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ORIGINAL ARTICLE

Development and Validation of Healthy and Unhealthy Plant-Based Diet Propensity Scores in European Children, Adolescents and Adults From the I.Family Study

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ABSTRACT

Introduction: Plant-based dietary patterns may reduce the risk of chronic diseases, but their benefits and risks in younger populations remain unclear due to variations in diet quality and nutrient adequacy. Robust tools to assess adherence to these patterns are essential. The aim of this study was to develop and validate three plant-based diet propensity (PBDP) scores – overall, healthy and unhealthy – to capture plant-based dietary patterns and assess their associations with nutrient intakes and health indicators in children, adolescents and adults.

Methods: This cross-sectional study of children, adolescents and adults used data from the I.Family study ($n = 15{,}780$ participants) from eight European countries. Dietary intake was assessed using a food frequency questionnaire. The overall PBDP score was constructed by categorising all plant-based food groups as positive and animal-based food groups as negative. The healthy PBDP emphasised healthy plant-based food groups, whereas the unhealthy PBDP emphasised less healthy plant-based food groups. Validity was assessed through correlations with nutrient intakes and comparison across demographic groups. Associations with health indicators were also analysed.

Results: PBDP scores showed expected associations with nutrient intakes. Higher overall and healthy PBDP scores were observed in females, adults, individuals with higher parental educational levels and those from Belgium and Spain. The healthy PBDP score was associated with higher HDL cholesterol, improved bone stiffness and lower triglycerides. The unhealthy PBDP score was associated with lower HDL cholesterol in adults, but not in children or adolescents.

Conclusion: PBDP scores describe plant-based dietary patterns across demographic groups and are valid and reliable in adults. The findings highlight challenges in assessing dietary patterns in children and adolescents. Future research should address these challenges to enhance the validity of PBDP scores in younger populations and further explore their potential in guiding dietary recommendations across all age groups.

1 | Introduction

Plant-based dietary patterns are characterised by including at least two-thirds of plant-based foods (e.g., fruits, vegetables, plant proteins, vegetable oils, nuts, seeds or grains), with a reduced consumption of animal-based food products, ideally accounting for one-third or less of the plate of a meal [1]. Unlike vegan dietary patterns, plant-based diets do not exclude animal products. Plant-based dietary patterns exist on a continuum, ranging from entirely plant-exclusive diets, such as veganism, to predominantly plant-focused diets that may include small or occasional amounts of animal-derived products, such as eggs, dairy, meat, fish or honey [1].

Several studies have indicated that diets emphasising plant-based foods may improve overall health [2–5]. They are associated with lower risk of cardiovascular disease [6], obesity [7] and type 2 diabetes [8]. During childhood, dietary patterns characterised by high intakes of fibre, fruits and vegetables are associated with a lower adulthood cardiovascular disease risk [9]. Previous research suggests that children who are vegan or vegetarian have a reduced risk of overweight or obesity and a healthier cardiovascular disease risk profile compared to children who are omnivorous [10, 11]. However, a recent study showed that children who follow a vegan diet and do not consume supplements of vitamins B12 and D may have lower bone mineral content, resulting in reduced height and micronutrient deficiencies such as vitamin B12, vitamin D and iron [11].

To date, two primary plant-based dietary scores have been developed: the Planetary Health Diet Index, based on the Eat Lancet recommendations [12], and the plant-based diet scores developed by Satija et al. [13], which distinguish between healthy and unhealthy plant-based dietary patterns. Although these scores have been established for adults, challenges remain in developing and validating similar scores for children and adolescents. Previous research has highlighted the importance of understanding these dietary patterns in younger populations, as evidenced by studies that showed associations between plant-based dietary patterns and obesity outcomes in adolescents [14] and adults [15]. Moreover, whereas previous studies have shown beneficial associations between plant-based dietary patterns and cardiometabolic outcomes, to our knowledge, no previous studies have assessed the impact of these dietary patterns on bone health in children, adolescents or adults.

To our knowledge, plant-based diet scores have not yet been developed and validated for children and adolescents. In this study, we constructed and validated three plant-based diet propensity (PBDP) scores – overall, healthy and unhealthy – from a food frequency questionnaire (FFQ), to estimate the different plant-based dietary patterns of children, adolescents and adults from the European multi-centre I.Family Study.

2 | Material and Methods

2.1 | Study Population

The data for this study were derived from the I.Family study, aimed at investigating eating habits and lifestyle factors in children, adolescents and their parents [16]. Conducted between 2013 and 2014, the I.Family study involved eight European countries: Belgium, Cyprus, Estonia, Germany, Hungary, Italy, Spain and Sweden.

The I.Family study sought to re-examine a subset of the original IDEFICS study, comprising 7117 children who had taken part in either the baseline survey or the first follow-up. Additionally, to enable a comprehensive examination of familial influences, 2501 siblings were newly recruited for the subsequent I.Family follow-up, conducted 4–6 years later. The study also aimed to include at least one parent from each participating family, resulting in a total sample of 17,600 participating children and parents. For this study, we included all participants providing at least half of the FFQ responses ($n = 15{,}780$).

Ethics approval was obtained from the research ethics committees in each country, and all study measures were conducted adhering to the ethics principles outlined in the Declaration of Helsinki in 1964. Written consent was obtained from all parents and children aged 12 years and older for examinations, sample collection, subsequent analyses and storage of personal data and collected samples, whereas younger children provided oral consent directly before their participation in the examinations.

2.2 | Dietary Assessment and Construction of the PBDP Scores

Food and beverage consumption was assessed using an adapted 59-item FFQ based on the validated and reproducibility-tested FFQ [17, 18]. Parents or legal guardians completed the FFQs for themselves and for their children under 12 years of age. Adolescents aged 12 years or older also self-reported their dietary intake using the FFQ. Participants were asked to select the option that best described their own and their children's dietary intake over the preceding 4 weeks, with adolescents also self-reporting their dietary habits during the same period. Response options were as follows: 'never/less than once a week', '1–3 times a week', '4–6 times a week', '1 time per day', '2 times per day', '3 times per day' and '4 or more times per day'.

To assess adherence to plant-based dietary patterns, three PBDP scores – overall, healthy and unhealthy – were developed for our study, adapting the approach described by Satija et al. [13]. We derived 16 food groups based on the 59-item FFQ, encompassing both plant- and animal-based food categories; see

Summary

- The PBDP scores effectively captured plant-based dietary patterns across different socio-demographic groups and showed associations with nutrient intakes in the expected direction.
- The healthy PBDP score in adults was associated with improved cardiometabolic health and bone stiffness. However, these associations were not observed in children and adolescents.

Table 1 for more details. For the overall PBDP score, we categorised as positive the healthy plant-based food groups: whole grains, fruits, vegetables, nuts, vegetable oils and tea and coffee. Less healthy plant-based food groups such as refined grains, snacks (e.g., fried potatoes or crisps), sugar-sweetened beverages and sweets and desserts were also categorised as positive. Animal-based food groups such as animal fat, dairy, egg, fish, meat and miscellaneous were categorised as negative. The overall PBDP score, therefore, includes all plant-based food groups, regardless of their healthiness. For the healthy PBDP score, only healthy plant-based food groups were categorised as positive, whereas for the unhealthy PBDP score, only less healthy plant-based food groups were categorised as positive. The remaining food groups were categorised as negative. Table 1 provides additional details on the different PBDP scores.

In this study, we utilise propensity scores to provide a comprehensive understanding of dietary patterns while controlling for energy intake. The rationale for using propensity scores was because we wanted to assess the usual dietary patterns in a semi-quantitative manner, while mitigating the potential confounding effect of energy intake [18]. Propensity scores were defined based on the frequency of consuming specific food groups relative to the total frequencies reported by each individual in the FFQs. Although the definition of plant-based diets often considers the proportions of plant-based foods on a plate or meal, our study uses frequency of consumption to capture habitual dietary intake patterns over time. This frequency-based approach allowed us to capture how often participants consumed various food groups, aligning with the proportion-based definition by emphasising the regular intake of plant-based foods and reduced consumption of animal-based products. By doing so, we were able to examine dietary patterns in a manner that accounts for individual differences in overall food consumption, thus avoiding potential biases associated with energy intake variations and capturing a more general understanding of dietary quality [18]. The use of propensity scores to characterise dietary habits in children has been previously adopted in the IDEFICS study, where they were found to better capture eating habits and show strong correlations with nutrient intakes reported in 24-h dietary recalls (24-HDR) [19].

The propensity to consume these food categories was determined by dividing the weekly frequency of each food group by the total frequency of all food groups. The overall PBDP score was calculated as the weekly consumption frequency of whole grains, fruits, vegetables, nuts, vegetable oils, tea and coffee, refined grains, snacks, sugar-sweetened beverages and sweets and desserts, divided by the total frequency of all food groups assessed in the FFQ. The healthy PBDP score represented the weekly frequency of whole grains, fruits, vegetables, nuts, vegetable oils and tea and coffee, divided by the total frequency of all food groups assessed in the FFQ. Conversely, the unhealthy PBDP score reflected the weekly consumption of refined grains, snacks, sugar-sweetened beverages and sweets and desserts, divided by the total frequency of all foods assessed in the FFQ (Table 1).

In this study, the food group labelled as vegetables also included legumes and cooked potatoes, whereas the food group labelled sugar-sweetened beverages was expanded to include fruit juices. We included honey in the sweets and desserts food group following the original scoring system developed by Satija et al. [13]. This decision was made to maintain consistency with the scoring methodology used in the reference study. Although honey is derived from animals, it is commonly categorised as a sweetener and used in dessert recipes, aligning with its inclusion in this food group for dietary assessment purposes.

To accommodate the limited scope of our FFQ and to better reflect our variety of snack options, we created a broader group called snacks, which includes items such as popcorn and crisps (both potato and non-potato), instead of following the original score, which included a separate group for potatoes. Consequently, we included boiled potatoes in the vegetables group, as mentioned above, and categorised fried potatoes and potato croquettes into the newly created snacks group. This decision was made to ensure that our scores encompassed a variety of snack options, not just potatoes. This decision was made independently of the miscellaneous food group, as snacks and miscellaneous items represent distinct food groups in our classification. Additionally, the food group labelled as animal foods included margarine, as our FFQ inquired about the consumption of both butter and margarine simultaneously. Furthermore, the category of miscellaneous items included certain plant-based products such as falafel, as our FFQ inquired about the consumption of this product alongside other animal-based food products.

2.3 | Assessment of 24 h Recalls and National Cancer Institute Correction

Dietary intake was also assessed using the 24-HDR method conducted through the computer-based assessment tool SACANA (Self-Administered Children, Adolescent and Adult Nutrition Assessment) [20, 21]. This tool provides complementary information to the FFQ, which contained 59 items comparable to those in the SACANA web tool, ensuring consistency and comparability between assessment methods [22, 23].

Furthermore, we applied the National Cancer Institute (NCI) method [24] to calculate individual usual nutrient intakes. This method incorporates information from FFQs and 24-HDRs, accounts for differences in intake between weekdays and weekend days and corrects for variance caused by daily dietary changes. The analyses were stratified by sex and adjusted for age.

TABLE 1 | Overview of the development of the plant-based diet propensity (PBDP) scores.

Food groups	Food items	Categorisation		
		Overall PBDP score	Healthy PBDP score	Unhealthy PBDP score
Healthy				
Whole grains	Porridge, oatmeal, gruel, cereals and muesli (unsweetened), whole-meal bread, dark roll, dark crispbread, whole-meal pasta, noodles, brown rice and other cereals unrefined	Positive categorisation	Positive categorisation	Negative categorisation
Fruits	Fruits without added sugars	Positive categorisation	Positive categorisation	Negative categorisation
Vegetables	Cooked vegetables, boiled potatoes, beans, raw vegetables, legumes, meat replacement products (tofu, tempe, quorn, soy milk)	Positive categorisation	Positive categorisation	Negative categorisation
Nuts	Nuts, seeds, dried fruits	Positive categorisation	Positive categorisation	Negative categorisation
Vegetable oils	Olive oil	Positive categorisation	Positive categorisation	Negative categorisation
Tea and coffee	Coffee and tea unsweetened	Positive categorisation	Positive categorisation	Negative categorisation
Less healthy				
Refined grains	Breakfast cereals, muesli, sweetened cereals, white bread, white roll, white crispbread, pasta, noodles, rice, dish or milled cereals	Positive categorisation	Negative categorisation	Positive categorisation
Snacks	Fried potatoes, potato croquettes, ketchup, crisps, corn crisps, popcorn	Positive categorisation	Negative categorisation	Positive categorisation
Sugar-sweetened beverages	Fruit juices, sugar-sweetened drinks not carbonated, carbonated sugar-sweetened drinks, diet drinks, artificially sweetened drinks not carbonated, sweetened coffee and tea	Positive categorisation	Negative categorisation	Positive categorisation
Sweets and desserts	Fruits with added sugars, jam, honey, chocolate or nut-based spread, chocolate, candy bars, candies, loose candies, marshmallows, biscuits, packaged cakes, pastries, puddings	Positive categorisation	Negative categorisation	Positive categorisation
Animal food groups				
Animal fat	Butter or margarine, reduced-fat products on bread	Negative categorisation	Negative categorisation	Negative categorisation
Dairy	Plain unsweetened milk, sweetened milk, milky desserts, plain unsweetened yoghurt or kefir, sweet yoghurt, fermented milk, sliced cheese, spreadable cheese, grated cheese, fat-reduced cheese	Negative categorisation	Negative categorisation	Negative categorisation
Egg	Fried, scrambled, boiled or poached eggs	Negative categorisation	Negative categorisation	Negative categorisation
Fish or seafood	Boiled, grilled, oven-baked or raw not fried fish, fried and/or coated fish, canned fish	Negative categorisation	Negative categorisation	Negative categorisation

(Continues)

TABLE 1 | (Continued)

Food groups	Food items	Categorisation		
		Overall PBDP score	Healthy PBDP score	Unhealthy PBDP score
Meat	Cold cuts and preserved, ready to cook meat product, fresh meat not fried, fried meat, fresh meat, not fried poultry (cooked), fried poultry	Negative categorisation	Negative categorisation	Negative categorisation
Miscellaneous	Mayonnaise, mayonnaise-based products, pizza as main dish, hamburger, hot dog, kebab, wrap, falafel, savoury pastries, fritters, ice cream, milk or fruit-based bars	Negative categorisation	Negative categorisation	Negative categorisation

2.4 | Assessment of Health Indicators

Height and weight were measured to calculate body mass index (BMI, kg/m^2), whereas waist circumference (WC) was measured midway between the lowest rib and the iliac crest. In children and adolescents, BMI *z*-scores specific to age and sex were calculated using the Cole and Lobstein [25] methodology, and WC *z*-scores were based on IDEFICS reference values [26].

Blood pressure measurements, including both systolic and diastolic readings, were conducted using standardised procedures with two readings taken, spaced 2 min apart, using an automatic sphygmomanometer.

Blood samples were collected to assess several metabolic parameters, including HDL cholesterol, triglycerides, fasting glucose and plasma insulin concentrations. Insulin resistance in children and adolescents was evaluated using the homoeostasis model assessment (HOMA-IR), which is derived from fasting glucose and plasma insulin concentrations [27]. Metabolic syndrome (MetS) in children and adolescents was assessed by combining various parameters, including HOMA-IR, WC, blood pressure, HDL cholesterol and triglycerides, utilising the continuous score proposed by Ahrens et al. [28] for the baseline study IDEFICS. For some individuals, HOMA-IR was collected under non-fasting conditions in this study.

The bone stiffness index was assessed by quantitative ultrasound on both the left and right calcaneus. Further details can be found elsewhere [29].

2.5 | Assessment of Covariates

Parental education levels were determined based on the International Standard Classification of Education (ISCED) [30], reported by one of the parents by questionnaire. The highest ISCED level attained by both parents was computed. ISCED categories encompassed low (levels 1–2), medium (levels 3–4) and high (levels 5–6) educational backgrounds. The reported parental educational level serves as a proxy for socioeconomic status within the entire family unit, encompassing the adults who participated in the study as well as their children and adolescents.

2.6 | Statistical Analyses

Mean and standard deviations (SD) were calculated for the PBDP scores and food group propensities, followed by quintile division for construct validity assessment. Pearson's partial correlations, adjusted for age, sex, country and parental education level, were used to determine the relationship between nutrient intakes from 24-HDR and PBDP scores.

Concurrent criterion validity was examined by calculating means and SDs across sex, age, parental education level and country, with *t*-tests and ANOVA for normally distributed variables and Mann–Whitney *U* and Kruskal–Wallis tests for non-normally distributed variables. Predictive validity was

assessed through linear regression analyses of PBDP scores and health indicators, adjusted for age, sex, country and parental education level.

Principal component analysis (PCA) was used to determine the dimensions of PBDP scores. Reliability was assessed using Cronbach's alpha, measuring consistency among the 16 food group components. Pearson's correlation coefficients were computed to examine relationships between food groups within PBDP scores, excluding the specified group to identify influential propensities.

Descriptive analyses, correlations, regressions, PCA and Cronbach's alpha calculations were conducted using Stata 17.0. Correlation heatmaps were generated using R-studio, and nutrient intake corrections were performed using SAS 9.3. Family clustering effects were accounted for using survey methods with cluster variance estimators. A false discovery rate (FDR) correction at $q = 0.05$ was applied, with p-values < 0.03 (FDR-adjusted $p < 0.05$) considered significant.

3 | Results

3.1 | Construct Validity

The mean total values of PBDP scores were $56.4 \pm 11.8\%$ for the overall score, 27.9 ± 13.8 for the healthy score and $28.5 \pm 12.1\%$ for the unhealthy score (Table 2). Among the mean total values of food groups, individuals showed a higher consumption of dairy per week ($24.8 \pm 11.4\%$) compared to nuts ($1.3 \pm 2.1\%$) and eggs ($1.5 \pm 1.6\%$), indicating a higher proportion of dairy in their diet and lower proportion of nuts and eggs. PBDP scores categorised by quintiles (Table S1) ranged from $39.4 \pm 6.6\%$ to $72.2 \pm 5.2\%$ for the overall PBDP score, from $10.9 \pm 3.6\%$ to $49.2 \pm 8.2\%$ for the healthy PBDP score and from $12.0 \pm 4.4\%$ to $46.0 \pm 6.6\%$ for the unhealthy PBDP score (Table 1). Moreover, all food group propensities showed a substantial range from the 1st quintile to the 5th quintile in the expected direction based on their categorisation criteria (Table S1).

Figure 1 and Table S2 show the correlations between PBDP scores and nutrient intakes, with the most pronounced associations observed in the adult age group. The overall PBDP score showed associations with several nutrient intakes on analysing the whole sample. It showed positive correlations with carbohydrates, fibre, folate, vitamin C, potassium, magnesium, iron and sugar, while displaying inverse correlations with fat, protein, riboflavin, sodium, calcium, phosphorus, zinc, saturated fatty acids, monounsaturated fatty acids and cholesterol. On analysing by age group, similar correlations were observed; however, in adolescents, no negative correlations between the overall PBDP score and nutrient intakes were observed.

Similar results were observed for the healthy PBDP score and nutrient intakes with positive correlations for fibre, folate, vitamin C, potassium, magnesium and iron. However, reversed correlations were shown for carbohydrates and sugar compared to the overall PBDP score. Inverse correlations were also observed for energy, fat, protein, sodium, starch and saturated fatty acids. Additionally, on analysing correlations between the healthy PBDP score and nutrient intakes by age groups, children only showed positive correlations for sugar intake, whereas adolescents showed positive correlations for energy intake and sugar.

The unhealthy PBDP score showed correlations in the expected direction, with positive correlations for energy, carbohydrates, sugar and saturated fatty acids and negative correlations for fibre, riboflavin, folate, vitamin C, potassium, calcium, magnesium, phosphorus and zinc. Additionally, children also showed inverse associations for retinol and cholesterol. However, adolescents did not show any significant negative correlation between the unhealthy PBDP score and nutrient intakes.

3.2 | Concurrent Criterion Validity

PBDP scores and food groups differed by sex, age group, parental educational level and country (Tables 3, 4, S3 and S4). Overall, females showed higher overall PBDP scores ($57.2 \pm 11.7\%$) and higher healthy PBDP scores ($29.9 \pm 14.3\%$) compared to males. Conversely, males showed higher unhealthy PBDP scores ($30.1 \pm 11.6\%$) compared to females.

Adults also showed higher overall PBDP scores ($59.8 \pm 11.0\%$) and healthy PBDP scores ($34.1 \pm 14.7\%$) compared to children and adolescents. Children showed a higher consumption of meat and adults and adolescents showed a higher consumption of sugar-sweetened beverages (Table S3).

Furthermore, individuals with higher parental education levels had higher overall PBDP scores ($56.8 \pm 11.2\%$) and healthy PBDP scores ($30.0 \pm 13.8\%$) compared to those with lower and medium parental education levels (Table 3). However, individuals with lower parental education levels showed slightly higher consumption of vegetable oil (Table S3).

We also observed significant differences in PBDP scores by country (Table 4). Higher overall PBDP scores were observed in individuals from Cyprus ($58.4 \pm 12.0\%$), Belgium ($59.4 \pm 10.2\%$) and Spain ($58.3 \pm 10.9\%$). For the healthy PBDP scores, Belgium ($30.4 \pm 13.4\%$) Spain ($31.5 \pm 12.2\%$), and Sweden ($32.8 \pm 13.6\%$) were particularly high. Although individuals with the high healthy PBDP scores consumed healthier PB food groups, differences were observed. Individuals from Southern countries (Italy, Cyprus, and Spain) had lower whole grains, but higher vegetable oil consumption compared to individuals from Central and Northern European countries (Table S4).

Despite high overall and healthy PBDP scores in Belgium and Spain, meat consumption remained high. Individuals from Italy ($30.1 \pm 12.5\%$), Germany ($30.7 \pm 12.8\%$) and Hungary ($31.6 \pm 12.0\%$) had the highest unhealthy PBDP scores (Table 4). Individuals from Germany and Hungary had higher sugar-sweetened beverage consumption, whereas individuals from Italy had higher refined grain consumption (Table S4).

3.3 | Predictive Validity

Additionally, we assessed associations between the PBDP scores and health indicators in children and adolescents (Table S5)

TABLE 2 | Estimated mean and standard deviations of plant-based diet propensity scores and food group by quintiles of overall, healthy and unhealthy PBDP scores.

	Mean	Q1	Q2	Q3	Q4	Q5
N	15,780	3158	3164	3147	3156	3155
Overall PBDP score (%), mean (SD)	56.4 (11.8)	39.4 (6.6)	50.7 (2.1)	56.9 (1.6)	62.7 (1.9)	72.2 (5.2)
Healthy PBDP score (%), mean (SD)	27.9 (13.8)	10.9 (3.6)	19.3 (1.9)	25.8 (2.0)	34.0 (2.8)	49.2 (8.2)
Unhealthy PBDP score (%), mean (SD)	28.5 (12.1)	12.0 (4.4)	21.8 (2.1)	28.3 (1.8)	34.7 (2.0)	46.0 (6.6)

Abbreviations: %, percentage of weekly consumption frequency; PBDP, plant-based diet propensity; Q, quintile; SD, standard deviation.

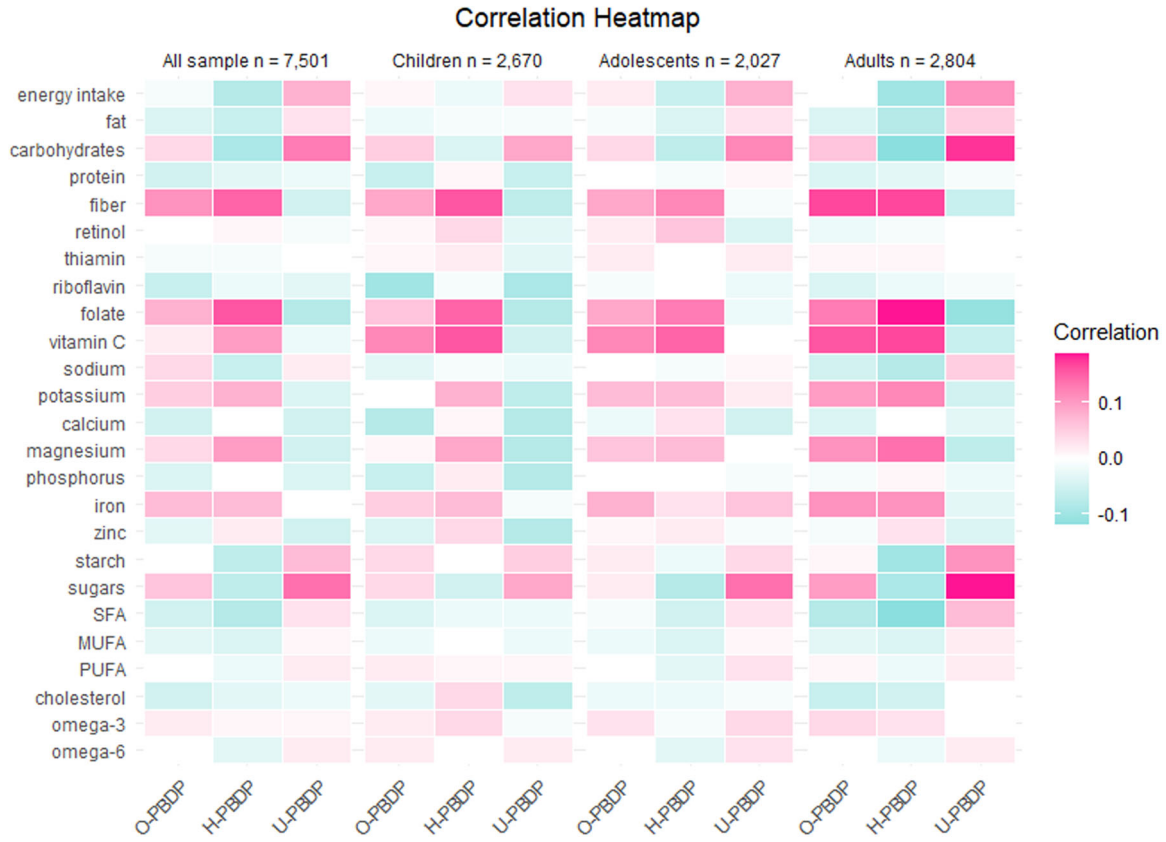

FIGURE 1 | Heatmap of Pearson partial correlations between the PBDP scores and nutrient intakes. Correlations were adjusted for age, sex, country and parental education. H, healthy; MUFA, monounsaturated fatty acids; O, overall; PBDP, plant-based diet propensity; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids; U, unhealthy.

TABLE 3 | Estimated mean and standard deviations of plant-based diet propensity scores and food groups by sex, age group and parental education.

	Sex		Age group			Parental education		
	Males	Females	Children	Adolescents	Adults	Low	Medium	High
N	6834	8946	5061	3653	7066	739	6594	7866
Overall PBDP score (%), mean (SD)	55.3 (11.8)	57.2 (11.7)*	55.1 (10.2)	51.6 (13.1)	59.8 (11.0)*	55.9 (14.5)	55.9 (12.1)	56.8 (11.2)*
Healthy PBDP score (%), mean (SD)	25.2 (12.7)	29.9 (14.3)*	23.7 (10.5)	21.6 (10.9)	34.1 (14.7)*	24.7 (13.5)	25.7 (13.5)	30.0 (13.8)*
Unhealthy PBDP score (%), mean (SD)	30.1 (11.6)	27.3 (12.4)*	31.4 (10.7)	30.0 (11.6)	25.7 (12.7)*	31.2 (12.9)	30.3 (12.4)	26.7 (11.6)*

Note: Differences by sex were determined using *t*-tests and Mann–Whitney *U* tests; differences by age group and parental education were determined using ANOVA and Kruskal–Wallis tests. Significance levels were indicated by $p < 0.03$ (*).
Abbreviations: %, percentage of weekly consumption frequency; PBDP, plant-based diet propensity; SD, standard deviation

TABLE 4 | Estimated mean and standard deviations of plant-based diet propensity scores and food groups by country.

	Italy	Estonia	Cyprus	Belgium	Sweden	Germany	Hungary	Spain	*p*-value
N	2729	2342	3408	497	1400	2152	2305	947	
Overall PBDP score (%), mean (SD)	54.4 (13.6)	55.7 (10.7)	58.4 (12.0)	59.4 (10.2)	52.9 (10.7)	56.2 (11.3)	53.7 (11.3)	58.3 (10.9)	< 0.001
Healthy PBDP score (%), mean (SD)	27.3 (13.8)	29.5 (12.4)	29.1 (15.1)	30.4 (13.4)	32.8 (13.6)	25.5 (13.2)	22.1 (12.1)	31.5 (12.2)	< 0.001
Unhealthy PBDP score (%), mean (SD)	30.1 (12.5)	26.2 (10.5)	29.2 (11.9)	29.0 (12.7)	20.1 (10.3)	30.7 (12.8)	31.6 (12.0)	26.8 (9.5)	< 0.001
Whole grains (%), mean (SD)	2.4 (3.8)	6.7 (4.2)	2.9 (4.0)	6.4 (5.1)	6.1 (4.6)	4.1 (3.7)	3.5 (4.0)	2.6 (3.6)	< 0.001
Fruits (%), mean (SD)	5.6 (5.3)	5.0 (3.9)	5.7 (4.9)	3.5 (4.4)	5.3 (4.4)	4.6 (4.0)	4.4 (3.9)	6.7 (4.8)	< 0.001
Vegetables (%), mean (SD)	9.2 (6.5)	9.0 (5.0)	9.5 (5.8)	13.0 (5.2)	10.8 (6.1)	8.6 (5.1)	8.3 (5.0)	9.9 (5.2)	< 0.001
Nuts (%), mean (SD)	0.6 (1.4)	1.8 (2.5)	1.4 (2.2)	0.9 (2.0)	1.4 (2.2)	0.9 (1.6)	1.7 (2.3)	1.4 (1.9)	< 0.001
Vegetable oils (%), mean (SD)	6.8 (5.7)	3.3 (2.6)	4.4 (3.8)	2.4 (2.7)	2.3 (2.5)	1.8 (2.2)	1.2 (1.9)	9.0 (5.7)	< 0.001
Tea and coffee (%), mean (SD)	2.7 (6.0)	3.6 (6.4)	5.2 (8.3)	4.1 (7.8)	6.9 (9.0)	5.5 (8.5)	3.2 (5.6)	3.2 (5.6)	< 0.001
Refined grains (%), mean (SD)	10.4 (6.9)	6.8 (4.3)	10.5 (6.2)	6.0 (4.9)	7.0 (4.7)	6.5 (4.4)	9.2 (5.9)	10.1 (6.2)	< 0.001
Snacks (%), mean (SD)	2.3 (2.7)	2.7 (2.7)	2.9 (2.7)	3.2 (2.5)	2.7 (2.3)	2.5 (2.3)	2.6 (2.4)	2.5 (2.2)	< 0.001
Sugar-sweetened beverages (%), mean (SD)	9.6 (9.2)	9.4 (7.0)	8.5 (8.2)	8.1 (7.9)	5.2 (5.7)	12.6 (10.2)	12.6 (9.4)	7.4 (6.8)	< 0.001
Sweets and desserts (%), mean (SD)	7.8 (6.4)	7.3 (4.7)	7.3 (5.3)	11.6 (6.9)	5.1 (3.8)	9.2 (5.8)	7.1 (4.6)	6.8 (5.0)	< 0.001
Animal fat, %, mean (SD)	0.27 (1.0)	4.1 (3.6)	3.3 (3.3)	3.1 (4.0)	6.6 (4.2)	5.7 (4.9)	5.5 (4.4)	1.0 (1.7)	< 0.001
Dairy (%), mean (SD)	25.9 (13.1)	25.4 (11.4)	23.9 (10.8)	22.6 (9.9)	25.8 (10.7)	23.9 (11.1)	25.4 (11.2)	23.1 (9.7)	< 0.001
Egg (%), mean (SD)	1.2 (1.5)	1.8 (1.8)	1.2 (1.5)	0.9 (1.3)	1.6 (2.1)	1.6 (1.7)	1.6 (1.6)	2.0 (1.3)	< 0.001
Fish (%), mean (SD)	3.1 (2.6)	1.8 (1.9)	2.3 (2.4)	1.6 (1.6)	2.4 (1.6)	1.4 (1.8)	1.4 (1.9)	3.8 (1.9)	< 0.001
Meat (%), mean (SD)	8.6 (5.1)	8.0 (4.3)	7.6 (4.6)	9.9 (5.6)	8.7 (4.4)	8.8 (5.4)	9.1 (4.5)	9.3 (4.3)	< 0.001
Miscellaneous (%), mean (SD)	3.6 (3.5)	3.2 (2.6)	3.3 (3.1)	2.5 (2.5)	1.9 (2.0)	2.4 (2.6)	3.3 (2.8)	2.5 (2.5)	< 0.001

Note: Differences by country were determined using ANOVA and Kruskal–Wallis tests.
Abbreviations: %, percentage of weekly consumption frequency PBDP, plant-based diet propensity; SD, standard deviation.

and adults (Table S6). Both children and adolescents showed associations between PBDP scores and anthropometric measures, although with negligible effect sizes. In children, both overall and unhealthy PBDP scores were associated with *z*-score BMI, *z*-score WC and *z*-score MetS, with effect sizes close to zero and confidence intervals spanning zero ($\beta = -0.01$, 95% CI: −0.01, 0.00 for all). Similarly, adolescents showed significant but small associations between *z*-score BMI and *z*-score WC with healthy PBDP scores ($\beta = 0.01$, 95% CI: 0.00, 0.01 for both) and negative associations with unhealthy PBDP scores ($\beta = -0.01$, 95% CI: −0.01, 0.00 for both).

Similar results were observed in adults, with BMI and WC negatively associated with both overall and unhealthy PBDP scores. However, the association between WC and the unhealthy PBDP was attenuated upon FDR correction in adults ($\beta = -0.03$, 95% CI: −0.06, 0.00, FDR-adjusted $p = 0.06$). Moreover, significant associations were observed in adults between HDL cholesterol and both the healthy PBDP score ($\beta = 0.06$, 95% CI: 0.03, 0.09) and the unhealthy PBDP score ($\beta = -0.06$, 95% CI: −0.10, −0.03), triglycerides and the healthy PBDP score ($\beta = -0.17$, 95% CI: −0.26, −0.07) and bone stiffness with the healthy PBDP score ($\beta = 0.07$, 95% CI: 0.02, 0.13) (Table S6).

3.4 | Underlying Structure and Reliability of the PBDP Scores

The PCA analysis of the PBDP scores showed substantial variability without a dominant linear combination (Figure 2), revealing six distinct factors with eigenvalues above 1. The Cronbach's alpha value was 0.43, increasing to 0.50 in adults but decreasing to 0.38 in children and 0.42 in adolescents. Food group correlations were generally low, except for snacks and miscellaneous items ($r = 0.37$) (Table 5). These correlations ranged from −0.94 for dairy to −0.01 for nuts with the overall PBDP score, and from −0.79 for dairy to 0.20 for vegetables with the healthy PBDP score. Correlations with the unhealthy PBDP score ranged from −0.81 for dairy to 0.16 for snacks.

4 | Discussion

This study describes the construction and validation of three distinct PBDP scores – overall, healthy and unhealthy – using comprehensive data from the European multi-centre I.Family study during 2013–2024. The PBDP scores accurately capture plant-based dietary patterns between different demographic groups. Importantly, we observed parallel trends between PBDP scores and associations with nutrient intakes, offering valuable insights into dietary quality and potential nutritional adequacy. Furthermore, although associations between PBDPs and health indicators were notable in adults, particularly in cardiometabolic traits and bone stiffness, such associations were not evident in children and adolescents. Notably, our study revealed a novel association between PBDP scores and bone stiffness, a measure that reflects the structural integrity of bone and is relevant for assessing bone health [29, 31]. This finding aligns with the expected patterns and suggests potential implications for bone health in adults.

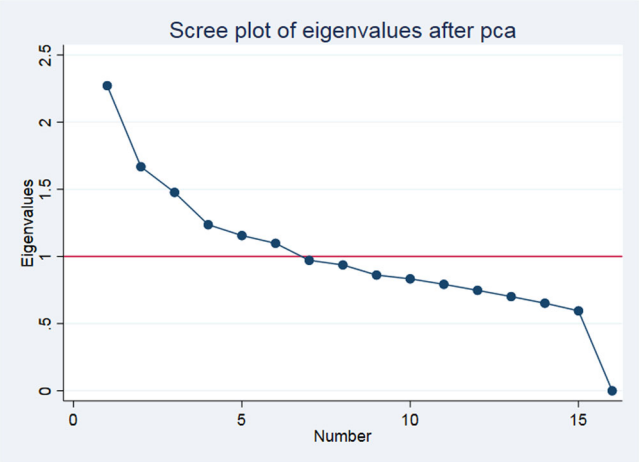

FIGURE 2 | Scree plot from principal component analysis of the plant-based diet propensity scores showing the amount of variance accounted for by each of the principal components or dimensions.

In this study, we found significant differences in adherence to overall, healthy and unhealthy plant-based dietary patterns across quintiles of the different PBDP scores, indicating the sensitivity of PBDP scores in capturing variations in diet quality similar to other validation studies with the Healthy Eating Index score [32], the Nordic diet score [33] and the Planetary Health Diet Index [14]. In addition, our PBDP scores differed across demographic groups, e.g., by sex, with females having a higher overall and healthy PBDP score compared to males. This result is not surprising, as females tend to have healthier eating habits compared to males, as evidenced by a study encompassing participants from 23 countries [34].

Our study revealed significant differences in plant-based dietary patterns across age groups, with adults demonstrating higher overall and healthy PBDP scores compared to children and adolescents, who showed higher unhealthy PBDP scores. However, when observing the different food groups, we found that across all age groups, there was a consistently higher consumption of less healthy plant-based foods such as refined grains, sweets and desserts or sugar-sweetened beverages compared to the other healthy food groups included in the PBDP scores. These findings underscore the pervasive influence of the obesogenic environment, characterised by the generalised availability of energy-dense foods [35]. Additionally, adolescents' spending habits, particularly their utilisation of pocket money for purchasing unhealthy breakfasts or snacks [36, 37], as well as the practice of using food as a reward by adults among children [38], could further contribute to poor dietary choices, highlighting the importance of analysing age-specific dietary preferences and habits. Furthermore, recent findings from the HELENA Study in European adolescents suggested that health motivation may influence food choices in relation to the consumption of healthy foods, while discouraging the consumption of less healthy options such as alcohol or savoury snacks [39]. Hence, future studies should explore further the behavioural aspects driving food choices within these age groups to inform targeted interventions aimed at promoting healthier eating habits. PBDPs showed variability across parental educational levels; individuals with a high parental educational level showed higher overall and healthy PBDP

TABLE 5 | Estimated correlations of plant-based diet propensity scores and food groups ($n = 15{,}780$).

	Whole grains	Fruits	Vegetables	Nuts	Vegetable oils	Tea and coffee	Refined grains	Snacks	Sugar-sweetened beverages	Sweets and desserts	Animal fat	Dairy	Egg	Fish	Meat	Miscella-neous
Whole grains	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fruits	0.02*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Vegetables	0.08*	0.23*	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nuts	0.12*	0.07*	0.06*	—	—	—	—	—	—	—	—	—	—	—	—	—
Vegetable oils	−0.06*	0.13*	0.08*	−0.01	—	—	—	—	—	—	—	—	—	—	—	—
Tea and coffee	0.10*	0.02*	0.06*	0.09*	−0.02*	—	—	—	—	—	—	—	—	—	—	—
Refined grains	−0.25*	−0.05*	−0.15*	−0.14*	0.13*	−0.24*	—	—	—	—	—	—	—	—	—	—
Snacks	−0.16*	−0.21*	−0.14*	−0.06*	−0.15*	−0.23*	0.08*	—	—	—	—	—	—	—	—	—
Sugar-sweetened beverages	−0.15*	−0.17*	−0.19*	−0.07*	−0.17*	−0.21*	−0.12*	0.03*	—	—	—	—	—	—	—	—
Sweets and desserts	−0.11*	−0.08*	−0.18*	−0.05*	−0.12*	−0.22*	0.04*	0.20*	0.00	—	—	—	—	—	—	—
Animal fat	0.12*	−0.13*	−0.10*	−0.03*	−0.26*	−0.03*	−0.03*	0.02	−0.03*	−0.03*	—	—	—	—	—	—
Dairy	−0.12*	−0.21*	−0.26*	−0.14*	−0.16*	−0.16*	−0.14*	−0.11*	−0.22*	−0.21*	−0.10*	—	—	—	—	—
Egg	0.02*	−0.05*	−0.01	0.09*	−0.03*	−0.03*	−0.07*	0.03*	−0.05*	−0.04*	−0.01	−0.10*	—	—	—	—
Fish	−0.03*	0.05*	0.12*	0.03*	0.15*	−0.04*	−0.02*	0.00	−0.12*	−0.08*	−0.19*	−0.14*	0.12*	—	—	—
Meat	−0.09*	−0.16*	−0.08*	−0.11*	−0.07*	−0.13*	0.02	0.12*	−0.06*	−0.02*	0.04*	−0.19*	0.09*	0.09*	—	—
Miscella-neous	−0.14*	−0.18*	−0.21*	0.00	−0.10*	−0.21*	0.06*	0.37*	0.04*	0.23*	−0.08*	−0.12*	0.07*	0.02	0.08*	—
Overall PBDP score	−0.21*	−0.05*	−0.14*	−0.01	−0.03*	−0.34*	−0.35*	−0.25*	−0.44*	−0.27*	−0.50*	−0.94*	−0.25*	−0.22*	−0.58*	−0.37*
Healthy PBDP score	0.10*	0.18*	0.20*	0.13*	0.05*	0.09*	−0.59*	−0.50*	−0.73*	−0.58*	−0.41*	−0.79*	−0.14*	−0.07*	−0.50*	−0.50*
Unhealthy PBDP score	−0.58*	−0.53*	−0.64*	−0.31*	−0.45*	−0.75*	−0.06*	0.16*	−0.07*	0.07*	−0.36*	−0.81*	−0.22*	−0.30*	−0.38*	−0.01

Note: Pearson's correlations and *p*-values were corrected for clustering of family members by survey methods; significance levels were indicated by $p < 0.03$ (*).
Abbreviation: PBDP, plant-based diet propensity.

scores, along with lower unhealthy PBDP scores, compared to those individuals from low and medium levels of education. This finding aligns with a previous systematic review, which revealed that high education levels in developed countries were associated with higher adherence to healthy dietary patterns [40].

Another important finding is that we observed notable differences in PBDP scores among participants from different European countries. Specifically, Mediterranean countries such as Spain and Cyprus showed higher adherence to overall plant-based dietary patterns. Belgium, despite not being a Mediterranean country, showed similar overall PBDP scores, likely due to public health initiatives promoting such dietary patterns. Interestingly, Sweden also showed high adherence to the healthy plant-based dietary pattern alongside Belgium and Spain. This finding aligns with a previous study in this cohort, which found that adherence to the Mediterranean diet, known for promoting high consumption of plant-based foods, was higher in participants from Sweden [41]. However, it is important to highlight that adherence to the Mediterranean diet was lower in Cyprus and average in Spain according to this prior study. These findings suggest that factors other than geography, such as cultural influences or global trends, substantially shape dietary habits, leading to common or similar patterns across countries.

Our study revealed associations between PBDP scores and most of the nutrient intakes in the expected direction, consistent with previous research examining associations with the Planetary Health Diet Index [14, 42, 43]. However, when analysing correlations by age group, children showed positive correlations between the healthy PBDP and sugar intake, and adolescents showed positive correlations between the healthy PBDP and energy intake and sugar. This might be partly explained by children's preference for fruit and fruit juices [44], which are typically high in sugar, whereas adolescents may consume a wide variety of energy-dense food options [45].

Overall, although our associations between nutrient intakes and the different scores are consistent, variations in analytical approaches make direct comparisons challenging in our study. Although nutrient intakes were obtained from 24-HDR and corrected using the NCI method, which incorporates information from the FFQs, the limited scope of our FFQ (59 items) may have contributed to less accurate nutrient intakes. Additionally, FFQs were used to derive PBDP scores. Previous research has indicated that more extensive FFQs tend to yield stronger associations with nutrient intake and overall diet quality [46]. Despite the comparability between our FFQs and 24-HDR methodologies, the restricted item range in the FFQ could reflect less precise dietary patterns, leading to weak or non-existent correlations. Incorporation of more comprehensive dietary assessments may enhance the robustness of correlations between dietary patterns and nutrient intakes.

Our findings are consistent with previous research that analysed associations using plant-based diet scores in adolescents [14] and adults [47]. In line with these previous studies, the overall PBDP was inversely associated with BMI and WC across all age groups. However, our study unveiled unexpected results; the unhealthy PBDP score showed inverse associations with BMI and WC across all age groups, along with an inverse association with MetS in children. Conversely, the healthy PBDP score showed positive associations with BMI and WC in adolescents. These results may be explained by the categorisation of dairy, the most consumed food group, as negative in our study, as dairy consumption has been associated with a reduced risk of obesity and cardiovascular disease [48]. Moreover, a recent article [49] highlighted the issue of underreporting dietary intake from food records among adolescents, which may be influenced by body weight status and body image. This underreporting can lead to biases in estimates of particular food and nutrient intakes. Hence, underreporting may attenuate the associations between PBDPs and health outcomes, rather than reverse them. Notably, in adults, we observed associations between PBDP scores and HDL cholesterol and triglycerides in the expected directions. These results were consistent with previous research, such as the study carried out by Satija et al. [13], which found inverse associations of the overall and healthy plant-based score and a positive association of the unhealthy plant-based score with coronary heart disease risk in US adults. Furthermore, healthy plant-based dietary patterns have been associated with a reduced risk of cardiovascular disease in adults from the UK Biobank [50].

In addition, this study unveiled a novel finding: a positive association between the healthy PBDP score and bone stiffness in adults. Although previous research has indicated lower bone density and impaired bone health among individuals adhering to vegan or vegetarian diets [51, 52], our study suggests a relationship dependent on the quality of plant-based dietary intake. Interestingly, we also observed that higher unhealthy PBDP scores seem to be associated with lower bone stiffness. Similarly, a recent study that used the same plant-based diet scores reported that in postmenopausal women from the Nurses Health Study, the most recent scores for healthy plant-based diet scores were associated with a reduction of hip fracture, whereas unhealthy plant-based diet scores were associated with increased risk [53]. Nevertheless, no association was found between long-term adherence to these patterns and hip fracture. These findings suggest that the association between plant-based dietary patterns and bone health may vary depending on the quality of the diet. This discrepancy with vegan or vegetarian diets may be attributed to the inclusion of animal-based food products in our participants' diets, challenging the notion that plant-based dietary patterns inherently compromise bone health. Particularly, a systematic review and meta-analysis further support this notion, as vegetarian and vegan diets were associated with low bone mass density. Vegans showed a higher risk of fracture compared to omnivores; also, their bone mass density was lower and their risk of fracture more pronounced compared to vegetarians [54].

Mirroring the findings of previous studies [32, 42], our PCA analysis revealed that no single linear combination of the 16 food groups within the PBDP scores accounted for a substantial proportion of the covariance. This underscores the intricate and multidimensional nature of dietary patterns, emphasising the necessity of considering various factors when evaluating dietary patterns.

Our study assessed the reliability of the PBDP scores using Cronbach's alpha coefficient, revealing a value of 0.43 for all

individuals. Although this value falls below the commonly accepted threshold of 0.70 for internal consistency, it is consistent with findings from a previous study examining plant-based dietary scores [42]. Moreover, within our sample, the reliability of PBDP scores appears to vary across demographic groups, with adults demonstrating a higher Cronbach's alpha coefficient of 0.50.

Consistent with findings from previous research [42], we observed generally low correlations between food groups. Notably, snacks and miscellaneous food groups showed a moderate correlation, suggesting potential clustering of certain dietary choices. Furthermore, similar to the findings of Guenther et al. [32], correlations between individual food groups and the PBDP scores varied in strength. These results underscore the multidimensional nature of dietary patterns and highlight the importance of considering specific food group contributions when evaluating overall diet. Although the reliability of the PBDP scores may be influenced by factors such as age or dietary behaviour, understanding these specific contributions is crucial for accurately interpreting dietary data. This suggests that a more nuanced analysis is needed to fully capture the complexity of dietary patterns across diverse populations, emphasising the need for further investigation into the determinants of reliability [29].

Our study has several potential limitations. The main limitation is that we cannot draw conclusions on causality due to the cross-sectional nature of this study [55]. Further, the use of a short FFQ, which is qualitative, may have restricted the accuracy of dietary assessments and introduced measurement error. Our FFQ cannot assess individual portion sizes and does not include many food items, and combines butter and margarine under the same category, resulting in the inclusion of margarine in the food group labelled as animal foods. Our dietary data were collected in 2013–2014. We acknowledge that dietary patterns may have evolved in the past decade, with a notable increase in the adoption of plant-based diets, especially among children and adolescents [56]. Although dietary trends do change, patterns often show stability over time [57]. Our study aims to provide a baseline understanding of dietary patterns from that period and to validate a scoring system that can be applied to this population. Additionally, the relatively weak associations with health indicators, except for adults, suggest potential limitations in the predictive ability of our PBDP scores. Moreover, data were missing on health indicators; hence, our study may not fully capture the associations between PBDP scores and health indicators. The inherent nature of self-reported questionnaires introduces the possibility of social desirability bias, particularly among certain demographic groups such as females or individuals with overweight. This bias may lead to underreporting of unhealthy habits or over-reporting or normative ones, potentially confounding associations [58, 59]. Another limitation of our study is that HOMA-IR was calculated even for non-fasting individuals, which may affect the validity of some values. Lastly, the inclusion of food groups containing both plant- and animal-based foods may introduce challenges in interpreting PBDP scores accurately.

Our study has several notable strengths that contribute to the robustness and significance of our findings. First, the inclusion of a large and diverse sample from multiple European countries enhances the generalisability of our results, providing valuable insights into plant-based dietary patterns beyond the study population. This broad representation strengthens the external validity of our findings and underscores their relevance to diverse populations. Moreover, our study introduces a valuable tool for screening diet quality, particularly in relation to plant-based food products, through the development and validation of PBDP scores. To enable broader use of these scores, consistency in dietary assessment methods is crucial. This includes using either the same FFQ as our study or a similar one and applying the same categorisation strategy to compute the three PBDP scores. These scores offer a comprehensive means of assessing dietary habits across different demographic groups, thereby facilitating health promotion and disease prevention efforts.

5 | Conclusion

Our results showed that the three PBDP scores are effective measures for evaluating plant-based dietary patterns across a wider range of demographic groups in a broad European population. PBDP scores reflected key nutrient intakes and were associated with cardiometabolic traits and bone stiffness in adults. Specifically, the healthy PBDP score was associated with higher bone stiffness, indicating that the relationship may be dependent on the quality of the plant-based dietary pattern. These results underscore the utility of PBDP scores as reliable indicators of plant-based adherence in adults, while cautioning against their applicability in children and adolescents. Considering that dietary habits and preferences are likely age-dependent, the development of age-specific tools for assessing plant-based dietary adherence will be of utmost importance to improve assessment accuracy in young populations. Moreover, future research needs to address underreporting issues, particularly among individuals with overweight and obesity, to ensure more accurate dietary data.

These findings highlight the potential role of plant-based dietary patterns in promoting overall health and guiding dietary recommendations. However, further research is needed to explore the long-term health implications of adhering to plant-based dietary patterns in mitigating chronic diseases. An increased understanding of the impact of plant-based dietary patterns on human health and well-being will ultimately inform more targeted and effective public health interventions aimed at disease prevention and health promotion.

Author Contributions

Drafting of the manuscript: Guiomar Masip. Statistical analysis: Guiomar Masip. Study concept and design: Guiomar Masip and Leonie H. Bogl. Acquisition, analysis and/or interpretation of data: All authors. Critical revision of the manuscript for important intellectual content: All authors. The authors read and approved the final manuscript. Guiomar Masip had full access to add the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Transparent Peer Review

The peer-review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/jhn.70021.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.