Spring 5-1-2022

Plant-Based Diets and Metabolic Syndrome: Evaluating the Influence of Diet Quality

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Honors Scholar Thesis

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Spring 2022

Abstract

Background: Diet plays a critical role in the prevention and treatment of metabolic syndrome (MetS). Plant-based diets (PBDs) have demonstrated a broad range of health benefits, including a protective effect against MetS. Most research on this topic has focused on PBDs as a whole, without considering the influence of diet quality. The purpose of this study was to investigate the relationship between plant-based diet quality and biomarkers of MetS.

Methods: Data were obtained from a clinical nutrition study at the University of Connecticut. 29 participants with MetS were included. PBD quality was assessed using 2 measures: healthful PBD index (hPDI) and unhealthful PBD index (uPDI). Higher hPDI represented greater consumption of healthy plant foods (whole grains, fruits, vegetables, nuts, legumes, unsweetened tea and coffee, low-fat dairy), and lower consumption of less-healthy plant foods (sugar-sweetened beverages, refined grains, potatoes, sweets, high-fat dairy). Higher uPDI represented greater consumption of less-healthy plant foods and lower consumption of healthy plant foods. Both indices were determined by measuring the number of healthful and unhealthful plant foods consumed over a 3-day period. For each participant, hPDI and uPDI scores were calculated at both baseline (2 weeks) and at 9-weeks follow-up. Participants were divided into quintiles according to their hPDI and uPDI scores. Unpaired *t*-tests were performed to assess differences in mean biomarkers between quintiles, for both hPDI and uPDI. Correlation analyses were performed to investigate cross-sectional associations between biomarker measures and PBD quality scores.

Results: Using baseline data, mean weight was significantly lower in hPDI quintile 5 compared to hPDI quintile 1, and significantly higher in uPDI quintile 5 compared to uPDI quintile 1 ($p < .05$). Significant associations were observed between PBD quality score and weight at baseline, with hPDI inversely associated with weight ($r = -.445$, $p < .05$), and uPDI positively associated with weight ($r = .437$, $p < .05$). Using follow-up data, HDL-C was significantly associated with hPDI ($r = .411$, $p < .05$) and significantly associated with uPDI ($r = -.411$, $p < .05$).

Conclusions: In individuals with metabolic syndrome, adherence to a healthful plant-based diet was associated with lower weight and higher HDL cholesterol, thus highlighting the influence of diet quality on the health effects associated with plant-based diets.

Acknowledgements

I would like to give many thanks to Dr. Maria-Luz Fernandez for her continued support and guidance as my Thesis Advisor. I would also like to thank Minu Thomas for being another helpful resource and allowing me to assist in her study for these past few years. Additionally, I wish to thank my Honors Advisor, Dr. Ock K. Chun, for guiding me through my academic requirements and endeavors. Finally, I want to extend my thanks to the UConn Honors program and UConn Nutritional Sciences Department for providing this invaluable opportunity for hands-on experience and in-depth study.

Table of Contents

1 Introduction

Plant-based diets (PBDs) have been shown to lower the risk of chronic diseases such as ischemic heart disease, cancer, high blood pressure, and diabetes.[1, 2, 3] There is also emerging evidence on the cognitive benefits of PBDs, including protection against age-related cognitive decline.[4] However, prior studies have focused largely on PBDs defined exclusively as vegetarian or vegan eating patterns. Fewer studies have assessed the influence of plant-based diet quality. Vegetarian diets may include less healthy foods, such as refined grains and sweetened beverages. Such foods have been associated with various negative health outcomes, including overweight/obesity and increased risk of cardiovascular disease and type 2 diabetes.[5, 6, 7, 8] Thus, the impact of plant-based diet quality is an important area of focus.

1.1 Metabolic Syndrome

MetS an increasingly prevalent issue, affecting an estimated one quarter of the world's population.[9] MetS is a clinical condition characterized by a cluster of risk factors for cardiovascular disease (CVD).[9] It is defined by the presence of metabolic abnormalities such as abdominal obesity, insulin resistance, hypertension, and hyperlipidemia.[10] There are substantial health consequences associated with MetS, including increased risk for heart disease, type 2 diabetes (T2D), and stroke.[9] MetS is also associated with comorbidities such as proinflammatory and prothrombotic states, nonalcoholic fatty liver disease, cholesterol gallstone disease, and reproductive disorders.[10] The syndrome has an enormous economic burden as well, through increased health care costs and lost productivity.[9] Lifestyle modifications, including changes in diet and physical activity, are routinely recommended in the management of MetS.[10] However, there is no distinct dietary pattern that is deemed most beneficial for patients with MetS.[11]

1.2 Plant-Based Diets

A plant-based diet (PBD) can be defined as an eating pattern that focuses on plant foods and includes minimal or no animal foods.[12] Interest in PBDs has been growing in recent years in both the general population as well as the scientific community.[13] PBDs can be categorized into 3 general models: vegan (including exclusively plant foods), lacto-ovo vegetarian (including plant foods as well as dairy products, eggs, and honey), and fish-vegetarian (including plant foods as well as fish and seafoods).[13] This study will focus on the effects of lacto-ovo vegetarian diets in particular.

1.3 Literature Review

1.3.1 PBDs and MetS

Prior research has found PBDs to be effective in the treatment and prevention of MetS. In a cross-sectional analysis of 773 individuals, a vegetarian diet appeared to lower the risk of developing MetS by about one-half.[14] Compared to nonvegetarians, vegetarians in this study had significantly lower measures for all metabolic risk factors except high density lipoprotein cholesterol (HDL-C), and semi-vegetarians had significantly lower waist circumference (WC) and body mass index (BMI) than nonvegetarians. MetS prevalence was highest among nonvegetarians (39.7%), intermediate among semi-vegetarians (37.6%), and lowest among vegetarians (25.2%). Vegetarians had an OR for MetS of 0.44 (95% CI 0.30–0.64, $p < .001$) compared to nonvegetarians.

Other studies have found promising effects of PBDs on individual biomarkers of MetS. In a historical cohort study with 201 individuals, adherence to a vegetarian diet was associated with lower blood pressure (BP), fasting plasma glucose, total cholesterol (TC), low density lipoprotein cholesterol (LDL-C), and triglycerides (TG).[15] Vegetarians in this study also had

significantly lower calculated cardiovascular risk scores. Consistent with these findings, various meta-analyses have reported vegetarian diets as effective in lowering blood pressure,[2] improving glycemic control,[16] and promoting weight loss,[17] among other favorable health outcomes.

1.3.2 PBD Quality and MetS

With specific regard to diet quality, there is evidence supporting the benefits of healthful PBDs on features of MetS. Baden, et al. assessed the associations between PBD adherence and changes in biomarkers related to cardiometabolic disease, with a focus on the influence of diet quality.[18] This study included 831 randomly selected women who participated in the Nurses' Health Study (NHS) II. Cross-sectional analyses were performed to examine associations between PBD quality scores and biomarkers at baseline, and longitudinal analyses were performed to assess associations over an average 13-year period. PBD quality was measured in 3 indices: overall plant-based diet index (PDI), healthful plant-based diet index (hPDI), and unhealthful plant-based diet index (uPDI). Higher hPDI was associated with favorable changes in biomarker concentrations: lower levels of leptin, insulin, and high-sensitivity C-reactive protein (hsCRP), and higher levels of soluble leptin receptor and adiponectin. High uPDI was also associated with improvements in leptin, hsCRP, and interleukin-6. Interestingly, the researchers observed no significant associations between overall PDI and biomarker concentrations, thus highlighting the importance of diet quality. It should be noted that participants were primarily Caucasian females without CVD and T2D, so the generalizability of this study is limited. Nonetheless, this study offers strong evidence to suggest a favorable correlation between hPDI and biomarkers relating to cardiometabolic disease.

The relationship between hPDI and MetS was further demonstrated in a prospective cohort study of over 5,600 South Korean men and women.[19] Plant-based diet indices (including

hPDI and uPDI) were calculated using food-frequency questionnaires, and MetS incidence was assessed over a mean follow-up of 8 years. Compared to those in the lowest uPDI quintile, participants in the highest uPDI quintile had an approximately 50% higher risk of developing MetS, after adjusting for demographic characteristics and lifestyle factors. Focusing on an Asian population, this study corroborates similar associations observed in Western populations.

1.3.3 Other Health Benefits of Healthful PBDs

In addition to MetS, healthful PBDs have been associated with numerous related health benefits. Using data from three prospective cohort studies with over 200,000 participants, Satija, et al. revealed a strong inverse association between hPDI and risk of T2D.[20] In this study, researchers documented T2D incidence during a follow-up period of over 20 years. A significant inverse association was observed between T2D and hPDI, while T2D was significantly positively associated with uPDI.

Kim, et al. evaluated the relationship between PBD quality and hypertension, using a sample of over 8,000 adults.[21] Over a medium follow-up of 13 years, 6,044 participants developed hypertension. After adjusting for sociodemographic characteristics and lifestyle factors, higher hPDI was associated with a 12-16% lower hypertension risk. In contrast, higher uPDI was associated with a 13% increased hypertension risk.

This PBD classification scheme was also used by Baden, et al. to assess the relationship between PBD quality and physical and mental health-related quality of life.[22] This study followed 50,290 women in who participated in the NHS and 51,784 women who participated in the NHSII, over an 8-year period. Higher hPDI was significantly associated with improvements in both physical and mental health-related quality of life, while uPDI was associated with unfavorable changes in both dimensions of health-related quality of life. The psychological

benefits of a healthful PBD were further demonstrated in a cross-sectional study by Lee, et al., in which adherence to a high quality PBD was associated with reduced risk of depressive symptoms.[23]

Altogether, these findings highlight the importance of accounting for diet quality when considering the health benefits of PBDs. The aim of the present study was to assess the relationship between PBD quality and biomarkers of MetS in individuals following a lacto-ovo vegetarian diet. Based on the existing literature, it was hypothesized that healthful PBD quality would be associated with improved biomarkers of MetS, including increased HDL-C and reductions in weight, BMI, WC, BP, TC, LDL-C, TG, and fasting glucose.

2 Methods

2.1 Study Population

The present study is a secondary analysis, using data from a study titled "Effects of a Plant-Based Diet with Whole Eggs or Egg Substitute on Parameters of Metabolic Syndrome, Plasma Choline and TMAO Concentrations." This study compared the effects of consuming eggs in combination with a plant-based diet on biomarkers of metabolic syndrome. The study protocol was approved by the Institutional review board of the University of Connecticut (Protocol H19-178).

Participants were recruited from Mansfield and neighboring communities in Connecticut. 29 total participants were included. These individuals were men and women with MetS, aged 35 to 70 years, of any ethnic group. MetS was defined according to the National Cholesterol Education Program guidelines as having at least 3 of the 5 characteristics: high plasma TG (≥150 mg/dL), high fasting glucose (≥100 mg/dL), low HDL-C (<40 mg/dL for men; <50 mg/dL for women), high BP (≥130/≥85 mm Hg), and large WC (>102 cm for men; >88 cm for women).[24]

2.2 Experimental Period

All participants were instructed to follow a lacto-ovo vegetarian diet for the entire duration of this study. Participants first underwent a 2-week washout period in which they abstained from eating eggs. They were then randomly assigned to one of two groups in a crossover design: whole egg or egg substitute. Participants were asked to consume either 2 whole eggs with 70 grams spinach or ½ cup egg substitute with the same amount of spinach each day. After a 3-week washout period, they were allocated to the alternative treatment.

The present study used data from phase *a* (weeks 0-2) and phase *c* (weeks 6-9), for several reasons. First, all participants abstained from eating eggs during these periods, thereby eliminating any confounding effect of egg consumption. Additionally, these washout periods were, in a sense, less rigid than the intervention periods, as participants were not provided with eggs and spinach. Thus, participant food records during the washout periods may be more reflective of their typical eating habits.

2.3 Dietary Assessment

Participants completed 3-day self-reported dietary records, outlining all food and beverages consumed over a 3-day period (including 2 weekdays and 1 weekend day). Diet records were reviewed with the researcher at each data collection point to allow for clarifying questions. The records were analyzed using Nutrition Data Systems for Research software (NDSR) (Minneapolis, MN, USA).

2.4 Anthropometric Measures

Height (cm) was measured at screening using a wall-mounted stadiometer. Weight (kg) was measured at screening and at each consecutive visit, using a digital scale. Waist

circumference was measured against the skin approximately 1" above the hipbone using a flexible measuring tape. Three waist circumference measures were taken to the nearest 0.5cm and averaged. Blood pressure was measured using an OMRON automated blood pressure cuff, with 3 measures collected and averaged.

2.5 Blood Sample Collection and Biomarker Measurements

Blood samples were collected at screening and at the end of each dietary treatment phase (weeks 2, 6, 9, and 13). Samples were taken from the antecubital vein and centrifuged at 2000 x g for 20 minutes. Plasma was collected and stored at -80°C for analyses. Plasma lipids (TC, TG, HDL-C, and LDL-C) and glucose were measured using a Cobas c-111 analyzer (Roche Diagnostics, Indianapolis, IN, USA).

2.6 Plant-Based Diet Indices

The procedure used to determine plant-based diet quality was adopted from that used by Satija, et al., with various adjustments.[20] PBD quality was assessed using 2 indices: healthful plant-based diet index (hPDI) and unhealthful plant-based diet index (uPDI). Overall plant-based diet index (assessed by Satija, et al.) was not measured in this study, as all participants were adhering to a plant-based diet, as defined as lacto-ovo vegetarian for the purposes of this study. Thirteen plant-based food groups were created based on shared nutritional and culinary characteristics. These food groups were further classified as healthy plant foods (whole grains, fruits, vegetables, nuts, legumes, vegetable oils, tea/coffee, low-fat dairy) or unhealthy plant foods (sweetened beverages, refined grains, potatoes, sweets/desserts, high-fat dairy/other animal fats). Healthy and unhealthy plant foods were distinguished using existing evidence on the associations between consumption of these foods and health outcomes such as T2D, CVD,

certain cancers, obesity, hypertension, dyslipidemia, and inflammation. Eleven of these food groups were already established as healthy or unhealthy (whole grains, fruits, vegetables, nuts, legumes, vegetable oils, tea/coffee, sweetened beverages, refined grains, potatoes, sweets/desserts).[20] Dairy was added to this classification scheme, as all participants were consuming a lacto-ovo vegetarian diet, which allows for the inclusion of dairy products. Low-fat dairy was classified as healthy, as research has consistently demonstrated an association between low-fat dairy intake and positive health outcomes.[25] High-fat dairy, in contrast, was classified as unhealthy. While research on the health effects of high-fat dairy is mixed, high-fat dairy consumption does appear to be associated with unfavorable health outcomes. For instance, in a prospective cohort study of over 80,000 individuals, Bernstein, et al. observed a significant association between high-fat dairy consumption and coronary heart disease risk.[26] This is in line with the current U.S. Dietary Guidelines for Americans, which encourages the consumption of low-fat dairy over high-fat dairy.[27] High-fat dairy was grouped alongside other miscellaneous animal fats, such as butter, which have also been associated with unfavorable cardiometabolic health outcomes.[28]

Examples of foods constituting the 13 groups are presented in **Table 1**. Since all participants were abstaining from eggs during phases *a* and *c*, eggs were not included in these indices. Alcoholic beverages were not included either, given the mixed findings on the associations between alcohol and health outcomes.[29] Other foods not accounted for, due to their unclear effects on health outcomes, include sweetened low-fat yogurt, dairy-based sweetened meal replacements/supplements, reduced-fat or fat-free margarine/cream, vegetable-based savory snacks (e.g., onion rings), sauces and condiments, and artificially sweetened desserts.

Table 1. Examples of food items constituting the 13 food groups.

Healthy Plant Foods	
Whole grains	Whole grain breakfast cereal, other cooked breakfast cereal, cooked oatmeal, dark bread, brown rice, other grains, bran, wheat germ, popcorn
Fruits	Raisins or grapes, prunes, bananas, cantaloupe, watermelon, fresh apples or pears, oranges, grapefruit, strawberries, blueberries, peaches, apricots, plums
Vegetables	Tomatoes, tomato juice, tomato sauce, broccoli, cabbage, cauliflower, Brussels sprouts, carrots, mixed vegetables, yellow or winter squash, eggplant, zucchini, yams/sweet potatoes, spinach, kale, mustard/chard greens, lettuce (romaine, leaf, iceberg), celery, mushrooms, beets, alfalfa sprouts, garlic, corn, vegetable soup
Nuts & Seeds	Nuts, seeds, peanut butter, nut/seed butter
Legumes	String beans, tofu, soybeans, beans, lentils, peas, lima beans, meat alternatives
Vegetable oils / fats	Oil-based salad dressing, vegetable oils, avocados, olives
Tea & Coffee	Unsweetened tea, coffee, decaffeinated coffee
Low-fat dairy	Reduced-fat, low-fat, or fat-free milk, cheese, yogurt (including artificially sweetened), dairy alternatives
Unhealthy Plant Foods	
Refined grains	Refined grain breakfast cereal, white bread, English muffins, bagels, rolls, muffins, biscuits, taco shells, white tortilla, white rice, pancakes/waffles, crackers, pasta, pizza, cake, cookies, pies, pastries, danish, doughnuts, cobblers
Potatoes	French fries, baked or mashed potatoes, potato or corn chips
Sweetened beverages[1]	Fruit juices, Colas with caffeine & sugar, colas without caffeine but with sugar, other carbonated beverages with sugar, non-carbonated fruit drinks with sugar
Sweets and Desserts	Sugar, syrup, honey, jams/jellies/preserves, chocolates, candy bars, candy without chocolate, frosting or glaze, sweetened flavored milk beverage powders with non-fat dry milk (e.g., hot cocoa drink mix)
High-fat dairy	Whole milk, whole milk yogurt, full-fat cheese

[1] Does not include artificially sweetened beverages.

For each participant, the number of servings of each food group consumed over 3 days was determined by creating Food Group Serving Count System Totals Reports in NDSR. Using an excel spreadsheet, each of the 13 food groups was divided into quintiles. Each individual's intake of these foods was assigned a score from 1 to 5, positively or reversely. For positive scores, participants received a score of 5 for food groups for which they exceeded the highest quintile of consumption, a 4 for groups for which they exceeded the second highest quintile, a 3 for exceeding the third highest quintile, a 2 for exceeding the lowest quintile, and a score of 1 for consumption below the lowest quintile. For reverse scores, this pattern was inversed, with participants who exceeded the highest quintile receiving a score of 1, and so on. To determine hPDI, healthy plant foods were scored positively, and less healthy plant foods were scored reversely. To determine uPDI, less healthy plant foods were scored positively, and healthy plant foods reversely. Scores across all food groups were summed. Potential scores ranged from 13 to 65, with a higher score indicative of adherence to each plant-based diet version.

2.7 Statistical Analysis

Descriptive analyses were used to assess mean values for continuous variables, and frequency analyses were used to assess categorical variables. An unpaired *t*-test was performed to compare mean biomarker values between the lowest and highest hPDI quintiles, as well as between the lowest and highest uPDI quintiles. Associations between hPDI, uPDI, and biomarkers were further assessed through Pearson's correlation analyses. All analyses were conducted for both baseline (2 weeks) and follow-up (9 weeks) data, using IBM SPSS Statistics, Version 28. All tests were two-sided, and p values $< .05$ were considered significant.

3 Results

3.1 Participant Characteristics

Characteristics of participants at baseline and follow-up are shown in **Table 2**. Approximately half of participants identified as male. Participants were, on average, about 50 years old with a BMI of 34 kg/m^2. Data was available for 25 participants at follow-up (week 9). No significant changes in mean anthropometric measures or lab values were observed between baseline and follow-up.

Table 2. Initial characteristics of study participants.[1]

	Baseline	**Follow-up**
n	29	25
Sex, *n* (percent)		
Male	14 (48)	12 (48)
Female	15 (52)	13 (52)
Ethnicity, *n* (percent)		
African American	3 (10)	3 (12)
Caucasian	26 (90)	22 (88)
Age (years)	49.6 ± 8.3	49.0 ± 8.0
Weight (kg)	100.1 ± 18.2	99.2 ± 19.4
BMI (kg/m^2)	34.3 ± 4.7	34.5 ± 4.7
WC (cm)	113.0 ± 11.5	113.1 ± 12.8
Systolic BP (mmHg)	126.8 ± 10.0	128.7 ± 10.9
Diastolic BP (mmHg)	86.3 ± 5.7	86.3 ± 6.1
TC (mg/dL)	185.1 ± 29.4	179.2 ± 33.8
HDL-C (mg/dL)	40.9 ± 10.3	40.5 ± 11.2
LDL-C (mg/dL)	109.7 ± 24.8	104.8 ± 30.3
LDL/HDL ratio	2.8 ± .90	2.7 ± .90
TG (mg/dL)	172.4 ± 91.0	167.8 ± 83.7
Glucose (mg/dL)	91.2 ± 12.0	90.2 ± 10.7

[1]Data are expressed as mean ± SD for continuous variables. Baseline measurements were taken at week 2 and follow-up measurements at week 9.

Participants were categorized into quintiles according to hPDI and uPDI. Unpaired *t*-tests were performed to determine the extent to which mean biomarkers varied between the lowest and highest hPDI and uPDI quintiles. A significant difference in weight was observed between those in the lowest hPDI quintile (106 ± 12) and those in the highest hPDI quintile (83 ± 19), $p < .05$. Similarly, there was a significant difference in weight between those in the lowest uPDI quintile (78 ± 13) and those in the highest uPDI quintile (108 ± 18), $p < .05$. Comparisons of mean weight across the lowest and highest quintiles are illustrated in **Figure 1**. Additional baseline characteristics categorized by hPDI and uPDI are shown in **Table 3** and **Table 4**, respectively.

Figure 1. Mean weight across lowest and highest quintile groups at baseline, compared using unpaired *t*-tests. Different subscripts (a, b) indicate statistically significant difference at $p < .05$ (two-tailed).

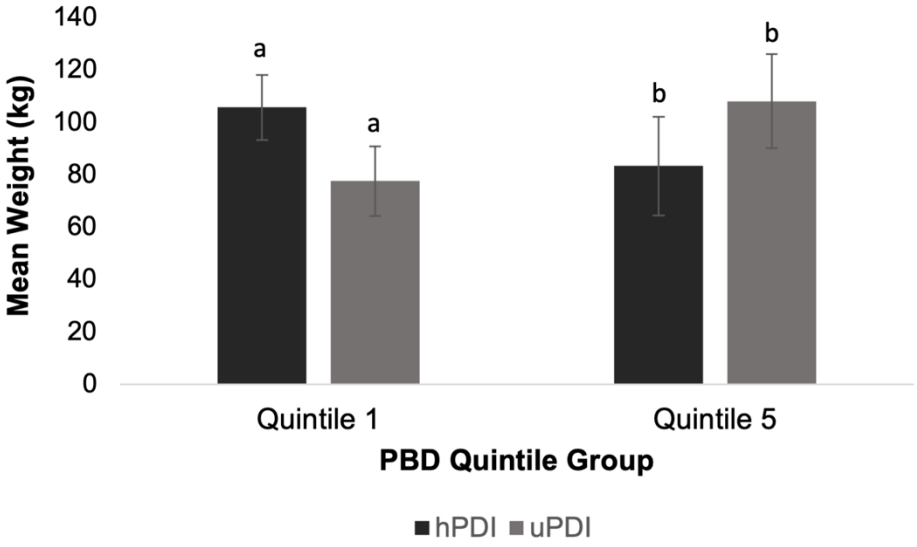


Table 3. Baseline characteristics by hPDI quintile group.[1]

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
n	5	5	7	5	7
hPDI range	33-34	35-36	37-41	42-45	46-51
Female (%)	40	40	43	60	71
Age (years)	53.6 ± 10.3	50.4 ± 6.8	51.0 ± 8.2	47.4 ± 8.4	46.1 ± 8.3
Weight (kg)	105.9 ± 12.4[a]	106.0 ± 19.5	106.6 ± 16.5	102.8 ± 13.6	83.5 ± 18.8[b]
BMI (kg/m2)	35.0 ± 4.9	36.0 ± 5.2	34.3 ± 6.5	34.6 ± 2.9	32.3 ± 3.5
WC (cm)	117.3 ± 11.6	116.8 ± 14.4	113.0 ± 14.0	114.1 ± 6.5	106.7 ± 9.7
Systolic BP (mmHg)	123.0 ± 15.2	127.8 ± 7.9	132.1 ± 10.5	129.0 ± 5.6	121.9 ± 8.0
Diastolic BP (mmHg)	85.4 ± 6.9	86.6 ± 3.7	86.0 ± 5.9	89.6 ± 3.8	84.9 ± 7.3
TC (mg/dL)	171.4 ± 42.9	180.8 ± 16.6	186.7 ± 34.4	186.0 ± 27.5	195.7 ± 25.3
HDL-C (mg/dL)	41.4 ± 10.9	36.2 ± 7.6	40.7 ± 11.2	39.8 ± 3.9	45.0 ± 14.2
LDL-C (mg/dL)	92.3 ± 27.3	110.6 ± 23.2	107.1 ± 26.5	121.2 ± 27.4	115.8 ± 20.1
LDL/HDL ratio	2.4 ± 0.9	3.2 ± 1.1	2.9 ± 1.2	3.0 ± 0.5	2.7 ± 0.7
TG (mg/dL)	188.6 ± 68.2	169.8 ± 60.4	194.7 ± 136.2	124.6 ± 45.7	174.4 ± 102.3
Glucose (mg/dL)	98.8 ± 17.2	88.0 ± 12.6	92.9 ± 9.6	86.4 ± 15.0	89.7 ± 6.7

[1] Data are presented as mean ± SD for continuous variables. Values in the same row with different superscripts (a, b) are significantly different from each other at $p < .05$ (two-tailed).

Table 4. Baseline characteristics by uPDI quintile group.[1]

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
n	4	7	4	7	7
uPDI range	27-31	32-35	36-40	41-42	43-47
Female (%)	100	43	50	43	43
Age (years)	48.3 ± 9.9	44.9 ± 7.4	53.0 ± 8.0	51.7 ± 6.6	50.9 ± 9.8
Weight (kg)	77.8 ± 13.3 [a]	100.2 ± 18.8	103.6 ± 13.9	102.7 ± 15.9	108.3 ± 18.0 [b]
BMI (kg/m2)	31.9 ± 4.5	33.9 ± 2.9	33.3 ± 2.8	35.2 ± 6.3	35.7 ± 5.6
WC (cm)	104.0 ± 8.9	113.3 ± 8.5	112.5 ± 8.7	113.9 ± 14.7	117.5 ± 13.2
Systolic BP (mmHg)	119.0 ± 8.0	128.6 ± 6.0	129.5 ± 9.7	129.0 ± 10.6	125.7 ± 13.5

Diastolic BP (mmHg)	83.5 ± 6.9	87.9 ± 6.0	88.5 ± 6.5	85.7 ± 5.2	85.9 ± 5.7
TC (mg/dL)	201.8 ± 27.4	185.4 ± 26.5	192.8 ± 38.4	182.0 ± 21.6	174.0 ± 37.2
HDL-C (mg/dL)	51.5 ± 15.3	38.7 ± 5.7	36.5 ± 9.0	41.3 ± 10.2	39.3 ± 10.2
LDL-C (mg/dL)	123.9 ± 23.9	114.2 ± 24.3	110.9 ± 17.3	109.2 ± 26.3	96.9 ± 28.5
LDL/HDL ratio	2.6 ± 0.7	3.0 ± 0.6	3.2 ± 1.0	2.8 ± 1.0	2.7 ± 1.2
TG (mg/dL)	131.8 ± 48.5	162.4 ± 106.6	227.0 ± 183.3	157.7 ± 49.1	189.0 ± 55.8
Glucose (mg/dL)	93.5 ± 5.1	83.1 ± 9.9	92.5 ± 9.1	94.1 ± 12.4	94.1 ± 16.3

[1] Data are presented as mean ± SD for continuous variables. Values in the same row with different superscripts (a, b) are significantly different from each other at $p < .05$ (two-tailed).

For the follow-up data (weeks 6-9), participants were again categorized into hPDI and uPDI quintiles. These follow-up characteristics categorized by hPDI and uPDI are shown in **Table 5** and **Table 6**, respectively. While those in the highest hPDI group had the lowest average weight, the difference between the mean weight of Quintile 1 (97 ± 26) and Quintile 5 (88 ± 26) was not statistically significant, $p > .05$. Likewise, while weight was lowest in uPDI Quintile 1, the difference between mean weight in the lowest (88 ± 26) and highest (97 ± 26) uPDI quintiles was not significant, $p > .05$. Diastolic BP appeared to decrease with increasing hPDI and increase with increasing uPDI. Nonetheless, the difference in mean diastolic BP between the lowest and highest quintiles was not quite significant ($p = .051$ for both hPDI and uPDI). Despite these findings, no statistically significant differences in mean biomarkers were observed in this follow-up data.

Table 5. Follow-up characteristics by hPDI quintile group.[1]

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
n	5	5	4	6	5
hPDI range	27-34	36-38	39-41	42-45	46-55
Female (%)	40	60	25	50	80
Age (years)	48.0 ± 7.6	56.2 ± 5.3	44.3 ± 5.7	50.3 ± 7.6	45.2 ± 9.6
Weight (kg)	97.3 ± 26.0	102.4 ± 13.2	105.0 ± 11.0	103.4 ± 17.8	88.4 ± 26.3

BMI (kg/m2)	34.1 ± 5.4	34.6 ± 2.7	34.7 ± 2.1	34.4 ± 6.8	34.5 ± 5.9
WC (cm)	111.4 ± 14.0	114.9 ± 7.8	115.0 ± 8.7	113.4 ± 17.4	111.0 ± 16.4
Systolic BP (mmHg)	132.0 ± 8.0	130.4 ± 7.3	132.0 ± 10.9	129.0 ± 12.6	120.6 ± 14.0
Diastolic BP (mmHg)	88.6 ± 2.6	88.8 ± 7.3	88.5 ± 6.9	84.6 ± 5.4	81.6 ± 6.3
TC (mg/dL)	181.6 ± 53.3	165.6 ± 23.6	175.8 ± 12.2	190.7 ± 34.3	179.6 ± 37.9
HDL-C (mg/dL)	34.8 ± 9.5	42.2 ± 6.9	35.5 ± 6.6	43.0 ± 8.9	45.6 ± 19.4
LDL-C (mg/dL)	108.2 ± 58.9	97.4 ± 17.8	108.2 ± 11.3	104.1 ± 30.9	107.0 ± 17.8
LDL/HDL ratio	3.2 ± 1.4	2.3 ± .54	3.1 ±.42	2.5 ±.95	2.6 ± .80
TG (mg/dL)	192.8 ± 74.6	121.2 ± 46.0	160.5 ± 41.1	218.0 ± 128.5	134.8 ± 61.4
Glucose (mg/dL)	94.0 ± 10.6	92.8 ± 14.9	86.5 ± 4.4	90.8 ± 13.2	86.0 ± 7.4

[1] Data are presented as mean ± SD for continuous variables. No statistically significant differences ($p < .05$) were observed between Quintile 1 and Quintile 5.

Table 6. Follow up characteristics by uPDI quintile group.[1]

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
n	5	4	6	5	5
uPDI range	23-32	33-35	36-39	40-42	44-51
Female (%)	80	50	33	60	40
Age (years)	45.2 ± 9.6	50.8 ± 9.1	46.0 ± 5.9	56.2 ± 5.3	48.0 ± 7.6
Weight (kg)	88.4 ± 26.3	95.7 ± 15.9	109.6 ± 12.2	102.4 ± 13.2	97.3 ± 26.0
BMI (kg/m2)	34.5 ± 5.9	31.6 ± 4.6	36.5 ± 5.0	34.6 ± 2.7	34.1 ± 5.4
WC (cm)	111.0 ± 16.4	107.6 ± 14.8	118.3 ± 12.7	114.9 ± 7.8	111.4 ± 14.0
Systolic BP (mmHg)	120.6 ± 14.0	123.5 ± 11.9	134.7 ± 9.4	130.4 ± 7.3	132.0 ± 8.0
Diastolic BP (mmHg)	81.6 ± 6.3	83.6 ± 6.3	87.8 ± 5.6	88.8 ± 7.3	88.6 ± 2.6
TC (mg/dL)	179.6 ± 37.9	208.0 ± 27.0	169.2 ± 14.6	165.6 ± 23.6	181.6 ± 53.3
HDL-C (mg/dL)	45.6 ± 19.4	42.5 ± 9.9	38.3 ± 8.1	42.2 ± 6.9	34.8 ± 9.5
LDL-C (mg/dL)	107.0 ± 17.8	114.5 ± 33.9	99.9 ± 15.7	97.4 ± 17.8	108.2 ± 58.9
LDL/HDL ratio	2.6 ±.80	2.8 ± 1.0	2.7 ±.71	2.3 ±.54	3.2 ± 1.4
TG (mg/dL)	134.8 ± 61.4	255.3 ± 147.3	154.8 ± 35.3	121.2 ± 46.0	192.8 ± 74.6
Glucose (mg/dL)	86.0 ± 7.4	93.8 ± 14.7	86.0 ± 6.2	92.8 ± 14.9	94.0 ± 10.6

[1] Data are presented as mean ± SD for continuous variables. No statistically significant differences ($p < .05$) were observed between Quintile 1 and Quintile 5.

3.2 Correlation Analysis

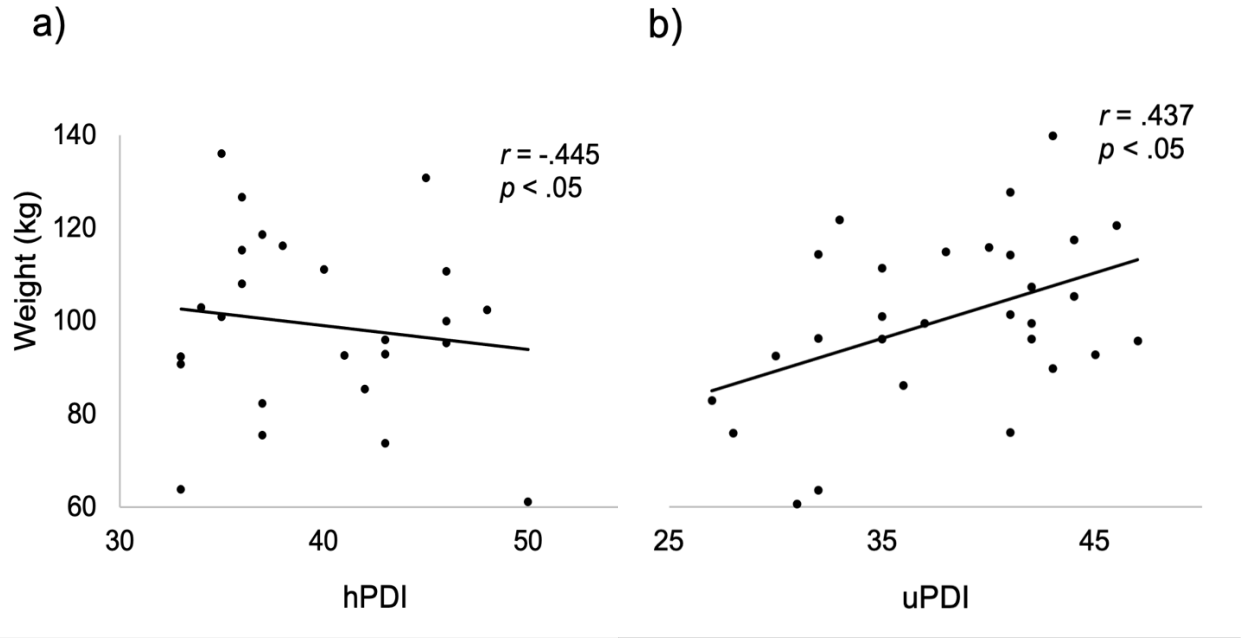
Pearson correlation analyses were performed to investigate the relationship between PBD quality scores and biomarkers relating to MetS. Correlation analyses were performed using data from both baseline (2 weeks) and follow-up (9 weeks). Results of the baseline correlation analysis are shown in **Table 7**. Statistically significant correlations were observed between PBD index and weight, for both hPDI and uPDI. hPDI was negatively correlated with weight (r = -.445, $p < .05$), while uPDI was positively correlated with weight (r = .437, $p < .05$). These correlations are illustrated in **Figure 2**.

Table 7. Baseline Pearson correlation analysis.[1]

	hPDI		uPDI	
	r	*p*	*r*	*p*
Weight	-.445*	.016	.437*	.018
BMI	-.206	.284	.193	.316
WC	-.296	.119	.293	.123
Systolic BP	-.144	.457	.117	.545
Diastolic BP	.011	.957	-.019	.921
TC	.322	.088	-.310	.101
HDL-C	.249	.193	-.236	.218
LDL-C	.342	.069	-.337	.074
LDL/HDL ratio	.032	.869	-.038	.843
TG	-.087	.653	.091	.639
Glucose	-.196	.309	.190	.323

[1] Correlation coefficient (r) and p values from Pearson correlation analysis performed between initial hPDI, uPDI, and biomarkers. *Correlations are significantly different from each other at $p < .05$ (two-tailed).

Figure 2. Correlations between baseline weight and plant-based diet quality scores. Data collected from 29 participants. Significant associations seen for both (a) healthful plant-based diet index score and (b) unhealthful plant-based diet index score ($p < .05$).



For the follow-up data, the results of the Pearson correlation analysis are shown in **Table 8**. There was a significant positive association between hPDI and HDL-C ($r = .411$, $p < .05$) and a significant negative association between uPDI and HDL-C ($r = -.411$, $p < .05$). These associations are illustrated in **Figure 3**. No other significant associations were observed.

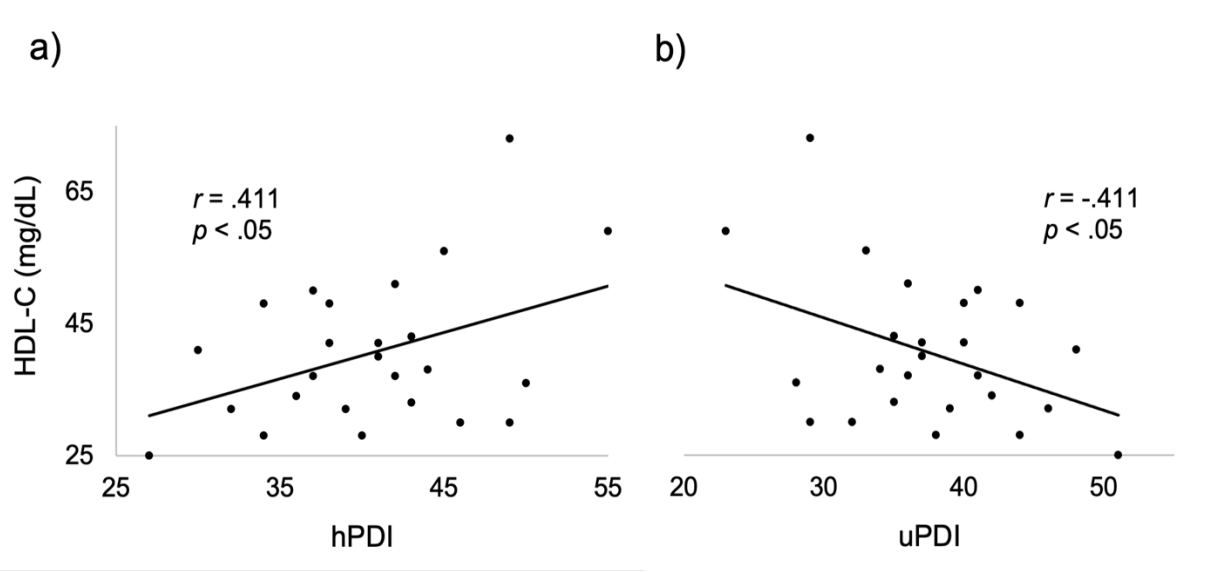
Table 8. Follow-up Pearson correlation analysis.[1]

	hPDI		uPDI	
	r	*p*	*r*	*p*
Weight	-.184	.379	.184	.379
BMI	.003	.987	-.003	.987
WC	-.065	.759	.065	.759
Systolic BP	-.341	.095	.341	.095
Diastolic BP	-.355	.081	.355	.081

TC	.169	.419	-.169	.419
HDL-C	.411*	.041	-.411*	.041
LDL- C	.048	.819	-.048	.819
LDL/HDL ratio	-.217	.298	.217	.298
TG	-.013	.949	.013	.929
Glucose	-.414	.501	.141	.501

[1] Correlation coefficient (r) and p values from Pearson correlation analysis performed between follow-up hPDI, uPDI, and biomarkers. *Correlations are significantly different from each other at $p < .05$ (two-tailed).

Figure 3. Correlations between follow-up HDL cholesterol and plant-based diet quality scores. Data collected from 24 participants. Significant associations seen for both (a) healthful plant-based diet index score and (b) unhealthful plant-based diet index score ($p < .05$).



4 Discussion

The objective of this study was to investigate the relationship between plant-based diet quality and biomarkers relating to metabolic syndrome. The results of this study suggest a favorable association between healthful PBDs and various biomarkers of MetS, namely weight and HDL-C. First off, higher PBD quality was associated with lower weight, and lower PBD

quality was associated with higher weight. These findings were as expected, as previous studies have shown favorable associations between body weight and adherence to a healthful plant-based diet.[30, 31] Additionally, healthful PBD quality was positively associated with HDL-C, and unhealthful PBD quality was inversely associated with HDL-C. This was also consistent with prior research, as healthy plant food consumption has been positively associated with HDL-C. For instance, adherence to the Mediterranean diet, which is characterized by a high intake of whole grains, fruits, vegetables, legumes, and vegetable oils, and a low intake of meat, poultry, and high-fat dairy products, has been positively associated with HDL-C levels.[32]

4.1 Mechanisms of Healthful and Unhealthful Plant-Based Diets

There are several possible mechanisms to explain the benefits of healthful PBDs. To start, these diets are rich in dietary fiber, which has been shown to play a role in promoting weight loss and offsetting chronic disease development.[33] For instance, fiber may increase gastric distention, thereby slowing gastric emptying and promoting satiety.[34] The satiating effects of fiber may also be attributed to the fermentation of fiber in the large intestine.[34] This process produces short-chain fatty acids, which may trigger the release of appetite-regulating hormones such as glucagon-like peptide and peptide YY.[34] Additionally, dietary fiber can promote the fecal excretion of bile acids, thereby lowering serum cholesterol and improving the lipid profile.[35] Healthful PBDs are also rich in antioxidant compounds such as polyphenols, which have been shown to exert cardioprotective effects.[36] Furthermore, the benefits of healthful PBDs may be attributed to their dietary fat content. Healthful PBDs are relatively low in saturated fat and higher in unsaturated fat. Replacement of saturated fat with unsaturated fat is associated with considerable health benefits, including reduced cardiovascular risk.[37] For example, in a recent systematic review, replacement of saturated fat with polyunsaturated fat suggested a 27%

reduced risk of cardiovascular events.[37] Healthful PBDs are also likely to be rich in micronutrients that may support cardiovascular function and glucose homeostasis. For instance, potassium has been shown to reduce blood pressure and stroke risk,[38] and magnesium has been shown to improve insulin sensitivity and protect against oxidative and inflammatory stress.[39]

The negative health outcomes associated with unhealthful PBDs may be in part due to their inclusion of foods high in added sugar. Excess consumption of added sugar has been linked with various cardiovascular risk factors, including weight gain,[40] high blood pressure,[41] and abnormal blood lipid levels.[42] An unhealthful PBD may also be high in sodium, which can lead to elevated blood pressure or hypertension.[43] Furthermore, less healthy plant foods may be rich in trans fatty acids. High trans-fat intake is associated with various biomarkers of MetS, including lipid abnormalities[44] and high fasting glucose.[45] Similarly, less healthy plant foods may be rich in saturated fatty acids (SFA). Studies have shown associations between high SFA intake and increased heart disease risk,[46, 47, 48] which may be explained by the potentially inflammatory effects of SFA. For example, SFA may mimic the action of lipopolysaccharide, a proinflammatory endotoxin.[49] SFA may also directly stimulate the expression of proinflammatory cytokines such as interleukin-6 and tumor necrosis factor-alpha.[49] Nonetheless, the effects of SFA on cardiovascular risk has been a topic of controversy in recent years, as more research is needed to clarify this relationship.[50]

4.2 Strengths and Limitations

This study has various strengths. The use of 3-day food records, including 2 weekdays and 1 weekend day, provides a comprehensive overview of participants' eating habits in each phase of the study. In addition, the use of NDSR, a scientifically credible nutrient analysis software, allows for a high level of detail when analyzing dietary intake.

Nonetheless, numerous limitations should be noted. First, only 29 participants were included in this study. Recruiting participants was difficult due to COVID-19 restrictions, including an inability to meet with participants in-person during the height of the COVID-19 pandemic. The narrow inclusion criteria also made recruitment challenging. The limited ethnic diversity among participants should also be considered, as participants were predominantly non-Hispanic Caucasian. As a result, extending these findings to the general population should be done with caution. The self-reporting nature of the 3-day food records introduces another potential source of error. Participants may have over- or under-reported amounts of food consumed, or mis-reported types of food consumed.

Additionally, while there were significant associations between weight and diet quality, these associations were not observed in both cross-sectional analyses (i.e., at both 2 weeks and 9 weeks). Similarly, the significant association between HDL-C and diet quality scores was only apparent in the follow-up data. Thus, this inconsistency is a notable limitation, as it may reduce the reliability of these findings.

Furthermore, the healthfulness of various plant-based food groups was determined based on prior evidence on the health effects of these foods. While there is strong evidence to support this classification scheme, the categorization of foods as healthful or unhealthful carries some degree of subjectivity. For example, potatoes were classified as unhealthy, while they could be deemed healthful depending on their method of preparation. Also, high fat dairy was considered unhealthy, due to the associations between dietary saturated fat intake and adverse health outcomes. Nonetheless, the literature on this topic is not entirely clear, as numerous studies demonstrate no adverse effects of high-fat dairy consumption on CVD risk factors.[51, 52, 53] In fact, some research suggests a possible health-promoting effect of high fat dairy. For instance, a met-

analysis examining the relationship between high-fat dairy consumption and obesity, CVD, and MetS found high-fat dairy consumption to be inversely associated with adiposity in 11 of the 16 included observational studies.[54] Additionally, in a cross-sectional analysis of over 15,000 individuals, an inverse association was observed between MetS and high-fat dairy consumption, which was even stronger than that observed for total dairy consumption.[55] Along similar lines, various foods were not accounted for, due to their unclear effects on health. Such foods include reduced-fat animal fats, vegetable-based savory snacks, and sweetened low-fat dairy products. Lastly, due to the observational nature of this study, these findings cannot be used to infer causality.

4.3 Future Directions

Future large-scale intervention studies should explore the relationship between diet quality and biomarkers of MetS in individuals following a lacto-ovo vegetarian diet. While prior studies have examined the association between plant-based diet quality and health outcomes,[18-23] the classification schemes used in these studies scored all animal foods negatively. Some animal foods, such as low-fat dairy and eggs, are associated with favorable health outcomes.[25, 56] Additionally, a complete exclusion of animal foods may be impractical for certain individuals, for reasons such as cost, accessibility, and time constraints. An entirely plant-based diet may also increase susceptibility to nutrient deficiencies, such as vitamin B12 deficiency.[57] A lacto-ovo vegetarian diet may address these concerns, by including some healthful animal foods, while remaining predominantly plant-focused.

5 Conclusions

In sum, adherence to a healthful plant-based diet was associated with lower weight and higher HDL cholesterol levels in individuals with MetS. These findings demonstrate the importance of accounting for diet quality when considering the influence of eating patterns on health outcomes. In other words, while emphasis is commonly placed on plant-based diets as a whole, the benefits of these diets may be lost with the inclusion of less healthy plant foods. These findings have important implications for dietary recommendations, highlighting the potential benefits of a healthful plant-based diet in the prevention and treatment of metabolic syndrome.

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