Review

Global Warming May Affect Type 2 Diabetes Incidence. A Possible Contribution of Gender-Related Dietary Choices

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Global Warming May Affect Type 2 Diabetes Incidence. A Possible Contribution of Gender-Related Dietary Choices

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Abstract

Growing evidence suggests that the increase in global temperatures is partly driving the rise in type 2 diabetes (T2D), with dietary choices playing a key mediating role. Diets high in red meat and ultra-processed foods contribute substantially to greenhouse gas emissions (GHGE), while plant-based diets offer both environmental and health benefits. Notably, gender differences influence dietary patterns, with women typically consuming less meat and generating lower diet-related GHGE than men, potentially reducing their risk of T2D. We performed a comprehensive literature search to collect information on dietary behaviours, GHGE, ambient temperature, and diabetes outcomes, with a particular focus on gender differences. Evidence indicates that rising global temperatures impair glucose homeostasis, partly through reduced brown adipose tissue activity and increased insulin resistance, thereby exacerbating diabetes risk. Gender-specific dietary choices not only affect individual and collective contributions to climate change but also modulate vulnerability to climate-related health risks, including gestational diabetes. Modeling studies suggest that shifting to plant-based diets, especially among men, could significantly reduce both GHGE and diabetes burden. These findings highlight the importance of incorporating gender perspectives into dietary strategies in order to develop targeted mitigation measures against climate change and global warming, while also improving metabolic health outcomes worldwide.

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1. Introduction

How do diets indirectly affect diabetes outcomes? It is well known that climate change represents the most urgent and complex challenge of the 21st century, exerting profound and multifaceted effects on both the environment and human health. Over the past few decades, the scientific community has increasingly focused on the intricate relationships among dietary choices, environmental sustainability, and public health. It is now recognized that what individuals consume not only affects personal well-being but also has far-reaching consequences for planetary health and the progression of chronic diseases such as type 2 diabetes (T2D). Unhealthy diets, particularly those rich in red meat and ultra-processed foods, disproportionately contribute to global warming: livestock production accounts for approximately 14.5% of all anthropogenic greenhouse gas emissions (GHGE). Ruminant meat, in particular, generates between 20 and 100 times more emissions per gram of protein compared to plant-based sources [1]. This striking disparity highlights the immense environmental burden imposed by animal-based diets - especially those centered on ruminant meat - highlights the urgent need for a systemic shift toward more sustainable food systems

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that prioritize plant-derived protein sources. Such dietary habits influence every aspect of the food supply chain, from agriculture and land use to deforestation for grazing and fodder production—activities that further increase CO_2 emissions [2].

Emerging evidence indicates that the rising of global temperatures are linked to the increasing prevalence of T2D. This relationship appears to be mediated by a range of physiological and environmental mechanisms that are still under active investigation. For instance, exposure to elevated ambient temperatures has been associated with impaired glucose metabolism and reduced insulin sensitivity, which in turn increases vulnerability to metabolic disorders like T2D [3]. Heat stress has been shown to disrupt the activities of brown adipose tissue (BAT)—a key regulator of glucose homeostasis— thus promoting insulin resistance by inducing mitochondrial dysfunction [4,5]. BAT, essential for thermogenesis and energy expenditure, becomes less active in warmer conditions, weakening its beneficial effects on glucose regulation. Additionally, heat-induced mitochondrial damage worsen metabolic imbalance, creating a physiological environment conducive to the onset and progression of diabetes. Thus, higher global temperatures may disrupt key metabolic pathways - impairing glucose metabolism - potentially accelerating the onset and the progression of diabetes.

In this context, the adoption of plant-based diets offers a dual benefit: reducing GHGE and mitigating food sector's impact on global warming, while also simultaneously helping to decrease the global burden of non-communicable diseases like T2D [6,7]. Making a transition to more plant-centric diets provides the simultaneous benefit of supporting environmental sustainability and improving metabolic health. Such transitions can also lower the carbon footprint of food systems, conserve natural resources, and enhance resilience against climate-related health risks.

Within this broader framework, a growing body of evidence highlights the significant role that gender and sex play in shaping dietary behaviors and health outcomes. These differences can help foster improved understanding and educational outcomes in food and nutrition sciences [8,9]. On average, women consume 40–60% less meat than men, leading to 20–30% lower diet-related greenhouse gas emission and lower rates of T2D [10].

These gender disparities arise from a complex interplay of biological, cultural, and socioeconomic factors. Women, on average, tend to demonstrate greater awareness of environmental issues and a stronger inclination to adopt sustainable eating habits. Such behavior patterns not only reduce their individual diabetes risk but also contribute to collective efforts to mitigate climate change. These differences in food choices and "climate friendly" attitudes influence individual and collective contributions to GHGE. Additionally, biological sex factors—such as hormonal changes during pregnancy and menopause—interact with heat exposure, making women particularly vulnerable to climate-related health risks, including gestational diabetes mellitus (GDM) [11,12]. Hormonal fluctuations during these key life stages can modify metabolic responses to environmental changes, further underlining the importance of integrating sex and gender perspectives in dietary and public health strategies for climate adaptation.

This review aims to explore how gender-specific dietary behaviors influence feedback loops between climate change and diabetes. Modeling studies suggest that replacing half of all animal-derived protein intake with plant-based alternatives could prevent up to 8.1 million diabetes-related disability-adjusted life years (DALYs) annually, while simultaneously reducing agricultural emissions by approximately 35% [13].

Our research specifically investigates how gender-based differences in dietary behavior affect GHGE and how resulting global warming may further impair glucose metabolism. By applying a gender lens to the intersection of diet, health, and climate, we propose targeted solutions such as promoting sustainable food practices in male-dominated dietary cultures and reducing climate-induced health risks—especially those related to diabetes. Ultimately, a comprehensive and gender-sensitive approach is essential for designing effective public health interventions that can simultaneously address the intertwined challenges of environmental sustainability, dietary behavior, and metabolic disease prevention in an era of rapid climate change.

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2. Methods

We carried out a comprehensive literature search until 30 May 2025 using PubMed and Scopus. We selected studies that provided quantitative data on diabetes outcomes, fasting blood glucose levels, brown adipose tissue activity, as well as sex, combined with outdoor temperature data. No restrictions were applied regarding geographic location or language of publication to ensure a comprehensive review. Relevant data from the included studies were systematically extracted and entered into an Excel spreadsheet for detailed analysis. To enhance the robustness and reliability of our findings, two independent reviewers screened all articles for eligibility, resolving discrepancies through discussion or consultation with a third reviewer when necessary.

In total, 396 articles were initially identified through the search process, of which 35 met all predefined inclusion criteria and were included in the final analysis. The selected studies encompassed a diverse range of research designs, including cross-sectional, cohort, and case-control studies, as well as randomized controlled trials where available. This diversity allowed for a comprehensive synthesis of evidence, capturing both observational and experimental perspectives on the relationship between dietary behaviors, ambient temperature, and diabetes outcomes. The final dataset provided a robust foundation for subsequent analysis and interpretation.

3. Gender Differences in Dietary Choices and Their Impact on Climate Change

Recent research highlights the significant role of the food sector in driving climate change, with about one-third of global greenhouse gas emissions originating from food systems [14]. Among all food sources, meat—especially from ruminant animals—is a major contributor, with livestock production alone responsible for approximately 14% of global GHGE [15]. As a result, dietary guidelines increasingly recommend shifting towards plant-based protein sources to promote environmental sustainability, though the full impact of such changes is still being explored [16].

Transitioning to plant-forward diets offers significant climate benefits [17]. For example, a global move toward low-meat diets could cut the economic costs of climate change mitigation by up to 50% by 2050 [18]. The EAT–Lancet Commission's "planetary health diet" emphasizes plant-based foods and limited animal products, and its adoption could reduce global dietary emissions by approximately 17% and prevent millions of diet-related deaths annually [6,19]. Such dietary transitions, if widely implemented, could also improve resource efficiency, reduce water use, and promote biodiversity conservation, thereby addressing multiple environmental challenges simultaneously. The adoption of these diets requires coordinated efforts from governments, industry, and civil society to overcome barriers related to food preferences, cultural traditions, and economic constraints.

Western diets, high in red meat and dairy, contribute disproportionately to GHGE and resource depletion [20]. The environmental impact of food choices varies widely, and individual-level dietary data are essential for creating effective policies. Importantly, these behaviors differ across demographic groups, including gender [20]. Understanding these demographic differences is crucial for designing targeted interventions that can effectively shift consumption patterns toward more sustainable options. Gender, in particular, emerges as a key determinant, influencing not only what is eaten but also the motivations and attitudes underlying food choices.

Numerous studies have shown that women tend to express higher concern to animal welfare and environmental protection, which may partially explain their greater inclination towards plant-forward diets and their higher likelihood of adopting, be vegetarian or vegan lifestyles. Sociological and psychological research consistently finds that meat consumption is often linked to traditional masculinity, while women tend to eat less meat and more plant-based foods [21]. Women also express greater concern for animal welfare and environmental protection, which may explain their higher rates of vegetarianism and veganism [19]. Studies show that women generally have a better understanding of climate change and are more concerned about its effects than men [22]. These gender differences in food choices are influenced by cultural norms, education, socioeconomic status, and personal beliefs [21,23]. Furthermore, socialization processes from an early age reinforce these

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patterns, where boys and girls are often exposed to different messages about food, health, and environmental responsibility. Media representations and marketing strategies can also perpetuate gendered stereotypes about diet, further shaping consumption habits across the lifespan [24,25].

A recent cross-cultural study offers compelling and robust evidence that women generally consume less meat than men, and this difference in dietary behavior becomes even more pronounced in countries that are highly developed and exhibit greater gender equality [26]. The comprehensive research, which gathered data from a large sample of 20,802 participants across 23 diverse countries, consistently found that men reported higher levels of meat consumption than women, regardless of the specific region or cultural context. Interestingly, the gap between male and female meat consumption was most significant in countries distinguished by advanced levels of human development and strong gender equality indices. This finding suggests that as societies progress and achieve greater equality between the sexes, the differences in dietary patterns—particularly regarding meat intake—may actually become more marked rather than diminish, highlighting the complex interplay between social development and individual food choices.

Culliford et al. [27] have effectively demonstrated how education level further influences food choices, as individuals with higher education are more likely to recognize the environmental benefits and adopt sustainable diets. However, while environmental concerns motivate some to reduce meat intake, other factors—such as taste preferences, health considerations, and cultural tradition—also play a major role [27].

Changing consumer food behaviours remains challenging; for example, Downs et al. [28] reported that among individuals reducing red meat intake, only a small proportion (6%) cited environmental sustainability as their primary motivation, highlighting the complex interplay of factors influencing dietary decisions. This suggests that effective interventions must address a broad spectrum of motivations, including health, taste, cost, and cultural identity, in addition to environmental considerations.

The environmental impact of dietary choices is substantial and varies by gender. For instance, Auclair et al. [16] investigates the effects of partially replacing animal protein foods with plant protein foods in Canadian consumers, focusing on nutrition, health, and climate outcomes. The authors found that replacing 50% of red and processed meat with plant-based proteins could reduce GHGE by up to 25%, with men seeing a greater reduction than women due to higher baseline meat consumption.

Studies in the U.S. and Europe [29,30] consistently show that men have higher diet-related GHGE than women, largely due to greater overall food intake (2631 kcal/day for men, compared to 1906 kcal/day for women) and higher meat consumption. However, it has to be underlined that when adjusting for calorie intake, the difference in climate impact per unit of energy consumed is smaller [31]. Nonetheless, the cumulative effect of higher consumption patterns among men remains significant, reinforcing the importance of targeting male populations in climate and health interventions.

Switching to plant-based diets, such as vegan or Mediterranean diets, can significantly reduce GHGE compared to typical Western diets [32]. Modeling studies suggest that eliminating red meat could cut dietary emissions by nearly half [33]. Among various dietary patterns, vegan diets have the lowest environmental impact, while omnivorous diets have the highest.

Allenden et al. [34] assigned environmental impact scores from 1 to 10 to six dietary patterns, where higher scores represent greater environmental benefits. The diets evaluated were omnivore, Mediterranean, pescatarian, flexitarian/semi-vegetarian, vegetarian, and vegan. Their results showed that the omnivore diet received the lowest score of 1, while the vegan diet scored the highest with a 10. Among the intermediate diets, the pescatarian diet stood out with a relatively high score of 6.81.

In summary, gender differences in dietary choices are a key factor in shaping the environmental impact of food systems. Women's tendency to consume less meat and more plant-based foods leads to lower diet-related GHGE compared to men. Promoting plant-forward diets—especially among

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men—offers a promising strategy for reducing the climate impact of food consumption and supporting global sustainability goals.

4. Climate Change and Its Impact on Diabetes

Worldwide, approximately 537 million adults aged 20 to 79 live with T2D, a number expected to increase to 643 million by 2030 and 783 million by 2045. Notably, over three-quarters of these individuals reside in low- and middle-income countries, highlighting significant global health disparities [35,36]. This projected rise in diabetes prevalence underscores the urgent need for coordinated global action to address both the environmental and social determinants of metabolic health.

T2D is a major global health challenge due to its association with severe complications such as cardiovascular disease, nephropathy, retinopathy, neuropathy, and diabetic foot ulcers. These complications substantially increase morbidity and mortality and severely impair patients' quality of life [37,38]. The cumulative impact of these complications not only affects individuals but also places a significant strain on families, communities, and healthcare systems. Addressing the root causes and risk factors for T2D is therefore essential for improving public health outcomes and reducing long-term healthcare costs. The economic impact is profound: in 2021, global healthcare costs related to diabetes reached approximately USD 966 billion, placing a heavy financial burden on healthcare systems, especially in resource-limited settings [39]. Complications further escalate these costs through prolonged hospitalizations, complex treatments, and indirect losses like reduced productivity and workforce participation [38]. These challenges highlight the urgent need for effective prevention and management strategies [40].

The rising global temperatures and increased frequency of heat waves pose significant health risks, including impacts on metabolic health. Emerging research reveals complex interactions between ambient temperature and type 2 diabetes prevalence, including gestational diabetes mellitus (GDM).

Prolonged exposure to heat can overwhelm the body’s thermoregulatory systems, leading to heat-related illnesses such as heat exhaustion and heat stroke, conditions characterized by the body's inability to maintain its core temperature around the normal range (37°C or 98.6°F) [41].

Heat stress disrupts physiological processes like metabolism, vasodilation, and sweating, which can contribute to insulin resistance and the development of T2D and GDM [42,43]. Heat stress reduces insulin sensitivity, exacerbating metabolic dysfunction. These physiological disruptions may be further aggravated by dehydration, electrolyte imbalances, and changes in physical activity patterns during periods of extreme heat.

Brown adipose tissue (BAT) plays a crucial role in thermogenesis, which is the process of heat production in organisms [44]. Thermogenesis is primarily achieved through the activation of uncoupling protein 1 (UCP1) in the mitochondria, which allows the conversion of chemical energy into heat [45]. By burning lipids and glucose to produce heat, BAT helps maintain glucose homeostasis and improve insulin sensitivity. Its activity is temperature-dependent, increasing in cold environments and decreasing with higher ambient temperatures [46]. Recent advances in imaging and molecular biology have enhanced our understanding of BAT function and its potential as a therapeutic target for metabolic diseases. Strategies to activate or preserve BAT activity may offer novel approaches to improving glucose regulation and reducing diabetes risk in the context of rising global temperatures [47].

This thermogenic function of BAT is particularly important in preventing obesity and related metabolic disorders, including T2D [48]. Activation of BAT improves insulin sensitivity in both rodents and humans, enhancing glucose uptake and utilization by the cells [48].

A landmark study showed that exposing T2D patients to moderate cold (16°C) for 10 days significantly improved insulin sensitivity without weight changes, likely through increased fatty acid flux to BAT and compensatory glucose uptake by other tissues [47,50]. BAT activity is inversely correlated with outdoor temperature, being higher in winter [51,52]. Conversely, elevated

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temperatures reduce BAT activity, potentially worsening glucose regulation and increasing diabetes risk [53]. Rising global temperatures may thus contribute to the T2D epidemic by suppressing BAT function [54]. Supporting this, Lee P. [55] found a positive association between outdoor temperature and glycated hemoglobin (HbA1c) levels, indicating environmental temperature influences systemic glucose homeostasis.

In this context, a comprehensive epidemiological study linking outdoor temperature to T2D incidence [56] demonstrated that rising ambient temperatures are associated with an increase in diabetes incidence. Specifically, for every 1°C increase, the incidence of diabetes in the United States rises by 0.314 per 1000 people, and the global prevalence of glucose intolerance increases by 0.170% This suggests a strong correlation between higher temperatures and diabetes risk. Mechanistically, elevated temperatures impair insulin receptor signaling, reduce BAT thermogenic activity, and induce systemic inflammation and oxidative stress, all contributing to insulin resistance and impaired glucose metabolism. These mechanistic insights provide a foundation for developing targeted prevention strategies, such as promoting physical activity during cooler periods, optimizing indoor climate control, and encouraging dietary patterns that support metabolic resilience.

Temperature fluctuations also affect GDM risk. Studies show that exposure to extreme temperatures during pregnancy, particularly the second trimester, increases GDM risk [57]. Seasonal trends further support this, revealing higher GDM prevalence during warmer months [58]. Teyton et al. identified critical windows in the second trimester where temperature changes of 10°C increased GDM risk by 6–9% [59]. Other studies report similar seasonal and temperature-related increases in GDM incidence [58,60–62]. These findings underscore the importance of monitoring environmental conditions during pregnancy and implementing adaptive strategies to protect maternal and fetal health.

Higher daily mean temperatures correlate with increased diabetes-related hospitalizations, especially among older adults [63]. Ambient temperature also influences fasting plasma glucose and diabetes prevalence globally, with about a 0.5% increase in diabetes prevalence per 1°C rise in mean annual temperature [56]. Studies in Spain and China confirm these findings, showing stronger effects in males and older individuals [53]. Conversely, lower temperatures enhance BAT activity, improving glucose metabolism, with younger age, female sex, and non-diabetic status predicting higher BAT prevalence [64,65].

Climate change, through rising ambient temperatures and increased heat exposure, poses a growing risk to metabolic health by impairing insulin sensitivity, reducing BAT activity, and increasing the prevalence of T2D and GDM. Understanding these temperature-related mechanisms is critical for developing effective prevention and management strategies to mitigate the expanding global diabetes burden.

5. Conclusions and Future Perspective

This work highlights the complex and deeply interconnected relationship between climate change, gender-specific dietary behaviors, and the risk of developing diabetes. Rising global temperatures contribute significantly to an increased incidence of T2D by impairing brown adipose tissue function and promoting insulin resistance. Additionally, heat stress worsens GDM, particularly affecting pregnant women.

Our review reveals a feedback loop in which gendered dietary patterns influence GHGE, thereby accelerating climate change, which in turn adversely affects diabetes outcomes. Specifically, higher meat consumption, which is more common among men, has a greater impact on climate change, leading to increased emissions, faster global warming, and a higher risk of diabetes. Conversely, plant-based diets, which are predominantly followed by women, have the potential to mitigate these negative effects.

Encouraging the adoption of plant-based diets—especially targeting male-dominated food cultures—could reduce GHGE by up to 35%, thereby lowering the risk of diabetes and its complications. Women face additional vulnerabilities due to biological factors such as hormonal

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fluctuations during pregnancy and menopause. When combined with exposure to heat stress, these factors increase the susceptibility to diabetes-related conditions, including GDM.

Therefore, public health and climate policies should actively promote plant-forward diets with a strong gender-sensitive perspective. Such an approach would more effectively reduce emissions, prevent diabetes, and address both biological and social vulnerabilities. Future strategies should prioritize modifying male dietary behaviors, which currently contribute disproportionately to both climate change and diabetes risk.

There is an urgent need for further research to clarify the underlying biological mechanisms through which heat and climate change affect men and women differently. This includes investigating the influence of hormonal status and critical life stages in women. Additionally, epidemiological studies are essential to monitor how changes in ambient temperature, dietary patterns, and diabetes incidence differ by sex. These insights will refine risk assessments and enable the development of more targeted public health interventions.

In the near future, raising public awareness about the environmental impact of dietary choices and their health consequences—tailored by gender—can empower individuals to adopt healthier and more sustainable eating habits. Policymakers should develop integrated approaches that simultaneously address climate mitigation, dietary behavior change, and diabetes prevention, while considering gender-specific needs and vulnerabilities.

Ultimately, addressing these complex challenges requires a comprehensive and multifaceted approach that combines environmental sustainability with gender-sensitive health promotion, to reduce the growing global burden of T2D in the context of an evolving climate change era.

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