Diabetology & Metabolic Syndrome

REVIEW

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Insulinemic potential of diet and the risk of type 2 diabetes: a meta-analysis and systematic review

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Abstract

Background The possible role of the insulinemic potential of diet in the etiology of type 2 diabetes (T2D) has recently received significant attention in observational studies. This meta-analysis aimed to synthesize available evidence and quantify the potential association between the empirical dietary index for hyperinsulinemia (EDIH) score and T2D risk.

Methods Various electronic databases, including Scopus, PubMed, and Web of Science, were comprehensively searched up to January 2024 using related keywords to identify relevant studies. The hazard ratios (HR) or odds ratios were extracted from eligible cohort studies, and a random-effects model with an inverse variance weighting method was used to calculate the pooled effect size, which was expressed as HR.

Results The analysis included six cohort studies (four publications), with sample sizes ranging from 3,732 to 90,786 individuals aged 20 to 79 years. During follow-up periods of 5 to over 20 years, 31,284 T2D incidents were identified. The pooled results showed that a higher EDIH score was associated with an increased risk of T2D incidence (HR: 1.47; 95%CI 1.21–1.77; $I^2 = 91.3\%$). Significant publication bias was observed in the present meta-analysis ($P = 0.020$). Geographical region and follow-up period can be as sources of heterogeneity ($P_{heterogeneity} < 0.001$).

Conclusion Our meta-analysis of observational studies suggested that a diet with a higher EDIH score may be associated with an increased risk of incidence of T2D.

Keywords Dietary pattern, Insulin, Hyperinsulinemia, Type 2 diabetes, Meta-analysis

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Introduction

Type 2 diabetes (T2D), accounting for about 90% of diabetes cases, is often characterized by insulin resistance, where diminished response to insulin prompts increased production, leading to hyperinsulinemia to maintain glucose homeostasis [1]. However, over time, the pancreas's ability to produce insulin decreases, eventually leading to chronic hyperglycemia and the development of T2DM [1, 2]. The global prevalence of T2D has reached alarming levels, affecting over 460 million people worldwide, and its rise poses a serious public health challenge due to its substantial impact on quality of life and increased risks of morbidity and mortality [3–5]. While genetic predisposition plays a role, lifestyle factors such as sedentary lifestyle, smoking, alcohol consumption, and notably unhealthy eating habits are significant contributors to the development of hyperinsulinemia and T2D risk [6–9]. Recent research highlights the significant role of dietary patterns in modulating insulin levels and influencing the risk of T2D, underscoring the need for further investigation into how specific dietary choices influence disease development [10].

The insulinemic characteristics of dietary patterns are crucial in understanding the connection between nutrition and chronic diseases, such as T2D. Recent studies have highlighted that diets with a high potential to elevate glycemic parameters, such as glucose and insulin, are associated with an increased risk of various metabolic diseases, including cancers and T2D [11–13]. Recently, researchers have introduced the Empirical Dietary Index for Hyperinsulinemia (EDIH) as a novel approach to dietary assessment [14]. Unlike traditional indices, which focus primarily on nutrient intake, EDIH evaluates the overall insulinemic potential of the diet based on the insulin response triggered by different food components [14]. EDIH assesses specific food combinations and their ability to influence circulating levels of C-peptide [15], a reliable biomarker for hyperinsulinemia and a significant predictor of diabetes risk [16]. Higher EDIH scores are hypothesized to contribute to T2D development primarily by stimulating insulin secretion and leading to the eventual exhaustion of beta cells [14]. Despite its potential, studies on the association between EDIH scores and T2D risk have produced inconsistent results. While some research indicates that higher EDIH scores are linked to an increased risk of T2D [17, 18], other studies have found no significant association [19, 20].

Given the rising prevalence of T2D and the potential benefits of dietary interventions for its prevention and management [21], it is essential to synthesize the existing evidence on the relationship between EDIH and T2D risk. Therefore, this systematic review and meta-analysis aims to comprehensively evaluate and quantify the association between EDIH score and T2D risk by synthesizing all available research on this topic. Findings from this meta-analysis could enhance our understanding of how dietary patterns influence hyperinsulinemia and, consequently, T2D. This improved understanding may inform future dietary recommendations and preventive strategies, particularly for populations at high risk of developing T2D.

Materials and methods

Search strategy

Published articles were searched in online literature databases such as PubMed, Web of Science, and Scopus up to January 2024. Literature was searched using keywords and MeSH (Medical Subject Heading) terms, including: "EDIH" or "empirical dietary index" or "empirical dietary indices" or "dietary index for hyperinsulinemia" or "insulinemic dietary pattern" or "insulinemic potential of diet" or "dietary pattern of insulin" or "dietary insulinemic potential" or "hyperinsulinemic dietary score" or "hyperinsulinemia dietary score" combined with "Diabetes Mellitus" or " Diabetes" or " type 2 diabetes" or "T2D" (Supplementary Table 2). The reference lists of all relevant studies and review papers were hand-searched to avoid missing any publications. This meta-analysis is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline (version 2020) (Supplementary Fig. 2).

Inclusion criteria

The studies that met the following criteria were considered eligible for inclusion: (1) original article, (2) adult subjects, (3) cohort studies reporting the association between EDIH and the risk of T2D; (4) reported the Hazard Ratio (HR), Odds Ratio (OR) or Relative Risk (RR) with a 95% Confidence Interval (CI). PECO criteria are presented in Supplementary Table 1.

Exclusion criteria

The exclusion criteria for the present study were (1) studies conducted on other insulin indices of diet except for EDIH computed via the method presented by Tabung et al. [14]. ; (2) studies involving pregnant women and children; (3) randomized clinical trials, review articles, laboratory, and animal studies; and (4) unpublished data and grey literature, including congress abstracts, dissertations, and patents.

Data extraction

Information from each eligible study was independently reviewed and extracted by two reviewers, including the first author's name, publication year, cohort's name, country and setting of the study, study design, sample size, the number of cases, participant's age, sex, tools used for dietary measurement, compared categories,

reported HR with 95% CI for the association between EDIH and risk of T2D, diabetes incidence, adjusted variables, and follow-up time.

Validity and quality assessment of studies

We independently evaluated the methodological quality of included studies using the ROBINS-I tool (Supplementary Table S3) [22].

Statistical analysis

We extracted the HR or OR with 95% CI for all cohort studies and transformed them into log HR, and then their standard error (SE) was computed. A random-effects model with an inverse variance weighting method was used to estimate the overall effect size. Between-study heterogeneity was assessed using the I^2 statistic [23] (specific categories such as low=25%, moderate=50%, and high=75%) and Cochrane's Q statistic (with a *P*-value<0.10 considered significant) [24]. The visual observational of the funnel plot and Egger's regression test were used to evaluate potential publication bias. Furthermore, we used the trim-and-fill method to estimate the required articles. Sensitivity analysis was performed to assess the robustness of the findings. All statistical analyses were performed using the Stata version 11.2 software, and $P<0.05$ was considered statistically significant. All statistical tests were two-sided.

Results

Study selection

As shown in Fig. 1, we performed a systematic search across three databases, which yielded 3577 results. After removing duplicates, we screened 3441 articles by title and abstract and, subsequently, by full-text review if necessary. Ultimately, six eligible cohorts (four publications) [17–20] were included in the current meta-analysis.

Study characteristics

Table 1 shows the basic characteristics of the included cohort studies. Of these studies, two were conducted in Iran [19, 20] and the remaining four were conducted in the US [17, 18]. The sample sizes varied from 3,732 to 90,786 individuals, with participants aged between 20 and 79. Over the follow-up period, which ranged from 5 to over 20 years, a total of 31,284 incident cases of T2D were identified. The studies included both genders ($n=2$), men only ($n=1$), and women only ($n=3$). All studies used food frequency questionnaire (FFQ) to collect dietary data. While two studies [19, 20] reported a non-significant lower risk of T2D, the remaining four investigations [17, 18] found a higher risk of T2D in the highest EDIH score category compared to the lowest.

Meta-analysis

Association between the EDIH and the risk of T2D

Figure 2 shows the association between the EDIH and the risk of T2D. Compared to the lowest category of EDIH (Tertile 1, Quartile 1, or Quintile 1), the highest category of EDIH (Tertile 3, Quartile 4, or Quintile 5) was associated with a 47% increased risk of T2D (HR=1.47; 95% CI:1.21–1.77; $I^2=91.3\%$).

Egger's test ($P=0.020$) indicated a significant publication bias in the association between EDIH and the risk of T2D; however, visual inspection of the funnel plot indicated that there was no publication bias for the relationship between EDIH and the risk of T2D (Supplementary Fig. 1). The trim-and-fill method was performed to calibrate publication bias for studies related to EDIH and the risk of T2D and no missing studies were detected by the trim-and-fill method.

In our analysis, the I^2 statistic was 91.3%, and the *P*-value for Cochrane's Q was <0.001, indicating considerable heterogeneity. Therefore, we conducted a subgroup analysis based on geographical region and follow-up period. As shown in Table 2, geographical region and follow-up period were identified as significant sources of heterogeneity ($P<0.001$). Studies conducted in Iran, which had a follow-up period of <10 years, reported a non-significant lower risk of T2D for the highest compared to the lowest EDIH score (HR=0.82; 95% CI: 0.65, 1.03; $I^2=0.00\%$). However, pooled results from US cohorts (with a follow-up length ≥ 10 years) showed a significantly higher T2D risk for the highest EDIH score category compared to the lowest (HR=1.76; 95% CI:1.57, 1.97; $I^2=78.9\%$).

Risk of bias assessment

Supplementary Table 3 presents the quality assessment of included studies using the ROBINS-I tool and all included studies has moderate risk of bias.

Sensitivity analysis

The sensitivity analysis results for the association between the highest and lowest EDIH categories and the risk of T2D are presented in Table 3. The analysis showed that the exclusion of any single study did not substantially alter the overall results (range: 1.34–1.67).

Discussion

This systematic review and meta-analysis examined the relationship between dietary patterns and the development of hyperinsulinemia and T2D. The findings revealed that individuals with the highest EDIH scores had a 47% increased risk of T2D compared to those with the lowest scores. Our analysis also suggests potential variations in T2D risk associated with EDIH scores based on study location.

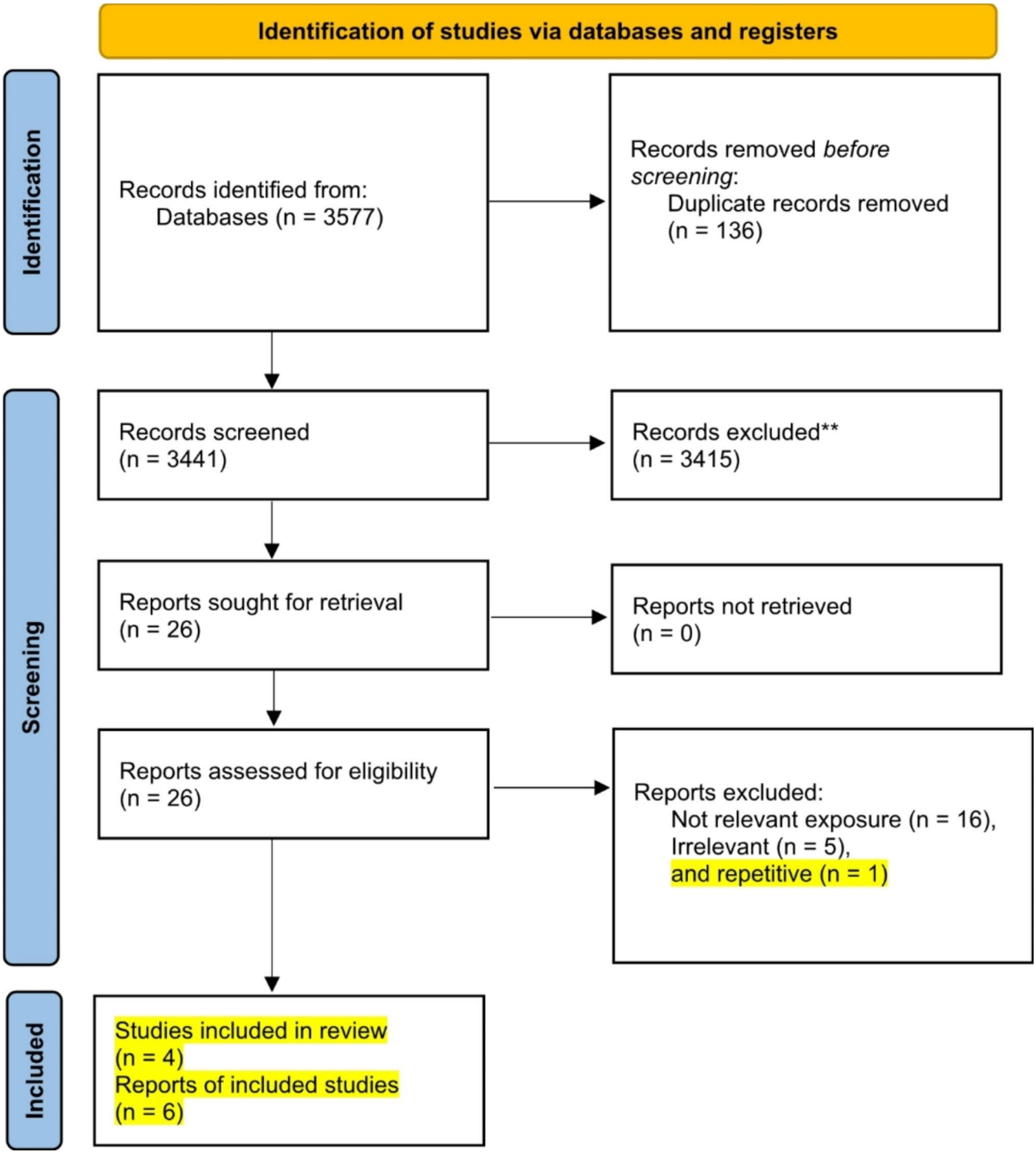

Fig. 1 Flow diagram of selection of the published studies

Diet plays a crucial role in T2D development, with approximately 80% of cases potentially preventable through healthy eating habits [25, 26]. These include increased consumption of fruits and vegetables and reduced intake of saturated fat, sodium, and sugar-sweetened drinks [27, 28]. Various dietary approaches, such as low-carbohydrate, Mediterranean, plant-based, and low-glycemic index, have shown effectiveness in managing glycemic levels and reducing cardiovascular risk in individuals with T2D [29]. Conversely, low-quality diets, characterized by low intake of vegetables, fruits, dairy, fish, and eggs, and high consumption of sodium, cholesterol, and saturated fatty acids, significantly increase T2D risk across diverse subgroups. These subgroups

Table 1 Characteristics of included studies in the meta-analysis*

Studies/ Year/ Cohort name	Country	Cases /Totals	Gender, Age range	Exposure assessment	Comparison	HR / OR (95% CI)	Incidence of T2DM (%)	Adjustment for covariate	Follow-up (Years)	Risk of bias assessment by ROBINS-I tool
Omrani, 2023 Yazd health study	Iran	343/5714	Both 36 ± 7.8 years	178-items FFQ	T3 vs. T1	0.77 (0.58–1.02)	% 6.0	Age, sex, BMI, smoking, physical activity, family history of diabetes, marital status, socio economic status, menopausal status and dietary intake of energy	5	Moderate
Farhadnejad, 2021 TLGS study	Iran	257/3732	Both ≥ 20 years	168-items FFQ	Q4 vs. Q1	0.95 (0.63–1.44)	% 6.8	Age, sex, energy, waist circumference, smoking, physical activity, education level, energy, smoking, education level, waist-adjusted BMI, fasting blood sugar and TAG: HDL-cholesterol at baseline	6.2	Moderate
Lee, 2020 Nurses' Health Study	US	8782/74,767	Women 30–55 years	130-items FFQ	Q5 vs. Q1	1.93 (1.79–2.09)	% 11.7	Energy, age, race, smoking, postmenopausal hormone use, oral contraceptive use, physical activity, family history of diabetes and BMI	> 20	Moderate
Lee, 2020 Nurses' Health Study II	US	7157/90,786	Women 25–42 years	130-items FFQ	Q5 vs. Q1	1.74 (1.59–1.91)	% 7.8	Energy, age, race, smoking, postmenopausal hormone use, oral contraceptive use, physical activity, family history of diabetes and BMI	> 20	Moderate

Table 1 (continued)

Studies/ Year/ Cohort name	Country	Cases /Totals	Gender, Age range	Exposure assessment	Comparison	HR / OR (95% CI)	Incidence of T2DM (%)	Adjustment for covariate	Follow-up (Years)	Risk of bias assessment by ROBINS-I tool
Lee, 2020 Health Professionals Follow-up Study	US	3727/39,442	Men 40–75 years	130-items FFQ	Q5 vs. Q1	1.94 (1.73–2.17)	% 9.4	Energy, age, race, smoking, postmenopausal hormone use, oral contraceptive use, physical activity, family history of diabetes and BMI	> 20	Moderate
Jin, 2021 Women's Health Initiative	US	11,018/73,495	Women 50–79 years	130-items FFQ	Q5 vs. Q1	1.41 (1.20–1.65)	% 14.9	Energy, Age, hypertension, family history of type 2 diabetes, hormone use, physical activity, education, race, pack-years of smoking, high cholesterol, WHI study arms, nonsteroidal anti-inflammatory drug use, statin use, nutritional supplement use and BMI	13.3	Moderate

*All included studies were cohort studies

Abbreviations: BMI: body mass index; CI: confidence interval; FFQ: food frequency questionnaire; HR: hazard ratio; OR: odds ratio; Q, quartile and quintile; T: Tertile; TLGS: Tehran Lipid and Glucose study; T2DM: Type 2 diabetes mellitus

include variations in sex, abdominal obesity, overweight status, age, hypertension, smoking habits, and alcohol and tea consumption [30, 31]. Hyperinsulinemia is a key mechanism linking poor dietary and lifestyle behaviors to T2D development [14]. The established relationship between diet quality and chronic diseases such as T2D underscores the importance of diet quality indices for rapid assessment of nutritional health [32, 33]. A novel dietary index, known as EDIH, evaluates the relationship between typical dietary patterns and insulin response. It helps identify populations at high risk for hyperinsulinemia by predicting fasting plasma C-peptide levels for hyperinsulinemia and the triglyceride-to- high-density lipoprotein (TG/HDL) ratio for insulin resistance [14]. The associations between EDIH and T2D risk suggest that certain dietary patterns may promote chronic inflammation and hyperinsulinemia [17]. A dietary pattern characterized by both pro-inflammatory and high insulinemic properties (indicated by the highest EDIH score) includes high intake of red meat, processed meat, sugar-sweetened beverages, and refined grains, coupled with low intake of green leafy vegetables, full-fat dairy, wine, coffee, and non-fatty fish [14, 18, 19]. It is possible that these dietary components impact hyperinsulinemia and insulin resistance differently among individuals, based on their genetic predisposition, lifestyles, and stage of disease progression [19].

While the exact mechanisms through which the insulinemic potential of dietary indices influences the risk of T2D remain unclear, the insulinemic effects of various food components are crucial in regulating long-term insulin secretion. Increased consumption of red and processed meats, as well as added sugars, has been associated with a higher risk of T2D in Western populations [34, 35]. These dietary components may contribute to T2D development through mechanisms involving oxidative stress, inflammation, and impaired insulin sensitivity [36, 37]. In contrast, diets rich in whole grains, fruits, vegetables, and healthy fats support better glycemic control and insulin sensitivity, potentially reducing the risk

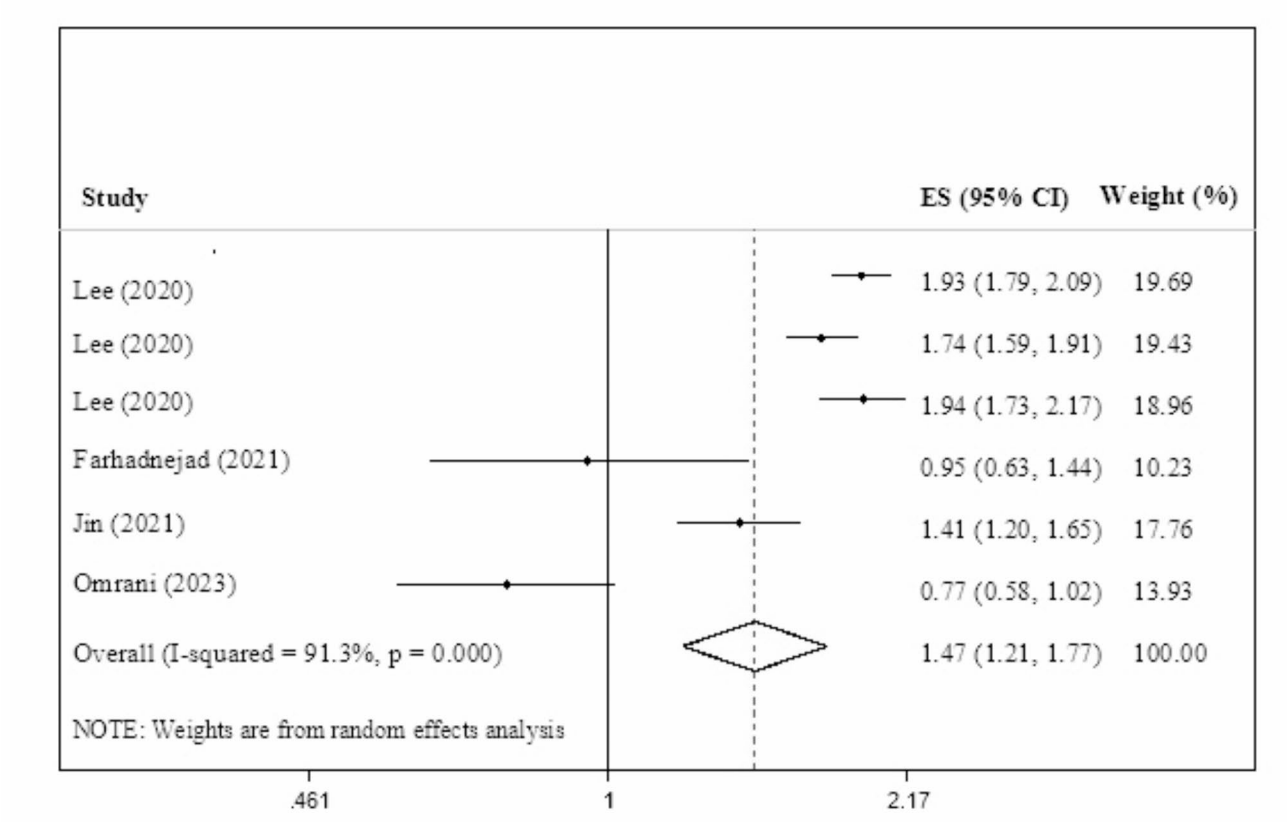

Fig. 2 Forest plot for the association between the empirical dietary index for hyperinsulinemia (EDIH) and the risk of type 2 diabetes, expressed as a comparison between the highest and lowest categories of EDIH

Table 2 Summary relative risk (RR) estimates [95% confidence intervals (CIs)] for sub-group analysis of the association between the empirical dietary index for hyperinsulinemia (EDIH) with the risk of type 2 diabetes

Subgroups	Study numbers	Summary RR (95% CI)	Between studies		Between subgroups	
			I^2	$P_{heterogeneity}$	Q	$P_{heterogeneity}$
Geographical region					42.3	< 0.001
Iran	2	0.82 (0.65–1.03)	0.00%	0.411		
US	4	1.76 (1.57–1.97)	78.9%	0.003		
Follow-up period					42.3	< 0.001
< 10 years	2	0.82 (0.65–1.03)	0.00%	0.411		
≥ 10 years	4	1.76 (1.57–1.97)	78.9%	0.003		

All statistical tests were two-sided

Table 3 Sensitivity analysis for the association between highest vs. lowest EDIH categories and the risk of type 2 diabetes

Study omitted	Estimate	[95% Conf. Interval]
Omrani, 2023	1.67	(1.46, 1.91)
Farhadnejad, 2021	1.54	(1.28, 1.86)
Lee, 2020	1.34	(1.05, 1.72)
Lee, 2020	1.37	(1.05, 1.78)
Lee, 2020	1.35	(1.07, 1.71)
Jin, 2021	1.47	(1.19, 1.81)
Combined	1.47	(1.21, 1.77)

of T2D [38]. While the role of fish and alcohol in T2D prevention remains inconclusive, some evidence suggests that these factors may influence glucose metabolism and inflammation [39–41]. Coffee consumption, although associated with mixed effects on insulin sensitivity, may offer benefits for subclinical inflammation and HDL cholesterol levels [42, 43].

Excess body fat, or adiposity, significantly increases T2D risk through various mechanisms. Primarily, adiposity promotes chronic low-grade inflammation, which impairs insulin signaling [44]. This process is driven by the dysregulation of adipokine secretion from excess

adipose tissue, a key factor that links obesity to reduced insulin sensitivity and an increased risk of developing T2D [44, 45]. The consumption of diets with a high insulinemic potential may contribute to obesity by increasing insulin secretion and altering fat and carbohydrate metabolism, further exacerbating T2D risk. These diets also promote inflammation, metabolic dysregulation, and increased T2D risk [18, 46, 47]. Additionally, higher insulinemic potential levels are linked to increased serum TG levels and reduced HDL cholesterol concentrations, both associated with insulin resistance and an increased risk of developing T2D [48–50].

The differences observed between the results of studies conducted in the US and Iran may be attributed to variations in dietary patterns, population characteristics, and length of studies follow-up. While studies by Farhadnejad et al. [19] and Omrani et al. [20] in Iran found no significant relationship between the EDIH score and the risk of T2DM, possibly due to lower intake of EDIH components and population diversity, US-based studies by Lee et al. [18] and Jin et al. [17] showed a significant association. Additionally, differences in the consumption of specific foods, such as coffee, dairy, and alcohol, which are more prevalent in the US, may also explain the variation in findings. Another reason for the heterogeneity based on the geographical region can be the difference in the follow-up period of the studies conducted in different regions of the world; the studies conducted in Iran had a follow-up period of fewer than 10 years and they did not observe a significant relationship between EDIH score and risk of T2D, however, the studies conducted in US has follow-up period more than 10 years and observed positive relationship between EDIH score and risk of T2D. Therefore, it seems that a longer period of time (more than 10 years) is needed to observe the noticeable influence of the insulinemic potential of individuals' diet in predicting the risk of T2D.

Our findings showed a significant 47% increase in the risk of T2D associated with the highest category of EDIH compared to the lowest category. However, interesting differences were observed when comparing studies from different regions, especially the US and Iran. Studies in the US revealed a higher risk of T2D among individuals with higher EDIH scores. On the other hand, research in Iran indicated a non-significant lower risk of T2D linked to elevated EDIH scores. These contrasting results between US and Iranian studies may be due to the regional dietary patterns and genetic factors on the risk of T2D. The US, known for its consumption of processed foods with high insulinemic effects [51], showed a stronger association between dietary insulin load and T2D risk. In contrast, Iranian dietary habits, reflecting a different food composition and cultural context, may lessen the impact of insulinemic diets on the development of T2D. Further studies across diverse populations are necessary to validate and enhance the robustness of these findings.

The EDIH score is a valuable tool for assessing T2D risk, with higher scores indicating greater risk. This index has potential applications in clinical practice, enabling personalized nutrition advice that could improve T2D prevention and management. Future dietary guidelines could incorporate these findings to emphasize the importance of considering not just the carbohydrate content of foods but also their overall insulinemic and inflammatory potential.

One of the strengths of this study is its comprehensive systematic search and analysis of cohort studies, allowing for more accurate results. Moreover, all studies included in the current meta-analysis were of good quality, with low risk of bias observed. However, we acknowledge the absence of a pre-registered protocol as a limitation, and our subgroup analysis should be considered exploratory. Despite the robust study selection and quality assessments, this meta-analysis exhibited considerable heterogeneity. This variability was primarily attributed to differences in geographical locations and gender-specific outcomes, with a predominance of US-based studies limiting generalizability. Additionally, the limited number of gender-specific studies, particularly for men, constrains our ability to conduct a sub-group analysis based on gender and so we cannot draw definitive conclusions about gender-based variations in EDIH-T2D risk associations. While sensitivity analysis confirmed the stability of the findings, the observational nature of the studies precludes establishing causality. Nevertheless, this meta-analysis offers valuable insights into the role of dietary patterns in T2D development, emphasizing the importance of considering dietary inflammatory potential in T2D prevention strategies.

Conclusions

In conclusion, our findings revealed that a high insulinemic dietary pattern, as indicated by a high EDIH score, is associated with an increased risk of T2D incidence. While these results are promising, future investigations should prioritize large-scale prospective studies and randomized controlled trials to establish a causal relationship between dietary patterns (specifically EDIH score) and the risk of T2D. Investigating the dose-response relationship, the impact of specific dietary patterns or food groups, and individual variability through integration with other omics data can provide comprehensive insights into the complex interactions between diet, inflammation, and metabolic health.

Abbreviations

CI	Confidence Interval
EDIH	Empirical Dietary Index for Hyperinsulinemia

FFQ	Food frequency questionnaire
HR	Hazard Ratio
HDL	High-density lipoprotein
OR	Odds Ratio
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
ROBINS-I	Risk of Bias in Non-randomized Studies of Interventions
RR	Relative Risk
SE	Standard error
TGs	Triglycerides
T2D	Type 2 diabetes

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

Supplementary Material 6

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Author contributions
HF and FT contributed to the study concept and design. HF, HA, FT, MKJ and PM developed the overall research plan and study oversight. MN and HA conducted the research. MN and MO independently screened all records based on their titles and abstracts. HA and FT performed the data extraction, data analyses, and interpretation of data. HF, MA, HA, MO, MN, NS, and MKJ drafted the manuscript. All authors provided intellectual comments and performed the critical revision of the manuscript. PM and FT supervised the study. All authors approved the final version of the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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