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Analysis of correlation between dietary fiber intake and risk of diabetic kidney disease in adults with type 2 diabetes mellitus: results from the United States National Health and Nutrition Examination Surveys 2009–2018

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ABSTRACT

Objective: Given the significant impact of diabetic kidney disease (DKD) on morbidity and mortality in patients with type 2 diabetes mellitus (T2DM) and the potential preventive role of dietary factors, particularly dietary fiber, this study aimed to investigate the relationship between dietary fiber intake and the risk of DKD in adults with T2DM.

Methods: The medical records and other relevant data from patients with T2DM were retrieved from the United States National Health and Nutrition Examination Surveys (U.S. NHANES) from 2009 to 2018. Multivariate logistic regression and restricted cubic spline (RCS) regression were employed to investigate the relationship between dietary fiber intake and the risk of DKD in adult T2DM patients.

Results: The study involved 4,520 T2DM patients with a mean age of 59.16 years, consisting of 2,346 male patients (51.9%) and 2,174 female patients (48.1%). The prevalence of T2DM patients with DKD was 37.92% in the overall population. Regression analyses, after adjusting for confounders, showed that dietary fiber intake was negatively correlated with the prevalence of DKD. RCS analysis demonstrated a nonlinear negative correlation between the level of dietary fiber intake and the prevalence of DKD, with a threshold inflection point of 13.96 g/day. Subgroup analyses revealed that age, gender, race, smoking status, body mass index, hypertension, diabetes duration, glycosylated hemoglobin, and ACEI/ARB medication use did not significantly affect the negative correlations ($p > 0.05$).

Conclusions: Dietary fiber intake was negatively correlated with the prevalence of DKD in T2DM patients.

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Dietary fiber; type 2 diabetes mellitus; diabetic kidney disease; population-based study; NHANES

Introduction

T2DM poses a serious public health issue because its prevalence continues to rise globally [1]. A large proportion of T2DM cases derive from long-term complications [2], such as diabetic kidney disease (DKD), resulting in substantial physical and financial burdens [2,3]. Approximately 20–40% of patients with T2DM develop DKD [4,5], which is the leading cause of chronic kidney disease (CKD) and end-stage kidney disease (ESKD) worldwide [5,6]. Currently, there are only a few clinical interventions that effectively halt the disease progression [7]. Therefore, it is crucial to explore new management strategies to reduce the prevalence of DKD for both patients and ease the high cost of health care [6,8,9]. Given the progressive nature of DKD, prevention and early intervention present the most promising options to limit the effects of this condition [3,6, 8,10].

Currently, there is growing interest in exploring the benefits of dietary fiber for disease prevention and health promotion. Dietary fibers cannot be hydrolyzed by endogenous hydrolytic enzymes in the small intestine but they can be partially or fully fermented in the colon. Such fibers consist mainly of plant fractions, carbohydrates, and other similar substances [11]. Dietary fiber, mainly derived from grains, fruits, and vegetables, can regulate intestinal microbiota and reduce the risk of many digestive diseases, such as esophageal cancer [12], inflammatory bowel disease [13], and colorectal cancer [7], prevent the harmful effects of other

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diseases, such as hypertension [10], diabetes mellitus [14], cardiovascular disease [15], and ovarian cancer [16], and has anti-inflammatory properties. Some previous studies have demonstrated that increased fiber intake, a protective factor for the kidney, was associated with a lower risk of CKD[16] and dietary fiber delays the progression of CKD by reducing inflammation and fibrosis[16]. The protective effects of dietary fiber against DKD have not been extensively studied and the findings remain inconclusive.

This present study aims to investigate the correlation between dietary fiber intake and the risk of developing DKD in adult T2DM patients and the STROBE guidelines for cohort studies were followed. We accessed the U.S. National Health and Nutrition Examination Survey (NHANES) database to retrieve medical records and other relevant materials of T2DM patients from 2009 to 2018. Subsequently, we outlined the basic characteristics of the adult T2DM population with DKD and examined the effect of dietary fiber intake on DKD as well as the dose-response relationship.

Methods

General information on the study population

The NHANES is a program conducted by the Centers for Disease Control and Prevention (CDC) in the U.S. and employs a multistage, stratified sampling design to ensure comprehensive representation of the non-institutionalized civilian population nationwide [17]. This involves selecting primary sampling units based on geographical regions, stratifying the population within these units by demographic characteristics, and employing cluster sampling to select households and individuals for participation. This sampling approach facilitates robust analyses and generalization of findings to the broader U.S. population. It collects data on the health and nutritional status of a nationally representative sample of non-institutionalized civilians through interviews, physical examinations, and laboratory tests. This comprehensive dataset is widely used by researchers to assess trends in health and nutrition and inform public health policy. In this study, data were obtained from the NHANES database from 2009 to 2018. This study involved 4,520 T2DM patients with supplementary information such as demographic counts, diet, physical examination, and questionnaires. The questionnaires were completed by staff at the National Center for Health Statistics. T2DM patients with DKD were determined under the following criteria: impaired glomerular filtration rate (<60 mL/min/1.73 m^2 assessed using the Chronic Kidney Disease Epidemiology Collaborative Group algorithm), albuminuria (urinary albumin/creatinine ratio ≥30 mg/g), or both.

Inclusion and exclusion criteria

Inclusion criteria: i) data from the NHANES database from 2009 to 2018; ii) patients with age ≥20 years; iii) patients clinically diagnosed with T2DM; and iv) information on dietary fiber intake. Exclusion criteria: (i) patients with missing data on urinary albumin-to-creatinine ratio; and (ii) patients with missing data on serum creatinine.

Assessment of dietary fiber intakes

Dietary fiber intake was assessed through a comprehensive methodology involving 24-h dietary recalls conducted with NHANES participants. These recalls utilized the Automated Multiple-Pass Method, capturing detailed information on food and beverage consumption over a 24-h period. Trained interviewers facilitated these assessments, ensuring consistency and accuracy. Dietary fiber intake was calculated based on the USDA Food and Nutrient Databases for Dietary Studies, with values derived from the first day of recall to maintain analytical robustness and sample consistency. This approach yielded reliable estimates of dietary fiber intake and has been used before in people with CKD, crucial for investigating its potential associations in the study [18].

Assessment of DKD

The diabetic condition was clinically diagnosed (1) by medical professionals; (2) based on laboratory tests such as fasting plasma glucose (7.0 mmol/L); (3) glycosylated hemoglobin (HbA1c) (>6.5 mmol/L); or (4) taking diabetes drugs. The ACR was measured based on the urine albumin/creatinine ratio. The eGFR scores were calculated using the Chronic Kidney Disease Epidemiology Collaboration algorithm. T2DM patients with DKD should fulfill the following criteria: ACR ≥ 30 mg/g and/or eGFR < 60 mL/min/1.73 m^2.

Assessment of covariates

Baseline characteristics of participants were collected, including age (continuous), sex (male or female), race (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black or Other), education level (below high school, high school, or above high school), family income-to-poverty ratio (≤1.0, 1.1–3.0, or >3.0), smoking status (never smoker, former smoker, or current smoker), drinking status (nondrinker, low-to-moderate drinker, or heavy drinker), body mass index (BMI) (continuous), total cholesterol (in quartiles), energy intake levels (in quartiles), physical activity (inactive, insufficiently active, or active), self-reported hypertension (yes or no), ACEI/ARB use (yes or no), diabetes duration (<3, 3–10, >10 years), HbA1c (<7% or ≥7%), and diabetes medication use (yes or no). All interview and questionnaire procedures and more detailed information on covariates are available at https://wwwn.cdc.gov/Nchs/Nhanes/continuousnhanes.

Statistical methods

To ensure that our data on participants with T2DM across the U.S. are representative, we adhered to the National Center for Health Statistics (NCHS) guidelines for sample selection weights. Specifically, we applied the Mobile Examination Center (MEC)

weights as recommended by the NHANES database to our study population data, thereby ensuring national representativeness. Normally distributed continuous variables were described as means ± SE, and continuous variables without a normal distribution were presented as medians (interquartile ranges). Comparisons of continuous data between two groups were performed using the independent samples *t*-test. Comparisons between multiple groups were examined using one-way analysis of variance (ANOVA). The chi-square test was used to compare data between counting data groups. Normality of the distribution of continuous variables was assessed using the Shapiro-Wilk test. Missing data for covariates were imputed using the "mice" package with the random forest algorithm, a reliable method for handling missing values by leveraging relationships between observed covariates. This approach has been utilized in previously studies for data imputation [19,20].

Dietary fiber intake levels were divided into quartiles, with Q1 (lowest quartile) as the reference. Quartile classification, a common approach for non-normally distributed variables in epidemiological studies, facilitates group comparisons and satisfies the linearity assumption for logistic regression. A logistic regression model was used to determine the relationship between the level of dietary fiber intake and the risk of DKD in adult T2DM patients. R^2 values were calculated to assess the goodness-of-fit for the logistic regression models. Additionally, restricted cubic spline (RCS) analysis was conducted to evaluate the potential dose-response relationship between dietary fiber intake and the prevalence of DKD. The RCS model used three knots placed at the 10th, 50th, and 90th percentiles of dietary fiber intake distribution. A likelihood ratio test was used to assess non-linearity by comparing the RCS model with a model assuming a linear association.

Three logistic regression models were formulated in this study. Model 1 was adjusted for age, gender, and race. Model 2 was further adjusted by adding more confounders such as education level, family income-to-poverty ratio, smoking status, drinking status, BMI, total cholesterol, energy intake level, physical activity, self-reported hypertension, and ACEI/ARB use. Model 3 was further adjusted by adding other confounders, including diabetes duration, glycosylated hemoglobin, and diabetes medication use. All statistical analyses were conducted using R statistical software version 4.2.0. Weighted analyses were performed with the "survey" package to ensure accurate national estimates.

Results

Baseline characteristics of participants

Based on the inclusion and exclusion criteria, our study enrolled a cohort comprising 5499 participants diagnosed with type 2 diabetes, aged over 20 years, spanning the years 2011 to 2016. After meticulous scrutiny, subjects with incomplete records pertaining to dietary fiber intake ($n = 631$), urinary albumin-to-creatinine ratio ($n = 121$), and serum creatinine ($n = 227$) were systematically excluded, resulting in the inclusion of 4520 subjects for subsequent analysis. The detailed screening process is presented in Figure 1.

A total of 4,520 subjects with T2DM were enrolled with a mean age of 59.16 years, including 2,346 male patients (51.9%) and 2,174 female patients (48.1%). The study compared baseline characteristics between participants with and without DKD in the NHANES 2009-2018 (Table 1). DKD participants, on average, were older (mean age 64.58 vs. 56.29 years), had lower education levels (24.26% vs. 19.92% below high school), and were more likely to have lower family poverty income ratios (17.96% vs. 15.78% ≤1.0 PIR). They also had a higher prevalence of current smoking (13.12% vs. 16.08%) and physical inactivity (42.66% vs. 30.86%), along with higher rates of HbA1c levels ≥ 7% (46.82% vs. 36.73%). Additionally, DKD participants exhibited lower total cholesterol levels, lower energy and dietary fiber intake, and poorer kidney function, as evidenced by lower eGFR and higher ACR. These findings underscore the significant differences in demographic, lifestyle, and clinical characteristics between DKD and non-DKD participants in the NHANES cohort.

T2DM subjects were divided into 4 groups based on the dosage of dietary fiber intake using the quartile method: <10.3 g/day, 10.3–14.6 g/day, 14.7–20.9 g/day, and >20.9 g/day. Gender, race, education level, family PIR, smoking status, physical activity, eGFR, ACR, energy intake, and diabetes medication use were statistically different ($p < 0.05$) across different groups (Table 2).

Logistic regression modeling of dietary fiber intake and prevalence of DKD in T2DM patients

The logistic regression analysis presented in Table 3 assessed the association between quartiles of dietary fiber intake levels and the prevalence of DKD among adults. The results showed a consistent trend across all models, indicating a significant inverse association between dietary fiber intake and the prevalence of DKD. In the crude model, participants in the highest quartile of dietary fiber intake (>20.9 g/day) had significantly lower odds of DKD compared to those in the reference group (10.3–14.6 g/day). These correlations remained statistically significant after adjusting age, gender, race, education level, family PIR, smoking status, drinking status, BMI, energy intake, physical activity, self-reported hypertension, and ACEI/ARB use. After correcting all confounders, dietary fiber intake (OR = 0.59 [0.44–0.79], $P_{trend}<0.001$) was negatively correlated with the prevalence of DKD in adult patients with T2DM.

RCS regression and threshold effects analysis

We used RCS regression to explore the dose–response relationship between the level of dietary fiber intake and the prevalence of DKD. After adjusting confounders, we found a negative and nonlinear correlation between the level of dietary fiber intake and the prevalence of DKD ($P_{nonlinearity}=0.004$), with a threshold inflection point of 13.96 g/day (Figure 2). Moreover, the threshold effect analysis conducted using piecewise binary logistic regression models identified that at this inflection point of 13.96 grams/day of

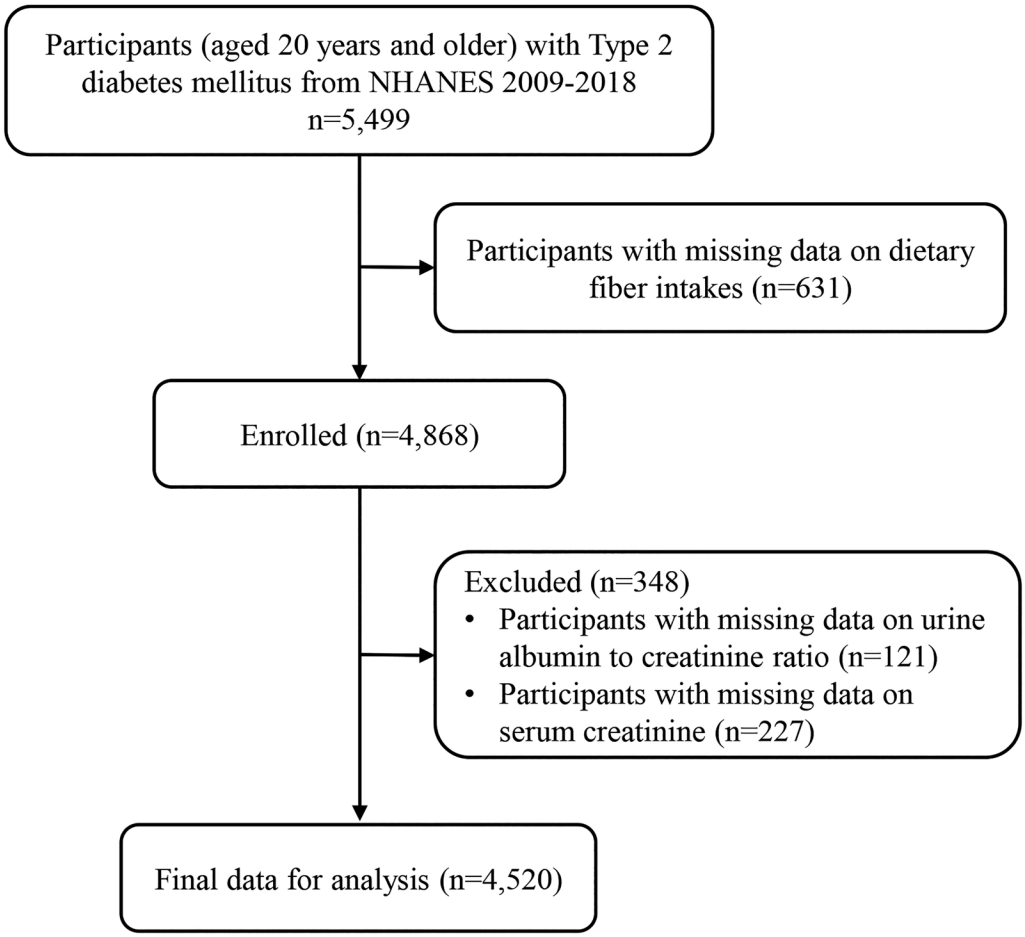

Figure 1. Flow chart describing the selection process of the participants.

dietary fiber intake, the odds of DKD displayed a significant change in direction (Table 4). Below this threshold (≤13.96 g/day), the odds of DKD were observed to be 0.86 times lower (95% CI: 0.64–1.15, $p = 0.031$), indicating a potential protective effect of dietary fiber intake against DKD, albeit not statistically significant. Conversely, above the inflection point (>13.96 g/day), a substantial reduction in the odds of DKD was noted, with participants exhibiting 0.43 times lower odds (95% CI: 0.29–0.64, $p < 0.001$). These findings suggest a nonlinear relationship between dietary fiber intake and DKD prevalence, with a notable protective effect observed beyond the inflection point of 13.96 grams/day.

Subgroup analysis and sensitivity analysis

The results of the subgroup analysis showed an inconsistent correlation between the level of dietary fiber intake and the prevalence of DKD (Table 5). We found that the correlation between dietary fiber intake levels and the prevalence of DKD was not affected by age, gender, race, smoking status, body mass index, hypertension, diabetes duration, glycosylated hemoglobin, and ACEI/ARB medication use. In addition, our analysis demonstrated a negative correlation between dietary fiber intake and the prevalence of DKD in almost all subgroups, except for the subgroups of females, current smokers, non-hypertensive, HbA1c < 7%, and no ACEI/ARB medication use.

To assess the stability of our results, we performed a sensitivity analysis by excluding participants with missing data on key variables. The results showed that compared with the lowest quartile of dietary fiber intake, the highest quartile remained inversely associated with the prevalence of diabetic kidney disease (OR = 0.51, 95% CI: 0.38–0.68) in Model 3 (Table 6). These results were consistent with the primary findings, further supporting the robustness of our conclusions.

Discussion

As far as we know, this is the first study that uses the NHANES database to explore the link between dietary fiber intake and the risk of DKD in adult T2DM patients. This study included 4,520 T2DM patients in 5 NHANES cycles (2009–2010, 2011–2012, 2013–2014, 2015–2016, and 2017–2018), with a prevalence of DKD of approximately 37.92%. The findings showed a nonlinear and negative correlation between the level of dietary fiber intake and the prevalence of DKD, with a threshold inflection point of 13.96 g/day.

Table 1. Characteristics of adult participants with diabetic kidney disease (DKD) in NHANES 2009–2018.

Characteristics	Total ($n=4,520$)	DKD		P
		No ($n=2,806$)	Yes ($n=1,714$)	
Age, years	59.16 (0.32)	56.29 (0.36)	64.58 (0.48)	<0.001
Male, *n* (%)	2,346 (52.09)	1,427 (52.29)	919 (51.72)	0.821
Race/ethnicity, *n* (%)				0.314
Mexican American	824 (10.02)	541 (10.31)	283 (9.46)	
Other Hispanic	520 (6.17)	351 (6.58)	169 (5.39)	
Non-Hispanic White	1,570 (61.97)	895 (61.25)	675 (63.33)	
Non-Hispanic Black	1,072 (13.19)	664 (13.03)	408 (13.50)	
Other race	534 (8.66)	355 (8.83)	179 (8.33)	
Education level, *n* (%)				0.042
Below high school	1,440 (21.43)	855 (19.92)	585 (24.26)	
High school	1,035 (24.77)	635 (24.19)	400 (25.86)	
Above high school	2,045 (53.81)	1,316 (55.89)	729 (49.88)	
Family PIR, *n* (%)				<0.001
≤1.0	1,080 (16.53)	653 (15.78)	427 (17.96)	
1.1–3.0	2,065 (41.17)	1,229 (38.22)	836 (46.74)	
>3.0	1,375 (42.30)	924 (46.00)	451 (35.31)	
Smoking status, *n* (%)				0.002
Never smoker	2,320 (49.83)	1,491 (51.34)	829 (46.98)	
Former smoker	1,496 (35.11)	852 (32.58)	644 (39.90)	
Current smoker	704 (15.06)	463 (16.08)	241 (13.12)	
Drinking status, *n* (%)				< 0.001
Nondrinker	1,371 (25.38)	790 (22.53)	581 (30.76)	
Low-to-moderate drinker	2,918 (69.14)	1,874 (71.91)	1044 (63.91)	
Heavy drinker	2,31 (5.48)	142 (5.56)	89 (5.32)	
Body mass index, kg/m^2	33.19 (0.18)	33.19 (0.22)	33.19 (0.27)	0.993
Physical activity, *n* (%)				<0.001
Inactive	1,708 (34.94)	937 (30.86)	771 (42.66)	
Insufficiently active	1,423 (32.61)	946 (34.32)	477 (29.39)	
Active	1,389 (32.44)	923 (34.82)	466 (27.95)	
Total cholesterol, mg/dL	179.00 (152.00,210.00)	182.00 (153.00,211.00)	174.00 (149.00,210.00)	0.013
eGFR, mL/min/1.73m^2	86.72 (68.34,101.73)	92.09 (79.19,104.08)	60.98 (49.53, 91.94)	<0.001
ACR, mg/g	11.03 (6.12,29.82)	7.90 (5.32, 12.77)	51.14 (22.71, 148.16)	<0.001
Energy intake, kcal/day	1,835.50 (1,394.00, 2,356.00)	1,887.00 (1,443.00, 2,418.00)	1,720.00 (1,311.00, 2,210.50)	<0.001
Dietary fiber intakes, g/day	15.00 (10.75, 20.95)	15.50 (11.00, 21.75)	13.80 (9.95, 19.30)	<0.001
HbA1c, *n* (%)				<0.001
< 7%	2,591 (59.77)	1,716 (63.27)	875 (53.18)	
≥ 7%	1,929 (40.23)	1,090 (36.73)	839 (46.82)	
Diabetes medication use, *n* (%)	2,856 (63.09)	1,665 (59.81)	1,191 (69.53)	<0.001
Diabetes duration, *n* (%)				<0.001
<3 years	1,970 (45.26)	1,394 (50.97)	576 (34.47)	
3–10 years	1,164 (25.79)	743 (26.13)	421 (25.16)	
>10 years	1,386 (28.95)	669 (22.90)	717 (40.36)	
ACEI/ARB use, *n* (%)	2,402 (52.97)	1,387 (49.40)	1,015 (59.91)	<0.001
Self-reported hypertension, *n* (%)	2,947 (64.52)	1,671 (59.34)	1,276 (74.30)	<0.001

DKD: diabetic kidney disease; PIR: poverty income ratio; eGFR: estimated glomerular filtration rate; ACR: urine albumin to creatinine ratio; HbA1c: HemoglobinA1c; ACEI: angiotensin converting enzyme inhibitor; ARB: angiotensin receptor blocker. Normally distributed continuous variables are described as means ± SE, and continuous variables without a normal distribution are presented as medians [interquartile ranges]. Categorical variables are presented as numbers (percentages). Sampling weights were applied for calculation of demographic descriptive statistics; N reflect the study sample while percentages reflect the survey weighted.

Stratified analyses revealed that age, gender, race, smoking status, body mass index, hypertension, diabetes duration, glycosylated hemoglobin, and ACEI/ARB medication use did not significantly affect the negative correlations.

Dietary fiber refers to edible plant-based carbohydrate polymers (e.g. non-starch polysaccharides, oligosaccharides, and starches) that are resistant to digestion by endogenous enzymes in the human gastrointestinal tract [21–23]. Each fiber has a distinct structure that determines its physicochemical properties and functional effects [24]. Regarding their physiochemical properties, dietary fibers are classified into three groups: bulking fibers, viscous fibers, and fermentable fibers [24,25]. Bulking fibers stimulate peristalsis and shorten intestinal passage time to increase fecal bulk and promote regular defecation [26]. In the presence of water, viscous fibers form into gels to prolong intestinal passage time while slowing the absorption of nutrients across the intestinal lumen [24,25]. Fermentable fibers can be fermented by specific symbiotic bacteria in the colon to promote a healthy gut environment and regulate the microbial community. Different fermentable fiber corresponds to different metabolic responses and physiological effects, depending on location, rate, and type of bacteria involved in the fermentation process [24,27]. While most fibers are associated with a specific functional type, they exert multiple effects. Given that no single fiber has all beneficial effects, it is essential to consume a large amount of fiber from all functional fiber types to optimize health outcomes [25]. Currently, there is a growing interest to explore the therapeutic effects of dietary fibers, especially in gastrointestinal disorders [24].

Table 2. Characteristics of adult participants with diabetic kidney disease (DKD) according to quartiles dietary fiber intakes in NHANES 2009–2018.

	Quartiles of dietary fiber intake levels, g/day				
Characteristics	<10.3	10.3–14.6	14.7–20.9	>20.9	*P*
Participants	1,140	1,120	1,130	1,130	
Age, years	58.52 (0.54)	59.74 (0.56)	60.23 (0.63)	58.04 (0.47)	0.027
Male, *n* (%)	478 (37.72)	533 (47.23)	611 (57.14)	724 (64.93)	<0.001
Race/ethnicity, *n* (%)					<0.001
Mexican American	122 (5.83)	168 (7.70)	215 (9.94)	319 (16.29)	
Other Hispanic	140 (7.39)	132 (5.79)	130 (5.34)	118 (6.30)	
Non-Hispanic White	409 (60.35)	421 (64.56)	408 (64.83)	332 (57.82)	
Non-Hispanic Black	346 (18.33)	295 (14.49)	243 (11.07)	188 (9.37)	
Other race	123 (8.10)	104 (7.46)	134 (8.82)	173 (10.22)	
Education level, *n* (%)					<0.001
Below high school	418 (27.69)	341 (21.05)	323 (18.62)	358 (19.00)	
High school	281 (26.25)	283 (28.58)	266 (24.78)	205 (19.51)	
Above high school	441 (46.06)	496 (50.36)	541 (56.60)	567 (61.49)	
Family PIR, *n* (%)					<0.001
≤1.0	351 (24.13)	278 (16.90)	219 (12.70)	232 (13.21)	
1.1–3.0	541 (46.36)	505 (40.29)	525 (38.86)	494 (39.73)	
>3.0	248 (29.52)	337 (42.81)	386 (48.44)	404 (47.06)	
Smoking status, *n* (%)					<0.001
Never smoker	525 (46.62)	580 (50.90)	589 (50.93)	626 (50.53)	
Former smoker	357 (29.96)	358 (33.58)	404 (38.29)	377 (38.07)	
Current smoker	258 (23.42)	182 (15.52)	137 (10.77)	127 (11.40)	
Drinking status, *n* (%)					0.056
Nondrinker	368 (29.11)	347 (26.93)	349 (24.26)	307 (21.55)	
Low-to-moderate drinker	699 (64.22)	711 (67.54)	736 (71.04)	772 (73.30)	
Heavy drinker	73 (6.67)	62 (5.53)	45 (4.71)	51 (5.15)	
Body mass index, kg/m^2	33.28 (0.43)	33.67 (0.30)	32.83 (0.26)	33.01 (0.35)	0.124
Physical activity, *n* (%)					<0.001
Inactive	518 (41.61)	452 (38.58)	397 (32.08)	341 (28.13)	
Insufficiently active	315 (28.43)	370 (35.25)	355 (33.88)	383 (32.45)	
Active	307 (29.96)	298 (26.17)	378 (34.03)	406 (39.43)	
Total cholesterol, mg/dL	184.00 (154.00,217.00)	182.00 (152.00,211.00)	176.00 (149.00,208.00)	176.00 (152.00,208.00)	0.089
eGFR, mL/min/1.73m^2	85.04 (64.14,102.09)	84.51 (65.49,100.01)	85.44 (68.08,100.75)	89.94 (76.58,103.33)	<0.001
ACR, mg/g	11.96 (6.76,35.00)	11.50 (6.28,35.79)	10.71 (6.09,26.73)	10.30 (5.77,24.95)	0.008
Energy intake, kcal/day	1,292.00 (988.00, 1,684.00)	1,676.50 (1,376.50, 2,062.50)	1,980.00 (1,614.00, 2,424.00)	2,385.00 (1,929.50, 3,015.00)	<0.001
HbA1c, *n* (%)					0.595
< 7%	670 (61.68)	635 (59.57)	641 (60.31)	645 (57.66)	
≥ 7%	470 (38.32)	485 (40.43)	489 (39.69)	485 (42.34)	
Diabetes medication use, *n* (%)	692 (58.44)	704 (62.74)	735 (64.14)	725 (66.94)	0.025
Diabetes duration, *n* (%)					0.576
<3 years	476 (42.55)	496 (47.62)	503 (45.49)	495 (45.11)	
3-10 years	301 (27.13)	281 (23.01)	280 (26.74)	302 (26.40)	
>10 years	363 (30.32)	343 (29.37)	347 (27.77)	333 (28.49)	
ACEI/ARB use, *n* (%)	579 (47.93)	604 (53.52)	618 (56.19)	601 (53.91)	0.054
Self-reported hypertension, *n* (%)	774 (67.14)	731 (62.87)	748 (66.18)	694 (62.04)	0.180
Diabetic kidney disease, *n* (%)	494 (40.629)	457 (37.251)	427 (33.854)	336 (27.262)	<0.001

PIR: poverty income ratio; eGFR: estimated glomerular filtration rate; ACR: urine albumin to creatinine ratio; HbA1c: HemoglobinA1c; ACEI: angiotensin converting enzyme inhibitor; ARB: angiotensin receptor blocker. Normally distributed continuous variables are described as means ± SE, and continuous variables without a normal distribution are presented as medians [interquartile ranges]. Categorical variables are presented as numbers (percentages). Sampling weights were applied for the calculation of demographic descriptive statistics; *N* reflects the study sample, while percentages reflect the survey weighted.

Given the role of the gut-kidney axis in DKD, fermentable fiber therapies may be beneficial, but the mechanism of action needs to be further explored.

The pathogenesis of DKD is a complex process that involves multiple factors such as high glucose, endothelial dysfunction, inflammation, activation of the renin-angiotensin system, reactive oxygen species, increased advanced glycosylation end products, and glomerular hyperfiltration [28]. Dietary fiber-rich diets can control blood glucose levels [29,30], improve endothelial function in patients with T2DM [31–33], reduce the risk of albuminuria [31], lower serum creatinine levels [34,35], and increase eGFR in CKD patients without DM [35]. The short-chain fatty acids (SCFAs) primarily originated from the fermentation of dietary fiber in the gut, attenuates inflammation and fibrosis in the prevention and treatment of DKD *via* histone butyrylation modification [36]. Additionally, every 5 g/day increase in fiber intake (primarily from legumes and vegetables) can reduce the incidence of

Table 3. ORs (95% CIs) of the prevalence of diabetic kidney disease (DKD) according to quartiles of dietary fiber intake levels among adults in NHANES 2009–2018.

		Quartiles of dietary fiber intake levels, g/day					
	Continuous*	<10.3	10.3–14.6	14.7–20.9	>20.9	P_{trend}	R^2 values
Crude	0.67 (0.59–0.77)	1 [Reference]	0.87 (0.69–1.09)	0.75 (0.59–0.95)	0.55 (0.44–0.69)	<0.001	0.011
Model 1	0.64 (0.56–0.73)	1 [Reference]	0.80 (0.64–1.01)	0.66 (0.53–0.82)	0.52 (0.41–0.65)	<0.001	0.097
Model 2	0.66 (0.56–0.78)	1 [Reference]	0.86 (0.66–1.13)	0.73 (0.58–0.93)	0.57 (0.43–0.76)	<0.001	0.121
Model 3	0.68 (0.58–0.80)	1 [Reference]	0.88 (0.67–1.16)	0.75 (0.59–0.96)	0.59 (0.44–0.79)	<0.001	0.141

*Continuous dietary fiber intake levels were ln-transformed. Model 1 was adjusted for age (continuous), sex (male or female), and race (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black or Other); Model 2 was adjusted for Model 1 plus education level (below high school, high school, or above high school), family income-to-poverty ratio (≤1.0, 1.1–3.0, or >3.0), smoking status (never smoker, former smoker, or current smoker), drinking status (nondrinker, low-to-moderate drinker, or heavy drinker), BMI (continuous), total cholesterol (in quartiles), energy intake levels (in quartiles), physical activity (inactive, insufficiently active, or active), self-reported hypertension (yes or no), and ACEI/ARB use (yes or no); Model 3 was adjusted for Model 2 plus diabetes duration (<3, 3–10, >10 years), HbA1c (<7% or ≥7%), diabetes medication use (yes or no).

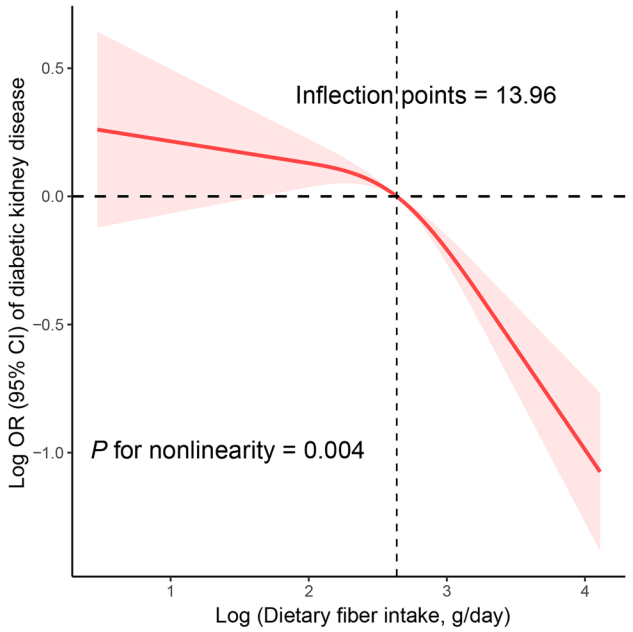

Figure 2. Restricted cubic spline (RCS) regression analysis. We found a nonlinear negative correlation between the level of dietary fiber intake and the prevalence of DKD with a threshold inflection point of 13.96 g/day.

CKD by 11% after 6 years of follow-up [36]. Recently, a study found that a vegetarian dietary pattern was correlated with lower mortality in patients with renal disease [37], and this result is similar to our findings. Moreover, systematic review suggests that dietary fiber pattern may have a beneficial effect on renal outcomes in patients with diabetes, particularly in reducing albuminuria [38]. However, the precise effects and mechanisms of dietary fiber to protect renal function from DKD remain unknown and require further exploration.

Although our study found a negative correlation between the level of dietary fiber intake and the prevalence of DKD in adult subjects, the evidence for the benefits of dietary fiber on renal disease outcomes in diabetic patients is still limited. More precise indications for dietary fiber intake level, the duration of dietary fiber effects, and specific dietary fiber type are needed. Unfortunately, we cannot assess the effect of different sources of dietary fiber (legumes, vegetables, or fruits) and different types of dietary fiber (non-starch polysaccharides, resistant oligosaccharides, and resistant starches) on the prevalence of DKD in adult T2DM patients. Nonetheless, the extrapolated data from the general population suggest that dietary fiber intake may offer protective effects against CKD and reduce mortality rates [29,36,39]. Therefore, it is crucial to encourage individuals, particularly DKD populations, to increase and diversify their dietary fiber intake. According to the present study, it is recommended that patients intake more than 13.96 g of dietary fiber per day, which is equivalent to 1110 g of fruits or vegetables and 330 g of grains. Fruits or vegetables or grains can be paired separately and divided into multiple intakes. Simultaneously, further investigations will be continued to design better trials and explore the effect and mechanism of dietary fiber on DKD.

In addition to dietary intake, various health conditions such as CKD, gastrointestinal disorders, liver disease, hypertension, and medication use can contribute to the leakage of dietary trace elements from the body in adult T2DM patients [40–42]. These factors may disrupt the balance of trace elements, including dietary fiber and zinc, potentially exacerbating the progression of DKD. Notably, zinc metabolism disturbances, such as zincuria, have been associated with microalbuminuria in individuals with type 1 diabetes mellitus (IDDM) [43]. Despite our focus on dietary fiber, these findings are pertinent as they highlight the intricate interplay between trace element homeostasis and renal health. The observed link between zincuria and microalbuminuria underscores the importance of considering various metabolic pathways in the context of DKD. Moreover, studies investigating the role of zinc supplementation in mitigating diabetes-induced zinc dyshomeostasis provide insights into potential therapeutic strategies[44]. Given the significant impact of dietary factors on overall metabolic health, including trace element metabolism, our study on dietary fiber and its potential protective effects against DKD aligns with broader considerations of metabolic pathways implicated in renal complications of T2DM. Further research into the interactions between dietary components, trace element metabolism, and renal outcomes is warranted to comprehensively understand the mechanisms underlying DKD development and identify effective preventive strategies.

The present study contributes novel insights into the relationship between dietary fiber intake and the risk of DKD in adult patients with T2DM. This study offers several notable strengths and contributions. Firstly, this is

Table 4. Threshold effect analysis of dietary fiber intake levels on the prevalence of diabetic kidney disease (DKD) using piecewise binary logistic regression models.

	Inflection point	Group	OR (95% CI)	*P* value	*P* for log likelihood ratio test
Dietary fiber intakes, g/day	13.96	≤13.96	0.86 (0.64–1.15)	0.300	<0.001
		>13.96	0.43 (0.29–0.64)	<0.001	

OR: Odds ratio; CI: confidence interval. Dietary fiber intake levels were ln transformed for fitting the piecewise binary logistic regression model. Analyses was adjusted for age (continuous), sex (male or female), race (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black or Other), education level (below high school, high school, or above high school), family income-to-poverty ratio (≤ 1.0, 1.1–3.0, or >3.0), smoking status (never smoker, former smoker, or current smoker), drinking status (nondrinker, low-to-moderate drinker, or heavy drinker), BMI (continuous), total cholesterol (in quartiles), energy intake levels (in quartiles), physical activity (inactive, insufficiently active, or active), self-reported hypertension (yes or no), ACEI/ARB use (yes or no), diabetes duration (< 3, 3–10, >10 years), HbA1c (< 7% or ≥ 7%), and diabetes medication use (yes or no).

Table 5. Stratified analyses of the associations between quartiles of dietary fiber intake levels and the prevalence of diabetic kidney disease (DKD) in NHANES 2013–2018.

		Dietary fiber intake levels, g/day				
Subgroups	*N*	Quartile 1	Quartile 2	Quartile 3	Quartile 4	$P_{interaction}$
Age, years						
20–65	2583	1 [Reference]	0.93 (0.63–1.38)	0.79 (0.55–1.13)	0.65 (0.43–0.98)	0.416
≥ 65	1937	1 [Reference]	0.84 (0.55–1.26)	0.74 (0.49–1.13)	0.50 (0.32–0.76)	
Sex, *n* (%)						
Male	2346	1 [Reference]	0.89 (0.57–1.39)	0.66 (0.47–0.93)	0.50 (0.33–0.77)	0.268
Female	2174	1 [Reference]	0.84 (0.59–1.18)	0.87 (0.59–1.29)	0.75 (0.47–1.18)	
Race, *n* (%)						
Non–Hispanic White	1570	1 [Reference]	0.81 (0.53–1.23)	0.74 (0.51–1.08)	0.63 (0.40–1.00)	0.359
Other	2950	1 [Reference]	0.97 (0.72–1.30)	0.80 (0.60–1.07)	0.53 (0.40–0.72)	
Smoking status, *n* (%)						
Never smoker	2320	1 [Reference]	0.69 (0.44–1.09)	0.61 (0.39–0.95)	0.48 (0.29–0.78)	0.191
Former smoker	1496	1 [Reference]	0.98 (0.60–1.62)	0.85 (0.51–1.42)	0.55 (0.33–0.91)	
Current smoker	704	1 [Reference]	1.15 (0.65–2.03)	0.83 (0.42–1.65)	1.39 (0.66–2.94)	
Body mass index, kg/m^2						
<30	1870	1 [Reference]	0.95 (0.62–1.45)	0.65 (0.44–0.97)	0.47 (0.30–0.74)	0.348
>30	2650	1 [Reference]	0.87 (0.62–1.21)	0.82 (0.59–1.15)	0.68 (0.47–0.98)	
Self–reported hypertension, *n* (%)						
No	1573	1 [Reference]	1.06 (0.68–1.68)	1.30 (0.83–2.05)	1.13 (0.76–1.69)	0.064
Yes	2947	1 [Reference]	0.79 (0.57–1.09)	0.60 (0.43–0.82)	0.43 (0.29–0.66)	
Diabetes duration, years						
< 3	1970	1 [Reference]	0.83 (0.59–1.18)	0.79 (0.55–1.12)	0.59 (0.39–0.91)	0.721
≥ 3	2550	1 [Reference]	0.94 (0.65–1.36)	0.74 (0.53–1.04)	0.59 (0.39–0.91)	
HbA1c, *n* (%)						
< 7%	2591	1 [Reference]	0.90 (0.65–1.26)	0.80 (0.55–1.18)	0.72 (0.48–1.06)	0.820
≥ 7%	1929	1 [Reference]	0.88 (0.54–1.42)	0.70 (0.45–1.08)	0.44 (0.26–0.75)	
ACEI/ARB use, *n* (%)						
No	2118	1 [Reference]	1.19 (0.82–1.75)	1.01 (0.70–1.46)	0.74 (0.50–1.10)	0.251
Yes	2402	1 [Reference]	0.70 (0.51–0.96)	0.60 (0.44–0.82)	0.48 (0.32–0.71)	

Analyses were adjusted for covariates age (continuous), sex (male or female), race (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black or Other), education level (below high school, high school, or above high school), family income-to-poverty ratio (≤ 1.0, 1.1–3.0, or >3.0), smoking status (never smoker, former smoker, or current smoker), drinking status (nondrinker, low-to-moderate drinker, or heavy drinker), BMI (continuous), total cholesterol (in quartiles), energy intake levels (in quartiles), physical activity (inactive, insufficiently active, or active), self-reported hypertension (yes or no), ACEI/ARB use (yes or no), diabetes duration (< 3, 3–10, >10 years), HbA1c (< 7% or ≥ 7%), and diabetes medication use (yes or no) when they were not the strata variables.

Table 6. Sensitivity analysis of ORs (95% CIs) for the prevalence of diabetic kidney disease (DKD) by quartiles of dietary fiber intake levels among adults, excluding participants with missing data (*n* = 3899).

		Quartiles of dietary fiber intake levels, g/day				
	Continuous*	OR	OR (95% CI)	OR (95% CI)	OR (95% CI)	P_{trend}
Crude	0.63 (0.55–0.73)	1 [Reference]	0.84 (0.66–1.08)	0.69 (0.54–0.88)	0.49 (0.39–0.63)	<0.001
Model 1	0.61 (0.52–0.70)	1 [Reference]	0.76 (0.60–0.97)	0.61 (0.48–0.78)	0.46 (0.37–0.59)	<0.001
Model 2	0.62 (0.53–0.73)	1 [Reference]	0.82 (0.63–1.07)	0.68 (0.52–0.87)	0.50 (0.38–0.66)	<0.001
Model 3	0.63 (0.54–0.74)	1 [Reference]	0.84 (0.64–1.09)	0.70 (0.54–0.91)	0.51 (0.38–0.68)	<0.001

*Continuous dietary fiber intake levels were ln-transformed. Model 1 was adjusted for age (continuous), sex (male or female), and race (Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black or Other); Model 2 was adjusted for Model 1 plus education level (below high school, high school, or above high school), family income-to-poverty ratio (≤1.0, 1.1–3.0, or >3.0), smoking status (never smoker, former smoker, or current smoker), drinking status (nondrinker, low-to-moderate drinker, or heavy drinker), BMI (continuous), total cholesterol (in quartiles), energy intake levels (in quartiles), physical activity (inactive, insufficiently active, or active), self-reported hypertension (yes or no), and ACEI/ARB use (yes or no); Model 3 was adjusted for Model 2 plus diabetes duration (<3, 3–10, >10 years), HbA1c (<7% or ≥7%), diabetes medication use (yes or no).

the first study that uses the NHANES database to explore the link between dietary fiber intake and the risk of DKD in adult T2DM patients. By leveraging this nationally representative dataset, the study achieves a robust and comprehensive understanding of the relationship, ensuring the generalizability of findings to the broader T2DM population in the U.S [17]. Secondly, the study's large sample size of 4,520 T2DM patients enhances statistical power and reliability, allowing for more precise estimates of effect sizes and reducing the likelihood of chance findings. This extensive sample size enables robust subgroup analyses, facilitating the exploration of potential modifiers and providing insights into the consistency and generalizability of observed associations across diverse demographic and clinical subgroups. Furthermore, the identification of a nonlinear negative correlation between dietary fiber intake and DKD prevalence is a significant finding. The detection of a threshold inflection point at 13.96 g/day highlights the potential dose–response relationship between dietary fiber intake and DKD risk, suggesting that increasing dietary fiber intake beyond this threshold may confer additional protective benefits against DKD development in T2DM patients. Together, these findings may influence dietary guidelines and clinical practice recommendations for dietary fiber intake in patients with type 2 diabetes.

This study has several limitations that should be considered. First, the observational nature of our study design does not allow for establishing a causal relationship between dietary fiber intake and DKD prevalence. Although we adjusted for multiple covariates, the possibility of residual confounding by unmeasured factors, such as additional dietary components, genetic predispositions, or socioeconomic variables, cannot be excluded. Future studies with improved data collection and advanced analytical approaches are needed to address these issues. Second, the dietary fiber intake was assessed at a single time point, while DKD develops over time. This temporal disconnect may introduce bias and limit the ability to infer the long-term impact of dietary fiber on DKD. Furthermore, reliance on self-reported dietary data is subject to recall bias and measurement error. Although standardized protocols were applied to minimize inaccuracies, future research using objective methods, such as biomarkers or comprehensive dietary records, would strengthen the reliability of these findings. Third, while we performed subgroup analyses across key factors such as age, sex, BMI, and diabetes duration, no significant interactions were observed, suggesting that the association between dietary fiber intake and DKD prevalence was consistent across these subgroups. However, residual confounding cannot be fully ruled out, and future studies with larger sample sizes and more detailed variable assessments could provide further insight into potential effect modifiers. Lastly, the findings are based on a U.S. population and may not be generalizable to other populations with different dietary habits, genetic backgrounds, or healthcare systems. Additional research in diverse settings is essential to validate these results and understand their broader applicability. Despite these limitations, this study highlights the potential role of dietary fiber in reducing DKD prevalence. Longitudinal studies and randomized controlled trials are necessary to confirm these findings and explore their implications for prevention and management strategies.

Conclusions

Our study using data from the NHANES 2009–2018 indicates a non-linear and negative correlation between dietary fiber intake and the prevalence of DKD in adults with T2DM. We found that higher dietary fiber intake was associated with a lower risk of DKD, with a threshold inflection point identified at 13.96 g/day. Importantly, this correlation remained consistent across various demographic and clinical subgroups. Although the data in this study came from the U.S. community, the sample size was large enough to suggest that dietary fiber plays a role in the prevalence of DKD. It may be of societal significance for China, which has a large population base and high rates of death and disability due to DKD. However, further large-scale prospective studies and clinical trials with diverse populations are required to confirm these findings.

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Ethical approval and consent to participate

Ethical clearance was granted by the U.S. NCHS Ethics Review Board (NCHSERB) to access the U.S. NHANES database, under protocol #2005-06 and #2011-17.

Disclaimer

The views and opinions described in this publication do not necessarily reflect those of the grantor.

Author contributions

LY and BR were major contributors in writing the manuscript. All authors read and approved the final manuscript.

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Data availability statement

The data that support the findings of this study are available from the U.S. CDC NHANES project (https://www.cdc.gov/nchs/nhanes/index.htm).

References

[1] Magliano DJ, Boyko EJ. IDF diabetes atlas (10th edn). Brussels: IDF; 2021.

[2] Forbes JM, Cooper ME. Mechanisms of diabetic complications. Physiol Rev. 2013;93(1):137–188. doi: 10.1152/physrev.00045.2011.

[3] Thornton Snider J, Sullivan J, van Eijndhoven E, et al. Lifetime benefits of early detection and treatment of diabetic kidney disease. PloS One. 2019;14(5):e0217487. doi: 10.1371/journal.pone.0217487.

[4] Alicic RZ, Rooney MT, Tuttle KR. Diabetic kidney disease: challenges, progress, and possibilities. Clin J Am Soc Nephrol. 2017;12(12):2032–2045. doi: 10.2215/CJN.11491116.

[5] White S, Chadban S. Diabetic kidney disease in Australia: current burden and future projections. Nephrology (Carlton). 2014;19(8):450–458. doi: 10.1111/nep.12281.

[6] Meng Y, Bai H, Yu Q, et al. High-resistant starch, low-protein flour intervention on patients with early type 2 diabetic nephropathy: a randomized trial. J Ren Nutr. 2019;29(5):386–393. doi: 10.1053/j.jrn.2018.12.005.

[7] Yamazaki T, Mimura I, Tanaka T, et al. Treatment of diabetic kidney disease: current and future. Diabetes Metab J. 2021;45(1):11–26. doi: 10.4093/dmj.2020.0217.

[8] Thomas MC, Brownlee M, Susztak K, et al. Diabetic kidney disease. Nat Rev Dis Primers. 2015;1:15018. doi: 10.1038/nrdp.2015.18.

[9] de Boer IH, Rue TC, Hall YN, et al. Temporal trends in the prevalence of diabetic kidney disease in the United States. JAMA. 2011;305(24):2532–2539. doi: 10.1001/jama.2011.861.

[10] Zac-Varghese S, Winocour P. Managing diabetic kidney disease. Br Med Bull. 2018;125(1):55–66. doi: 10.1093/bmb/ldx047.

[11] Howlett JF, Betteridge VA, Champ M, et al. The definition of dietary fiber - discussions at the Ninth Vahouny Fiber Symposium: building scientific agreement. Food Nutr Res. 2010;54:5750.

[12] Sun L, Zhang Z, Xu J, et al. Dietary fiber intake reduces risk for Barrett's esophagus and esophageal cancer. Crit Rev Food Sci Nutr. 2017;57(13):2749–2757. doi: 10.1080/10408398.2015.1067596.

[13] Liu X, Wu Y, Li F, et al. Dietary fiber intake reduces risk of inflammatory bowel disease: result from a meta-analysis. Nutrition Research (New York, NY). 2015;35(9):753–758. doi: 10.1016/j.nutres.2015.05.021.

[14] InterAct C. Dietary fibre and incidence of type 2 diabetes in eight European countries: the EPIC-InterAct Study and a meta-analysis of prospective studies. Diabetologia. 2015;58(7):1394–1408.

[15] Threapleton DE, Greenwood DC, Evans CEL, et al. Dietary fibre intake and risk of cardiovascular disease: systematic review and meta-analysis. BMJ. 2013;347:f6879. doi: 10.1136/bmj.f6879.

[16] Xu H, Ding Y, Xin X, et al. Dietary fiber intake is associated with a reduced risk of ovarian cancer: a dose-response meta-analysis. Nutr Res (New York, NY). 2018;57:1–11. doi: 10.1016/j.nutres.2018.04.011.

[17] Aggarwal R, Bibbins-Domingo K, Yeh RW, et al. Diabetes screening by race and ethnicity in the United States: equivalent body mass index and age thresholds. Ann Intern Med. 2022;175(6):765–773. doi: 10.7326/M20-8079.

[18] Li B, Zhang F, Jiang H, et al. Adequate intake of dietary fiber may relieve the detrimental impact of blood lead on dyslipidemia among US adults: a study of data from the National Health and Nutrition Examination Survey Database. Nutrients. 2023;15(20):4434. doi: 10.3390/nu15204434.

[19] Zhu X, Cheang I, Tang Y, et al. Associations of serum carotenoids with risk of all-cause and cardiovascular mortality in hypertensive adults. J Am Heart Assoc. 2023;12(4):e027568. doi: 10.1161/JAHA.122.027568.

[20] Ni G, Jia Q, Li Y, et al. Association of Life's Essential 8 with abdominal aortic calcification and mortality among middle-aged and older individuals. Diabetes Obes Metab. 2024;26(11):5126–5137. doi: 10.1111/dom.15854.

[21] Koh GY, Rowling MJ. Resistant starch as a novel dietary strategy to maintain kidney health in diabetes mellitus. Nutr Rev. 2017;75(5):350–360. doi: 10.1093/nutrit/nux006.

[22] Stephen AM, Champ MMJ, Cloran SJ, et al. Dietary fibre in Europe: current state of knowledge on definitions, sources, recommendations, intakes and relationships to health. Nutr Res Rev. 2017;30(2):149–190. doi: 10.1017/S095442241700004X.

[23] FAO. WHO: guidelines on nutrition labelling CXG 2-1985. Geneva: WHO; 2021.

[24] So D, Gibson PR, Muir JG, et al. Dietary fibres and IBS: translating functional characteristics to clinical value in the era of personalised medicine. Gut. 2021;70(12):2383–2394. doi: 10.1136/gutjnl-2021-324891.

[25] Dai F-J, Chau C-F. Classification and regulatory perspectives of dietary fiber. J Food Drug Anal. 2017;25(1):37–42. doi: 10.1016/j.jfda.2016.09.006.

[26] Dhingra D, Michael M, Rajput H, et al. Dietary fibre in foods: a review. J Food Sci Technol. 2012;49(3):255–266. doi: 10.1007/s13197-011-0365-5.

[27] Włodarczyk M, Śliżewska K. Efficiency of resistant starch and dextrins as prebiotics: a review of the existing evidence and clinical trials. In: nutrients. 2021;13(11):3808. doi: 10.3390/nu13113808.

[28] Maezawa Y, Takemoto M, Yokote K. Cell biology of diabetic nephropathy: roles of endothelial cells, tubulointerstitial cells and podocytes. J Diabetes Investig. 2015;6(1):3–15. doi: 10.1111/jdi.12255.

[29] Fujii H, Iwase M, Ohkuma T, et al. Impact of dietary fiber intake on glycemic control, cardiovascular risk factors and chronic kidney disease in Japanese patients with type 2 diabetes mellitus: the Fukuoka Diabetes Registry. Nutr J. 2013;12:159. doi: 10.1186/1475-2891-12-159.

[30] Silva FM, Kramer CK, de Almeida JC, et al. Fiber intake and glycemic control in patients with type 2 diabetes mellitus: a systematic review with meta-analysis of randomized controlled trials. Nutr Rev. 2013;71(12):790–801. doi: 10.1111/nure.12076.

[31] Metcalf PA, Baker JR, Scragg RK, et al. Dietary nutrient intakes and slight albuminuria in people at least 40 years old. Clin Chem. 1993;39(10):2191–2198. doi: 10.1093/clinchem/39.10.2191.

[32] Post RE, Mainous AG, King DE, et al. Dietary fiber for the treatment of type 2 diabetes mellitus: a meta-analysis. J Am Board Fam Med. 2012;25(1):16–23. doi: 10.3122/jabfm.2012.01.110148.
[33] Kondo K, Morino K, Nishio Y, et al. Fiber-rich diet with brown rice improves endothelial function in type 2 diabetes mellitus: a randomized controlled trial. PloS One. 2017;12(6):e0179869. doi: 10.1371/journal.pone.0179869.
[34] Chiavaroli L, Mirrahimi A, Sievenpiper JL, et al. Dietary fiber effects in chronic kidney disease: a systematic review and meta-analysis of controlled feeding trials. Eur J Clin Nutr. 2015;69(7):761–768. doi: 10.1038/ejcn.2014.237.
[35] Salmean YA, Segal MS, Langkamp-Henken B, et al. Foods with added fiber lower serum creatinine levels in patients with chronic kidney disease. J Ren Nutr. 2013;23(2):e29–32–e32. doi: 10.1053/j.jrn.2012.04.002.
[36] Mirmiran P, Yuzbashian E, Asghari G, et al. Dietary fibre intake in relation to the risk of incident chronic kidney disease. Br J Nutr. 2018;119(5):479–485. doi: 10.1017/S0007114517003671.
[37] Kelly JT, Palmer SC, Wai SN, et al. Healthy dietary patterns and risk of mortality and ESRD in CKD: a meta-analysis of cohort studies. Clin J Am Soc Nephrol. 2017;12(2):272–279. doi: 10.2215/CJN.06190616.
[38] Carvalho CM, Gross LA, de Azevedo MJ, et al. Dietary Fiber Intake (Supplemental or Dietary Pattern Rich in Fiber) and Diabetic Kidney Disease: A Systematic Review of Clinical Trials. Nutrients. 2019;11(2):347. doi: 10.3390/nu11020347.
[39] Krishnamurthy VMR, Wei G, Baird BC, et al. High dietary fiber intake is associated with decreased inflammation and all-cause mortality in patients with chronic kidney disease. Kidney Int. 2012;81(3):300–306. doi: 10.1038/ki.2011.355.
[40] Steinbrenner H, Duntas LH, Rayman MP. The role of selenium in type-2 diabetes mellitus and its metabolic comorbidities. Redox Biol. 2022;50:102236. doi: 10.1016/j.redox.2022.102236.
[41] Himoto T, Masaki T. current trends of essential trace elements in patients with chronic liver diseases. Nutrients. 2020;12(7):2084. doi: 10.3390/nu12072084.
[42] Hasanato RM. Trace elements in type 2 diabetes mellitus and their association with glycemic control. Afr Health Sci. 2020;20(1):287–293. doi: 10.4314/ahs.v20i1.34.
[43] Brun J-F, Fons C, Fussellier M, et al. Urinary zinc and its relationships with microalbuminuria in type I diabetics. Biol Trace Elem Res. 1992;32(1-3):317–323. doi: 10.1007/BF02784617.
[44] Barman S, Pradeep SR, Srinivasan K. Zinc supplementation mitigates its dyshomeostasis in experimental diabetic rats by regulating the expression of zinc transporters and metallothionein. Metallomics. 2017;9(12):1765–1777. doi: 10.1039/c7mt00210f.