–27]. A cohort study on fracture prediction across ethnicities suggested that the FRAX risk assessment tool should not be routinely used for screening decisions in young postmenopausal women^[28]. This finding highlights the need to consider the specific effects of different menopausal stages on bone health and implement individualized prevention and management strategies accordingly.

Additionally, our study analyzed variables closely related to bone health, such as calcium and vitamin D supplements and tea drinking habits. We did not observe a protective effect of vitamin D supplements on bone health ($P > 0.05$), which might be related to their lack of support for improving BMD in healthy premenopausal women^[29] and the relatively small number of supplement users in the other two menopausal groups. Consistent with multiple studies^[6, 30], we still emphasize the significant role of calcium supplements and tea drinking on bone health across different populations and included them as important confounding factors in our multivariate models.

Notably, our study found that the cumulative adequacy rate for the Recommended Nutrient Intake (RNI) across the nine major food groups was 0% in the female population of southwestern China, with the adequacy rate for each category below 50%. Particularly for soybeans and nuts, dairy and dairy products, and oils, the adequacy rates were below 10%. This reflects a dietary structure primarily based on plant-based foods, lacking in meat, eggs, dairy, soybeans, and nuts, and characterized by high oil and salt intake. This result is closely related to the extremely low overall awareness of Chinese dietary guidelines among the general population in southwestern China^[14].

Given the differences in dietary quality and structure among women of different menopausal statuses, we further applied the entropy-weighted TOPSIS method, which revealed a sequential decline in dietary quality from premenopausal to perimenopausal to postmenopausal women. Although their dietary structures differed (as shown in Figs. 1 and 2), they all tended towards plant-based diets. However, vegetarian patterns predominantly based on plant-based foods^[31] are associated with lower BMD and biomarkers of bone health^[10], while the protein, calcium, unsaturated fatty acids, minerals, vitamins, and phytochemicals contained in meat, dairy, fruits, and vegetables may all have favorable effects on bone health^[6, 31, 32], which is largely consistent with our subsequent single-component analysis results. Therefore, to further explore dietary patterns suitable for the current situation of our study population, and given the widespread insufficient intake of animal-based foods, we adapted the traditional DASH dietary pattern by changing red meat intake from a restricted item to an encouraged item, creating a contextually adapted "DASH-adjusted red meat pattern."

It is noteworthy that, compared with other sources of animal protein, dietary patterns dominated by red meat/processed meat have higher saturated fatty acid and sodium content, which may affect human calcium metabolism, increase bone resorption in women, and cause bone damage^[32, 33]. In addition, studies by Roberto F, Simone P, and others on the "meat or processed meat dietary pattern" highlighted the prominent role of red meat and processed meat in shaping overall dietary structure and exerting important impacts on long-term health. These studies elaborated on the negative effects of high intake of red meat, processed meat, eggs, refined grains, and high-saturated-fat foods on bone health^[34, 35]. However, this does not conflict with our study. Although higher intake of red meat and processed meat shows a linear association with an increased risk of hip fractures in women^[36], the compliance rate for total animal-based food intake in this study was only 26.9% (see Fig. 2), and 56.1% of women still had intake below the RNI. Meat is an important source of protein, and studies have shown that moderate meat intake—among those with high adherence to a healthy dietary pattern—is associated with a reduced risk of hip fractures^[36]. Therefore, we still emphasize that women in the five provinces of Southwest China should currently increase their intake of all types of animal-based foods, prioritizing lean meat and poultry over high-fat meats to meet the RNI^[37].

Further analysis revealed a clear "menopausal status dependency" in the association between dietary patterns and bone health. The DASH-adjusted red meat pattern exhibited a stable protective effect in postmenopausal women. This might be because sufficient estrogen levels in premenopausal women create a robust internal environment that can buffer or compensate for the negative effects of suboptimal diet. When this "protective umbrella" is removed after menopause, the fundamental supportive role of dietary quality becomes crucial and more apparent^[38, 39]. Stratified analysis confirmed that menopausal status is a key effect modifier contributing to heterogeneity in these studies. Through single-component analysis, we advanced the study of dietary patterns from "overall association" to "component analysis," preliminarily identifying population heterogeneity in the underlying mechanisms of the protective effect. The data suggest that for the general female population, ensuring adequate intake of animal-based foods remains a means to promote bone health, while also paying attention to the potential benefits of reasonable intake of whole grains, fruits, vegetables, and low salt, which may be related to minerals, dietary fiber, etc., indirectly improving inflammation and insulin sensitivity or directly affecting calcium metabolism^[31, 32, 40].

However, it is noteworthy that in the context of nutritional deficiency, previous risk factors (like red meat) might transform into protective factors. This study suggests that for postmenopausal women with severely insufficient intake of animal-

based foods, appropriately increasing red meat intake might be one of the potential core components of their dietary strategy for bone health. This finding might be related to the dynamic changes in the inorganic and organic phases of bone associated with menopause and aging^[10], leading to a sharp increase in the demand for bioavailability of dietary protein, calcium, and trace elements^[41–43]. Therefore, as for the general female population, we still emphasize supplementing with high-quality animal-based foods when conditions allow, to avoid the negative effects of increasing red and processed meat intake outweighing the positive ones^[32, 36, 37].

Regarding the paradoxical effects of fruits, vegetables, and legumes, we believe this precisely reflects the complexity of the overall diet. As mentioned earlier, the excessive reliance on plant-based diets in the postmenopausal group might significantly diminish the beneficial effects of fruits and vegetables, even highlighting a negative correlation with bone health^[44, 45], while soybeans, as a high-quality protein alternative to dairy, might partially compensate for this deficiency^[46]. Therefore, when the intake of animal-based foods in the study population reaches sufficient levels, the marginal effects and interactions of other foods might change accordingly^[47–49]. This highlights the limitations of observing single components and underscores the need to focus more on the comprehensive nutritional complementary benefits brought by diverse dietary integration.

We also found that Dietary Pattern 2 in this study may be a risk factor for bone health. This may be related to its plant-based dietary structure, which includes coarse grains, tea, wheat products, and tubers. This risk is more prominent in postmenopausal women, further confirming the increased sensitivity of bones to an unhealthy diet after losing the protective effect of estrogen^[50, 51]. These findings indicate the dynamic nature of relationships under specific dietary structures; general recommendations for a "healthy dietary pattern" may need to be fine-tuned according to the specific physiological status of the target population to maximize benefits.

In conclusion, women in the five provinces of Southwest China currently have a poor dietary environment. Diet is an important and modifiable factor affecting bone health, and adherence to healthy dietary guidance largely depends on access to high-quality food. For the entire female population, we advocate adhering to a dietary pattern framed by the DASH principle. On the basis of increasing overall dietary consumption to meet the standards of the *Chinese Residents' Balanced Diet Pagoda (2022)*^[19], for regions in Southwest China where animal-based food intake is insufficient—especially for postmenopausal women—dietary promotion should not simply replicate the Western recommendation of "restricting red meat." Instead, it should emphasize "balanced and adequate intake," ensuring sufficient intake of various nutrients (including those from red meat) when conditions are limited, while also focusing on daily calcium supplementation and developing the habit of moderate tea drinking.

To promote the bone health of women in the five provinces of Southwest China, it is necessary to address multiple challenges, including multi-ethnic cultures, relatively underdeveloped economies, and plateau environments. A multi-sectoral collaboration approach is required, with two key focuses: on the one hand, promoting culturally acceptable dietary guidance; on the other hand, ensuring the supply of scarce food resources. This dual approach will drive the overall improvement of women's comprehensive quality.

5. Strengths and limitations

This study, based on the CMEC—a large-scale epidemiological study—explores potential directions for improving dietary quality and the selection and adaptation of dietary patterns from multiple dimensions. This exploration considers both dietary cultural differences and different menstrual stages, focusing on the current status of dietary quality and the association between dietary patterns and impaired bone mass. Most importantly, the reliability and validity of the dietary survey data from this Southwest natural population cohort, upon which our results are based, meet general international standards^[52]. Moving beyond focusing on single dietary components, this study adopted a more realistic "dietary pattern" analysis approach and innovatively applied the entropy-weighted TOPSIS method for comprehensive dietary quality

evaluation, providing a more holistic dietary perspective. Through detailed contribution analysis, it preliminarily identified population heterogeneity in the effects of different food components within the protective dietary pattern, offering direct evidence for formulating specific and actionable dietary recommendations.

Secondly, this study addresses the gap in existing research regarding the prevalence of bone damage and differences in dietary quality and structure among women with different menstrual statuses in the five provinces of Southwest China. It further explores the importance of dietary proportions and components corresponding to different menstrual stages, and provides evidence for the association between dietary patterns and bone damage in these five provinces. The resulting findings on the correlations between women, diet, and bone health lay a knowledge foundation for subsequent follow-up studies.

However, this study is based solely on a cross-sectional design. Although it avoids reverse causality to a certain extent, it still lacks more robust research evidence. Additionally, the relatively high median age of "49 (42, 56)" is more reflective of the average levels of various indicators among middle-aged and elderly populations in Southwest China. With China's economy shifting from a phase of high-speed growth to one of high-quality development, the physiological indicators, dietary quality, and lifestyle behaviors of the new generation of young people have not been fully represented.

Notably, this study only examines the association between diet and bone health, and does not involve other pathological or physiological diseases. Therefore, dietary guidance should be provided only after comprehensively considering practical circumstances from multiple aspects. Finally, the study participants are relatively concentrated in specific geographical regions, which may have unique dietary cultures. As a result, the types of dietary patterns constructed and the observations obtained in this study are only applicable to the five provinces in Southwest China and specific age groups, which may limit the generalizability of the research conclusions.

6. Conclusion

In conclusion, this study found that the "DASH-adjusted red meat" dietary pattern, developed based on the standard DASH diet, better aligns with the practical needs for bone health among residents in underdeveloped regions of Southwest China, demonstrating particularly significant benefits in postmenopausal women. The findings from this large-scale population study suggest that dietary strategies should fully account for regional and ethnic variations, avoiding rigid adherence to any single fixed model. Instead, continuous optimization based on local contexts is essential, coupled with active efforts to guide reductions in unhealthy dietary tendencies.

Declarations

Ethics approval and consent to participate

The study was approved by the Kunming Medical University Medical Ethical Review Board (KMMU2020MEC078). All participants provided written informed consent prior to their involvement in the study.

Consent for publication

Not applicable.

Availability of data and materials

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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Authors' contributions

J.L., and J.Z. conceived the study design. J.L., J.Z., and J.Y. acquired and interpreted the data. J.L., and J.Z. drafted the manuscript. J.Y., and X.Z., critically revised manuscripts for important intellectual content. J.L., J.Z., and J.Y. did the statistical analysis. J.Y., and X.Z., provided administrative or material support. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted. J.Y. is the supervisor.

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Figures

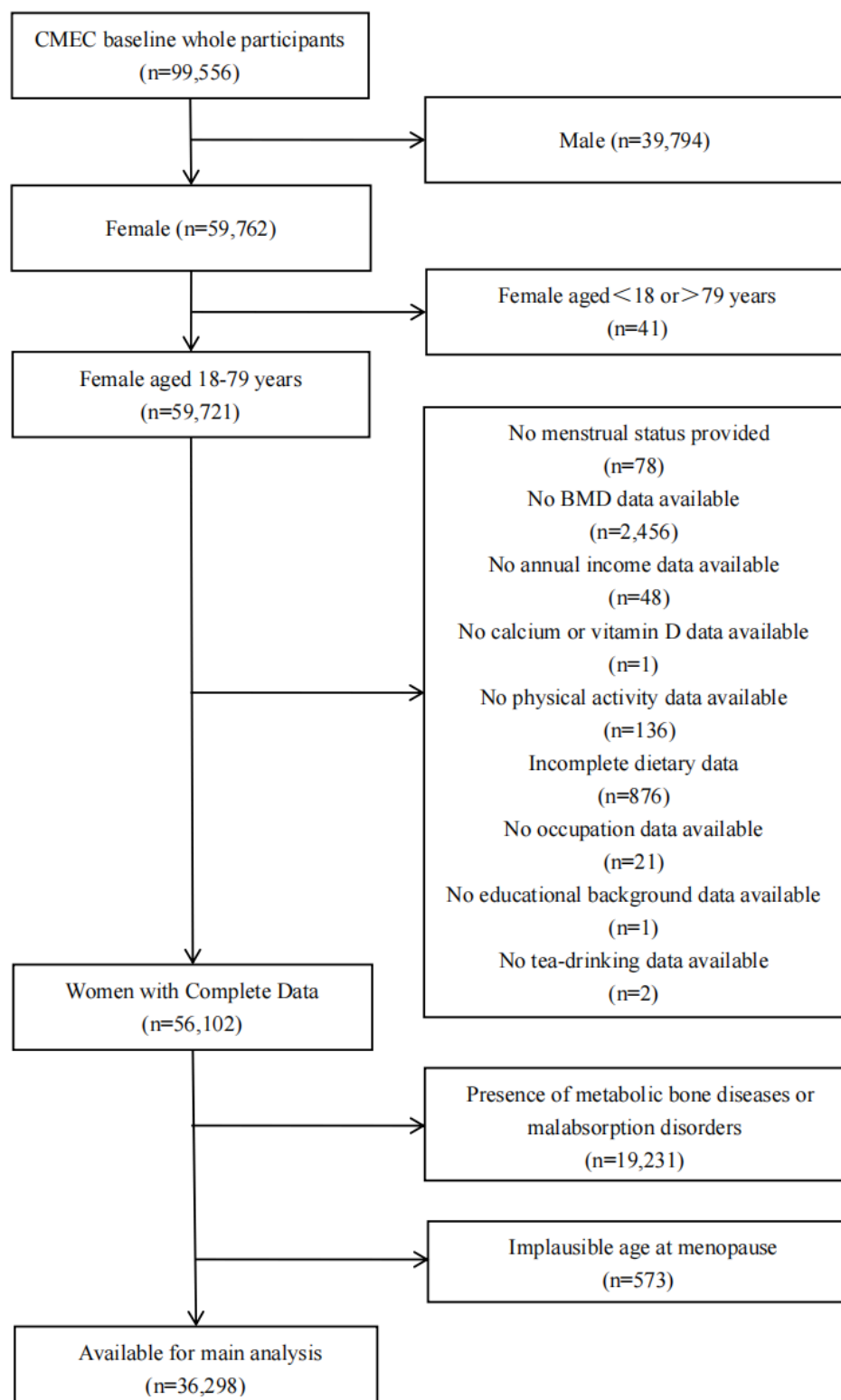


Figure 1

A schematic overview of the procedures for selecting and excluding study population

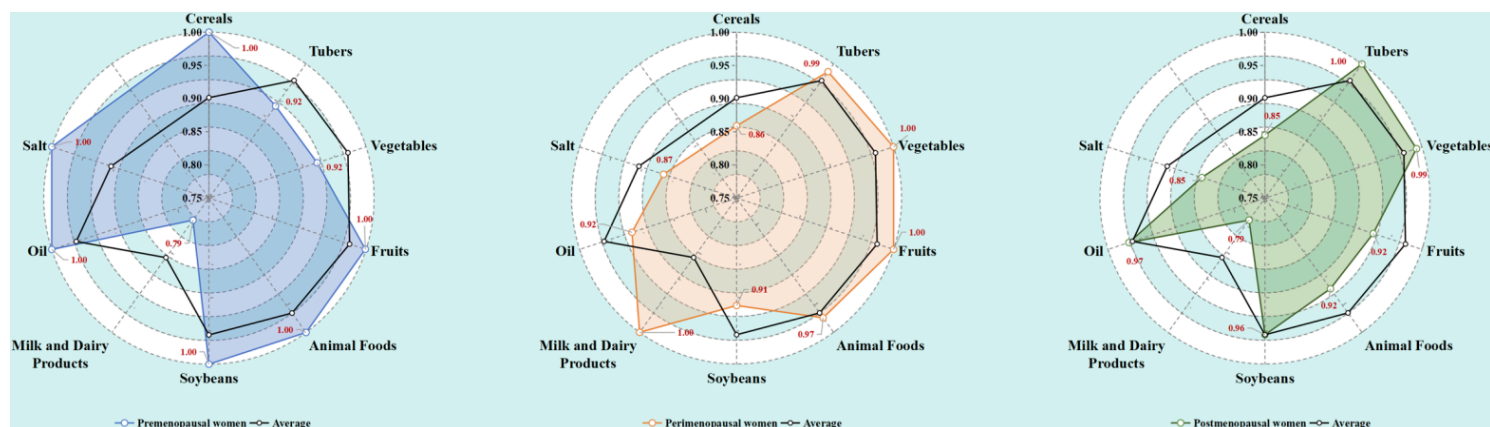


Figure 2

Comparison Line Chart of Achievement Rates for Each Dietary Component. Premenopausal women have optimal solutions in Oil, Salt, Cereals, Fruits, Animal Foods, and Soybeans; Perimenopausal women have optimal solutions in Fruits, Vegetables, Milk and Dairy Products; Postmenopausal women have optimal solutions in Tubers.

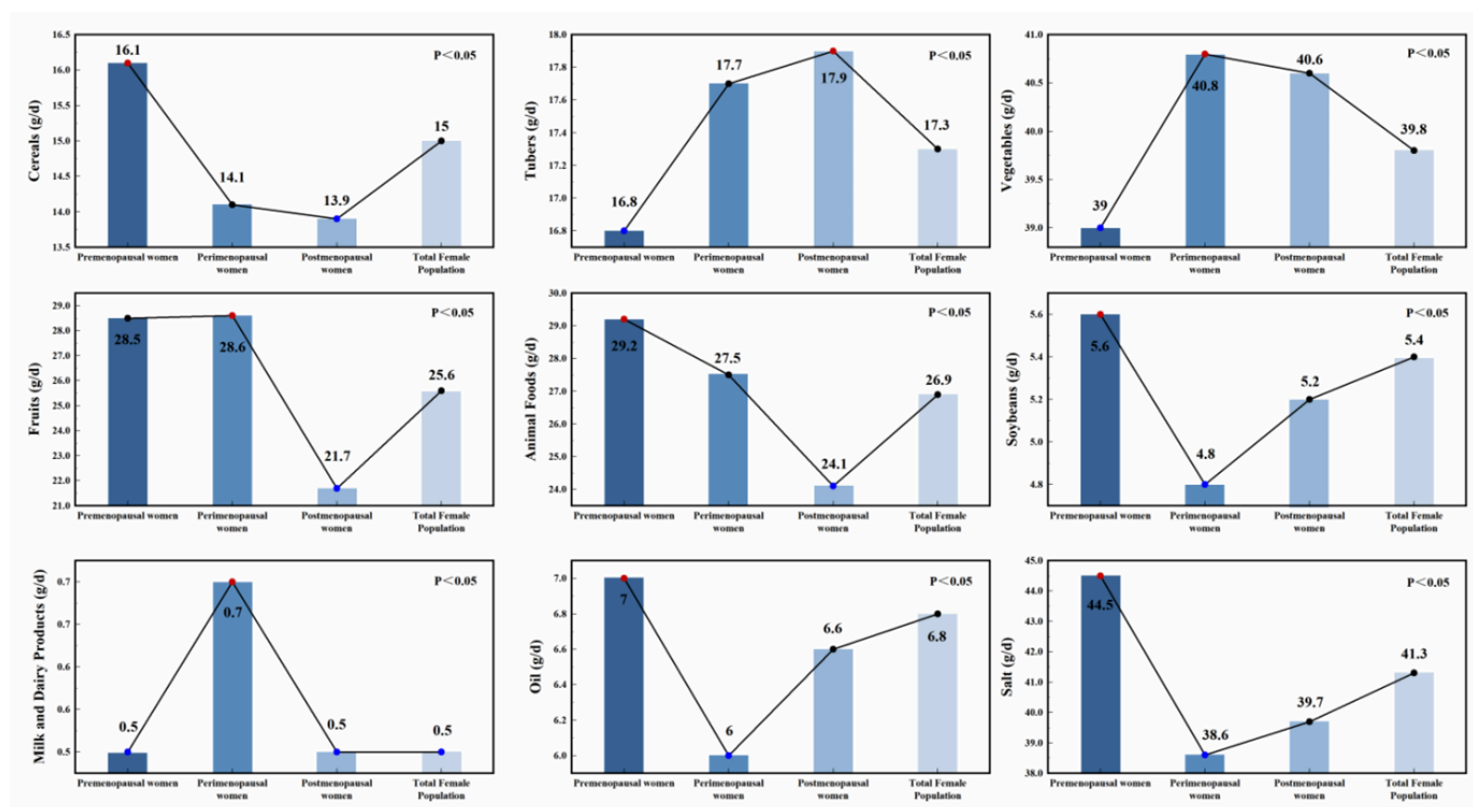


Figure 3

Analysis of Correlative Characteristics of Dietary Structure Among Women with Different Menopausal Statuses. Premenopausal, perimenopausal and postmenopausal women differ in the intake of nine food groups (Cereals, Tubers, Vegetables, Fruits, Animal Foods, Soybeans, Milk and Dairy Products, Oil, Salt), $P < 0.05$.

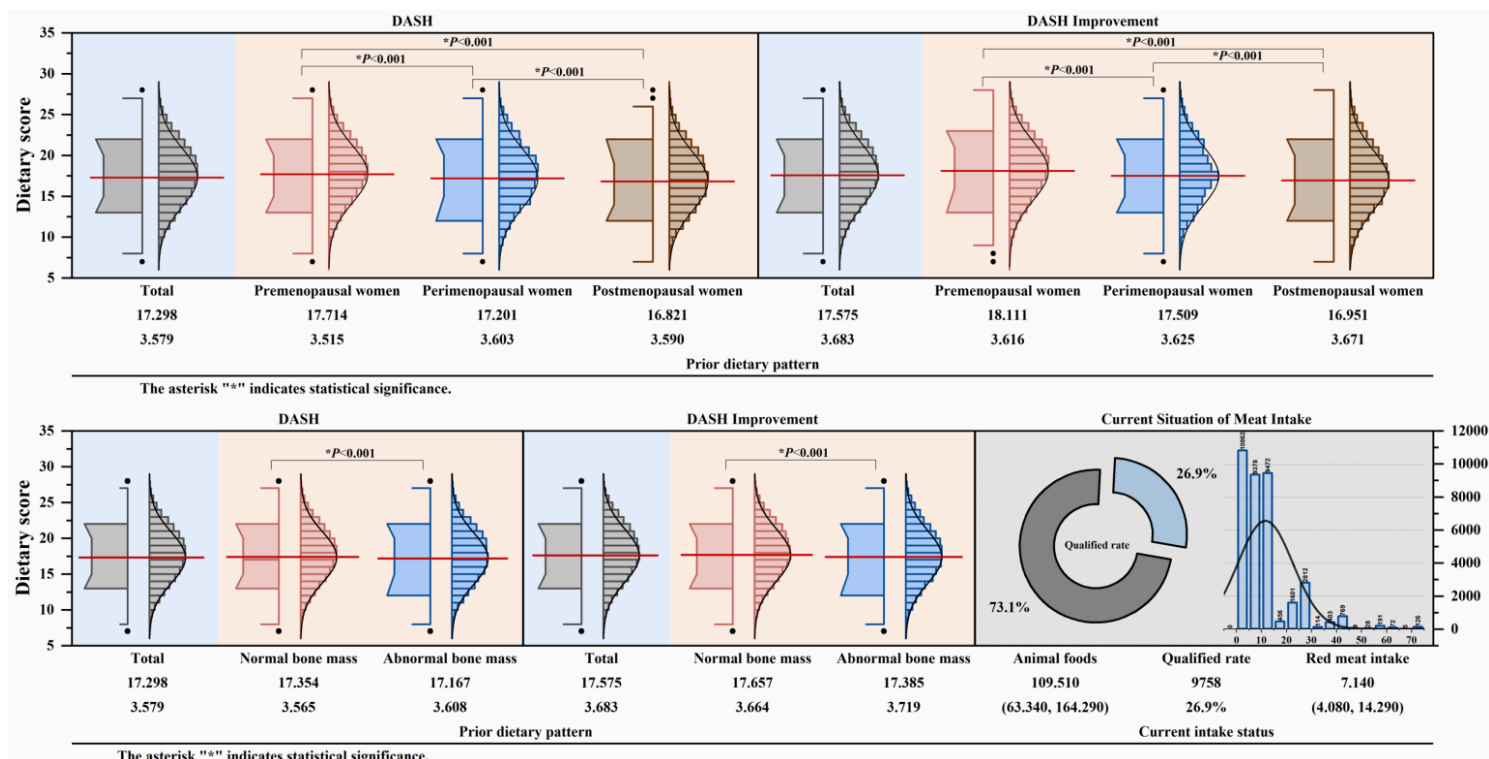


Figure 4

Comparison of DASH Dietary Pattern Scores and Its Modified Pattern Scores Among Populations with Different Bone Statuses. There were statistically significant differences in DASH diet pattern and DASH Improvement diet pattern scores among pre - menopausal, perimenopausal, and post - menopausal women ($P < 0.001$). There were also statistically significant differences in these scores between the normal bone mass and abnormal bone mass groups ($P < 0.001$). The qualified rate of animal food intake was 26.9%, and the median (inter - quartile range) of daily intake in the population was 7.140 (4.080 - 14.290).

Supplementary Files

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