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# *Nutrient Effects and Dietary Pattern Strategies in the Management of Type 2 Diabetes*

**Mingyu Sun**

*Southwest University, Chongqing, China*
*smy028@email.swu.edu.cn*

***Abstract:*** Type 2 diabetes (T2D) is a metabolic disorder affected by dietary patterns and nutrient intake. It is well established that macronutrients, such as carbohydrates, proteins, and fats, influence glycemic control and insulin sensitivity. Similarly, micronutrients, including vitamins and trace elements, are also essential for maintaining metabolic health and preventing T2D complications. However, research has often overlooked the integration of nutrient composition within specific dietary patterns. This paper analyzes three major dietary approaches—the Mediterranean diet (MD), Dietary Approaches to Stop Hypertension (DASH), and ketogenic diet (KD)—and studies their application on T2D management. Studies have found that MD improves glycemic control and enhances insulin sensitivity through anti-inflammatory effects and healthy fats, while the DASH diet contributes to better lipid profiles and blood pressure homeostatic control. KD has low-carbohydrate content, which can also significantly improve glycemic control and insulin sensitivity through ketosis.This review highlights the multiple factors of nutrients and dietary patterns, emphasizing the need for personalized dietary strategies taking into account individual metabolic responses. Future research should emphasize exploring long-term effects and further refine dietary guidelines to optimize T2D management with a focus on nutrient interactions and sustainable adherence to dietary patterns.

***Keywords:*** Type 2 diabetes, macronutrients, micronutrients, Mediterranean diet, DASH diet, ketogenic diet

## 1. Introduction

Type-2 diabetes (T2D) is a metabolic disease that is increasingly affecting global public health. According to a recent publication from The Lancet [1], approximately 800 million adults were living with diabetes in 2022. Similarly, data from the International Diabetes Federation (IDF) [2] indicate that one in ten adults (over 18) globally has diabetes. The T2D epidemic not only severely reduced the quality of life of patients, but significantly influenced the worldwide mortality, morbidity, and healthcare expenditure, for it is associated with a range of severe complications, including cardiovascular diseases (CVDs), kidney failure, neuropathy, and retinopathy [1]. T2D has become one of the major health burdens of noncommunicable diseases all over the world, especially in low and middle income countries [1].

Factors contributing to the rising prevalence of T2D can be genetic, environmental, and changing lifestyle patterns, particularly including unhealthy dietary habits, poor physical activity and increasing rates of obesity. Among these, lifestyle factors, especially diet, are significant determinants of T2DM.

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Due to the modifiability, lifestyle factors, especially diet, should be the focus in the effort to lower T2DM risk [3]. Diets that may induce T2DM are mostly ultra-processed foods, rich in refined sugars, and unhealthy fats [3], while diets consisting of whole grains, fruits, vegetables and healthy fats are considered to be associated with a decrease in T2D risk [3]. Thus, dietary interventions have emerged as a critical component in the management and prevention of T2D.

In recent years, a growing number of studies have focused on specific nutrients and dietary patterns in the treatment of T2D. It appears that macronutrients, especially carbohydrates and fats, as well as micronutrients like vitamins and minerals all play vital roles in influencing glucose metabolism, cardiovascular health, and insulin sensitivity in the background of T2D [4]. For example, replacing refined grains with whole grains is linked to reducing risk of T2D [4], while excessive consumption of trans fatty acid is positively correlated to the disease risk [3]. Additionally, micronutrients such as magnesium, zinc, and vitamin B9、E、D、B1、K are also shown to help with T2D management, which were included in the first category as having positive effects due to their association with improved metabolic outcomes [5]. A study in 2023 note that despite improvements in overall diet quality in older adults with type 2 diabetes following the Mediterranean diet (MD), most individuals still do not meet the recommended intakes of key micronutrients such as magnesium and vitamin D, indicating that nutrient intakes persist even in traditionally healthy dietary patterns [6]. Apart from individual nutrients, dietary patterns have also gained wide attention because of their beneficial effects on preventing and managing. The IDF has mentioned that the MD, which prioritises plant-based foods, nuts, and healthy fats while limiting consumption of red meat, sugar, and saturated fat, is considered one of the best dietary patterns for diabetes management [2]. A 2023 trial showed that MD reduced HbA1c by 0.5% and CVD risk by 28% in T2D patients [5]. Another promising diet with very low-carb (VLC) is known as the ketogenic or “keto” dietary pattern, which contains low-carb, medium-protein, and high-fat components [7,8]. There is a study concluded that ketogenic diet (KD) can achieve greater decrease in triglycerides (30%) and lose more weight (8% weight decreased) than MD, but less sustainable and may lead to elevated LDL cholesterol and lower nutrient intake [8,9]. Dietary Approaches to Stop Hypertension (DASH) is another additional dietary pattern that originally developed to treat hypertension without medication [1], study also found it associated with decreasing chance of CVD (20% risk decrease) and managing blood pressure in people with diabetes, which contributes to controlling blood sugar and improving overall metabolic health [10,11].

This paper aims to critically examine and compare various nutrients and dietary patterns, particularly the MD, KD, and DASH diet in managing T2D. By analyzing current evidence on their impact on glycemic control, weight management, and overall metabolic health, this paper aims to explore how these dietary patterns can be improved and incorporated into the treatment of T2D [12]. Furthermore, the study will highlight areas for future research, focusing on the long-term effects and suitability of the diets [8], ultimately contributing to more personalized and sustainable dietary recommendations for individuals with T2D [10].

## 2. Nutrient components

### 2.1. Macronutrients and their metabolic pathways

Macronutrients, including carbohydrates, proteins, and fats, are essential elements to human metabolism and energy homeostasis. The development and management of T2D closely linked to the type and composition of macronutrient intake, specifically influencing insulin sensitivity, glycemic control, and metabolic health.

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### 2.1.1. Carbohydrate

Carbohydrates is main component of a balanced diet, providing primary energy source for human body and playing a central role in the pathogenesis of T2D. The carbohydrates is first digested with salivary amylase in the mouth, then absorbed by the epithelial cells of the small intestine, and eventually enters the blood circulation. The postprandial blood sugar fluctuations are directly determined by the type of carbohydrate and rate of digestion [13]. Foods with high-glycemic index (GI) levels, such as refined sugars, are digested into glucose is rapidly absorbed . This stimulates excessive secretion of insulin and further cause failure of β-cell and insulin resistance in the long-term. Meanwhile,chronic hyperinsulinemia promotes hepatic de novo lipogenesis, which leads to liver lipid accumulation, particularly diacylglycerol (DAG). The elevated DAG levels then activate protein kinase C (PKC), which disrupts insulin signaling through interfering with the insulin receptor substrate (IRS) pathway. In addition, excessive lipid accumulation and insulin resistance can trigger the activation of inflammatory pathways such as JNK and IKK, further impairing insulin sensitivity and exacerbating the development of type 2 diabetes [14].

Conversely, foods with low GI, as table 1 shows, can delay glucose absorption and mitigate blood sugar peaks. Soluble fibers are fermented through gut microbiota to produce short-chain fatty acids (SCFAs), which enhance insulin sensitivity [15]. Notably, Chandalia et al. demonstrated that a high-fiber diet (50 g/day) significantly improved glycemic control in patients with T2DM, reducing both fasting and postprandial blood glucose levels, as well as HbA1c. This intervention also improved lipid profiles and insulin sensitivity, highlighting the multifaceted benefits of dietary fiber in metabolic regulation [15].

Table 1 summarizes the glycemic index values of various carbohydrate sources commonly discussed in T2D nutritional interventions, including refined sugars, whole grains, legumes, and dietary fibers. All data were obtained from the University of Sydney's official GI database (https://glycemicindex.com/), which is recognized as a global standard reference for GI measurements. GI categories are defined as follows: high GI (⩾70), medium GI (56–69), and low GI (⩽55). A dash (–) indicates unavailable data for that food or category.

Table 1: GI of representative carbohydrate-rich foods relevant to T2D dietary management

| No. | Food Category | Specific Food Example | Preparation Method | GI Value | GI Classification |
|---|---|---|---|---|---|
| 1 | Refined Carbohydrates | Glucose (reference) | Solution | 100 | High |
| 2 | | Jasmine rice | Cooked, white | 89 | High |
| 4 | | Watermelon | Raw | 76 | High |
| 5 | | White bread | Commercial, sliced | 75 | High |
| 6 | | Table sugar (sucrose) | Dissolved | 65 | Medium |
| 7 | Whole Grains | Brown rice | Medium-grain, cooked | 66 | Medium |
| 10 | | Buckwheat noodles (soba) | Cooked | 46 | Low |
| 12 | Legumes (Beans) | Chickpeas | Canned | 42 | Low |
| 13 | | Lentils | Boiled | 32 | Low |
| 14 | | Black beans | Boiled | 30 | Low |
| 16 | Dietary Fiber-Rich | Pear | Raw | 38 | Low |
| 18 | | Carrot | Raw | 35 | Low |
| 19 | | Barley | Pearled, boiled | 28 | Low |

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Replacing sucrose with fructose may improve HbA1c levels in the short term, but long-term consumption of fructose activates the ChREBP-FGF21 axis and promotes hepatic lipid production [16].

New alternatives such as polysaccharide alcohol (xylitol) can reduce fasting blood glucose by 10–15% [17], while resistant starch improves metabolism by activating PPAR-γ through butyric acid. The key molecular mechanisms involve ChREBP-regulated lipogenesis enzyme and mTOR pathway feedback inhibition of IRS-1 [18].

### 2.1.2. Protein

Dietary proteins are digested into amino acids, which enter the bloodstream and participate in critical physiological processes such as protein synthesis, gluconeogenesis, and energy production. Dietary protein intake plays a crucial role in modulating T2D risk, with growing evidence emphasizing that not only the quantity but also the source of protein significantly influences metabolic outcomes. Large-scale cohort studies, including the Women's Health Initiative and the UK Biobank, have revealed that higher consumption of animal protein is associated with an increased incidence of T2D [19]. This relationship is likely mediated through metabolic biomarkers, notably elevated circulating levels of branched-chain amino acids (BCAAs), insulin resistance, and chronic systemic inflammation. Mechanistically, BCAAs—particularly leucine, isoleucine, and valine—may activate mTORC1 signaling and impair insulin signaling through inhibitory phosphorylation of IRS-1, thereby contributing to insulin resistance [20]. Red and processed meats, which are rich in saturated fats and heme iron, may further exacerbate inflammatory pathways and negatively impact glucose metabolism. In contrast, plant-based proteins appears to reduce risk, which may due to anti-inflammatory properties and lower energy density [20]. Thus, protein source selection is also key points in managing metabolic health and reducing T2D risks.

### 2.1.3. Fat

The digestion of lipid primarily occurs in the small intestine, where bile acids emulsify dietary triglycerides into micelles. This enhances the action of pancreatic lipase, which breaks down triglycerides into monoglycerides and free fatty acids (FFAs). These lipolytic products then incorporated into micelles for efficient absorption by enterocytes.

Inside enterocytes, they are re-esterified into triglycerides and incorporated into chylomicrons, which are secreted into the lymphatic system and enter the circulation. Circulating chylomicrons are hydrolyzed by lipoprotein lipase (LPL), releasing FFAs that are either oxidized in peripheral tissues or stored in adipose depots.

In T2D individuals, lipid metabolic disturbances seriously affect the progression of insulin resistance and systemic metabolic dysfunction. Chronic over-consumption of dietary fats, especially saturated fats, promotes adipose tissue dysfunction and lipotoxicity. This leads to elevated levels of free fatty acids (FFAs) in circulation, which interfere with insulin signaling by activating inflammatory pathways and impairing glucose uptake in skeletal muscle and liver, exacerbating hyperglycemia and insulin resistance [21,22]. Furthermore, adipose tissue insulin resistance plays a crucial role in T2DM pathogenesis by reducing insulin's ability to suppress lipolysis, leading to excessive FFA release and systemic metabolic disturbances [22]. Addressing dietary fat intake and improving lipid metabolism through lifestyle and pharmacological interventions is essential for T2DM management.

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## 2.2. Micronutrients

Vitamins B1, B9, D, E, and K, along with zinc, are categorized as first-line nutrients positively linked to T2D. Their beneficial role in T2D prevention and control is largely attributed to their ability to enhance insulin sensitivity, alleviate oxidative stress, and modulate inflammatory pathways.

### 2.2.1. Vitamins

Vitamin D has been shown to improve insulin sensitivity and β-cell function. This enhance insulin receptor expression and modulate the activity of peroxisome proliferator-activated receptor gamma (PPAR-γ), which finally contributes significantly to glucose homeostasis [4]. Deficiency in vitamin D has been linked to increased systemic inflammation and impaired glucose tolerance, both of which are pivotal in the pathogenesis of T2D [23].

Vitamin B1 (thiamine) is essential in carbohydrate metabolism, serving as a coenzyme in key enzymatic pathways. Thiamine deficiency has been associated with elevated oxidative stress and endothelial dysfunction, which could potentially exacerbating complications such as neuropathy and nephropathy [4].

Vitamin B9 (folate) is also necessary for the regulation of homocysteine metabolism. Inadequate folate levels can cause hyperhomocysteinemia, which promotes oxidative damage and vascular injury, further worsening the insulin resistance, increasing cardiovascular risk in T2D patients [4].

Vitamin E is a lipid-soluble antioxidant. It helps to prevent lipid peroxidation and maintain membrane integrity. Clinical studies have linked vitamin E supplementation to better glycemic control and a reduction in oxidative stress markers among individuals with T2D [4].

Vitamin K has also been shown to improve glycemic regulation. Higher dietary intake has been inversely correlated with the risk of developing T2D, likely due to its regulatory role in osteocalcin activation and other metabolic processes involved in glucose homeostasis [4]

### 2.2.2. Trace elements

Selenium supports glucose homeostasis and pancreatic β-cell integrity via its incorporation into antioxidant selenoproteins, such as glutathione peroxidase (GPx), which mitigate oxidative and inflammatory stress in islet tissue. Adequate selenium intake has been shown to preserve β-cell viability and reduce local inflammation. Inorganic selenium compounds also exhibit insulin-mimetic properties by modulating key metabolic processes including glycolysis, gluconeogenesis, fatty acid synthesis, and the pentose phosphate pathway, all of which contribute to efficient glucose utilization and energy regulation [24,25].

Iron is an essential micronutrient involved in redox balance and mitochondrial function. However, excessive iron accumulation has been linked to increased oxidative stress, β-cell damage, and the development of insulin resistance. Elevated serum ferritin—a marker of iron stores—is frequently observed in patients with type 2 diabetes and correlates with chronic inflammation and disrupted glucose metabolism. Thus, it is critical to maintain iron homeostasis for preventing metabolic dysfunction and preserving insulin action [4].

## 3. Dietary patterns in diabetes management

### 3.1. DASH diet

The DASH diet has been recognized as a beneficial dietary pattern for T2D treatment due to its effects on glucose metabolism, lipid profiles, and cardiovascular health. The DASH diet emphasis the consumption of fruits, vegetables, whole grains, lean proteins and low-fat dairy while reducing

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sodium and saturated fat intake. Research suggests that adherence to the DASH diet contributes to improve insulin sensitivity and achieve better blood sugar control, since the high fiber content and low glycemic load can help moderate postprandial glucose fluctuations [26].

Beyond its macronutrient profile, the DASH diet is dense in micronutrients like magnesium, potassium, vitamin C, and folate—mainly derived from plant-based foods. These nutrients are linked to improved insulin signaling and reduced oxidative stress and inflammation, both key in preventing insulin resistance and β-cell dysfunction. Additionally, vitamin D and B vitamins from dairy and grains may help maintain β-cell performance and homocysteine metabolism, potentially lowering the risk of diabetes-related complications [23].

The inclusion of healthy fats supports lipid regulation, particularly lowering LDL levels. Clinical studies indicate that this lipid composition helps reduce LDL and total cholesterol levels, while elevating HDL cholesterol, thereby improving dyslipidemia in T2DM [27]. Moreover, the high antioxidant and anti-inflammatory compound intake—such as flavonoids and polyphenols—helps suppress chronic low-grade inflammation, thereby improving insulin resistance.

However, it is worth noting that although the DASH diet supports cardiometabolic health, its relatively higher carbohydrate content compared to ketogenic or low-carbohydrate diets may not be optimal for all T2DM patients. Some evidence suggests that restricting carbohydrate intake can further enhance insulin sensitivity and reduce glycemic variability. As such, personalized modifications of the DASH pattern, especially with adjusted macronutrient ratios, may offer improved outcomes for individuals with pronounced insulin resistance [26]. Nevertheless, adhering to the DASH approach can be difficult for some, particularly where cultural preferences, socioeconomic factors, or food access limit dietary choices [12,27].

Overall, the DASH diet offers a nutrient-rich, evidence-supported method for managing T2D, delivering benefits through both its nutrient profile and the physiological mechanisms it engages. Continued investigation into tailored adaptations may further enhance its effectiveness across diverse populations.

### 3.2. Mediterranean diet

The MD has been extensively studied for its beneficial effects on T2D. It emphasizes whole foods, healthy fats, and low-glycemic carbohydrates consumption. Mechanistically, MD improves glycemic control through enhanced insulin sensitivity, reduced inflammation, and beneficial modulation of gut microbiota. Studies have demonstrated that adherence to the MD is associated with a 19–23% reduction in diabetes incidence and improved HbA1c levels in T2D individuals [28].

One key mechanism involves its anti-inflammatory and antioxidative effects. The MD lowers circulating levels of C-reactive protein (CRP) and increases adiponectin, a hormone that enhances insulin sensitivity [28]. Additionally, the diet is rich in bioactive compounds such as polyphenols, monounsaturated fatty acids (MUFA), and omega-3 fatty acids from olive oil, nuts, and fish. These nutrients exert antioxidative effects that protect pancreatic β-cells from oxidative damage, then preserving insulin secretion capacity and mitigating the progression of insulin resistance [12].

Despite these benefits, some challenges still exist in its implementation and individual response. First, individual responses to the MD vary considerably due to genetic polymorphisms, epigenetic factors, and differences in metabolic phenotypes. Second, the long-term adherence to MD can be challenging, particularly in non-Mediterranean populations. Moreover, while MD shows promise in diabetes prevention, its effects on reversing established T2D are still debated [12]

DOI: 10.54254/2753-8818/110/2025.AU23360

### 3.3. Ketogenic diet (KD)

The KD, characterized by high fat, moderate protein, and extremely low carbohydrate content, has gained increasing attention for its therapeutic potential in managing T2DM. By inducing a state of nutritional ketosis—where ketone bodies become the primary energy source—the KD enhances glycemic control, improves insulin sensitivity, and modifies lipid metabolism. Research reported in a meta-analysis that overweight T2DM patients following a KD showed significant reductions in HbA1c (mean difference: −0.69%), fasting glucose (−1.29 mmol/L), and triglycerides, along with increased HDL cholesterol [8].

Furthermore, ketosis suppresses hunger hormones like ghrelin and insulin, leading to weight loss and long-term diabetes management. However, despite these benefits, the long-term sustainability of the KD remains controversial due to its highly restrictive nature, which may lead to nutrient deficiencies, elevated LDL cholesterol, and gut microbiome alterations. Additionally, concerns exist regarding its sustainability, as the restrictive nature of KD poses challenges for long-term compliance [7]. While KD presents a promising intervention for T2DM, future research should evaluate its long-term effects, optimize dietary composition, and assess individual metabolic responses to ensure both efficacy and safety (Table2).

Table 2: Comparative mechanisms and nutritional characteristics of the DASH, Mediterranean, and Ketogenic diets in the management of type 2 diabetes mellitus (T2DM)

| Diet Pattern | Key Nutrients | Mechanisms of Action | Glycemic Impact |
|---|---|---|---|
| **DASH** | High fiber, low sodium, $K^+$, $Mg^{2+}$ | ↑ Insulin sensitivity ↓ blood pressure, ↓ oxidative stress | Moderate postprandial control |
| **Mediterranean** | MUFA, polyphenols, omega-3, antioxidants | ↑ Adiponectin ↓ CRP β-cell preservation ↓ inflammation | Improved glycemic control |
| **Ketogenic** | High fat, very low carbs, ketone bodies | Nutritional ketosis ↓ insulin levels appetite suppression ↑ fat oxidation | Rapid blood glucose reduction |

## 4. Discussion

### 4.1. Individual variability and personalized nutrition

T2D is a heterogeneous disease influenced by genetic predisposition, gut microbiota composition, and lifestyle factors. Dietary patterns, such as the MD, KD, and DASH, may show different effects because of individual metabolic responses. However, many of the included studies overlooked this individual variability, highlighting the need for personalized dietary recommendations based on genetic, microbiome, and metabolic profiling.

### 4.2. Adherence and practical considerations

Among the diet patterns, the MD and DASH diets encourage balanced nutrient intake and are generally easier to maintain long term, while adherence to stricter regimens like the KD remains a challenge. Factors such as social dining environments, cultural food preferences, and potential dietary monotony can limit compliance. Moreover, the feasibility of implementing these diets in diverse

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populations requires consideration of local food availability, cost, and education. Future research should prioritize strategies that enhance dietary adherence while maintaining clinical efficacy.

### 4.3. Potential adverse effects and safety concerns

While dietary interventions can significantly improve glycemic control, safety concerns must not be overlooked. Very low-carbohydrate KDs may increase LDL cholesterol levels, cause micronutrient deficiencies, and elevate the risk of ketoacidosis, particularly in insulin-dependent patients. In contrast, the DASH and MD diets are generally considered safe, though high sodium restriction in DASH may affect adherence in some individuals. The high protein content of KD may raise concerns about renal stress in patients with impaired kidney function. Long-term studies are needed to assess the safety profiles across dietary types.

### 4.4. Mechanistic insights and multi-omics research

Most current research focuses on macronutrient distribution, while other factors—such as food processing, meal timing, and nutrient-nutrient interactions—remain underexplored. Furthermore, different diets may impact insulin sensitivity, inflammation, and gut microbiota composition through distinct pathways. Integration of multi-omics approaches, such as metabolomics, transcriptomics, and microbiome analysis, may reveal mechanistic insights into how each diet exerts its effect on T2D pathology.

### 4.5. Future directions

Future research should conduct long-term, large-scale randomized controlled trials to compare the efficacy, safety, and sustainability of the DASH, MD, and KD diets in diverse populations. Personalized nutrition strategies that incorporate genetic, microbial, and metabolic markers will be critical in tailoring interventions. Moreover, investigating the role of meal timing, food processing, and interactions among dietary components is essential to develop more refined and effective T2D dietary guidelines.

## 5. Conclusion

This review has comprehensively examined the effects of different nutrients and three primary dietary patterns—the MD, the DASH diet, and the KD—on glycemic control, insulin sensitivity, and related metabolic indicators in individuals with T2D. Each dietary intervention offers distinct metabolic benefits through various mechanisms, such as modulating lipid profiles, improving insulin signaling, reducing oxidative stress, and altering gut microbiota composition.

The MD and DASH diets are characterized by high intakes of fiber, polyphenols, and unsaturated fats, which contribute to long-term cardiovascular and glycemic benefits. The KD shows rapid improvements in glycemic control via carbohydrate restriction, increased intake of saturated fats, and enhanced ketone body metabolism, though it may be low in certain micronutrients such as vitamin C and fiber.

However, current research still has limitations in current research, including insufficient personalization, variable dietary adherence, and the need for long-term safety evaluations. Due to the inter-individual variability in metabolic response, such as genetic makeup, microbiota composition, and lifestyle factors, it is suggested that a “one-size-fits-all” dietary recommendation may not be optimal.

Future studies should adopt multi-omics approaches to elucidate the complex mechanisms underlying diet–disease interactions and develop individualized nutrition plans that ensure efficacy,

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safety, and feasibility. Furthermore, the impact of food processing method, meal timing, and nutrient interactions warrants deeper exploration in optimizing dietary strategies for T2D management.

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