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# Trajectories of plant-based diet indices and the associated risk of hypertension among Chinese adults: a cohort study based on the China Health and Nutrition Survey 2004–2015

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## Abstract

**Background** Plant-based diets have been found to be associated with hypertension. Dietary intake is a dynamic and changing process that can be better characterized by trajectories of dietary indices. However, the associations between plant-based diet trajectories and hypertension over time remained unknown.

**Methods** We used data from the China Health and Nutrition Survey 2004–2015 to analyze a cohort of Chinese adults ≥ 18 years of age who had no hypertension at baseline. Plant-based diets were measured by an overall plant-based diet index (PDI), healthful plant-based diet index (hPDI), and unhealthful plant-based diet index (uPDI) based on three 24-hour recalls. Trajectories of PDI, hPDI, and uPDI (2004 to 2011) were identified using group-based trajectory modeling. The associations between trajectories of PDIs and the risk of new-onset hypertension were estimated using Cox proportional hazard models.

**Results** We identified three trajectories for PDI, two for hPDI, and four for uPDI among the 2853 participants with a mean follow-up of 9.6 years. Compared with the PDI "low and stable" class, the PDI "high and decreasing" class had a 23% decreased risk (HR: 0.77; 95% CI: 0.62–0.95) of hypertension. There was no significant association with PDI "low and increasing" class. Compared with the hPDI "low and stable" class, the hPDI "high and stable" class had a 24% decreased risk (HR: 0.76; 95%CI: 0.64–0.91). For uPDI trajectories, compared with the "low and decreasing" class, the "high and increasing," "high and stable," and "low and increasing" classes had increased risks of 43% (HR: 1.43; 95% CI: 1.06–1.94), 77% (HR: 1.77; 95% CI: 1.26–2.49), and 72% (HR: 1.72; 95% CI: 1.26–2.33), respectively.

**Conclusions** This study underscores the importance of maintaining high intakes of healthful plant-based diets and low intakes of unhealthful plant-based diets overtime for hypertension prevention.

**Keywords** Plant-based diet indices, Trajectories, Hypertension, China Health and Nutrition Survey, Cohort

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## Background

Hypertension is a higher-than-normal blood pressure that elevates the risk for cardiovascular diseases (CVD), which was the leading cause of mortality and accounted for roughly 70% of total deaths among the Chinese population [1]. While the accessibility of treatment for high blood pressure has increased over the past decades in China, the high prevalence of hypertension remains uncontrolled [2]. Although a growing body of literature has identified numerous risk factors for hypertension in this population [3, 4], there is a scarcity of longitudinal studies that explore modifiable risk factors, particularly those related to changes in dietary patterns.

Existing evidence implies that adherence to healthy diets, such as the Mediterranean diet (MD) and the Dietary Approaches to Stop Hypertension (DASH) diet, is related to reduced blood pressure and a lower risk of hypertension [5–7]. However, conflicting findings regarding the impact of these diets on hypertension exist, likely due to the differing food compositions and food cultures [7]. Diverging from the aforementioned diets, plant-based diets, which emphasize a higher intake of plant-based foods and a lower intake of all animal foods, are garnering more attention due to their benefits for both human health and the environment [8]. The variations in the quality of plant-based diets are captured by three versions of plant-based diet indices (PDIs): the overall plant-based diet index (PDI), the healthful plant-based diet index (hPDI), and the unhealthful plant-based diet index (uPDI) [9]. Research indicates that a higher hPDI or PDI is associated with a lower risk of CVD and all-cause mortality [10, 11]. Diets higher in healthful plant-based foods and lower in animal foods may also help prevent hypertension, as suggested by several longitudinal cohort studies investigating the relationships between different PDIs and hypertension [12–14]. Nevertheless, the results from these studies have not been consistent. For example, a previous study conducted in China supported the positive relationship between high adherence to PDI and hypertension incidence [12], which contradicts the findings in a South Korean population showing no association between PDI and hypertension [13]. One possible reason for these discrepancies is that these studies relied on either a single measurement of plant-based dietary intakes at baseline or a cumulative average of dietary intakes at different time points, potentially overlooking the influence of longitudinal and dynamic patterns, referred to as "trajectories", of dietary intakes on hypertension outcomes.

The robustness of implementing trajectory methods has been well-documented in the field of nutritional epidemiology, as longitudinal measurements of dietary exposure can reflect the developmental patterns and their associations with cardiovascular and metabolic health outcomes, thereby offering reliable intervention strategies [15–18]. For instance, a longitudinal study using trajectory method to capture nuanced changes in the diet quality trends over a ten-year period in Australia found that the "always healthy" trajectory was associated with lower risk of hypertension [17]. However, to the best of our knowledge, little is known about the trajectories of adherence to plant-based diets or PDIs and their links to hypertension risk, especially among Chinese adults. Since hypertension is one of the most modifiable risk factors for CVD and CVD mortality, developing more targeted interventions for managing blood pressure is crucial. Therefore, our study aimed to capture the complex and time-varying nature of plant-based dietary consumption over time by identifying trajectories of PDIs and examine their associations with the risk of hypertension.

## Methods

### Data source and study design

In this retrospective cohort study, we used data from the China Health and Nutrition Survey (CHNS), which is an ongoing open cohort project launched in 1989 and conducted in 1991, 1993, 1997, 2000, 2004, 2006, 2009, 2011, and 2015 [19]. The survey utilized a multistage, random cluster approach to collect sample from 12 different provinces and autonomous cities, representing nearly half of the Chinese population [4]. It aims to gather demographic, socioeconomic, health, and nutrition information to reflect the transitions of various aspects of life among the general Chinese population [12]. Further details of the CHNS were described elsewhere [20]. The Carolina Population Center at the University of North Carolina at Chapel Hill and the National Institute for Nutrition and Health at the Chinese Center for Disease Control and Prevention approved the study [12]. A written informed consent was obtained from all participants [12].

Given that the latest hypertension data are available only until 2015, and the enhanced version of the China Food Composition Table (FCT) was initially employed in 2004 to obtain nutrient values [21], we used all five rounds of CHNS data between 2004 and 2015 (2004, 2006, 2009, 2011, and 2015). Since the latest available dietary data available was up to 2011, we included four rounds of CHNS data (2004, 2006, 2009, and 2011) in the trajectory analysis. A total of 8589 participants with at least three rounds of complete dietary data between 2004 and 2011 were included (Supplemental Fig. 1). We excluded 1057 participants aged under 18 years and 3297 who had hypertension during the trajectory period. Of the 4235 remaining participants, we further excluded pregnant women, those with diabetes, myocardial infarction, stroke, and extreme total energy intake (≥8000 and ≤800 kcal/day for men; ≥ 6000 and ≤600 kcal/day for women) [4]. Additionally, we excluded 1162 participants with missing data on marital status, income, energy intake, smoking, drinking, and body mass index (BMI) (Supplemental Fig. 1).

### Dietary assessment and calculation of the PDIs

The CHNS utilizes a consecutive 3-day 24-hour diet recall method combined with household weighing method to collect dietary data and assess individual diet. The accuracy of the 24-hour dietary recall method has been validated by the literature [22]. A detailed description of dietary assessment has been provided elsewhere [23]. In short, at each survey round, each participant was asked by qualified interviewers to report the amounts and types of foods consumed on the day before the survey for three consecutive days, which were randomly allocated from Monday to Sunday [4]. We calculated the three-day average intake (g/day) of foods and nutrients for each participant in each survey round (2004, 2006, 2009, and 2011) using the FCT [21]. Since hypertension is believed to be associated with certain nutrient intakes [24–27], we calculated the intakes of sodium, potassium, magnesium, calcium, fiber, saturated fats, unsaturated fats, folic acid, vitamin B6, and vitamin B12 during the trajectory period. The methods of calculating PDI, hPDI, and uPDI have been documented previously [9]. Briefly, by referring to the food codes and descriptions in the FCT [21], as well as food group classification from prior research [12], we created 17 food groups according to their nutrient and culinary characteristics. These food groups were further classified into three larger categories: healthy plant foods (whole grains, fruits, vegetables, nuts, legumes, tea and coffee, vegetable oil), unhealthy plant foods (refined grains, potatoes, sugar-sweetened beverages, sweets and deserts, fermented foods), and animal foods (animal fat, dairy, eggs, fish, meat). The 17 food groups in our study aligned with previous research that considered the unique characteristics of Chinese plant-based diets [12]. Specifically, we modified Satija et al.'s original 18 food groups [9] by removing "miscellaneous animal-based foods" and "fruit juices" due to virtually no reported consumption, and adding "fermented food" to the list. Following the basic scoring methods described in previous studies [9–12], we divided each food group into quintiles of intakes and assigned integer scores ranging from 1 to 5. For PDI, all plant foods were scored positively, with the lowest quintile receiving a score of 1 and the highest quintile receiving a score of 5. Conversely, all animal foods received reverse scores, with the highest quintile receiving a score of 1 and the lowest quintile receiving a score of 5. Thus, a higher PDI score indicates a diet higher in plant foods and lower in animal foods. For hPDI, all healthy plant foods were scored positively, while all unhealthy plant foods and animal foods were scored reversely, meaning that a higher hPDI score indicates a diet higher in healthy plant foods and lower in unhealthy plant foods or animal foods. For uPDI, all unhealthy plant foods were scored positively, while all healthy plant foods and animal foods were scored reversely, so a higher uPDI score indicates a diet higher in unhealthy plant foods and lower in healthy plant or animal foods. The total score for each index was the sum of the scores across all 17 food groups, with potential values ranging from 17 to 85 [12].

### Baseline covariates

In line with the literature [2], the following confounders were included in the analysis due to their established association with hypertension: age, sex, urban or rural residence, marital status (married and others), education level (primary school and below, middle school, high school, college degree and above), income, physical activity (PA), drinking, smoking, daily energy intake, and body weight status. The information on these sociodemographic factors and lifestyle factors was obtained from the questionnaires at baseline. Individual income was categorized into three levels: ≤ 16,000 Chinese yuan (CNY), > 16,000 and <32,000 CNY, and ≥32,000 CNY based on annual income [28]. The total metabolic equivalents of tasks (METs) of PA were calculated according to the reported hours per week of activity across four domains: occupational, transportation, leisure, and domestic [29]. Smoking status was classified into three categories: former smoker, current smoker, and non-smoker. Drinking status was divided into two categories: participants who drank beer/liquor in the year before and those who did not. Anthropometric parameters, such as participants' height and weight, were measured using standard procedures without wearing shoes or heavy clothing [4]. Body Mass Index (BMI) ($kg/m^2$) was calculated by dividing weight in kilograms by the square of height in meters [4]. Body weight status was categorized based on cut-off points recommended by the literature: underweight ($BMI \leq 18.5$ $kg/m^2$), normal ($BMI > 18.5$ and $< 24$ $kg/m^2$), overweight ($BMI \geq 24$ and $< 28$ $kg/m^2$), and obese ($BMI \geq 28$ $kg/m^2$) [30, 31].

### Outcome assessment

The primary outcome of the study was new-onset hypertension. Participants' sedentary blood pressures were measured by qualified investigators using a mercury sphygmomanometer three consecutive times at each round. The mean of the three independent measurements of diastolic blood pressure (DBP) and systolic blood pressure (SBP) on the same arm was calculated respectively [4]. Participants were considered having hypertension if they met at least one of the following conditions: a mean DBP ≥ 90 mmHg and/or a mean SBP ≥ 140 mmHg, a self-reported diagnosis of hypertension, or a prescription for anti-hypertension drugs [4]. For those identified with new-onset hypertension, follow-up time was calculated from the entry year until the year of first diagnosis of hypertension. For those free of hypertension, follow-up time was calculated from the entry year to the year before loss to follow-up or the study end year in 2015.

### Statistical analysis

We used a group-based trajectory model (GBTM) to construct trajectories of PDIs. This model allowed us to capture longitudinal growth curves of unknown shape within each class of participants sharing similar traits of interest and following a similar developmental trajectory [32]. To determine the appropriate shape of trajectories, we evaluated both linear and quadratic growth parameters. To choose the optimal number of classes for each trajectory, we mainly used the following model fit indices as suggested by the literature [33]: the adjusted Bayesian Information Criterion (aBIC), the Lo-Mendell-Rubin Likelihood Ratio Test (LMR-LRT), and the average posterior probability (APP). A lower absolute value of aBIC indicates a better fit. The LMR-LRT was used to compare the goodness-of-fit between the model with k classes and the model with k+1 classes. A $P$-value $<0.05$ suggests that the model with k classes has a better goodness of fit [33]. Additionally, an APP $\geq 0.7$ indicates a more accurate classification. Furthermore, to ensure the robustness of our models, any model with a trajectory class constituting $<5\%$ of the total sample size was excluded [34]. Details of the model selection criteria are shown in Supplemental Table 1.

We summarized baseline characteristics and average nutrient intakes according to trajectory classes of PDI, hPDI, and uPDI. Between-group comparisons were examined using chi-square tests for categorical variables and either Student's t-tests or analysis of variance for continuous variables, as appropriate.

We used Cox proportional hazards models to estimate HRs and 95% CIs for new-onset hypertension in relation to the trajectory classes of PDIs. The proportional hazards assumption of the covariates was tested using Schoenfeld residuals. The test results show that the model satisfies the proportional hazards assumption ($P=0.06$). We adjusted the potential covariates in three different models: Model 1 adjusted for age and sex; Model 2 further adjusted marital status, urban residence, education, and income; Model 3 added adjustments for smoking, drinking, BMI, MET, and daily energy intake.

In addition, we conducted stratified analyses to explore the possible effect modifications of other major risk factors for hypertension. These included sex, baseline age (<45 vs. ≥45 years), urban residence (urban vs. rural), marital status (married vs. unmarried), smoking status (non-smokers vs. smokers), drinking status (non-drinkers vs. drinkers), body weight status (non-overweight [$<24$ kg/m$^2$] vs. overweight [$\geq 24$ kg/m$^2$]), and physical activity (MET < 25 h/wk [median] vs. MET ≥ 25 h/wk). $P$ values for interactions were obtained from the product term of the trajectory classes of PDIs and binary variable, which was added as an independent variable to the multivariable models.

Sensitivity analyses were conducted to examine the robustness of our results. We employed the multiple imputation of chained equations method to impute missing values for the covariates, with the number of imputations set to 20. We also used Cox proportional hazard analysis to examine the association between PDIs at baseline and the risk of hypertension. We repeated analyses to include participants with baseline history of chronic diseases, such as diabetes, myocardial infarction, stroke, and cancer. Furthermore, for participants with new-onset hypertension, follow-up time was recalculated using the midpoint date between the survey of the first hypertension diagnosis and the nearest preceding survey [4, 35].

All statistical analyses were conducted using the Mplus version 8.3 and R version 4.0.3. A two-sided $p<0.05$ was determined as statistical significance.

## Results

After applying a series of exclusion criteria (see Supplemental Fig. 1), a total of 2853 participants who had at least three rounds of complete dietary data were included in the cohort. In an average 9.6 ± 1.9 years of follow-up, we documented 624 new-onset hypertension. The GBTM models with three PDI trajectories, two hPDI trajectories, and four uPDI trajectories were identified as the best fit (Supplemental Table 1). According the shape and patterns of each trajectory, the three PDI trajectories were named as "low and increasing" ($n=859$, 30.1%), "high and decreasing" ($n=556$, 19.5%), and "low and stable" ($n=1438$, 50.4%), respectively. The two hPDI trajectory classes were named as "high and stable" ($n=1176$, 41.2%) and "low and stable" ($n=1677$, 58.8%), respectively. The four uPDI trajectories were named as "low and decreasing" ($n=347$, 12.2%), "high and decreasing" ($n=1231$, 43.1%), "high and stable" ($n=342$, 12.0%), and "low and increasing" ($n=933$, 32.7%), respectively (Fig. 1).

### PDI trajectory summaries

Compared to participants in the "low and stable" class, participants in the "high and decreasing" class were less likely to be urban residents; they were less likely to have college degree or higher education and a high income (≥32000 CNY/yr), and had higher MET and daily energy intake (Table 1). The "high and decreasing" class also had higher intakes of potassium, magnesium, calcium, fiber, unsaturated fats, folic acid, vitamin B6, and vitamin B12,

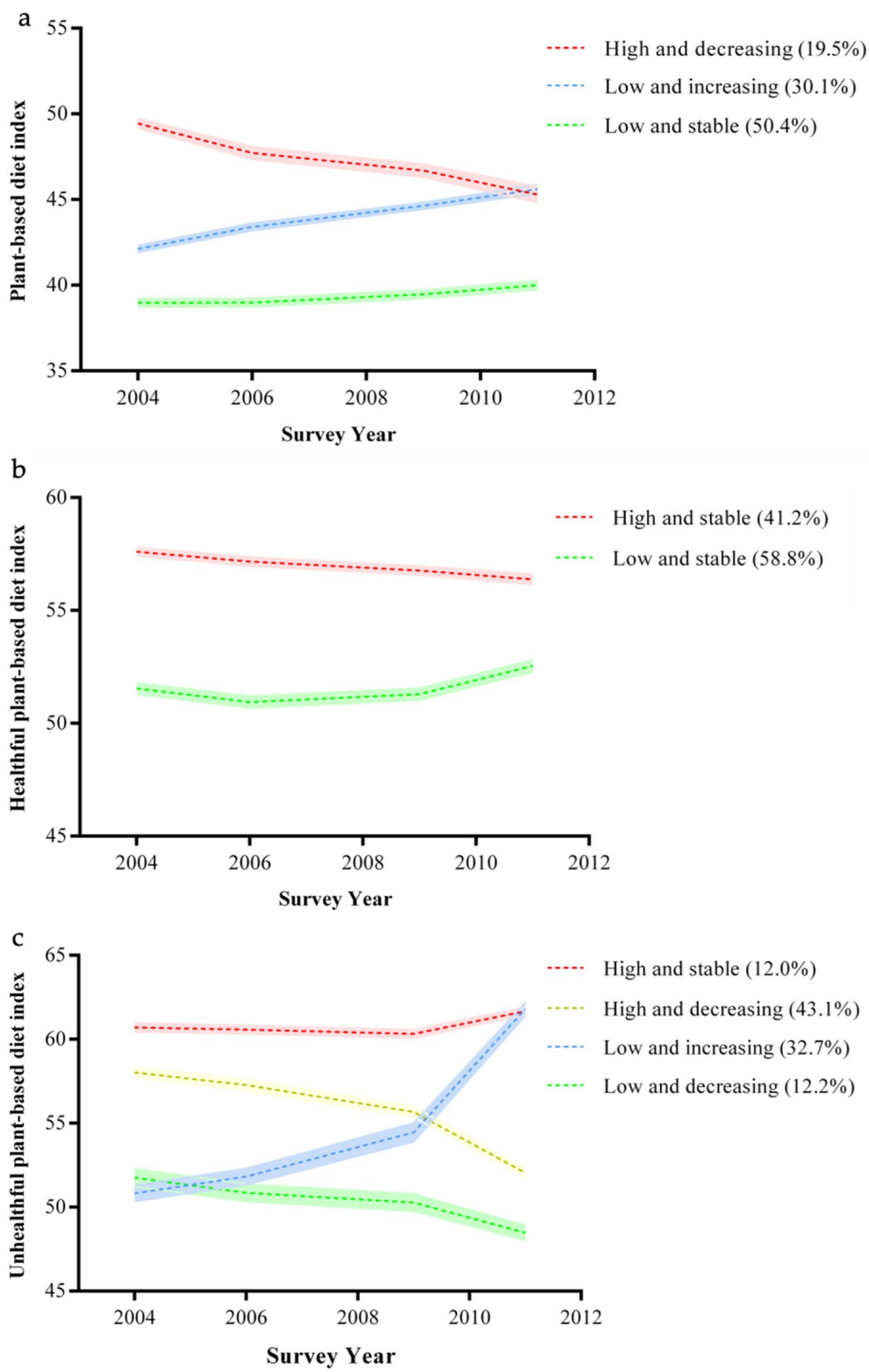


**Fig. 1** Mean and 95% confidence interval of (**a**) plant-based diet index, (**b**) healthy plant-based diet index, and (**c**) unhealthy plant-based diet index by trajectory classes in the China Health and Nutrition Study 2004–2015 cohort study

**Table 1** Baseline characteristics by different PDI trajectory classes in the China Health and Nutrition Study

| | Low and stable *n* = 1438 | Low and increasing *n* = 859 | High and decreasing *n* = 556 | *P* value |
|---|---|---|---|---|
| Men, *n* (%) | 622 (43.3) | 372 (43.3) | 255 (45.9) | 0.54 |
| Age, mean (SD), yr | 44.0 (11.4) | 43.4 (12.1) | 44.5 (10.9) | 0.29 |
| Urban residence, *n* (%) | 395 (27.5) | 334 (38.9) | 99 (17.8) | < 0.001 |
| Married, *n* (%) | 1302 (90.5) | 778 (90.6) | 518 (93.2) | 0.15 |
| Education, *n* (%) | | | | |
| Primary school and below | 622 (43.3) | 245 (28.5) | 302 (54.3) | < 0.001 |
| Middle school | 508 (35.3) | 306 (35.6) | 165 (29.7) | |
| High school | 174 (12.1) | 163 (19.0) | 51 (9.2) | |
| College degree and above | 134 (9.3) | 145 (16.9) | 38 (6.8) | |
| Income, *n* (%),CNY/yr | | | | |
| ≤ 16,000 | 1209 (84.1) | 622 (72.4) | 498 (89.6) | < 0.001 |
| 16,000 to 32,000 | 188 (13.1) | 191 (22.2) | 48 (8.6) | |
| ≥ 32,000 | 41 (2.9) | 46 (5.4) | 10 (1.8) | |
| Smoking status, *n* (%) | | | | |
| Non-smoker | 980 (68.2) | 621 (72.3) | 375 (67.4) | 0.11 |
| Former smoker | 30 (2.1) | 17 (2.0) | 7 (1.3) | |
| Current smoker | 428 (29.8) | 221 (25.7) | 174 (31.3) | |
| Drinking, *n* (%) | 460 (32.0) | 273 (31.8) | 180 (32.4) | 0.97 |
| Body weight status [a], *n* (%) | | | | |
| Underweight | 109 (7.6) | 67 (7.8) | 26 (4.7) | 0.29 |
| Normal | 938 (65.2) | 568 (66.1) | 375 (67.4) | |
| Overweight | 340 (23.6) | 200 (23.3) | 134 (24.1) | |
| Obese | 51 (3.5) | 24 (2.8) | 21 (3.8) | |
| MET, mean (SD), h/wk | 36.5 (42.1) | 27.2 (36.1) | 35.2 (34.9) | < 0.001 |
| Energy, mean (SD), kcal/d | 2269.0 (651.2) | 2156.4 (610.3) | 2472.0 (634.6) | 0.002 |

Data are presented as number of participants (%) or mean ± SD. To compare the differences between categorical and continuous variables, Chi-square and ANOVA were conducted, respectively

Abbreviations: PDI, plant-based diet index; SD, standard deviation; CNY/yr, Chinese yuan per year; MET, metabolic equivalents of tasks

[a] Body weight status was categorized based on cutoff points recommended by the literature: underweight (Body Mass Index [BMI] ≤ 18.5 kg/m$^2$), normal (BMI > 18.5 and < 24 kg/m$^2$), overweight (BMI ≥ 24 and < 28 kg/m$^2$), and obese (BMI ≥ 28 kg/m$^2$)

and lower intakes of sodium and saturated fats compared to the "low and stable" class (Supplemental Table 2).

We documented 168 (20.4%), 124 (22.3%), and 332 (24.3%) incidents of new-onset hypertension over average follow-up periods of 9.6 ± 2.0 years, 10.0 ± 1.7 years, and 9.5 ± 2.0 years for participants in the "low and increasing", "high and decreasing", and "low and stable" trajectories, respectively. The HRs (95% CI) of the association between PDI trajectories and hypertension risk are showed in Table 2. After adjusting for socioeconomic variables (urban/rural residence, education, income, and marital status), Model 2 shows that compared to those in the "low and stable" class, those in the "high and decreasing" class had a 20% decreased risk of hypertension (HR, 0.80; 95% CI, 0.65–0.99; $P = 0.04$). After further adjusting for lifestyle variables (smoking, drinking, BMI, MET, and energy intake), Model 3 shows that compared to those in the "low and stable" class, those in the "high and decreasing" class had a 23% decreased risk of hypertension (HR, 0.77; 95% CI, 0.62– 0.95; $P = 0.01$) (Table 2).

### hPDI trajectory summaries

Compared to participants in the "low and stable" class, those in the "high and stable" class were older and less likely to be urban residents; they were less likely to have college degree or higher education, a high income, and obesity; but had higher MET and daily energy intake (Supplemental Table 3). The "high and stable" class also had higher intakes of magnesium, fiber, unsaturated fats, folic acid, vitamin B6, and vitamin B12, and lower intakes of sodium and saturated fats compared to the "low and stable" class (Supplemental Table 4).

We documented 417 (25.7%) and 207 (18.4%) incidents of new-onset hypertension over average follow-up periods of 9.7 ± 1.9 years and 9.6 ± 2.0 years for participants in the "low and stable" and "high and stable" classes, respectively. All three models of Cox proportional hazard analysis show consistent and significant associations of hPDI trajectory classes with hypertension (Table 2). After adjusting for age and sex, model 2 shows that compared to those in the "low and stable" class, those in the "high and stable" class had a 20% decreased risk of hypertension (HR, 0.80; 95% CI, 0.67–0.96; $P = 0.02$). After

**Table 2** Hazard ratios (95% CI) for risk of hypertension per trajectory class of PDI, hPDI, and uPDI in the China Health and Nutrition Study 2004–2015 cohort study

| | Participants, *n* | Incidents rate [a] | Model 1 | | Model 2 | | Model 3 | |
|---|---|---|---|---|---|---|---|---|
| | | | HR (95%CI) | *P* value | HR (95%CI) | *P* value | HR (95%CI) | *P* value |
| **PDI trajectories** | | | | | | | | |
| Low and stable | 1438 | 24.3 | Reference | NA | Reference | NA | Reference | NA |
| Low and increasing | 859 | 20.4 | 0.86 (0.71, 1.03) | 0.10 | 0.90 (0.75, 1.09) | 0.27 | 0.92 (0.76, 1.12) | 0.42 |
| High and decreasing | 556 | 22.3 | 0.84 (0.68, 1.03) | 0.10 | 0.80 (0.65, 0.99) | 0.04 | 0.77 (0.62, 0.95) | 0.01 |
| **hPDI trajectories** | | | | | | | | |
| Low and stable | 1677 | 25.7 | Reference | NA | Reference | NA | Reference | NA |
| High and stable | 1176 | 18.4 | 0.75 (0.64, 0.89) | < 0.001 | 0.80 (0.67, 0.96) | 0.02 | 0.76 (0.64, 0.91) | 0.003 |
| **uPDI trajectories** | | | | | | | | |
| Low and decreasing | 347 | 15.3 | Reference | NA | Reference | NA | Reference | NA |
| High and decreasing | 1231 | 22.2 | 1.54 (1.15, 2.06) | 0.004 | 1.39 (1.03, 1.88) | 0.03 | 1.43 (1.06, 1.94) | 0.02 |
| High and stable | 342 | 27.8 | 1.77 (1.26, 2.48) | < 0.001 | 1.70 (1.21, 2.38) | 0.002 | 1.77 (1.26, 2.49) | < 0.001 |
| Low and increasing | 933 | 24.4 | 1.75 (1.30, 2.36) | < 0.001 | 1.61 (1.19, 2.18) | 0.002 | 1.72 (1.26, 2.33) | < 0.001 |

Results were obtained from cox regressions models; Model 1: adjusted for age and sex; Model 2: additionally adjusted for marital status, urban residence, education, and income; Model 3, further adjusted for smoking, drinking, BMI, MET, and daily energy intake

Abbreviations: PDI, plant-based diet index; hPDI, healthful plant-based diet index; uPDI, unhealthful plant-based diet index; HR, hazard ratios; CI, confidence interval

[a] Incident rate is reported as per 1000 person years

adjusting for all the other covariates, model 3 shows that compared to those in the "low and stable" class, those in the "high and stable" class had a 24% decreased risk of hypertension (HR, 0.76; 95% CI, 0.64–0.91; $P=0.003$) (Table 2).

### uPDI trajectory summaries

Compared to participants in the "low and decreasing" class, those in the other classes were less likely to be urban residents and non-smokers; they had less daily energy intake. Additionally, those in the "high and stable" class were more likely to be married; they were more likely to have college degree or higher education and a high income (Supplemental Table 5). The "high and stable" class also had lower intakes of potassium, magnesium, calcium, fiber, unsaturated fats, folic acid, vitamin B6, and vitamin B12, and higher intakes of sodium and saturated fats compared to the "low and decreasing" class (Supplemental Table 6).

We documented 54 (15.3%), 1231 (22.2%), 342 (27.8%), and 933 (24.4%) incidents of new-onset hypertension over average follow-up periods of 10.2±1.6 years, 9.6±1.9, 9.7±1.9, and 9.4±2.0 years for participants in the "low and decreasing," "high and decreasing," "high and stable," and "low and increasing" trajectories, respectively. All three models of Cox proportional hazard analysis show consistent and significant associations of uPDI trajectory classes with hypertension (Table 2). After adjusting for socioeconomic variables (urban/rural residence, education, income, and marital status) and lifestyle variables (smoking, drinking, BMI, MET, and energy intake), model 3 shows that compared to those in the "low and decreasing" class, those in the "high and decreasing," "high and stable," and "low and increasing" classes had increased risks of 43% (HR, 1.43; 95% CI, 1.06–1.94; $P=0.02$), 77% (HR, 1.77; 95% CI, 1.26, 2.49; $P<0.001$), and 72% (HR, 1.72; 95% CI 1.26, 2.33; $P<0.001$), respectively (Table 2).

### Stratified analyses and sensitivity analyses

The associations of PDI trajectory classes with the risk of hypertension remained consistent across all subgroups (Fig. 2).

The associations of hPDI trajectory classes with the risk of hypertension remained consistent across all subgroups except for sex, where the negative associations were more pronounced among women (Supplemental Fig. 2). The associations of uPDI trajectory classes with the risk of hypertension remained consistent across all subgroups (Supplemental Fig. 3).

The sensitivity analyses confirmed the robustness of our findings. Results remained consistent with the primary analyses after applying multiple imputations (Supplemental Table 7). The baseline measurements of PDI, hPDI, and uPDI showed no significant associations with the risk of hypertension, suggesting that trajectory might be a stronger indicator of the relationship between PDIs and hypertension (Supplemental Table 8). Including participants with baseline chronic diseases also yielded significant and robust reresults (Supplemental Table 9). Additionally, recalculating the follow-up time for those with new-onset hypertension using the midpoint date between the survey of the first hypertension diagnosis and the nearest preceding survey produced similar results (Supplemental Table 10).

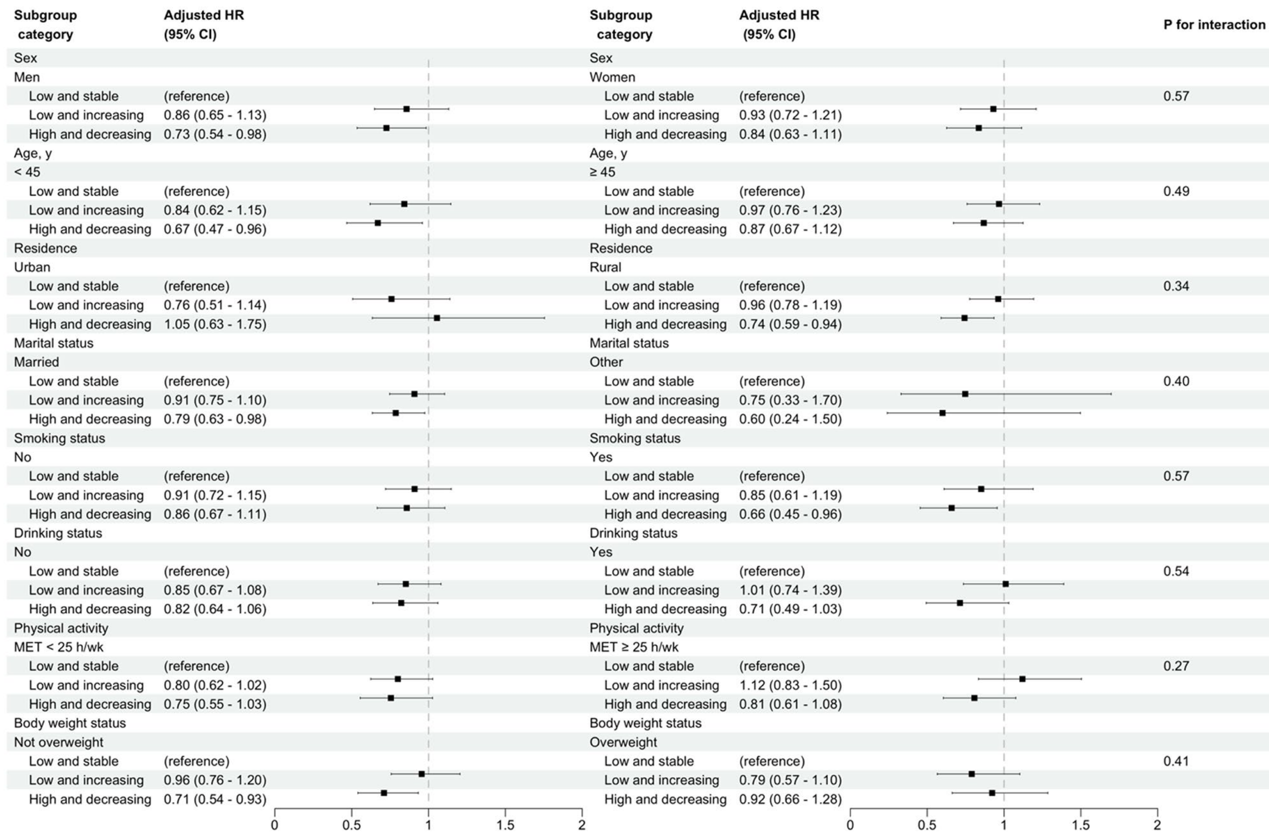


**Fig. 2** Stratified analyses by selected modifiers of the association between PDI trajectories and hypertension. Abbreviations: PDI, plant-based index; MET, metabolic equivalents of tasks; HR, hazard ratio; CI, confidence interval

## Discussion

In this retrospective cohort study of 2853 Chinese adults, we identified three PDI trajectories, two hPDI trajectories, and four uPDI trajectories. These trajectories captured variations in plant-based dietary patterns over time, revealing that the dynamic changing patterns of plant-based dietary intakes can influence the risk of new-onset hypertension over time.

We observed a lower risk of new-onset hypertension was particularly evident in the 19.5% of adults in the "high and decreasing" PDI trajectory and the 41.2% in the "high and stable" hPDI trajectory. Conversely, a higher risk was found in 43.2% of adults in the "high and decreasing," 12.0% in the "high and stable," and 32.7% in the "low and increasing" uPDI trajectories. Similarly, prior studies conducted in the US suggest that both PDI and hPDI are associated with reduced risk of CVD and CVD risk factors like hypertension [36, 37]. In line with our results, one cohort study in South Korea found a negative relationship between hPDI and risk of hypertension and a positive relationship between uPDI and risk of hypertension [13]. Another cohort study in China showed that PDI was inversely associated with the risk of three components of metabolic syndrome (MeS): hypertension, obesity, and diabetes [12]. Additionally, Kim et al.. revealed that uPDI was positively associated with most components of MeS, including hypertension [38]. Our findings enhance the literature by using a diverse cohort of participants free of hypertension during trajectory period to distinguish between different longitudinal patterns of plant-based diets and and to investigate new-onset hypertension incidents following the trajectory period. We demonstrated how the accumulation and variation in the quality of different plant-based diets are important for a comprehensive understanding of the risk of developing new-onset hypertension. Specifically, our results suggest that individuals following a "high and stable" hPDI trajectory or a "low and decreasing" uPDI trajectory experienced a lower hypertension risk, indicating the potential benefit of consistently high consumption of healthful plant-based foods and low consumption of unhealthy plant-based foods over time. Interestingly, our findings also demonstrate that compared to participants following a "low and stable" PDI trajectory, those following a "high and decreasing" trajectory experienced a lower risk of hypertension, whereas those following a "low and increasing" trajectory did not see a significant reduction in risk. One of the possible explanations is that by the end of trajectory period, the lowest average PDI score (approximately 45) of the "high and decreasing" group was still higher the highest PDI score of the "low and stable" group. This result aligns with the previous cohort study of Chinese adults [12], which showed a significant inverse linear association between the PDI score and hypertension risk –– a 50% reduced risk when the PDI score is above 40. Further study is needed to confirm these findings.

Our results for the associations between trajectories of PDIs and the risk of hypertension are biologically plausible when considering the nutrient profile of these dietary patterns. The "high and decreasing" PDI class has higher intake of minerals (potassium, calcium, magnesium), fiber, unsaturated fats, and B vitamins. Both the "high and decreasing" PDI class and the "high and stable" hPDI class had lower consumption of sodium and saturated fats. In contrast, the "high and stable" uPDI class had higher consumption of sodium and saturated fat and lower intakes of fiber, minerals, unsaturated fats, and B vitamins. Evidence suggests that higher intake of sodium leads to renal sodium retention, which results in elevated blood pressure [39]. Potassium, on the other hand, lowers blood pressure through inducing endothelium-dependent vasodilation [40] and reducing renal reabsorption of sodium to promote sodium excretion [25]. Furthermore, the intake of B vitamins—including folic acid, vitamin B6 and B12— has an inverse association with the risk of hypertension, likely due to their role in enhancing endothelial function [26]. Additionally, diets high in unsaturated fats and low in saturated fats have been shown to benefit blood pressure regulation [41], as chronic exposure to saturated fats could exacerbate endothelial damage, predisposing an individual to hypertension [42]. Taken together, maintaining a high consumption of a healthy plant-based diet while limiting unhealthy plant-based diet is crucial for preventing the onset of hypertension.

Furthermore, our stratified analysis reveals that the negative association between hPDI trajectories and the risk of hypertension was stronger in women. Although a clear reason for this has not been established, some evidence suggests that sex differences in hormonal regulation of blood pressure may influence the diet-disease relationship [13, 43]. For example, the release of estrogen induces endothelium-dependent vascular relaxation and the production of nitric oxide, a biomarker that relaxes endothelium of blood vessels and further improves blood pressure regulation [43].

To the best of our knowledge, our study is the first to use trajectory analysis to offer insights into the temporal relationship between plant-based diets and hypertension risk among Chinese adults. The GBTM approach takes into account the continuous changes of distinctive plant-based dietary patterns over time, setting our study apart from cross-sectional studies or other cohort studies based on a time-point exposure or a cumulative average of different time points, which may overlook the dynamic nature of changing diets and their impacts on heart health. The strengths of this study also lie in its relatively large and representative sample of the Chinese population and the careful control of multiple covariates. Furthermore, the subgroup and sensitivity analyses confirmed the robustness of our findings, enhancing the reliability of the findings. Importantly, results from our sensitivity analyses showed that, in contrast to single time-point assessments alone, which did not reveal any significant associations, trajectories of PDIs were significantly associated with hypertension risk.

Several limitations in this study should be considered. First, although we controlled for potential confounders, it is important to note that, as with all observational research, establishing causal evidence remains challenging due to the difficulty in eliminating all unobserved confounding variables. Second, despite the repeated collection of dietary data from an extensive dietary database, the 24-hour dietary recall method may not represent habitual dietary intakes of an individual. Additionally, the original CHNS dataset does not provide the exact date of new-onset hypertension, which makes it challenging to calculate the accurate follow-up time for partcipants. However, we addressed this issue through a sensitivity analysis by using the midpoint between the year of first diagnosis of hypertension and the nearest preceding year, which yielded similar results to those obtained using the regular method. Lastly, because the primary goal of this study was to delineate potential healthy patterns of consuming a plant-based diet for hypertension prevention in a diverse population of Chinese adults, generalizing the results to another cultural setting would require appropriate adjustments of the PDI scoring methods to match specific dietary habits.

## Conclusion

A reduced risk of new-onset hypertension was associated with maintaining high intakes of a healthful plant-based diet and low intakes of an unhealthful plant-based diet over time. The trajectories of PDIs identified in this retrospective cohort study could serve as a useful indicator, highlighting the long-term dynamic changes of plant-based dietary patterns and emphasizing the need for developing targeted dietary interventions for hypertension prevention. Further investigations in other populations are needed to confirm these findings.

### Abbreviations

BMI body mass index
CHNS China Health and Nutrition Survey
CI confidence interval
CNY Chinese yuan
CVD cardiovascular disease
hPDI healthful plant-based diet index

| | |
|---|---|
| HR | hazard ratio |
| MET | metabolic equivalents of tasks |
| PA | physical activity |
| PDI | overall plant-based diet index |
| PDIs | plant-based diet indices |
| Q | quintile |
| uPDI | unhealthful plant-based diet index |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12937-024-01053-w.

Supplementary Material 1

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**Author contributions**

YJZ: conceptualization, study design, literature search, data analysis, data interpretation, figure, and writing original draft; QG: methodology, review & editing; JYZ: writing-review & Editing; JPW: methodology, software, data analysis; TA: supervision; JKZ: conceptualization, study design, data collection, supervision, methodology, data analysis, review & editing; YJZ and JKZ accessed and verified the data. All authors have read and approved the final manuscript.

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**Data availability**

Data described in the manuscript are publicly and freely available without restriction at http://www.cpc.unc.edu/projects/china.

## Declarations

**Ethics approval and consent to participate**

The Carolina Population Center at the University of North Carolina at Chapel Hill and the National Institut for Nutrition and Health at the Chinese Center for Disease Control and Prevention approved the study. A written informed consent was obtained from all participants.

**Consent for publication**

consent to publish has been received from all participants.

**Competing interests**

The authors declare no competing interests.

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