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Nuts and diabetes management: Nutritional and metabolic benefits

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ABSTRACT

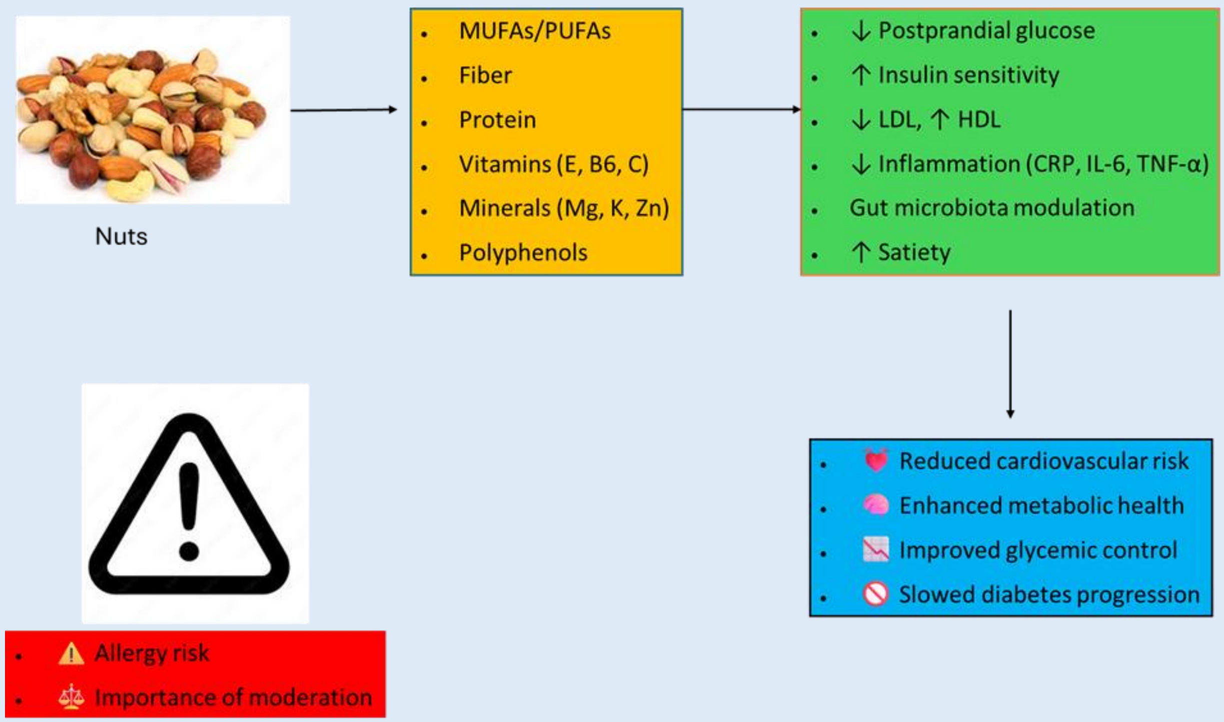
The escalating global prevalence of diabetes has spurred the urgency for effective management strategies. In recent years, there has been growing interest in the potential role of dietary interventions, particularly the incorporation of nuts, in the management of diabetes.

This review aims to elucidate the nutritional significance of nuts and their potential impact on diabetes management. Articles used in this narrative review were retrieved from Scopus, Google scholar, ResearchGate, and other research platforms using keywords/phrases such as 'diabetes', 'diabetes management' 'dietary strategies for diabetes' as well as 'nuts in diabetes management'. Only articles written in English, peer-reviewed, and focused on dietary strategies for managing diabetes were included in this narrative review.

Findings showed that nuts, abundant in unsaturated fats, fiber, protein, vitamins, and minerals, exhibit favourable effects on glycaemic regulation, insulin sensitivity and lipid profiles. Accumulated evidence from epidemiological studies, clinical trials, and meta-analyses suggests that habitual nut consumption holds promise in ameliorating glycaemic control, mitigating cardiovascular complications, and augmenting overall health outcomes among individuals with diabetes. However, the specific mechanisms underlying these effects remain to be fully elucidated, and further research is warranted to establish optimal recommendations for nut consumption in the context of diabetes management.

Although incorporating nuts into a balanced diet represents a promising and practical approach for enhancing the nutritional quality and metabolic health of individuals with diabetes, it is essential to address potential allergenicity and safety concerns associated with their consumption.

Keywords: nuts, diabetes, glycaemia, insulin resistance, lipid profile



Graphical Abstract: Nuts and Diabetes Management: Nutritional and Metabolic benefits

INTRODUCTION

Diabetes mellitus (DM) is a chronic global epidemic, a major health problem, and is one of the fastest-growing global health emergencies of the 21st century [1,2]. Diabetes has emerged as the ninth leading cause of mortality globally [3,4]. Approximately 10.5 million adults were diagnosed with diabetes, with over 90% suffering from Type 2 Diabetes (T2D) [1], making T2D the most common type of diabetes. In 2021, the International Federation of Diabetes reported that 537 million adults are now living with diabetes worldwide, an increase of 16% (74 million) since the previous IDF estimates in 2019 [4,5]. Projections suggest that this figure will escalate to 783 million or 1 in 8 people by 2045 [4,5] This would be an increase of 46%, more than double the estimated population growth (20%) over the same period [4]. The rise in the number of people with type 2 diabetes is of socio-economic, demographic, environmental and genetic factors [5]. The key contributors include urbanisation, an ageing population, decreasing levels of physical activity and increasing prevalence of overweight and obesity [5,6].

Diabetes not only elevates blood glucose levels but also triggers numerous long-term complications that significantly impact the health and well-being of individuals affected by it [7]. Of particular concern is its propensity to precipitate cardiovascular disease (CVD), encompassing conditions like coronary artery disease, heart failure, and stroke, which stand as leading causes of mortality and disability among those with diabetes [4,5]. Research consistently demonstrates that individuals with diabetes face a heightened risk, two to four times greater, of developing CVD compared to those without the condition [8,9] . This increased risk stems from various factors such as insulin resistance, dyslipidemia, hypertension, and systemic inflammation, all of which exacerbate atherosclerosis, the primary driver of most cardiovascular incidents [8,10]. Moreover, diabetes exacerbates endothelial dysfunction, oxidative stress, and abnormal platelet function, further amplifying the likelihood of cardiovascular complications [10,11]. Concurrently experiencing both diabetes and CVD compounds the situation, heightening the probability of recurrent episodes and driving up healthcare expenditures [12]. Inadequately managed diabetes can lead to numerous other issues, including kidney problems, nerve damage, eye issues, digestive disorders, erectile dysfunction, skin conditions, increased vulnerability to infections, and dental issues [8,13]. Considering this, it is important to find effective ways to manage the cardiovascular risk in diabetic patients. Lifestyle changes, such as those pertaining to diet, form the foundation of a broad strategy for reducing and managing the risk of diabetes [4,14].

The goal of diabetes treatment is to normalize fasting and postprandial blood glucose and lipids, to attain normal blood pressure, and to maintain a healthy weight [15,16]. Therefore, current guidelines for diabetes management advocate for dietary plans like the Mediterranean and vegetarian diets, which promote the consumption of nuts [17,18]. Nuts, including tree nuts (like almonds, Brazil nuts, cashews, hazelnuts, macadamias, pecans, pine nuts, pistachios, and walnuts) and peanuts are rich in nutrients and offer complex compositions containing unsaturated fatty acids, plant-based proteins, minerals without sodium, as well as phenolic and other bioactive compounds [14]. This review differs from previous studies by integrating evidence to explain how specific components in nuts improve diabetes and metabolic syndrome, including conditions like poor glycemic control, dyslipidemia, inflammation, and insulin resistance.. The novelty of this paper lies in its synthesis of multi-nutrient mechanisms, from unsaturated fats and fiber to phenolic compounds, and its emphasis on nut-specific bioactivity. By detailing molecular mechanisms such as AMPK activation, GLP-1 secretion, suppression of lipogenic genes, and modulation of gut microbiota, this review highlights how nuts can serve as a functional dietary therapy beyond traditional glycaemic management, positioning them as a holistic intervention for metabolic syndrome.

METHODS

This narrative review assesses the benefits of nut consumption for diabetes and metabolic syndrome.. The literature was sourced from multiple academic databases including Scopus, PubMed, Google Scholar, and ResearchGate, using the following keywords: *"nuts," "diabetes," "metabolic syndrome," "glycaemic control," "insulin resistance," "lipid profile," "dietary intervention."* Boolean operators (AND, OR) were applied to refine the search. Only peer-reviewed articles published in English between January 2000 and April 2024 were considered. Inclusion criteria encompassed original research articles, clinical trials, systematic reviews, and meta-analyses that investigated the relationship between nut consumption and glycaemic, lipid, or metabolic outcomes. Studies without nutritional data or mechanistic relevance were excluded. Screening of titles and abstracts was conducted manually by the author. A total of 23 studies were included in the final synthesis. Key data extracted included study population, nut type and dosage, duration of intervention, and main metabolic outcomes.

Nutrient composition of nuts: Nuts, typically characterized as dry fruits with an edible seed encased in a hard shell, such as cashews, walnuts, almonds, chestnuts, pistachios, and hazelnuts, are globally recognized for their nutritional richness[19,20]. They provide essential nutrients like monounsaturated and polyunsaturated fatty acids, vitamins E and K, as well as minerals such as magnesium, copper, potassium, and selenium, alongside dietary fibers, carotenoids, and phytosterols, which contribute to potential antioxidant benefits [20]. Their compact size also makes them convenient for consumption in various settings. Furthermore, incorporating nuts into the diet is often associated with mitigating risk factors for chronic diseases such as oxidative stress, inflammation, visceral adiposity, hyperglycemia, insulin resistance, endothelial dysfunction, and metabolic syndrome, thanks to their diverse nutrient profile [21,22]. Notably, many of the antioxidants in nuts are concentrated in their outer layers, such as the pellicle in almonds and peanuts [21] implying that when the skin is removed from the nuts the antioxidants may be lost.

Proteins: Nuts are a rich source of proteins and essential amino acids [21,22]. Pistachio has the highest protein content ranging from 19.4-22.1% [22], while chestnut has the lowest protein content (1.63%) [21]. In terms of the amino acid profile found in each type of nut, there is significant variability in both essential and non-essential amino acid content [21]. Variations may occur due to factors like variety and location. Glutamic acid stands out as the most abundant non-essential amino acid, ranging from 0.02 g/100 g in chestnuts to 6.21 g/100 g in almonds [23]. Arginine follows as the second most abundant non-essential amino acid, ranging from 0.12 g/100 g in chestnuts to 3.08 g/100 g in peanuts, with aspartic acid ranging between 0.03 g/100 g in chestnuts and 3.15 g/100 g in peanuts [21,23]. Among the essential amino acids, leucine is the most prominent, followed by phenylalanine and valine. Chestnuts exhibit the lowest levels of these essential amino acids (0.10 g/100 g, 0.07 g/100 g, and 0.09 g/100 g for leucine, phenylalanine, and valine, respectively), while peanuts are rich in leucine and phenylalanine, and pistachios are particularly high in valine [24]. Pecan can contain up to 17.84% protein content and all the amino acids essential for human diet (isoleucine, leucine, valine, lysine, threonine, tryptophan, phenylalanine, methionine and histidine) [25] . Although nut protiens when compared to animal protiens are ofthen considred incomplete, their consumption is linked to cardiovascular health [26]. Furthermore, the significant presence of arginine in all tree nuts offers benefits for immune response, inflammation, cardiovascular function, and reproductive performance, thereby reducing the risk of cardiovascular disease [21].

Vitamins: Nuts contain fat-soluble vitamins and antioxidants like α-tocopherol (known as vitamin E), which contribute to improved health, combat aging, enhance brain function, and promote healthy skin [21]. Various studies have reported an association between a increased dietary intake of fat-soluble vitamins K and E, with lowered risk of type 2 diabetes [27–29]. Specific nuts like walnuts, almonds, pine nuts, and hazelnuts are notably rich in vitamin E, while almonds, cashews, pistachios, walnuts, and peanuts are abundant in B vitamins[30]. Vitamin B_6 has been shown to protect endothelial function and improve insulin resistance and low Vitamin B_6 status might be a risk factor for non-alcoholic fatty liver disease (NAFLD) [31]. Pistachios and chestnuts have higher concentrations of folic acid, with chestnuts being the richest in vitamin C [32]. Supplemental vitamin C has been shown to potentially improve glycemic control and BP in people with type 2 diabetes [33,34].

Minerals: Nuts serve as valuable reservoirs of essential minerals like magnesium and potassium. In recent times, the promotion of increased nut consumption has been recognized as beneficial for human health due to their role in augmenting mineral intake [35]. When consumed moderately, nuts are deemed as heart-healthy snacks [35]. They are notably rich in minerals like copper and magnesium, which are believed to offer protective effects against coronary heart disease [21]. Moreover, certain varieties are particularly abundant in potassium, for example, pistachios (642-1025mg/100g) and cashews (660mg/100g)[21]. While most nuts contain notable amounts of zinc and iron, pine nuts (Zn: 3.08-6.45mg/100g; Fe: 5.53-6.64mg/100g), cashews (Zn: 0.96-5.78mg/100g; Fe: 3.82-6.68mg/100g), and almonds (1.91-3.12mg/100g; Fe: 3.71-6.21mg/100g) excel in this regard[21]. Despite not being notably rich in calcium overall, select nuts like almonds exhibit relatively higher calcium content (248mg/100g) [36].

Fiber: Dietary fiber, a vital component of human nutrition, can be categorized into two main types based on their behaviour in aqueous solutions: insoluble and soluble fiber. Insoluble fiber, comprising cellulose, lignin, and various hemicelluloses primarily found in grains and vegetables, serves as a bulking agent in the digestive system, promoting efficient intestinal transit[37]. In contrast, water-soluble dietary fibers encompass a diverse range of polysaccharides such as pectins, gums, mucilages, algal polysaccharides, and certain hemicelluloses and storage polysaccharides[38]. These fibers exhibit a notable capacity to absorb and retain water, often forming highly viscous solutions upon dissolution[38]. Scientific studies have shown that higher intake of dietary fiber is linked to lower risks of obesity, T2DM, cancer, and cardiovascular disease [39]. Almonds, among all nuts, contain the highest fiber content, influenced by genetic factors. Research indicates that the fiber content in almonds varies, ranging from 6.88% to 9.74%, with almond skin contributing significantly, comprising around 60% of the fiber. Cashews have the lowest fiber content, typically around 3% to 4%, while chestnuts are considered a good fiber source and that of hazelnuts ranges from 6.5 to 9.7%[40]. It is believed that an increase in dietary fiber intake results in a lower pH level in the gut, which increases the solubility of calcium ions there by increasing its absorption [41,42]. Calcium has a vital role in the prevention of diabetes by improving insulin sensitivity and pancreatic β-cell functions[43]. Additionally, fiber has been reported to reduce post prandial glycaemia[41]. The reduction in glucose levels due to fiber occurs by the soluble dietary fiber forming a gel, causing the contents of the gut to become thicker in both the stomach and intestines. This increased thickness slows down the diffusion of nutrients, gastric emptying, and absorption of nutrients in the small intestine[38]. Consequently, carbohydrates are absorbed into the bloodstream at a slower pace, resulting in more stable post prandial glycaemia[44].

Lipids: Dietary fats are divided into three subgroups: unsaturated FA, saturated fatty acids (SFA), and trans fatty acids (TFA)[45]. Unsaturated FA consists of monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) [46]. Although the fatty acid composition of the diet plays a significant role in enhancing insulin sensitivity and reducing T2DM and T2DM-related complications, the underlying mechanisms remain unclear[45]. It is claimed that saturated and trans fats are possible risk factors of T2DM while the poly-unsaturated fatty acids (PUFAs) may have positive effects on people with T2DM[45]. Nuts serve as an excellent source of fats following vegetable oil seeds [21]. The lipid content in nuts typically ranges from 40% to 75%[39]. Varieties such as walnut, macadamia, pine nut, and pecans tend to have higher lipid content (around 70%) compared to cashew, almond, pistachio, and hazelnut, which generally contain between 45% and 62% lipid[14]. The lipid profiles of different nuts are shown in Table 1. The PUFAs content ranges from 1.5-47.2g/100g, with the walnuts having the highest PUFAs content and macademia nuts having the least [40]. A diet high in unsaturated fatty acids, in particular, long-chain omega-6 and omega-3 polyunsaturated fatty acids, has been shown to lead to the suppression of lipogenic genes (genes of lipid synthesis) and induction of genes involved with fatty acid oxidation, which may reduce hepatic insulin resistance[14]. Additionally, nuts contain phytosterols which is a component of the cell membrane and is reported to interfere with cholesterol absorption and thus helping lower blood cholesterol when present in sufficient amounts in the intestinal lumen[14,39]. Fatty acid profiles of different nuts are shown in Table 1 below.

Table 1. Fatty acid profiles of different types of nuts.

Nuts	Total Fat	SFA	MUFAs	PUFAs	Omega-6	Omega-3
Almonds	50.6	3.9	32.2	12.2	12.2	0.00
Walnuts	65.2	6.1	8.9	47.2	38.1	9.08
Pistachio	44.4	5.4	23.3	13.5	13.2	0.25
Cashew	46.4	9.2	27.3	7.8	7.7	0.15
Pine nut	68.4	4.9	18.8	34.1	33.2	0.16
Pecan	72.0	6.2	40.8	21.6	20.6	1.00
Macadamia	75.8	12.1	58.9	1.5	1.3	0.21
Hazelnut	60.8	4.5	45.7	7.9	7.8	0.09
Peanut	49.2	6.8	24.4	15.8	15.6	0.00

Adopted from (Pradhan et al., nd) with slight modifications. All parameters are in g/100g. SFA means saturated fatty acids, MUFA means mono-unsaturated fatty acids and PUFA means poly-unsaturated fatty acids.

Phenolic compounds: Phytochemicals from tree nuts, including total phenols, flavonoids, proanthocyanidins (PAC), stilbenes, phytosterols, and carotenoids, exhibit diverse bioactivities such as antioxidant, antiviral, antiproliferative, hypocholesterolemic, and anti-inflammatory effects [47]. Polyphenolic compounds constitute the primary class of phytochemicals [48], with tree nuts serving as abundant sources of total phenolic compounds. Proanthocyanidins and hydrolysable tannins are generally the most abundantly found polyphenols in some nuts (Table 2). Nuts also have a significant phytate content as well as flavonoid, phenolic acid and stilbene polyphenol classes [47]. It is widely recognized that the development of diabetic complications is influenced by various factors, with metabolic inflammation being a significant contributor to this process [13]. A growing body of evidence from clinical studies demonstrates the notable benefits of inflammation-targeted therapies in hyperglycemia, β-cell dysfunction, and insulin resistance in T2DM [13]. The pleiotropic benefits of phytochemicals in diabetes include lowering LDL cholesterol as well as blood sugar, inhibiting inflammation, enhancing insulin sensitivity, alleviating oxidative stress, offering vascular protection as well as reducing retinal inflammation [13].

Table 2. List of important phytochemicals found in nuts and their role in diabetes management.

Nuts	Phenolic compound	Potential health benefits in diabetes	References
Almond	Catechin, epicatechin, naringenin, eriodictyol, gallic acid, caffeic acid, chlorogenic acid, o-coumaric acid, ρ-coumaric acid, ferrilic acid, hydroxybenzoic acid, protocatechuic, vanillic acid, quercetin, kaempferol, isorhamnetin	Antioxidant, Lipid lowering, hypoglycemic	[21,39,40,49]
Walnuts	Vanillic acid, catechin, pyrocatechin, protocatechuic acid, epicatechin, syringic acid, gallic acid, juglone and cinnamic acid, ellagic acid, rutin	Lipid lowering, anticholesteremic	[39,40,49]
Pistachio	Cyanidin, gallic acid, protocatechuic, eriodictyol, catechin, epicatechin, epicatechin gallate, luteolin, quercetin, myricetin, procyanidin B1, trimers, and tetramers	Lipid lowering, hypoglycaemic	[39,40,49]
Cashew	(+)- catechin, (-)-epicatechin, epigallocatechin and catechin gallate, syringic acid, gallic acid, delphinidin, cyanidin, quercetin, catechin, myricetin	Antiobesity, cardiovascular protection, antidiabetic	[39,40,50–53]
Pinenut	Catechin, epicatechin, vanillic acid, syringic acid, caffeic, hydroxycinnamic acid	Antioxidant, anti-inflammatory, antidiabetic, antihypertensive	[40,49]
Pecan	Ellagic acid, catechin, gallic acid, hydroxybenzoic acid, trans-cinnamic acid, syringic acid, caffeic acid, p-coumaric acid, ferulic acid, naringenin, apigenin, quercetin, rutin, kaempferol, isorhamnetin, resveratrol	Lipid lowering, hypoglycaemic	[39,40,49]
Macadamia	ampesterol, clerosterol, β-sitosterol, campestanol, Δ5-avenasterol + β-sitostanol, Δ5,24(25)-stigmastadienol, Δ7-stigmastenol, 24- methylenecycloartenol, citrostadienol	Antioxidant, anti-dyslipidaemia, anti-inflammatory	[39,40,49,54]
Hazelnut	Gallic acid, protocatechuic acid, caffeic acid, o-coumaric acid, p-coumaric acid, ferullic acid, catechin, epicatechin, epicatechin gallate, rutin	Lipid lowering	[39,40,49]
Peanut	Catechin, epicatechin, quercetin, isorhamnetin, gallic acid, protocatechuic, caffeic acid, p-coumaric acid, procyanidins A and B, trimers and tetramers, prodelphinidin	Hypoglycaemic, antioxidant	[39,40,49]

Evidence of the impact of nuts on post prandial hyperglycaemia: Persistent elevation of blood sugar levels exerts detrimental effects on the initiation and advancement of both microvascular and macrovascular complications in individuals diagnosed with T2DM [55]. It has been demonstrated that postprandial hyperglycaemia (PPHG) may yield comparable or even more detrimental consequences than hyperglycaemia observed during fasting periods [56]. Previous approaches to reduce PPHG in patients with diabetes have included improving insulin sensitivity (via exercise and weight loss), limiting total carbohydrate intake, and use of post-prandial glucose regulator drugs like Acarbose, Nateglinide, Repaglinide etc [55]. There is relatively poor long term adherence to most of these recommendations, additionally, drugs can be expensive for some patients, in some cases (20-30% of the users) the drugs have been shown to have adverse health effects such as stomach aches, bloating and indigestion [55]. Tree nuts, on the other hand are a novel approach in the management of PPHG considering their nutrient and phytochemical composition [39,57].

The effects of nuts have been investigated in several studies. Gulati et al showed that dietary intervention with a premeal load (20g) of almonds (before breakfast, lunch and dinner daily) resulted in reduced postprandial glucose and insulin spikes, consequently mitigating the overall hyperglycaemic state in a cohort of Asian Indian individuals diagnosed with prediabetes[55]. Additionally, the intervention by Gulati et al led to a reversal to normal glucose regulation from the state of prediabetes. All these achievements were reached without restricting the carbohydrate intake of the participants meaning the almond nut can be used by diabetic patients to control blood glucose without the discomfort of altering their normal diet thus making it easier to incorporate as part of their lifestyle. Interestingly, the almond nuts used in Gulati et al's study did not have any adverse effects on the pre-diabetic participants, making it more superior and safer compared to the conventional postprandial glucose regulator drugs. The salutary effects of almond nuts on blood glucose level can be attributed to the MUFAs and soluble fiber in the nuts [57]. These have been shown to lead to the release of peptides such as GLP-1, GIP, and cholecystokinin (CCK) which can slow gastric emptying and stimulate insulin secretion [58]. Furthermore, the inclusion of almonds increases a feeling of satiety and leads to a strong dietary compensation effect[58]. In line with the above report, Li et al showed that almonds replacing 20% calories of the control diet improved glycemic control in Chinese T2DM patients, it however did not reduce glucose level to the unimpaired range (110-125 mg/dL [6.1- 6.9 mmol/L]) [59]. Another study by reported that the consumption of almonds with white bread was shown to significantly lower the postprandial area under the insulin concentration vs. time curve when compared to a high glycaemic index (GI) meal (instant mashed potatoes) and significantly lowered the glucose peak height when compared with white bread, implying that, nuts consumption resulted in a lower postprandial hyperglycaemia[60]. Although almonds are rich in fat, they possess a low-glycemic index and could alter the glycemic index of co-consumed foods [59].

A comprehensive meta-analysis of twelve randomized controlled trials (RCTs) with a follow-up period exceeding three weeks indicates that the ingestion of an average daily quantity of 56 grams of tree nuts can enhance glycemic regulation among individuals diagnosed with Type 2 Diabetes (T2D) when compared to an isocaloric diet devoid of tree nuts [61]. Furthermore, findings from the investigation conducted by Kendall et al. underscore that the consumption of nuts either independently or in conjunction with a high glycemic index (GI) regimen contributes to the reduction of postprandial blood glucose levels[62]. Numerous dietary components found in nuts such as fiber and polyphenols, including both flavonoids and non-flavonoids, have been suggested to exhibit prebiotic properties and influence the regulation of glucose metabolism [63]. Studies have demonstrated that the alteration of gut microbiota through prebiotic interventions can enhance glycemic regulation in both healthy individuals and those with diabetes [64,65].

On the contrary, a study by Graveinstejin et al, showed that long term consumption of almonds significantly decreased insulin sensitivity, and increased postprandial glucose concentrations in prediabetics [57]. The inconsistent reports regarding the hypoglycaemic effects of almonds can possibly be attributed to the different designs used in these studies. Additionally, almond dosage, background diet, and ethnicity might be accountable for the underlying factors for the discrepancy in the benefits of almond consumption in diabetes[59]. Nuts affect glycaemic response in a dose-dependent manner. The dose and duration of supplementation in studies that observed a significant effect of nuts consumption on glycaemic factors ranged from 30–60 g/day and 4–24 weeks, respectively[66]. Although findings from a few earlier studies suggest a notable decrease in fasting insulin levels or enhancement in insulin resistance after the ingestion of nuts[66,67], later studies such as that of Palacios et al recently reported conflicting results regarding effect of nuts on insulin sensitivity [68] suggesting that there is still need for more studies to get more clarity on this matter.

Evidence of nut consumption on Metabolic Parameters: It is widely agreed that cardiovascular diseases and diabetes share some risk factors such as increased adiposity and dyslipidaemia [69,70]. Thus, interventions aimed at preventing T2D should also target the cardiovascular-related risk factors such as dyslipidaemia. Several studies have reported the beneficial effects of nuts consumption on lipid profiles, especially total cholesterol (TC) and low-density lipoprotein cholesterol (LDL-C), in both healthy and high-cholesterolemic individuals from various geographical areas[66]. Nuts are rich in bioactive nutrients, such as γ -tocopherol, polyphenols, monounsaturated fatty acid (MUFA; oleic acid) and polyunsaturated fatty acid (PUFA; linoleic acid), known to have cardioprotective, antioxidant and lipid lowering properties[66]. Several studies have demonstrated these beneficial effects, for example, Cogan et al reported that peacan nuts significantly reduced post prandial blood lipids (total cholesterol, LDL cholesterol and non HDL cholesterol)[70]. Similarly, Jung et al showed that consumption of 56g of almonds for a period of 4 weeks decreased TC, LDL-C, and non-HDL-C among obese Korean adults compared to those on the control diet [71]. Several other randomised controlled trials reported the beneficial effects of consuming almonds on lipid profiles of either health or diabetic participants [72–76] even though they were done on different ethnic populations using different doses (56g/day) and intervention periods (4-24weeks). Another study with pistachios revealed lipid lowering effects on TC as well as the ratio of total HDL-C and triglycerides on participants with well controlled T2DM [77]. Like almonds, pistachios have these lipid lowering effects in both healthy and diabetic individuals as shown by Gulati et al and Sari et al [78,79]. These observations imply that nuts can be used both in the prevention and management of diabetes by different ethnic groups. Other studies have shown that beyond lipid lowering, nuts have other favourable effects such as improving indices of inflammation and oxidative status [77,79]. Inflammation is a constant feature associated with the onset and progression of many chronic degenerative diseases, all three types of diabetes and one of the leading causes of its insurgence is the high adipose tissue content[80]. A study by Renzo et al showed that feeding 40g/day to healthy individuals over 4 weeks resulted in a significant up-regulation of sodium dismutase (SOD), catalase (CAT), peroxisome proliferator-activated receptor gamma (PPAR-γ), and Angiotensin I-converting enzyme (ACE) at the end of the study[81]. A clinical trial by Liu et al showed that almond diet (56 g/day) for 4 weeks reduced C-reactive protein (CRP) by a median 10.3 % (95% CI: −24.1, 40.5), tumor necrosis factor (TNF-α) by a median 15.7 % (95% CI: −0.3, 29.9), and interleukin-6 (IL-6) by a median 10.3 % (95% CI: 5.2, 12.6 %) in participants with T2DM in comparison to those in the control diet[82].

Mechanisms by which nuts ameliorate diabetes and metabolic syndrome: Metabolic syndrome is characterized by central obesity, insulin resistance, dyslipidaemia, and hypertension, all of which are also key risk factors for Type 2 Diabetes Mellitus (T2DM) [7]. Nuts have shown unique potential in addressing multiple features of this syndrome through interconnected nutritional and biochemical pathways[16]. The diverse biochemical profiles of nuts confer unique health effects through multifactorial mechanisms relevant to diabetes management [16,17]. For instance, walnuts are distinguished by their high α-linolenic acid (omega-3) content, which modulates inflammatory pathways via eicosanoid biosynthesis [16,17]. Almonds, rich in MUFAs and vitamin E, improve insulin sensitivity and exert antioxidative actions through the enhancement of glutathione peroxidase and catalase activity [17]. Pistachios, uniquely high in lutein and zeaxanthin, promote vascular health by upregulating endothelial nitric oxide synthase (eNOS), reducing oxidative stress and improving vasodilation [17]. Cashews, noted for their high magnesium and zinc levels, influence insulin receptor activity and β-cell preservation. Mechanistically, polyphenols in all nuts modulate AMP-activated protein kinase (AMPK) pathways, thus enhancing glucose uptake and fatty acid oxidation. Additionally, nut-derived dietary fiber modulates gut microbiota composition, leading to increased production of short-chain fatty acids (SCFAs) like butyrate, which has anti-inflammatory effects and improves insulin sensitivity [22].

- **Improvement of insulin sensitivity:** Monounsaturated and polyunsaturated fatty acids (especially oleic and linoleic acids in almonds, walnuts, and pistachios) upregulate PPAR-γ and downregulate inflammatory cytokines (e.g., TNF-α, IL-6), improving insulin signalling and β-cell function.
- **Modulation of postprandial glycaemia:** Soluble dietary fiber forms viscous gels that delay carbohydrate absorption, while phenolics and lipids in nuts enhance GLP-1 and CCK release, delaying gastric emptying and reducing glucose spikes.
- **Lipid-lowering and anti-atherogenic effects:** Phytosterols in nuts reduce intestinal cholesterol absorption, and their high PUFA/MUFA content improves lipid profiles by lowering LDL and raising HDL cholesterol.
- **Reduction of inflammation and oxidative stress:** Polyphenols, flavonoids (like quercetin, catechin), and tocopherols act on NF-κB and Nrf2 pathways to reduce systemic inflammation, a key driver of metabolic syndrome progression.
- **Gut microbiota modulation:** Prebiotic fibers and polyphenols from nuts alter gut microbial composition, increasing the production of short-chain fatty acids like butyrate, which improves insulin sensitivity and reduces systemic inflammation.

Together, these mechanisms explain why nuts are effective and how they intervene at multiple pathophysiological points relevant to both diabetes and metabolic syndrome. This multifaceted functionality makes nuts distinct among dietary interventions.

Safety considerations: Nut consumption can offer numerous health benefits due to their nutrient-rich profile, including healthy fats, protein, fiber, vitamins, and minerals. However, tree nuts have been reported to contain allergens such as seed storage proteins, pathogenesis-related (PR) proteins, profilins and lipid transfer proteins (LTP) [83] which may affect both children and adults. These allergens found in nuts can trigger allergic reactions ranging from mild to severe [84]. An allergic reaction to nuts can manifest as hives, itching, swelling, difficulty breathing, or even anaphylaxis, a life-threatening condition. Some individuals may experience adverse effects from consuming certain nuts due to natural toxins or anti-nutrients present in them. For instance, raw cashews contain urushiol, the same compound found in poison ivy, which can cause skin irritation or allergic reactions in susceptible individuals[85]. However, commercially available cashews are typically heat-treated to remove this toxin. Food processing has been proposed as the method of choice to alter the allergenicity and toxicity of most foods including nuts to ensure their safety and improve their organoleptic properties [83,84]. While nuts offer numerous health benefits, excessive consumption can lead to nutritional imbalances. Nuts are energy-dense and high in fat, albeit predominantly healthy unsaturated fats. Overconsumption of nuts, especially if not balanced with other nutrient-rich foods, could contribute to weight gain or other health issues [86]. Lastly, whole nuts, particularly for young children or elderly individuals, can pose a choking hazard [87]. Chopping or grinding nuts before serving can help reduce the risk of choking

CONCLUSIONS

Nuts (mainly pistachios, almonds, and walnuts) have been shown to have beneficial effects on post prandial glycemic and lipid parameters. The higher monounsaturated fatty acid content and a lower polyunsaturated/saturated fat ratio reported in most edible nuts such as almond and pistachio nuts may be responsible for their favourable effect on lipids. Nuts can therefore be recommended as a dietary intervention for reversing the prediabetic stage and its related complications as well as reducing the progression to diabetes. While nuts offer numerous health benefits, individuals with nut allergies should take precautions to avoid exposure, and everyone should practice moderation and be mindful of portion sizes when incorporating nuts into their diet. There are fewer studies that have evaluated the effects of nuts on insulin resistance, and the few that are there report conflicting results. There is need for more studies to investigate the effects of nuts on insulin resistance in diabetic individuals. Although several studies have shown the pleiotropic benefits of nuts in diabetes, there is still a lack of clarity on the dose and duration of the intervention, more research should focus on bring light on these issues to make it easier to incorporate nuts into as a dietary therapy.

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