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Association between the dietary index for gut microbiota and all-cause/cardiovascular mortality in patients with metabolic dysfunction-associated steatotic liver disease

Wenhao Wu¹, Jiacheng Cheng¹, Zebin Hou², Qi Yan¹, Xiaojuan Wang¹, Junhua He¹, Yikun Zhu¹ and Jin Li^{1*}

Abstract

Background Nutrient interactions with the gut microbiome modulate the development of metabolic dysfunction-associated steatotic liver disease (MASLD) and cardiovascular disease. The dietary index for gut microbiota (DI-GM) is an innovative and comprehensive diet index to assess quality for health of gut microbiota.

Method This is a cohort study from the interview date to the date of death or the end of follow-up (December 31, 2019). Involving 13,390 participants in National Health and Nutrition Examination Survey (NHANES), including 3538 with MASLD and 9852 without MASLD. DI-GM was calculated using 14 foods and nutrients with clear positive or negative impacts on gut microbiota, and MASLD was assessed based on liver steatosis and cardiometabolic risk factors, with all-cause and cardiovascular mortality determined through probabilistic matching and death certificate review. Restricted Cubic Spline (RCS) analysis and Cox regression were played for the DI-GM-mortality correlation. Subgroup analyses to identify the interactive factors that influence their relationship in MASLD. Six sensitivity analyses reinforced findings.

Results MASLD participants exhibited lower DI-GM levels, which were statistically associated with higher mortality. Each DI-GM unit increase in MASLD was associated with a 13% lower all-cause mortality (HR = 0.87, 95% CI 0.78–0.98) and a 19.5% lower cardiovascular mortality (HR = 0.805, 95% CI 0.690–0.938). In advanced fibrosis MASLD, this increase was linked to a 20% lower cardiovascular mortality risk (HR = 0.800, 95% CI 0.691–0.927). Age and prediabetes significantly modified DI-GM's effect on mortality risk.

Conclusions The study revealed a significant inverse correlation between the DI-GM and all-cause/cardiovascular mortality in patients with MASLD, which provide dietary suggestions and guidance for MASLD patients in preventing early mortality. However, limitations such as the cross-sectional design, potential residual confounding, and population-specific generalizability should be considered when interpreting these findings.

Keywords Metabolic dysfunction-associated steatotic liver disease, Dietary index for gut microbiota, Cardiovascular mortality, All-cause mortality, Gut microbiota, National Health and Nutrition Examination Survey

*Correspondence:

Jin Li

jinli807@126.com

Full list of author information is available at the end of the article



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Graphical abstract

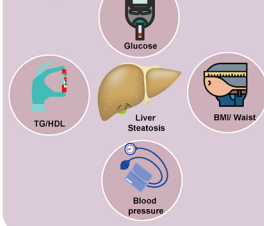
Association between the dietary index for gut microbiota and all-cause/cardiovascular mortality in patients with metabolic dysfunction-associated steatotic liver disease

Definition

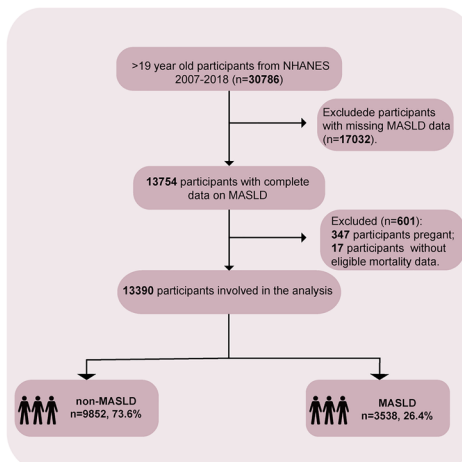
DI-GM:

- **Beneficial components:** avocados, broccoli, chickpeas, coffee, cranberries, fermented dairy products, fiber, green tea, soy, and whole grains.
- **Detrimental components:** red meat, processed meat, refined grains, and high-fat diets (constituting $\geq 40\%$ of energy from fat)

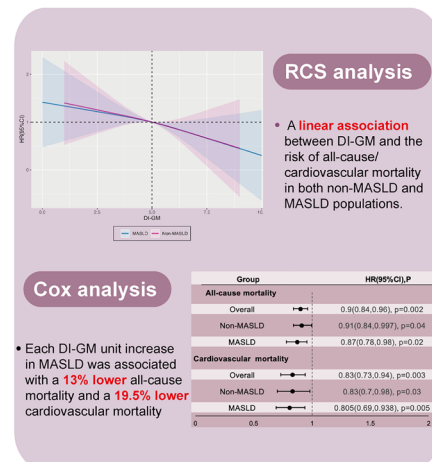
MASLD



Participants selection process



Result



Introduction

Metabolic dysfunction-associated steatotic liver disease (MASLD), a common chronic liver disease, has grown significantly over three decades, imposing a major health-care burden [1–3]. In particular, its global prevalence surged 50% from 2005 to 2020 and may affect half of the US population by 2040 [4]. This new terminology was developed from earlier concepts, such as Nonalcoholic Fatty Liver Disease (NAFLD), which has limitations, as it relies on exclusion criteria and fails to capture the underlying pathophysiology [5]. In 2020, Eslam et al. proposed a new term, Metabolic Dysfunction-Associated Fatty Liver Disease (MAFLD), which encompasses a spectrum of liver diseases associated with metabolic disorders, emphasizing the metabolic abnormalities underlying fatty liver disease [5]. Nevertheless, concerns remain regarding the heterogeneous etiology of MAFLD and the potential stigmatizing language associated with its terminology. Recently, through a Delphi consensus process involving global experts, MASLD was recommended as an alternative to MAFLD [5]. The change from NAFLD to MAFLD/MASLD is not solely a nomenclature change, but it is acquiring a more comprehensive scope over a multi-organ metabolic dysfunction rather than a disease solely associated to an abnormal liver ultrasound imaging

[6]. It has been shown that MAFLD can be a better predictive and prognostic diagnosis compared to NAFLD in cardiovascular adverse events [7]. MASLD's diagnostic criteria are less restrictive compared to MAFLD's rigid requirement of two metabolic risk factors, as it allows the use of any single risk factor that is supported by easily accessible data [8]. Currently, cardiovascular mortality has surpassed liver-related deaths as the leading cause of mortality among patients with MASLD [9, 10]. MASLD highlighting metabolic dysfunction and cardiovascular risks, expanding the scope to a broader population, emphasizing cardiovascular risk factors, and providing enhanced flexibility in assessing the risk of cardiovascular disease (CVD), thus improving the awareness and management of CVD risk [8]. Despite prevalent use of outdated terms, this study adopts the new terminology.

MASLD represents a spectrum of liver diseases characterized by hepatic steatosis (fat accumulation) driven by metabolic dysfunction, independent of alcohol consumption. Its pathogenesis involves a complex interplay of metabolic, inflammatory, environmental, and dietary factors et al. [11]. While extensive understanding has been gained regarding the dietary mechanisms underlying MASLD, the role of the gut microbiota in its pathogenesis remains poorly understood. The intestinal

microbiome, an intricate ecosystem encompassing bacteria, archaea, fungi, and viruses, resides symbiotically within the human body [12]. Notable alterations in the gut microbiome and disruptions of the gut-liver axis (GLA) contribute substantially to the pathogenesis of human MAFLD [13]. Additionally, the gut microbiome plays a multifaceted role in cardiovascular health, with microbial dysbiosis acting as a common trigger in the pathogenesis of both MAFLD and CVD [14, 15]. Dietary factors and alterations are pivotal in shaping the composition of the microbiota. MASLD is now known to have both genetic and environmental risk factors. It has been shown in the last 15 years that several gene variants are closely associated with hepatosteatosis, the most important of which being PNPLA3 [16]. Diet is one of the key environmental risk factors influencing the development of MASLD [17–19]. Therefore, the manipulation of dietary habits to cultivate a healthy gut microbiota has emerged as both effective and economical intervention for MASLD patients. While numerous dietary indices are currently available, their associations with indices of gut microbiota diversity and richness are not uniform [20–22].

To address this gap, Bezawit E. Kase and colleagues developed the dietary index for gut microbiota (DI-GM) through a systematic review of interventional and longitudinal observational studies, identifying 14 food items and nutrients that significantly influence the gut microbiota [23]. The DI-GM comprises 4 detrimental ones (e.g., refined grains, and high-fat diets) and 10 beneficial foods (e.g., fermented dairy products, fiber), which collectively enhance alpha and beta diversity indices, increase concentrations of short-chain fatty acids (SCFAs) such as butyrate and acetate, and modulate the Bacteroidetes-to-Firmicutes ratio [24–26].

The DI-GM stands out as a scientifically robust and innovative tool, offering a comprehensive and specific assessment of diet-gut microbiota interactions. Importantly, the DI-GM fosters interdisciplinary collaboration, bridging nutrition, microbiology, medicine, and epidemiology to advance our understanding of diet-microbiota-host interactions. Previous research has demonstrated the broader implications of DI-GM, linking higher scores to reduced biological age, lower incidence of depression, and alleviation of specific symptoms, underscoring the profound influence of a gut microbiota-healthy diet on overall human health [27, 28].

Specifically, DI-GM incorporates key nutrients and food components with well-defined mechanistic roles in modulating gut microbiota and disease outcomes. For example, Dietary fiber (e.g., from whole grains, vegetables, and fruits) acts as a prebiotic, promoting the growth of *Bifidobacterium* and *Lactobacillus* while enhancing

short-chain fatty acid (SCFA) production (e.g., butyrate, acetate) [29, 30]. These SCFAs improve intestinal barrier integrity, reduce systemic inflammation, and modulate lipid metabolism, thereby mitigating hepatic steatosis and cardiovascular risk [29, 30]. Fermented dairy products (e.g., yogurt, kefir) introduce probiotic strains that restore microbial balance, suppress pathogenic bacteria, and enhance anti-inflammatory cytokine production [31, 32]. This dual action reduces gut permeability and systemic endotoxemia, which are critical drivers of both MASLD progression and CVD development [31, 32]. Polyphenol-rich foods (e.g., berries, tea, dark chocolate) act as postbiotics, modulating microbial fermentation patterns to increase SCFA production and reduce oxidative stress. These effects are linked to improved insulin sensitivity and reduced atherosclerosis risk [33, 34]. These mechanistic insights underscore the importance of DI-GM in capturing diet-microbiota interactions that directly influence MASLD and CVD outcomes.

Despite these advancements, the association between DI-GM and mortality risk in MASLD patients remains unexplored. Given the gut microbiome's dual role in the pathogenesis of MASLD and cardiovascular disease (CVD), we hypothesize that DI-GM may serve as a pivotal indicator for mitigating mortality risk in this vulnerable population. This study seeks to address this critical gap by investigating the relationship between DI-GM and all-cause/cardiovascular mortality in MASLD patients. By doing so, it aims to provide evidence-based dietary recommendations for maintaining gut microbiome stability and designing targeted interventions to counteract the mortality risks associated with gut microbiota dysbiosis in MASLD.

Method

Study participants

NHANES is a US health and nutrition survey of civilians, combining interview and physical exam data. Methodologies are detailed in separate publications [35]. The survey includes demographics, socioeconomic factors, diet, and health status. Approved by the National Center for Health Statistics (NCHS) Ethics Board, the study adheres to STROBE guidelines and used data from 2007 to 2018 cycles [36]. Pregnant individuals were excluded due to the potential confounding effects of pregnancy on metabolic and hepatic parameters, as well as the unique physiological changes in the gut microbiome during gestation. Participants with missing MASLD data were excluded because the primary outcome of this study (MASLD status) relies on accurate diagnosis via liver steatosis and cardiometabolic risk factors. Incomplete data on these key variables would compromise the validity of our analysis. The population was 30,786 individuals aged ≥ 20 ,

excluding pregnant individuals (n=347), those with missing MASLD data (n=17,032), or inadequate follow-up (n=17), leaving a final sample of 13,390 (9852 non-MASLD, 3538 MASLD) (Fig. 1).

Definition of DI-GM

Drawing from the research conducted by Kase et al., a total of 14 food items or nutrients were identified as constituent elements of the DI-GM [23]. These included avocados, broccoli, chickpeas, coffee, cranberries, fermented dairy products, fiber, green tea, soy, and whole grains, categorized as beneficial components. In contrast, red meat, processed meat, refined grains, and high-fat diets (constituting $\geq 40\%$ of energy from fat) were classified as detrimental components. The DI-GM scoring system employs gender-specific medians to account for inherent differences in dietary patterns, nutrient metabolism, and gut microbiota composition between males and females. Studies have shown that sex differences influence dietary intake (e.g., protein, fiber, and fat consumption) and microbial diversity, which may affect the relationship between diet and disease outcomes [37, 38]. Using gender-specific medians to reduce potential confounding and improve the accuracy of DI-GM as a proxy for gut microbiota health in each sex. For beneficial foods, participants whose intake exceeded the gender-specific median were

assigned a score of 1, whereas those with intake below the median received a score of 0. Conversely, for detrimental foods, a score of 0 was assigned to participants with intake above the gender-specific median, and a score of 1 to those with intake below the median. The DI-GM score was computed by summing the scores from each component, resulting in a range of 0 to 14.

Definition of MASLD and advanced fibrosis

Fatty liver index (FLI) score ≥ 60 is diagnosed as steatotic liver disease (SLD) [39, 40]. Participants with were excluded adhering to the Delphi procedure to meet the diagnostic criteria for MASLD. Finally, MASLD is defined as SLD that is co-existent with at least one cardiometabolic risk factor. Exclusion criteria and cardiometabolic risk factor were provided in the Supplementary Methods.

For the assessment of advanced fibrosis, we utilized three non-invasive scoring systems: the NAFLD fibrosis score (NFS), the fibrosis-4 (FIB4) score, and the aspartate aminotransferase to platelet ratio index (APRI). A patient was considered to have advanced fibrosis if at least one of these scores indicated a high probability of advanced fibrosis. The specific cut-off values for these scores were provided in the Supplementary Methods [41].

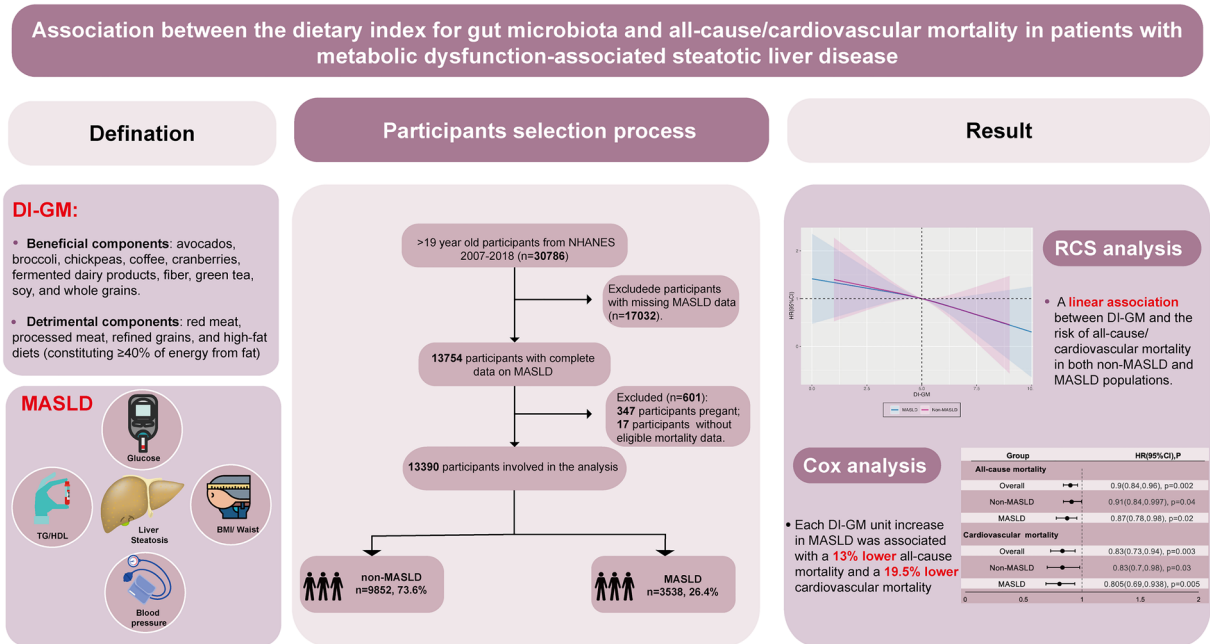


Fig. 1 Graphical abstract and flowchart of studied participants selection. MASLD metabolic dysfunction-associated steatotic liver disease; Non-MASLD without MASLD, DI-GM dietary index for gut microbiota, RCS restricted cubic spline

Outcomes and covariates

NHANES data were linked to the National Death Index (NDI) to determine survival status through probabilistic matching and death certificate review, which can calculate all-cause and cardiovascular mortality. Causes of death were categorized using the Tenth Revision of the International Classification of Diseases (ICD-10). All-cause mortality was defined as deaths occurring due to any etiology. Cardiovascular mortality was defined as fatalities resulting from primary cardiovascular disorders (e.g., ischemic heart disease, heart failure) and cerebrovascular events, categorized under ICD-10 codes I00–I09, I11, I13, I20–I51, and I60–I69. The time to event, measured in months, was computed from the date of the NHANES interview to the date of death or the conclusion of follow-up (December 31, 2019), whichever came first.

In addition to the primary outcomes, a comprehensive set of potential confounding factors was gathered and included as covariates in the analysis. These covariates encompassed age, sex, race/ethnicity, education level, marital status, poverty income ratio (PIR), presence of prediabetes mellitus (preDM), history of CVD, and cancer, as well as measures of energy intake, physical activity and alcohol consumption. Alanine aminotransferase (ALT) and aspartate aminotransferase (AST) as well-established markers of hepatocellular injury and hepatic inflammation, which are central to the pathophysiology of MASLD [42].

Detail definitions of these covariates was shown in the Supplementary Methods.

Statistical analyses

To uphold NHANES analysis integrity, we adhered to NCHS weighting guidelines. We calculated weighted means ($\pm$ standard deviation [SD]) for continuous variables and assessed the frequency (proportions) for categorical variables, utilizing weighted t-tests and chi-square tests accordingly. We utilized RCS analysis to visualize DI-GM-mortality linear association while adjusting for a multitude of potential covariates. The knot placement in the RCS curves was determined through the minimization of Akaike's Information Criterion (AIC) [43].

Furthermore, we used Cox regression to estimate mortality risk ratios, reporting hazard ratios (HR) with 95% confidence intervals (CI) and tested the assumption of proportional hazards using Schoenfeld residuals. We adjusted for confounders in a three-model stepped approach: Model 1 remained unadjusted; Model 2 incorporated adjustments for age, sex, race/ethnicity, education level, marital status, and PIR levels; while Model 3 further adjusted preDM, history of CVD

and cancer, energy intake, physical activity, ALT, AST, and alcohol consumption. Missing data were handled using multiple imputation techniques to maintain the integrity of the dataset [44].

Subgroup analyses, incorporating multiplicative interaction terms, were carried out to investigate whether the associations between the DI-GM and all-cause/cardiovascular mortality were modified by variables such as sex, age (<40 or ≥ 40 years), race/ethnicity, education level, marital status, PIR levels, preDM, history of CVD, history of cancer, energy intake (<2400 or ≥ 2400 kcal), and physical activity (<200 or ≥ 200 METs-hour/week). To evaluate the robustness of our results, 6 sensitivity analyses were conducted. Sensitivity assessments were conducted exclusively based on model 3. Detail process was shown in the Supplementary Methods. All statistical analyses were performed using R software version 4.1.2, and a two-tailed P value with a significance level of 0.05 was used for all statistical tests to determine significance.

Result

Baseline characteristics and comparative analyses

Supplementary Table S1 presents the baseline characteristics of the 13,390 participants enrolled in the study. Participants were categorized into two groups based on their survival status: Survivor group ($n=12,219$) and non-Survivor group ($n=1171$). It was found that, compared to the Survivor group, the non-Survivor group exhibited a lower DI-GM score (Survivors vs non-Survivors: 5.12 ± 0.03 vs 4.95 ± 0.07 , $p=0.009$). Additionally, a higher prevalence of MASLD was observed in the non-Survivor group (Survivors vs non-Survivors: 25.33% vs 31.82%, $p=0.001$).

To further investigate the demographic characteristics of MASLD patients, participants were divided into two subgroups: MASLD ($n=3538$, 26.4%) and non-MASLD ($n=9852$, 73.6%). The results are presented in Table 1. It showed that compared to non-MASLD participants, MASLD patients were more likely to be male, non-Hispanic white, married, older, and have a lower educational level. They also more frequently had comorbidities such as cancer and CVD, a history of preDM, and engaged in less physical activity. Importantly, MASLD patients exhibited a lower DI-GM score (non-MASLD vs MASLD: 5.15 ± 0.03 vs 5.00 ± 0.04 , $p=0.002$) and had a higher mortality (non-MASLD vs MASLD: 5.66% vs 7.62%, $p=0.001$). Among all causes of death, cardiovascular mortality was the most common, with a higher incidence in the MASLD group compared to the non-MASLD group (non-MASLD vs MASLD: 25.31% vs 33.74%, $p<0.001$).

Table 1 Weighted sample characteristics of non-MASLD and MASLD participants in NHANES 2007–2018

Variable	Total	Non-MASLD (n = 9852)	MASLD (n = 3538)	P-value
DI-GM ^a	5.11 (0.03)	5.15 (0.03)	5.00 (0.04)	0.002
Causes of mortality ^b				< 0.001
Cancer-specific deaths	302 (1.67)	206 (27.12)	96 (27.23)	
Cardiovascular-specific deaths	342 (1.73)	222 (25.31)	120 (33.74)	
Diabetes-specific deaths	51 (0.25)	22 (2.40)	29 (7.67)	
Other	476 (2.51)	359 (45.17)	117 (31.35)	
Non-survivors ^b	1171 (6.16)	809 (5.66)	362 (7.62)	0.001
Sex ^b				< 0.001
Female	6808 (51.01)	5088 (52.67)	1720 (46.22)	
Male	6582 (48.99)	4764 (47.33)	1818 (53.78)	
Age (years) ^a	47.91 (0.26)	46.19 (0.31)	52.88 (0.37)	< 0.0001
Race and ethnicity ^b				0.004
Mexican American	2073 (8.53)	1485 (8.62)	588 (8.28)	
Non-Hispanic Black	2663 (10.26)	1935 (10.26)	728 (10.25)	
Non-Hispanic White	5666 (67.93)	4097 (67.12)	1569 (70.27)	
Other Race	2988 (13.28)	2335 (14.01)	653 (11.20)	
Education level ^b				0.002
High school or more	10,750 (86.25)	7979 (87.00)	2771 (84.24)	
Less than high school	2628 (13.71)	1861 (13.00)	767 (15.76)	
Marital status ^b				< 0.0001
Married	7908 (61.28)	5541 (58.26)	2367 (70.03)	
Unmarried	5480 (38.70)	4310 (41.74)	1170 (29.97)	
Poverty income ratio level ^b				0.23
Middle	3677 (39.63)	2757 (42.91)	920 (41.17)	
High	3865 (19.87)	2829 (21.46)	1036 (20.80)	
Low	4680 (33.82)	3432 (35.63)	1248 (38.03)	
preDM ^b				< 0.0001
No	4618 (39.33)	3981 (45.51)	637 (21.50)	
Yes	5890 (44.34)	4254 (42.79)	1636 (48.81)	
DM	2882 (16.33)	1617 (11.70)	1265 (29.69)	
History of CVD ^b	1495 (9.10)	936 (7.49)	559 (13.75)	< 0.0001
History of Cancer ^b	1237 (9.74)	828 (9.05)	409 (11.77)	0.001
Energy intake, kcal/d ^a	2175.55 (11.49)	2187.49 (13.27)	2141.08 (22.39)	0.08
Physical Activity, h/wk ^a	4840.02 (105.39)	4959.08 (110.39)	4456.37 (195.09)	0.01
ALT, U/L ^a	25.20 (0.19)	24.28 (0.24)	27.85 (0.31)	< 0.0001
AST, U/L ^a	25.10 (0.17)	25.07 (0.21)	25.19 (0.30)	0.75
Alcohol consumption, g/d ^a	8.91 (0.34)	10.86 (0.44)	3.40 (0.23)	< 0.0001

^a Weighted mean value ($\pm$ standard deviation [SD])^b Frequencies (proportions) as appropriate

DI-GM dietary index for gut microbiota, MASLD metabolic dysfunction-associated steatotic liver disease, Non-MASLD without MASLD, preDM prediabetes mellitus, DM diabetes mellitus, CVD cardiovascular disease, ALT alanine aminotransferase, AST aspartate aminotransferase

Association between DI-GM and all-cause/cardiovascular mortality outcomes of adults with MASLD

To delve deeper into the correlation between the DI-GM and all-cause/ cardiovascular mortality, we employed Restricted Cubic Spline (RCS) analysis to visually represent the relationship between DI-GM and all-cause/ cardiovascular mortality (Fig. 2). The findings indicated

a clear linear association between DI-GM and the risk of all-cause/cardiovascular mortality in both the non-MASLD and MASLD populations (non-linear $P > 0.05$). Additionally, we compared the fit of a linear model (DI-GM as a linear term) and an RCS model (DI-GM as a restricted cubic spline with 3 knots). The linear model had a lower AIC compared to the RCS model

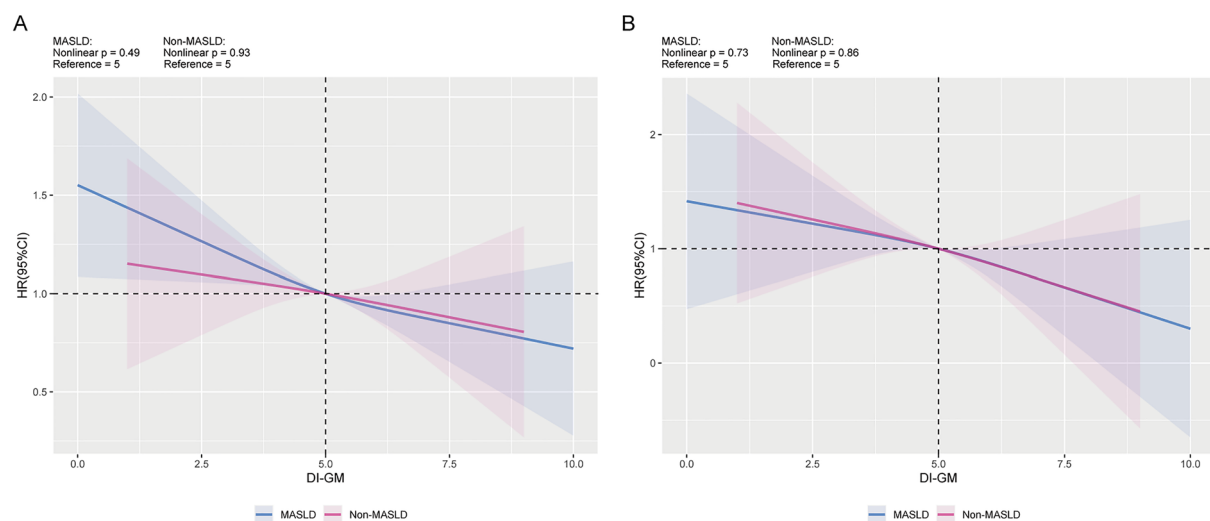


Fig. 2 Analysis of the association between DI-GM and all-cause/cardiovascular mortality by MASLD status in participants in NHANES 2007–2018 using the RCS. **A** All-cause mortality. **B** Cardiovascular mortality. Hazard ratios (solid lines) and 95% confidence intervals (shaded areas) were estimated in model 3. DI-GM dietary index for gut microbiota, MASLD metabolic dysfunction-associated steatotic liver disease, Non-MASLD without MASLD, RCS restricted cubic spline

(All-cause mortality: Liner model=20,978.36, RCS model=20,974.82; Cardiovascular mortality: Liner model=6088.961, RCS model=6088.032), suggesting that the linear relationship is sufficient.

Subsequent cox proportional hazard models, conducted across three distinct models, were used to further examine the influence of DI-GM on all-cause and cardiovascular mortality (Fig. 3). The adjusted analysis demonstrated that the global p -value of the Schoenfeld residuals exceeded 0.05, implying that the proportional hazards assumption was satisfied (Figure S1). The analyses revealed a significant inverse correlation between an increase in DI-GM and a decrease in the risk of all-cause and cardiovascular mortality in both the presence and absence of MASLD. Notably, in Model 3, the reduction in all-cause and cardiovascular mortality risk was more pronounced among MASLD with higher DI-GM, compared to non-MASLD (all-cause mortality, HR=0.87, 95% CI=0.78 to 0.98, $p=0.02$; cardiovascular mortality, HR=0.805, 95% CI=0.690 to 0.938, $p=0.005$). Specifically, each unit increase in DI-GM was associated with a 13% decrease in the risk of all-cause mortality and a 19.5% decrease in the risk of cardiovascular mortality.

All-cause/cardiovascular mortality associated with DI-GM in MASLD with advanced fibrosis

To ascertain the association between the DI-GM and all-cause/cardiovascular mortality within MASLD with advanced fibrosis, we further identified individuals at advanced fibrosis using the FIB4, NFS, and AIRP

scoring systems (Table 2). Result uncovered a marked inverse association between the DI-GM and cardiovascular mortality specifically in MASLD at advanced fibrosis (Model 1, HR=0.87, 95% CI=0.78–0.98, $p=0.02$; Model 2, HR=0.86, 95% CI=0.77–0.97, $p=0.01$; Model 3, HR=0.800, 95% CI=0.691–0.927, $p=0.003$), while no such correlation was observed with all-cause mortality ($p>0.05$). Notably, each unit increase in DI-GM was associated with a 20% reduction in the risk of cardiovascular mortality.

Subgroup analyses and sensitivity analysis

To investigate the impact of the DI-GM on mortality within different subgroups of MASLD participants, we conducted subgroup analyses (Figs. 4, 5). The results indicated that age and preDM played significant roles in the relationship between DI-GM and mortality. Specifically, a significant inverse association between DI-GM and all-cause mortality was observed only in participants under the age of 40 (age < 40, HR=0.67, 95% CI=0.51 to 0.89, $p=0.006$; p for interaction=0.043). In participants aged 40 years or older, higher DI-GM was more strongly associated with a reduced risk of cardiovascular mortality (age < 40, HR=0.89, 95% CI=0.80 to 0.997, $p=0.044$; age $\geq$ 40, HR=0.6, 95% CI=0.44 to 0.81, $p=0.001$; p for interaction=0.014). Among individuals with different preDM states, DI-GM was significantly inversely associated with all-cause mortality only in those without diabetes (non-preDM, HR=0.78, 95% CI=0.59 to 0.98, $p=0.03$; preDM, HR=0.87, 95%

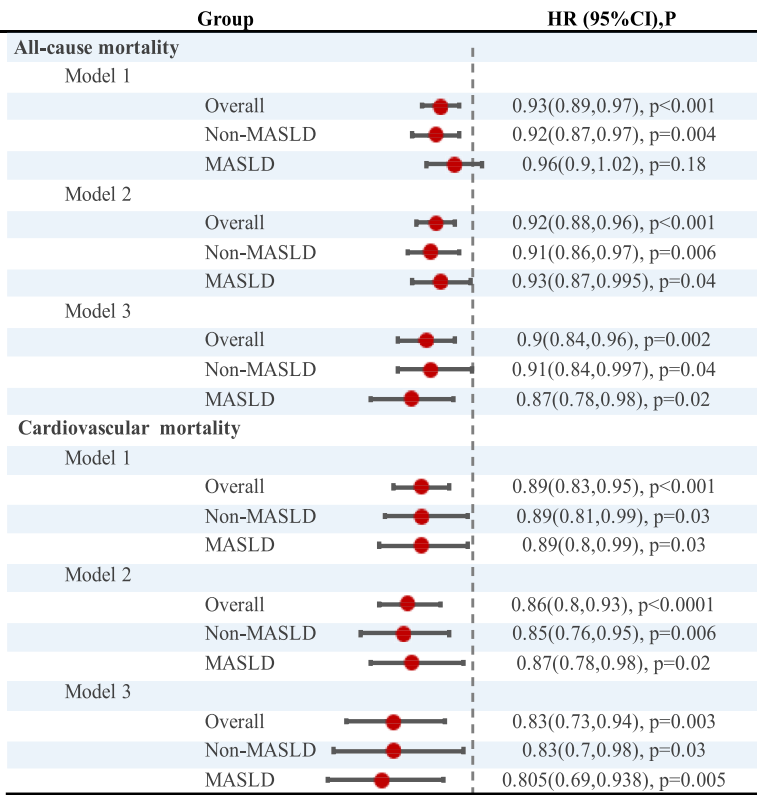


Fig. 3 Association between DI-GM and all-cause/cardiovascular mortality. Model 1 remained unadjusted; Model 2 adjusted for age, sex, race/ethnicity, education level, marital status, and PIR levels; Model 3 further adjusted for preDM, history of CVD and cancer, energy intake, physical activity, ALT, AST, and alcohol consumption. *DI-GM* dietary index for gut microbiota, *MASLD* metabolic dysfunction-associated steatotic liver disease, *Non-MASLD* without MASLD, *preDM* prediabetes mellitus, *DM* diabetes mellitus, *CVD* cardiovascular diseases, *ALT* alanine aminotransferase, *AST* aspartate aminotransferase, *HR* hazard ratios, *CI* confidence interval

Table 2 Association between the DI-GM and all-cause/ cardiovascular mortality within MASLD with advanced fibrosis

	Model 1		Model 2		Model 3	
	HR (95%CI)	P	HR (95%CI)	P	HR (95%CI)	P
All-cause	0.96 (0.89,1.03)	0.21	0.94 (0.88, 1.01)	0.09	0.89 (0.79, 1.01)	0.07
Cardiovascular cause	0.87 (0.78,0.98)	0.02	0.86 (0.77, 0.97)	0.01	0.800 (0.691, 0.927)	0.003

Model 1 remained unadjusted; Model 2 adjusted for age, sex, race/ethnicity, education level, marital status, and PIR levels; Model 3 further adjusted for preDM, history of CVD and cancer, energy intake, physical activity, ALT, AST, and alcohol consumption

DI-GM dietary index for gut microbiota, *MASLD* metabolic dysfunction-associated steatotic liver disease, *Non-MASLD* without MASLD, *preDM* prediabetes mellitus, *DM* diabetes mellitus, *CVD* cardiovascular diseases, *ALT* alanine aminotransferase, *AST* aspartate aminotransferase, *HR* hazard ratios, *CI* confidence interval

CI=0.76 to 0.998, p=0.047; p for interaction=0.02), while the inverse association with cardiovascular mortality was observed only in preDM (HR=0.81, 95% CI=0.70 to 0.94, p=0.006; p for interaction=0.04). To validate the robustness of our findings, we conducted 6 sensitivity analyses (Table 3). In all sensitivity analyses, the negative association between DI-GM and all-cause/cardiovascular mortality remained significant, demonstrating the robustness of our results.

Discussion
This study innovatively identified a significant inverse association between an elevated DI-GM and the risk of all-cause and cardiovascular mortality, with particularly pronounced effects observed in participants with MASLD. Specifically, for every one-unit increase in DI-GM, there was a 13% reduction in the risk of all-cause mortality and a 19.5% reduction in the risk of cardiovascular mortality. Moreover, a more marked

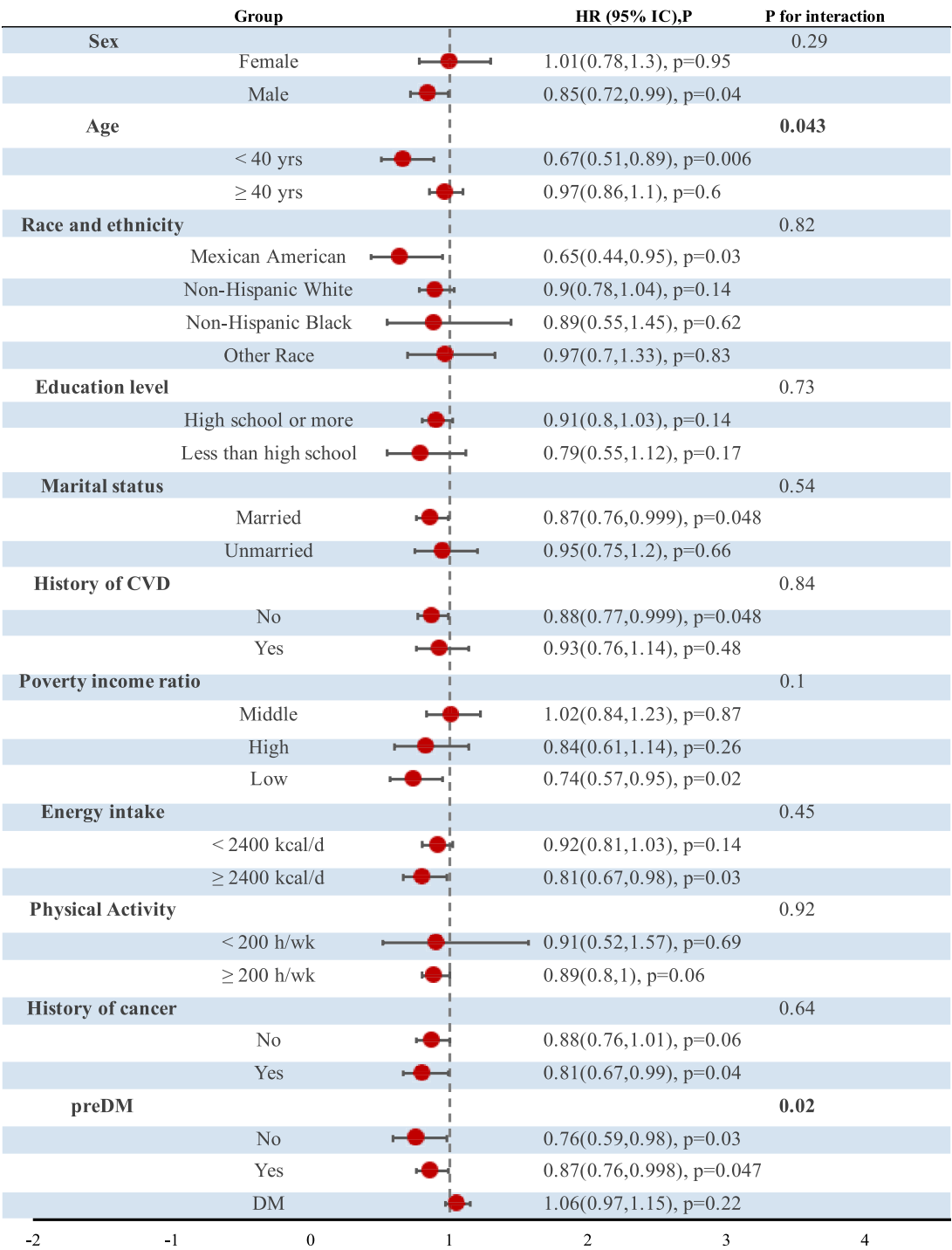


Fig. 4 Subgroup analysis of the association between DI-GM and all-cause mortality in MASLD. Each subgroup adjusted for all factors in model 3 except the stratification factor itself. *DI-GM* dietary index for gut microbiota, *MASLD* metabolic dysfunction-associated steatotic liver disease, *preDM* prediabetes mellitus, *DM* diabetes mellitus, *CVD* cardiovascular diseases

negative correlation between DI-GM and cardiovascular mortality was detected in MASLD with advanced fibrosis. Subgroup analyses revealed interactions between DI-GM and the risk of all-cause/cardiovascular mortality, including age and prDM status. Upon stratifying by age, a significant negative correlation between the DI-GM

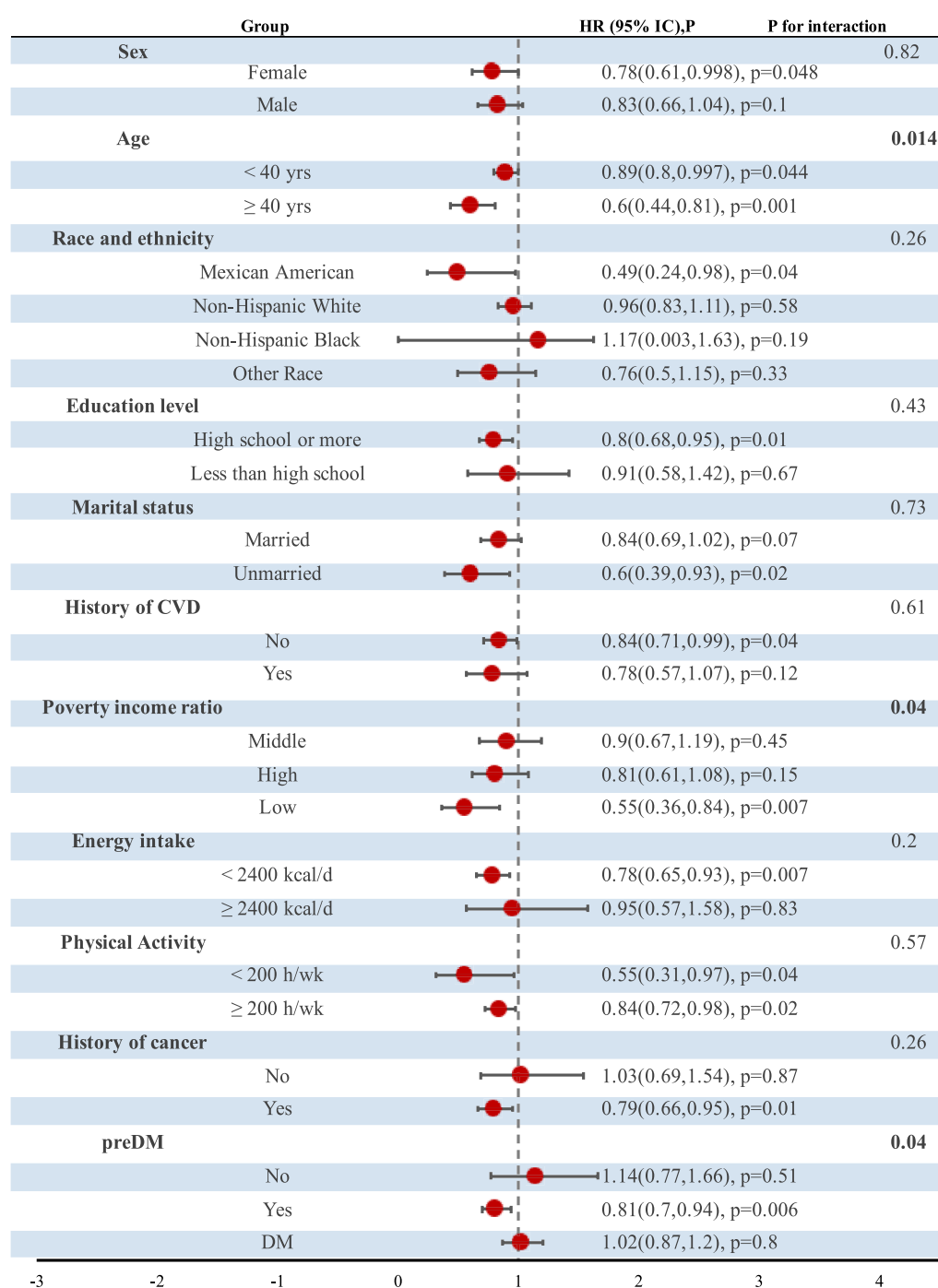


Fig. 5 Subgroup analysis of the association between DI-GM and cardiovascular mortality in MASLD. Each subgroup adjusted for all factors in model 3 except the stratification factor itself. *DI-GM* dietary index for gut microbiota, *MASLD* metabolic dysfunction-associated steatotic liver disease, *preDM* prediabetes mellitus, *DM* diabetes mellitus, *CVD* cardiovascular diseases

and all-cause mortality was observed solely within the MASLD patients aged below 40 years. In contrast, among patients over the age of 40, the negative correlation between the DI-GM and cardiovascular mortality was more pronounced. In terms of prDM status, a significant

negative correlation between DI-GM and all-cause mortality was found only in participants (included preDM) without diabetes mellitus (DM), whereas a higher DI-GM score was associated with a significant reduction in cardiovascular mortality risk in those with prDM.

Table 3 Sensitivity analyses of the association between DI-GM and cardiovascular mortality

	HR (95% CI)	P
Sensitivity analysis 1		
All-cause mortality	0.85 (0.75, 0.95)	0.004
Cardiovascular-cause mortality	0.78 (0.66, 0.92)	0.004
Sensitivity analysis 2		
All-cause mortality	0.875 (0.768, 0.997)	0.046
Cardiovascular-cause mortality	0.848 (0.720, 0.999)	0.048
Sensitivity analysis 3		
All-cause mortality	0.87 (0.78, 0.97)	0.02
Cardiovascular-cause mortality	0.81 (0.69, 0.94)	0.01
Sensitivity analysis 4		
All-cause mortality	0.86 (0.75, 0.99)	0.03
Cardiovascular-cause mortality	0.77 (0.63, 0.95)	0.02
Sensitivity analysis 5		
All-cause mortality	0.86 (0.75, 0.99)	0.03
Cardiovascular-cause mortality	0.77 (0.63, 0.95)	0.02
Sensitivity analysis 6		
All-cause mortality	0.89 (0.83, 0.97)	0.01
Cardiovascular-cause mortality	0.80 (0.70, 0.92)	0.001

Sensitivity analysis 1: Excluded participants aged ≥ 80 years in the overall population. Sensitivity analysis 2: Excluded individuals with a history of cardiovascular disease. Sensitivity analysis 3: Excluded individuals with a history of cancer. Sensitivity analysis 4: Excluded participants who died within two years post-interview. Sensitivity analysis 5: Examined adults interviewed between 2007 and 2016. Sensitivity analysis 6: Examined a broader population by using a FLI ≥ 30 as a diagnostic criterion for SLD

DI-GM Dietary index for gut microbiota, MASLD Metabolic dysfunction-associated steatotic liver disease, HR Hazard ratios, CI Confidence interval, FLI Fatty liver index, SLD Steatotic liver disease

Alternatively, six sensitivity analyses further validated the robustness of our findings.

MASLD is a well-established independent risk factor for mortality, with growing evidence highlighting CVD as a predominant concern in this population [45]. Notably, MASLD patients face a substantially higher risk of CVD-related mortality compared to liver-related mortality [46, 47]. Consistent with this, our study revealed that the mortality rate among MASLD participants was significantly elevated compared to non-MASLD individuals (MASLD vs. non-MASLD: 7.62% vs. 5.66%, $p=0.001$). Strikingly, cardiovascular mortality represented the leading cause of death in MASLD patients, accounting for 33.74% of all deaths. This phenomenon can be attributed to shared pathophysiological mechanisms, including insulin resistance (IR), endothelial dysfunction, oxidative stress (OS), systemic inflammation, dysregulated lipoprotein metabolism, increased thrombogenicity, ectopic fat deposition, and gut microbiota dysbiosis [46, 48, 49]. These interconnected pathways underscore the intricate relationship between MASLD and CVD, emphasizing the need for targeted interventions. Given the profound

impact of MASLD on cardiovascular health and overall mortality, there is an urgent imperative to identify and implement daily interventions capable of mitigating these risks.

Dietary indices serve as invaluable tools for characterizing dietary patterns based on dietary assessment data [50, 51]. Among these, the DI-GM, developed by Beza-wit E. Kase and colleagues, represents a groundbreaking advancement. DI-GM uniquely captures the beneficial or detrimental effects of dietary components on gut microbiota, as evidenced by changes in microbial diversity indices, short-chain fatty acid (SCFA) production, and the abundance of specific bacterial species [23].

In this study, the correlation between DI-GM and indirect biomarkers of gut microbiota diversity provides compelling evidence of reduced microbial diversity in MASLD patients. Notably, our findings reveal that DI-GM were significantly lower in MASLD patients compared to non-MASLD individuals, suggesting that MASLD patients exhibit a diminished capacity to maintain a healthy gut microbiome through their regular dietary intake. This observation aligns with a robust body of prior research highlighting systemic pathological alterations in the gut microbiota of MASLD patients [52, 53]. For instance, a recent systematic review demonstrated that MASLD patients exhibit reduced alpha diversity, decreased populations of beneficial genera such as *Coprococcus*, *Faecalibacterium*, and *Ruminococcus* genera,, and an overgrowth of *Escherichia* compared to healthy controls [54].

Furthermore, a distinct microbial signature, particularly the prominence of *Faecalibacterium prausnitzii*, has been identified as uniquely associated with MASLD in human studies [55]. Mechanistically, the bidirectional communication between the gut microbiota and the liver, termed the "gut-liver axis" (GLA), plays a pivotal role in the pathogenesis and progression of MASLD [56, 57]. Collectively, these studies, along with our findings, underscore the critical role of gut microbiota in the mortality process of MASLD patients.

Dietary nutrients exert profound effects on MASLD by modulating gut microbiota diversity, altering the *Bacteroidetes*-to-*Firmicutes* ratio, and promoting the growth of beneficial microbial species [58]. Fiber, a key beneficial dietary component included in DI-GM, has been shown to enhance gut microbes that metabolize choline, thereby reducing its bioavailability and generating metabolites such as trimethylamine [59, 60]. Conversely, a fiber-deficient diet leads to mucin-degrading bacteria overgrowth, compromising mucosal thickness [61, 62]. DI-GM further distinguishes itself from other dietary indices by incorporating fermented dairy products as a unique component. These products, including

yogurt, cheese, and kefir, are rich in *Lactobacilli* and lactic acid, which have been scientifically validated to increase the abundance of *Lactobacillus* species within the gut microbiota [63]. Recent evidence highlights that fermented dairy products, particularly yogurt, are more effective than non-fermented dairy in reducing liver fat and improving metabolic risk biomarkers [64]. On the other hand, high-fat diets, recognized as detrimental dietary components in DI-GM, disrupt the gut microbiome, impair intestinal and vascular barriers, promote bacterial translocation, and exacerbate systemic inflammation and metabolic dysregulation [65]. The liver, being highly exposed to portal systemic products, is particularly vulnerable to these effects. High-fat diets are also associated with elevated levels of lipopolysaccharides (LPS), a known risk factor for MASLD [66]. Consistent with these findings, our study demonstrates that improving DI-GM scores in MASLD patients is associated with a significant reduction in all-cause mortality. These results underscore the critical importance of dietary interventions that target gut microbiota modulation as a strategy to enhance survival outcomes in MASLD patients.

This study further revealed that higher DI-GM scores in MASLD patients are associated with lower cardiovascular mortality. Mechanistically, gut microbiota plays a pivotal role in this process by converting dietary choline and L-carnitine into trimethylamine (TMA), which is subsequently oxidized in the liver to form trimethylamine N-oxide (TMAO). TMAO has been implicated in endothelial dysfunction and is strongly associated with cardiovascular risks such as atherosclerosis and myocardial infarction [14, 67]. Additionally, systemic inflammation triggered by gut dysbiosis and the translocation of microbial products exacerbates endothelial dysfunction and accelerates atherosclerosis, both of which are central to the pathogenesis of cardiovascular disease (CVD) [15]. Furthermore, microbial metabolites, including short-chain fatty acids (SCFAs) and bile acids, influence blood pressure regulation and vascular health, further underscoring the gut microbiota's role in cardiovascular outcomes [30]. These findings, combined with our research, highlight the critical importance of a gut microbiota-healthy diet, as quantified by DI-GM, in mitigating cardiovascular mortality among MASLD patients. By modulating gut microbiota composition and function, dietary interventions can address the underlying mechanisms linking gut dysbiosis to cardiovascular risks, offering a promising avenue for improving clinical outcomes.

Dysbiosis of the gut microbiota in MASLD is a key driver of increased liver fibrosis, and as liver disease progresses to advanced stages, the risk of cardiovascular disease (CVD) becomes significantly elevated [53, 68]. Our findings underscore this relationship, revealing a

particularly strong association between the DI-GM and mortality in MASLD patients with advanced fibrosis, especially those at high risk of cardiovascular events. This suggests that the interplay between gut microbiota dysbiosis, liver fibrosis, and cardiovascular health is a critical axis in the pathophysiology of MASLD. In light of these insights, we propose that dietary interventions aimed at enhancing gut microbiota health should be prioritized for MASLD patients with advanced fibrosis and elevated cardiovascular risk. Such targeted dietary modifications, guided by the DI-GM, have the potential to significantly improve cardiovascular outcomes. By addressing the gut-liver-heart axis, this approach offers a holistic strategy to reduce mortality in this high-risk population.

The global prevalence of MASLD is on a concerning upward trajectory, with the most pronounced increase observed among individuals under the age of 40 [45]. Our subgroup analyses revealed that younger MASLD patients (under 40 years) can more effectively reduce their risk of all-cause mortality by improving their DI-GM through targeted dietary modifications, thereby promoting gut microbiota stability. In contrast, for patients over 40, an elevated DI-GM was more strongly associated with a reduction in cardiovascular mortality risk. From a mechanistic perspective, the regenerative capacity of liver cells in younger individuals is relatively stronger [69]. Higher DI-GM score may exert hepatoprotective effects by modulating gut microbiota composition, thereby creating a more favorable microenvironment for liver function. This could promote hepatic cell repair and regeneration [70]. For instance, metabolites produced by certain beneficial bacteria may stimulate hepatic cell proliferation, alleviate steatosis and fibrosis, and reduce the risk of complications arising from progressive liver disease, ultimately lowering all-cause mortality [70]. Furthermore, the immune system in younger populations is more active and sensitive. Higher DI-GM scores may enhance the interaction between gut microbiota and the immune system, activating beneficial immune components such as T and B cells. This could enhance the secretion of anti-inflammatory cytokines by immune cells, thereby reducing all-cause mortality [71, 72]. However, with aging, the elasticity and function of vascular walls progressively decline [73]. Higher DI-GM scores may confer vascular protective effects by modulating gut microbiota to produce beneficial metabolites, such as SCFAs [74]. These SCFAs can act on vascular endothelial cells, enhancing endothelial function, increasing vascular elasticity, and reducing vascular resistance [74]. Improved vascular function may mitigate the risk of cardiovascular diseases, thereby lowering cardiovascular mortality [75]. Moreover, older individuals often exhibit dyslipidemia and chronic low-grade inflammation, which

are critical risk factors for cardiovascular diseases [76, 77]. Higher DI-GM scores may alleviate these risks by regulating gut microbiota to modulate lipid absorption and metabolism, while simultaneously suppressing the activation of inflammatory signaling pathways [77]. This age-dependent association underscores the importance of tailoring dietary strategies to the unique physiological and microbial profiles of different age groups. For younger patients, interventions focused on enhancing gut microbiota diversity and stability may offer a proactive approach to mitigating long-term health risks. For older patients, dietary modifications that specifically target cardiovascular risk factors through gut microbiota modulation could provide significant clinical benefits. These insights not only emphasize the critical role of the gut-liver axis in MASLD progression but also pave the way for personalized, age-stratified nutritional strategies to improve outcomes across the lifespan.

Subgroup analyses further illuminated that the prediabetes (preDM) status of patients significantly modulates the efficacy of the DI-GM in reducing mortality risk. Specifically, while DI-GM was more effective in lowering overall mortality risk in non-diabetic patients, elevating the DI-GM in prediabetic patients demonstrated a stronger association with reducing cardiovascular mortality. This differential effect underscores the complex interplay between metabolic health and gut microbiota in shaping clinical outcomes. This may be attributed to the synergistic interplay between DI-GM and metabolic pathways. Prediabetes is associated with a heightened cardiovascular risk [78, 79]. A high DI-GM score may confer protective effects by enhancing gut barrier integrity through mechanisms involving short-chain fatty acids, prebiotics, and dietary fiber etc [80]. Furthermore, it may mitigate cardiovascular mortality risk through multiple pathways, including improved insulin sensitivity, reduced oxidative stress, regulated immune responses, and modulation of choline-metabolizing bacteria to suppress trimethylamine N-oxide (TMAO) production [81].

In the context of cardiovascular mortality, insulin resistance is a central driver. It impairs glucose output and fatty acid metabolism, leading to elevated triglyceride levels and increased secretion of very low-density lipoprotein (VLDL) by the liver [82, 83]. These metabolic disturbances are compounded by endothelial dysfunction, characterized by reduced nitric oxide production and increased release of procoagulant factors, which promote platelet aggregation and vascular inflammation [84, 85]. Collectively, these mechanisms contribute to the development of atherosclerotic plaques and elevate the risk of cardiovascular mortality [86]. These findings highlight the potential of DI-GM as a tool for personalized dietary strategies tailored to the metabolic status

of MASLD patients. Notably, individuals without diabetes, including those with prediabetes (preDM), appear to derive greater mortality reduction benefits from such dietary improvements. This suggests that early intervention, particularly in prediabetic patients, could disrupt the progression of metabolic dysfunction and its downstream consequences.

Given the pivotal role of the gut microbiota in various diseases, DI-GM can be utilized to investigate diet-disease associations similar to those of established indices such as Alternate Healthy Eating Index (AHEI) and Alternate Mediterranean Diet (aMED) et al. However, a key distinction of DI-GM lies in its inclusion of specific foods rather than broad food groups for certain components [87, 88]. During the development of DI-GM, most review articles primarily focused on dietary intervention studies targeting specific foods. Incorporating specific foods into DI-GM may offer potential benefits in refining dietary recommendations [23]. Additionally, the aMED emphasizes the consumption of olive oil, whole grains, vegetables, and fish, but its core assumption—that "food itself directly determines health outcomes"—fails to account for individual variations in gut microbiota-mediated metabolism of dietary components [89]. In contrast, DI-GM quantifies the regulatory effects of dietary patterns on gut microbiota, thereby more accurately reflecting the impact of diet on metabolic health (e.g., MASLD). Recent studies have highlighted the association between higher aMED, Dietary Approach to Stop Hypertension (DASH), and AHEI scores and reduced all-cause and cardiovascular mortality in MASLD patients [90]. A cross-sectional study further demonstrated a linear inverse relationship between dietary quality and all-cause mortality in MASLD patients, suggesting that improved dietary quality may enhance survival outcomes [91]. However, contradictory evidence also exists: Yoo et al. found that while higher dietary quality was linked to reduced all-cause mortality in individuals without MASLD, no such association was observed in MASLD patients [92]. These findings underscore the importance of dietary quality as a modifiable factor in MASLD management. Notably, this study did not further explore the comparative effectiveness of DI-GM against established indices (e.g., aMED, DASH) in predicting MASLD outcomes. Future research should integrate DI-GM with traditional dietary indices through multivariable models to evaluate their independent predictive value for MASLD-related endpoints.

A notable strength of our study including the analysis of a nationally representative sample of diverse populations in the United States, and the inclusion of a large number of potential confounding factors in the availability of data on analysis and long-term mortality. These

strengths enhance the generalizability of the findings to the general population. Secondly, To the best of our knowledge, this is the first investigation to examine the relationship between the DI-GM and mortality risk in both MASLD and non-MASLD populations, we have found that MASLD patients can reduce their mortality risk by improving their daily diet, a finding that was confirmed to be robust through six sensitivity analyses. Lastly, in comparison with other dietary indices, DI-GM encompasses a broader spectrum of targets, incorporating measures such as diversity indices, the production of short-chain fatty acids, variations in phyla, and the outcomes of specific bacterial species. This comprehensive approach allows for a more nuanced understanding of the dietary influences on gut microbiota composition and function. The scoring system of DI-GM is straightforward and user-friendly, making it highly suitable for widespread adoption in both clinical and public health settings. By quantifying the impact of dietary patterns on gut microbiota, DI-GM offers actionable and specific dietary recommendations for MASLD patients, demonstrating significant practical value in guiding personalized nutrition strategies. This ease of application, combined with its scientific rigor, positions DI-GM as a valuable tool for improving patient outcomes and advancing dietary interventions in metabolic health management.

Despite these strengths, our study has several limitations. Firstly, the NHANES data, which are based on self-reported information from individuals, may be prone to recall bias. Self-reported dietary data, while commonly used in large-scale cohort studies, are subject to limitations such as recall bias, social desirability bias, and underreporting, particularly for complex dietary patterns. These factors could introduce measurement error into DI-GM scores, potentially affecting the observed associations with MASLD and mortality. To mitigate these biases, we utilized standardized dietary assessment tools—24-h dietary recalls. However, we recognize that these limitations may still impact the precision of DI-GM as a dietary biomarker. Secondly, the cross-sectional design of NHANES precludes the provision of insights into the temporal changes of these variables, which limits the further exploration of the dynamics of the DI-GM. Thirdly, the use of non-invasive FLI, NFS, APRI, and FIB4 scores as diagnostic criteria for steatosis and advanced liver fibrosis may introduce inaccuracies in estimating the true risk extent of MASLD and advanced liver fibrosis, although these scores have been validated as reliable diagnostic tools in the U.S. population [93]. Fourthly, the relatively small number of cancer-related deaths in the MASLD patient population led us to exclude cancer-related mortality from our focus. Therefore, well-designed prospective longitudinal studies are

warranted to further investigate the impact of the DI-GM on all-cause mortality risk in patients with MASLD. Lastly, In the subgroup analysis of this study, the limited sample sizes in certain specific subgroups may restrict the generalizability of the findings, and further in-depth analyses of these subgroups are warranted. Meanwhile, future studies should validate our findings using histological confirmation of MASLD and fibrosis, particularly in populations with high variability in diagnostic accuracy. Additionally, advanced imaging techniques (e.g., MRI-based proton density fat fraction) could reduce misclassification bias.

Conclusion

In this study, the DI-GM has filled a critical research gap by revealing a significant inverse correlation between DI-GM scores and both all-cause and cardiovascular mortality in patients with MASLD. This groundbreaking finding not only validates the scientific value of DI-GM but also provides robust evidence to support dietary interventions aimed at improving outcomes in MASLD patients. Furthermore, our study demonstrated that the mortality-reducing effects of DI-GM are particularly pronounced in MASLD patients with advanced fibrosis and are influenced by age and prediabetes status. These insights highlight the potential of DI-GM to offer personalized dietary recommendations tailored to specific patient subgroups, thereby advancing the application of precision medicine in MASLD management. The application of DI-GM opens new avenues for future research, such as exploring its relationship with other metabolic diseases (e.g., diabetes, obesity) or using multi-omics technologies to further elucidate the mechanisms underlying diet-microbiota-host interactions.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13098-025-01846-x>.

Supplementary Material 1.

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Author contributions

W.W.: Conceptualization, methodology, writing—original draft; J.C.: Writing—review and editing, resources; Z.H.: Writing—review and editing, Investigation; Q.Y.: Writing—review and editing, Software; X.W.: Writing—review and editing, Visualization; J.H.: Writing—review and editing, methodology; Y.Z.: Writing—review and editing, Software, validation; J.L.: Conceptualization, methodology, supervision, writing—review & editing. All authors have approved the submitted version.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

All survey protocols were approved by the institutional review board of the National Center for Health Statistics. All participants provided written informed consent before participation.

Competing interests

The authors declare no competing interests.

Author details

¹Department of Endocrinology and Metabolism, The Second Hospital of Shanxi Medical University, Shanxi Medical University, 56 Xin Jian Road, Taiyuan 030000, Shanxi, People's Republic of China. ²Department of Thyroid Surgery, Shanxi Provincial People's Hospital, Taiyuan 030000, Shanxi, People's Republic of China.

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References

- Younossi ZM, Stepanova M, Lawitz EJ, Reddy KR, Wai-Sun Wong V, Mangia A, Muir AJ, Jacobson I, Djedjos CS, Gaggari A, Myers RP, Younossi I, Nader F, Racila A. Patients with nonalcoholic steatohepatitis experience severe impairment of health-related quality of life. *Am J Gastroenterol*. 2019;114(10):1636–41.
- Wong RJ, Aguilar M, Cheung R, Perumpail RB, Harrison SA, Younossi ZM, Ahmed A. Nonalcoholic steatohepatitis is the second leading etiology of liver disease among adults awaiting liver transplantation in the United States. *Gastroenterology*. 2015;148(3):547–55.
- Younossi ZM, Otgonsuren M, Henry L, Venkatesan C, Mishra A, Erario M, Hunt S. Association of nonalcoholic fatty liver disease (NAFLD) with hepatocellular carcinoma (HCC) in the United States from 2004 to 2009. *Hepatology*. 2015;62(6):1723–30.
- Le MH, Yeo YH, Zou B, Barnett S, Henry L, Cheung R, Nguyen MH. Forecasted 2040 global prevalence of nonalcoholic fatty liver disease using hierarchical bayesian approach. *Clin Mol Hepatol*. 2022;28(4):841–50.
- Eslam M, Sanyal AJ, George J, International Consensus P. MAFLD: a consensus-driven proposed nomenclature for metabolic associated fatty liver disease. *Gastroenterology*. 2020;158(7):1999–20141.
- Zheng KI, Fan JG, Shi JP, Wong VW, Eslam M, George J, Zheng MH. From NAFLD to MAFLD: a "redefining" moment for fatty liver disease. *Chin Med J (Engl)*. 2020;133(19):2271–3.
- Ramandi A, George J, Merat S, Jafari E, Sharafkhan M, Radmard AR, Nateghi Baygi A, Delavari A, Mohammadi Z, Poustchi H, Malekzadeh R. Polypill protects MAFLD patients from cardiovascular events and mortality: a prospective trial. *Hepatol Int*. 2023;17(4):882–8.
- Hoofnagle JH, Doo E. Letter to the editor: a multi-society Delphi consensus statement on new fatty liver disease nomenclature. *Hepatology*. 2024;79(3):E91–2.
- Morvaridi M, Rayyani E, Jaafari M, Khiabani A, Rahimlou M. The effect of green coffee extract supplementation on cardio metabolic risk factors: a systematic review and meta-analysis of randomized controlled trials. *J Diabetes Metab Disord*. 2020;19(1):645–60.
- Keshavarz Z, Rahimlou M, Farjam M, Homayounfar R, Khodadost M, Abdollahi A, Tabrizi R. Non-alcoholic fatty liver disease and dairy products consumption: results from FASA Persian cohort study. *Front Nutr*. 2022;9:962834.
- Simancas-Racines D, Annunziata G, Verde L, Fasci-Spurio F, Reytor-Gonzalez C, Muscogiuri G, Frias-Toral E, Barrea L. Nutritional strategies for battling obesity-linked liver disease: the role of medical nutritional therapy in metabolic dysfunction-associated steatotic liver disease (MASLD) management. *Curr Obes Rep*. 2025;14(1):7.
- Fan Y, Pedersen O. Gut microbiota in human metabolic health and disease. *Nat Rev Microbiol*. 2021;19(1):55–71.
- Song Q, Zhang X. The role of gut-liver axis in gut microbiome dysbiosis associated NAFLD and NAFLD-HCC. *Biomedicines*. 2022;10(3).
- Querio G, Antoniotti S, Geddo F, Levi R, Gallo MP. Modulation of endothelial function by TMAO, a gut microbiota-derived metabolite. *Int J Mol Sci*. 2023;24(6).
- Nesci A, Carnuccio C, Ruggieri V, D'Alessandro A, Di Giorgio A, Santoro L, Gasbarrini A, Santoliquido A, Ponziani FR. Gut microbiota and cardiovascular disease: evidence on the metabolic and inflammatory background of a complex relationship. *Int J Mol Sci*. 2023;24(10).
- Ramandi A, Diehl AM, Sanyal AJ, de Jong YP. Experimental Models to Investigate PNPLA3 in Liver Steatosis. *Liver Int*. 2025;45(5): e70091.
- Yki-Jarvinen H, Luukkainen PK, Hodson L, Moore JB. Dietary carbohydrates and fats in nonalcoholic fatty liver disease. *Nat Rev Gastroenterol Hepatol*. 2021;18(11):770–86.
- Yki-Jarvinen H, Luukkainen PK. Diabetes, liver cancer, and cirrhosis: what next? *Hepatology*. 2018;68(4):1220–2.
- Luukkainen PK, Sadevirta S, Zhou Y, Kayser B, Ali A, Ahonen L, Lallukka S, Pelloux V, Gaggini M, Jian C, Hakkarainen A, Lundborn N, Gylling H, Salonen A, Oresic M, Hyotylainen T, Orho-Melander M, Rissanen A, Gastaldelli A, Clement K, Hodson L, Yki-Jarvinen H. Saturated fat is more metabolically harmful for the human liver than unsaturated fat or simple sugars. *Diabetes Care*. 2018;41(8):1732–9.
- Maskarinec G, Hullar MAJ, Monroe KR, Shepherd JA, Hunt J, Randolph TW, Wilkens LR, Boushey CJ, Le Marchand L, Lim U, Lampe JW. Fecal microbial diversity and structure are associated with diet quality in the multiethnic cohort adiposity phenotype study. *J Nutr*. 2019;149(9):1575–84.
- Bowyer RCE, Jackson MA, Pallister T, Skinner J, Spector TD, Welch AA, Steves CJ. Use of dietary indices to control for diet in human gut microbiota studies. *Microbiome*. 2018;6(1):77.
- Cotillard A, Cartier-Meheust A, Litwin NS, Chaumont S, Saccareau M, Lejzerowicz F, Tap J, Koutnikova H, Lopez DG, McDonald D, Song SJ, Knight R, Derrien M, Veiga P. A posteriori dietary patterns better explain variations of the gut microbiome than individual markers in the American Gut Project. *Am J Clin Nutr*. 2022;115(2):432–43.
- Kase BE, Liese AD, Zhang J, Murphy EA, Zhao L, Steck SE. The development and evaluation of a literature-based dietary index for gut microbiota. *Nutrients*. 2024;16(7).
- Asnicar F, Berry SE, Valdes AM, Nguyen LH, Piccinno G, Drew DA, Leeming E, Gibson R, Le Roy C, Khatib HA, Francis L, Mazidi M, Mompeo O, Valles-Colomer M, Tett A, Beghini F, Dubois L, Bazzani D, Thomas AM, Mirzayi C, Khleborodova A, Oh S, Hine R, Bonnett C, Capdevila J, Danzanvilliers S, Giordano F, Geistlinger L, Waldron L, Davies R, Hadjigeorgiou G, Wolf J, Ordovas JM, Gardner C, Franks PW, Chan AT, Huttenhower C, Spector TD, Segata N. Microbiome connections with host metabolism and habitual diet from 1,098 deeply phenotyped individuals. *Nat Med*. 2021;27(2):321–32.
- Parida S, Sharma D. Microbial alterations and risk factors of breast cancer: connections and mechanistic insights. *Cells*. 2020;9(5).
- Zitvogel L, Galluzzi L, Viaud S, Vetzizou M, Daillere R, Merad M, Kroemer G. Cancer and the gut microbiota: an unexpected link. *Sci Transl Med*. 2015;7(271):271.
- An S, Qin J, Gong X, Li S, Ding H, Zhao X, He H, Zhou L, Deng X, Chu X. The mediating role of body mass index in the association between dietary index for gut microbiota and biological age: a study based on NHANES 2007–2018. *Nutrients*. 2024;16(23).
- Zhang X, Yang Q, Huang J, Lin H, Luo N, Tang H. Association of the newly proposed dietary index for gut microbiota and depression: the mediation effect of phenotypic age and body mass index. *Eur Arch Psychiatry Clin Neurosci*. 2024;.
- Albillos A, de Gottardi A, Rescigno M. The gut–liver axis in liver disease: pathophysiological basis for therapy. *J Hepatol*. 2020;72(3):558–77.

30. Al Khodor S, Reichert B, Shatat IF. The microbiome and blood pressure: can microbes regulate our blood pressure? *Front Pediatr*. 2017;5:138.
31. Lee JH, Lee HS, Ahn SB, Kwon YJ. Dairy protein intake is inversely related to development of non-alcoholic fatty liver disease. *Clin Nutr*. 2021;40(10):5252–60.
32. Nestel PJ, Mori TA. Dairy foods: beneficial effects of fermented products on cardiometabolic health. *Curr Nutr Rep*. 2023;12(3):478–85.
33. Musolino V, Cardamone A, Mare R, Coppoletta AR, Lorenzo F, Noto FR, Galluccio A, Tucci L, Lupia C, Carresi C, Marrelli M, Maurotti S, Gliozzi M, Montalcini T, Pujia A, Mollace V. Antioxidant and in vitro hepatoprotective activities of a polyphenol-rich fraction from the peel of citrus *lunaria* risso (Rutaceae). *Plants (Basel)*. 2025;14(8).
34. Pushpass RAG, Alzoufari S, Jackson KG, Lovegrove JA. Circulating bile acids as a link between the gut microbiota and cardiovascular health: impact of prebiotics, probiotics and polyphenol-rich foods. *Nutr Res Rev*. 2022;35(2):161–80.
35. National Health and Nutrition Examination Survey. <https://www.cdc.gov/nchs/nhanes.htm>.
36. NCHS research ethics review (ERB) approval. <https://www.cdc.gov/nchs/nhanes/irba98.htm>.
37. Tacad DKM, Borkowski K, Keim NL. Differential associations of eating behavior traits, food preference, motivations of food choice on diet intake and diet quality in adult females and males from the USDA nutritional phenotyping study. *Appetite*. 2025;213: 108048.
38. Mogna-Pelaez P, Riezu-Boj JI, Milagro FI, Clemente-Llarramendi I, Esteban Echeverria S, Herrero JJ, Elorz M, Benito-Boillos A, Tobaruela-Resola AL, Gonzalez-Muniesa P, Tur JA, Martinez JA, Abete I, Zulet MA. Sex-dependent gut microbiota features and functional signatures in metabolic dysfunction-associated steatotic liver disease. *Nutrients*. 2024;16(23).
39. Park J, Kim G, Kim BS, Han KD, Kwon SY, Park SH, Lee YB, Jin SM, Kim JH. The associations of hepatic steatosis and fibrosis using fatty liver index and BARD score with cardiovascular outcomes and mortality in patients with new-onset type 2 diabetes: a nationwide cohort study. *Cardiovasc Diabetol*. 2022;21(1):53.
40. Bedogni G, Bellentani S, Miglioli L, Masutti F, Passalacqua M, Castiglione A, Tiribelli C. The Fatty Liver Index: a simple and accurate predictor of hepatic steatosis in the general population. *BMC Gastroenterol*. 2006;6:33.
41. Han Y, Tang J, Wu N, Li Z, Ren H, Hu P, Chen Z. Association between the Life's essential 8 health behaviors score and all-cause mortality in patients with metabolic dysfunction-associated steatotic liver disease. *Metabolism*. 2024;163:156096.
42. Mari L, Lazzar S, Gatti A, D'Alleva M, Zaccaron S, Stafuzza J, Rejc E, Vandoni M, Bondesan A, Caroli D, Frigerio F, Abbruzzese L, Ventura E, Sartorio A. Visceral adiposity, anthropometric and liver function indexes for identifying metabolic dysfunction associated steatotic liver disease (MASLD) in adolescents with obesity: which performs better? *J Clin Med*. 2025;14(6).
43. Li W, Wu H, Xu X, Zhang Y. Environmental exposure to perchlorate, nitrate, and thiocyanate in relation to chronic kidney disease in the general US population, NHANES 2005–2016. *Chin Med J (Engl)*. 2023;136(13):1573–82.
44. Min Y, Wei X, Wei Z, Song G, Zhao X, Lei Y. Prognostic effect of triglyceride glucose-related parameters on all-cause and cardiovascular mortality in the United States adults with metabolic dysfunction-associated steatotic liver disease. *Cardiovasc Diabetol*. 2024;23(1):188.
45. Allen AM, Therneau TM, Larson JJ, Coward A, Somers VK, Kamath PS. Non-alcoholic fatty liver disease incidence and impact on metabolic burden and death: a 20 year-community study. *Hepatology*. 2018;67(5):1726–36.
46. Targher G, Byrne CD, Lonardo A, Zoppini G, Barbui C. Non-alcoholic fatty liver disease and risk of incident cardiovascular disease: a meta-analysis. *J Hepatol*. 2016;65(3):589–600.
47. Janssen A, Grobbee DE, Dendale P. Non-alcoholic fatty liver disease, a new and growing risk indicator for cardiovascular disease. *Eur J Prev Cardiol*. 2020;27(10):1059–63.
48. Francque SM, van der Graaff D, Kwanten WJ. Non-alcoholic fatty liver disease and cardiovascular risk: pathophysiological mechanisms and implications. *J Hepatol*. 2016;65(2):425–43.
49. Stahl EP, Dhindsa DS, Lee SK, Sandesara PB, Chalasani NP, Sperling LS. Nonalcoholic fatty liver disease and the heart: JACC state-of-the-art review. *J Am Coll Cardiol*. 2019;73(8):948–63.
50. Gil A, Martinez de Victoria E, Olza J. Indicators for the evaluation of diet quality. *Nutr Hosp*. 2015;31(Suppl 3):128–44.
51. Steck SE, Murphy EA. Dietary patterns and cancer risk. *Nat Rev Cancer*. 2020;20(2):125–38.
52. Wieland A, Frank DN, Harnke B, Bambha K. Systematic review: microbial dysbiosis and nonalcoholic fatty liver disease. *Aliment Pharmacol Ther*. 2015;42(9):1051–63.
53. Boursier J, Mueller O, Barret M, Machado M, Fizanet L, Araujo-Perez F, Guy CD, Seed PC, Rawls JF, David LA, Hunault G, Oberti F, Cales P, Diehl AM. The severity of nonalcoholic fatty liver disease is associated with gut dysbiosis and shift in the metabolic function of the gut microbiota. *Hepatology*. 2016;63(3):764–75.
54. Cai W, Qiu T, Hu W, Fang T. Changes in the intestinal microbiota of individuals with non-alcoholic fatty liver disease based on sequencing: An updated systematic review and meta-analysis. *PLoS ONE*. 2024;19(3): e0299946.
55. Aron-Wisniewsky J, Vigliotti C, Witjes J, Le P, Holleboom AG, Verheij J, Nieuwdorp M, Clement K. Gut microbiota and human NAFLD: disentangling microbial signatures from metabolic disorders. *Nat Rev Gastroenterol Hepatol*. 2020;17(5):279–97.
56. Schwirtz A, Taras D, Schafer K, Beijer S, Bos NA, Donus C, Hardt PD. Microbiota and SCFA in lean and overweight healthy subjects. *Obesity (Silver Spring)*. 2010;18(1):190–5.
57. Backhed F, Ding H, Wang T, Hooper LV, Koh GY, Nagy A, Semenkovich CF, Gordon JI. The gut microbiota as an environmental factor that regulates fat storage. *Proc Natl Acad Sci USA*. 2004;101(44):15718–23.
58. Yao N, Yang Y, Li X, Wang Y, Guo R, Wang X, Li J, Xie Z, Li B, Cui W. Effects of dietary nutrients on fatty liver disease associated with metabolic dysfunction (MAFLD): based on the intestinal-hepatic axis. *Front Nutr*. 2022;9: 906511.
59. Dumas ME, Barton RH, Toye A, Cloarec O, Blancher C, Rothwell A, Fearnside J, Tatoud R, Blanc V, Lindon JC, Mitchell SC, Holmes E, McCarthy MI, Scott J, Gauguier D, Nicholson JK. Metabolic profiling reveals a contribution of gut microbiota to fatty liver phenotype in insulin-resistant mice. *Proc Natl Acad Sci USA*. 2006;103(33):12511–6.
60. Chen YM, Liu Y, Zhou RF, Chen XL, Wang C, Tan XY, Wang LJ, Zheng RD, Zhang HW, Ling WH, Zhu HL. Associations of gut-flora-dependent metabolite trimethylamine-N-oxide, betaine and choline with non-alcoholic fatty liver disease in adults. *Sci Rep*. 2016;6:19076.
61. Desai MS, Seekatz AM, Koropatkin NM, Kamada N, Hickey CA, Wolter M, Pudlo NA, Kitamoto S, Terrapon N, Muller A, Young VB, Henrissat B, Wilmes P, Stappenbeck TS, Nunez G, Martens EC. A dietary fiber-deprived gut microbiota degrades the colonic mucus barrier and enhances pathogen susceptibility. *Cell*. 2016;167(5):1339–1353e21.
62. Wrzosek L, Miquel S, Noordine ML, Bouet S, Joncquel Chevalier-Curt M, Robert V, Philippe C, Bridonneau C, Cherbuy C, Robbe-Masselot C, Langella P, Thomas M. Bacteroides thetaiotaomicron and Faecalibacterium prausnitzii influence the production of mucus glycans and the development of goblet cells in the colonic epithelium of a gnotobiotic model rodent. *BMC Biol*. 2013;11:61.
63. Bolte LA, Vich Vila A, Imhann F, Collij V, Gacesa R, Peters V, Wijmenga C, Kurilshikov A, Campmans-Kuijpers MJE, Fu J, Dijkstra G, Zhernakova A, Weersma RK. Long-term dietary patterns are associated with pro-inflammatory and anti-inflammatory features of the gut microbiome. *Gut*. 2021;70(7):1287–98.
64. Sandby K, Magkos F, Chabanova E, Petersen ET, Krarup T, Bertram HC, Kristiansen K, Geiker NRW. The effect of dairy products on liver fat and metabolic risk markers in males with abdominal obesity—a four-arm randomized controlled trial. *Clin Nutr*. 2024;43(2):534–42.
65. Mouries J, Brescia P, Silvestri A, Spadoni I, Sorribas M, Wiest R, Mileti E, Galbiati M, Invernizzi P, Adorini L, Penna G, Rescigno M. Microbiota-driven gut vascular barrier disruption is a prerequisite for non-alcoholic steatohepatitis development. *J Hepatol*. 2019;71(6):1216–28.
66. Cani PD, Amar J, Iglesias MA, Poggi M, Knauf C, Bastelica D, Neyrinck AM, Fava F, Tuohy KM, Chabo C, Waget A, Delmee E, Cousin B, Sulpice T, Chamontin B, Ferrieres J, Tanti JF, Gibson GR, Casteilla L, Delzenne NM, Alessi MC, Burcelin R. Metabolic endotoxemia initiates obesity and insulin resistance. *Diabetes*. 2007;56(7):1761–72.
67. Zhen J, Zhou Z, He M, Han HX, Lv EH, Wen PB, Liu X, Wang YT, Cai XC, Tian JQ, Zhang MY, Xiao L, Kang XX. The gut microbial metabolite trimethylamine N-oxide and cardiovascular diseases. *Front Endocrinol (Lausanne)*. 2023;14:1085041.

68. Mantovani A, Csermely A, Petracca G, Beatrice G, Corey KE, Simon TG, Byrne CD, Targher G. Non-alcoholic fatty liver disease and risk of fatal and non-fatal cardiovascular events: an updated systematic review and meta-analysis. *Lancet Gastroenterol Hepatol*. 2021;6(11):903–13.
69. Matsuguma K, Hara T, Miyamoto D, Soyama A, Matsushima H, Fukumoto M, Imamura H, Yamashita M, Adachi T, Eguchi S. Improvement in aged liver regeneration using cell transplantation with chemically induced liver progenitors. *J Hepatobiliary Pancreat Sci*. 2024.
70. Guo M, Jiang X, Ouyang H, Zhang X, Zhang S, Wang P, Bi G, Wu T, Zhou W, Liang F, Yang X, Fan S, Fang JH, Chen P, Bi H. Parabacteroides distasonis promotes liver regeneration by increasing beta-hydroxybutyric acid (BHB) production and BHB-driven STAT3 signals. *Acta Pharm Sin B*. 2025;15(3):1430–46.
71. Visekruna A, Luu M. The role of short-chain fatty acids and bile acids in intestinal and liver function, inflammation, and carcinogenesis. *Front Cell Dev Biol*. 2021;9: 703218.
72. Mann ER, Lam YK, Uhlig HH. Short-chain fatty acids: linking diet, the microbiome and immunity. *Nat Rev Immunol*. 2024;24(8):577–95.
73. Carmo GP, Szumiejko A, Fernandes FAO, Alves de Sousa RJ, MacManus DB. A computational study on the effect of age and sex on arterial wall biomechanics. *J Mech Behav Biomed Mater*. 2025;169: 107073.
74. Guo J, Terhorst I, Stammer P, Ibrahim A, Oberhuber A, Eierhoff T. The short-chain fatty acid butyrate exerts a specific effect on VE-cadherin phosphorylation and alters the integrity of aortic endothelial cells. *Front Cell Dev Biol*. 2023;11:1076250.
75. Andersson CX, Gustafson B, Hammarstedt A, Hedjazifar S, Smith U. Inflamed adipose tissue, insulin resistance and vascular injury. *Diabetes Metab Res Rev* Nov-Dec. 2008;24(8):595–603.
76. Yao S, Marron MM, Tian Q, Watts EL, Clish CB, Shah RV, Murthy VL, Newman AB. Metabolomic pathways of inflammation and mitochondrial dysfunction are related to worsening healthy aging index and mortality. *J Gerontol A Biol Sci Med Sci*. 2025;80(6).
77. Li Q, Xiao N, Zhang H, Liang G, Lin Y, Qian Z, Yang X, Yang J, Fu Y, Zhang C, Liu A. Systemic aging and aging-related diseases. *FASEB J*. 2025;39(5): e70430.
78. Cusi K, Abdelmalek MF, Apovian CM, Balapattabi K, Bannuru RR, Barb D, Bardsley JK, Beverly EA, Corbin KD, ElSayed NA, Isaacs S, Kanwal F, Pekas EJ, Richardson CR, Roden M, Sanyal AJ, Shubrook JH, Younossi ZM, Bajaj M. Metabolic dysfunction-associated steatotic liver disease (MASLD) in people with diabetes: the need for screening and early intervention. A Consensus Report of the American Diabetes Association. *Diabetes Care*. 2025.
79. Ellegaard AM, Winther-Jensen M, Karhus LL, Knop FK, Karhus ML. Bile acid diarrhea is associated with an increased risk of type 2 diabetes and cardiovascular disease: a nationwide cohort study. *Clin Transl Gastroenterol*. 2025.
80. Han J, Meng X, Kong H, Li X, Chen P, Zhang XA. Links between short-chain fatty acids and osteoarthritis from pathology to clinic via gut-joint axis. *Stem Cell Res Ther*. 2025;16(1):251.
81. Snelson M, R RM, Liu CF, Marko L, Forslund SK, Marques FZ, Tang WHW. Gut-Heart Axis: The Role of Gut Microbiota and Metabolites in Heart Failure. *Circ Res*. May 23 2025;136(11):1382–1406.
82. Wilcox G. Insulin and insulin resistance. *Clin Biochem Rev*. 2005;26(2):19–39.
83. Reaven GM. Pathophysiology of insulin resistance in human disease. *Physiol Rev*. 1995;75(3):473–86.
84. Wu G, Meininger CJ. Nitric oxide and vascular insulin resistance. *Biofactors* Jan-Feb. 2009;35(1):21–7.
85. Wang CC, Gurevich I, Draznin B. Insulin affects vascular smooth muscle cell phenotype and migration via distinct signaling pathways. *Diabetes*. 2003;52(10):2562–9.
86. Ormazabal V, Nair S, Elfeky O, Aguayo C, Salomon C, Zuniga FA. Association between insulin resistance and the development of cardiovascular disease. *Cardiovasc Diabetol*. 2018;17(1):122.
87. Kirkpatrick SI, Reedy J, Krebs-Smith SM, Pannucci TE, Subar AF, Wilson MM, Lerman JL, Tooze JA. Applications of the healthy eating index for surveillance, epidemiology, and intervention research: considerations and caveats. *J Acad Nutr Diet*. 2018;118(9):1603–21.
88. Trichopoulou A, Orfanos P, Norat T, Bueno-de-Mesquita B, Ocke MC, Peeters PH, van der Schouw YT, Boeing H, Hoffmann K, Boffetta P, Nagel G, Masala G, Krogh V, Panico S, Tumino R, Vineis P, Bamia C, Naska A, Benetou V, Ferrari P, Slimani N, Pera G, Martinez-Garcia C, Navarro C, Rodriguez-Barranco M, Dorronsoro M, Spencer EA, Key TJ, Bingham S, Khaw KT, Kesse E, Clavel-Chapelon F, Boutron-Ruault MC, Berglund G, Wirfalt E, Hallmans G, Johansson I, Tjønneland A, Olsen A, Overvad K, Hundborg HH, Riboli E, Trichopoulos D. Modified Mediterranean diet and survival: EPIC-elderly prospective cohort study. *BMJ*. 2005;330(7498):991.
89. Trichopoulou A, Costacou T, Bamia C, Trichopoulos D. Adherence to a Mediterranean diet and survival in a Greek population. *N Engl J Med*. 2003;348(26):2599–608.
90. Huang X, Zhang X, Hao X, Wang T, Wu P, Shen L, Yang Y, Wan W, Zhang K. Association of dietary quality and mortality in the non-alcoholic fatty liver disease and advanced fibrosis populations: NHANES 2005–2018. *Front Nutr*. 2025;12:1507342.
91. Vilar-Gomez E, Vuppalanchi R, Gawrieh S, Pike F, Samala N, Chalasani N. Significant dose-response association of physical activity and diet quality with mortality in adults with suspected NAFLD in a population study. *Am J Gastroenterol*. 2023;118(9):1576–91.
92. Yoo ER, Kim D, Vazquez-Montesino LM, Escobar JA, Li AA, Tighe SP, Fernandes CT, Cholaneril G, Ahmed A. Diet quality and its association with nonalcoholic fatty liver disease and all-cause and cause-specific mortality. *Liver Int*. 2020;40(4):815–24.
93. Ruhl CE, Everhart JE. Fatty liver indices in the multiethnic United States National Health and Nutrition Examination Survey. *Aliment Pharmacol Ther*. 2015;41(1):65–76.

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