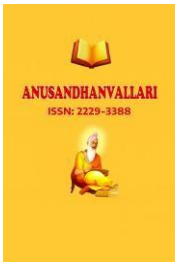

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Role of Nutraceuticals and Ayurvedic ingredients in Prevention and Management of Diabetes Mellitus

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Abstract

Diabetes mellitus is a multifactorial metabolic disorder and a growing global health concern, with India at the forefront in terms of disease burden. Lifestyle factors such as sedentary behaviour and poor diet have accelerated the onset of type 2 diabetes and its associated complications including cardiovascular disease, obesity, nephropathy, and neuropathy. Conventional therapies often require long-term use and are associated with multiple side effects, creating a need for safer adjunctive strategies. This review explores the synergistic role of nutraceuticals and Ayurvedic interventions in the prevention and management of diabetes and its secondary complications. Nutraceuticals—including omega-3 fatty acids, curcumin, alpha-lipoic acid, polyphenols, dietary fiber, and bioactive peptides—exert antidiabetic effects via modulation of oxidative stress, inflammation, and insulin signalling pathways. Similarly, Ayurvedic herbs such as Gymnema sylvestre, Neem, Karela, Triphala, and Guduchi demonstrate glucose-lowering activity by enhancing insulin secretion, improving β-cell function, and inhibiting carbohydrate-digesting enzymes. Integrative use of nutraceuticals and classical Ayurvedic formulations offers a holistic and multi-targeted approach for diabetes management, with potential benefits in glycemic control, lipid profile improvement, and prevention of long-term complications. Although promising, these interventions require further standardisation and clinical validation to determine optimal dosing, safety, and efficacy. Ultimately, a personalised and evidence-based integration of nutraceuticals and Ayurveda may provide an effective complementary strategy alongside conventional therapies in the comprehensive management of diabetes mellitus.

Keywords: Nutraceuticals, Ayurveda, Diabetes type 2, glycemic index

Introduction

In the past few decades, humanity has gravitated toward a more sedentary lifestyle, especially in large metros around the world. This is mainly attributable to multiple reasons, such as increasingly mechanised jobs, excessive time spent on social media apps, and overall reduction in physical activity. In addition, there has been a significant change in the human population's overall dietary patterns. A higher intake of ultra-processed and low-nutrient-density foods, high in both fat and sugar content. These deteriorating lifestyle choices have generated numerous metabolic disorders and diseases, such as diabetes mellitus, cardiovascular diseases, obesity, and hypertension. Approximately 41 million Indians are currently affected by diabetes mellitus, making India the diabetic capital of the world[1]. Type 2 diabetes predominantly arises due to a lack of physical activity and overconsumption of hyperglycemic foods; therefore, it is often associated with obesity, cardiovascular diseases, and hypertension. To combat and control various health disorders, Indians have always relied heavily on herbs, spices, and ayurvedic medicines. The same is true for diabetes. Ayurveda, the ancient Indian science of medicine, offers a treasure trove of herbs thought to be beneficial in the management and control of diabetes. The objective of this review is to focus not only on diabetes mellitus but also on its secondary complications and the possible role of nutraceuticals available today and those already explored in Ayurvedic medicine that may help prevent the onset of diabetes or its subsequent management (Figure 1).

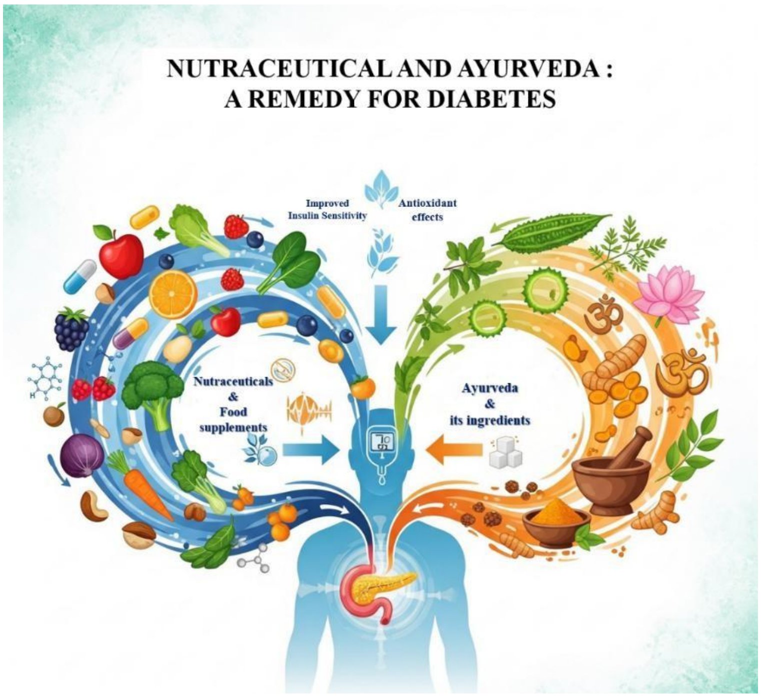

Figure 1: Schematic diagram showing role of nutraceuticals and ayurveda in diabetes management

1. Diabetes:

Diabetes mellitus (DM) is a chronic metabolic disorder marked by sustained hyperglycemia that disrupts lipid and creatine metabolism and is associated with a range of metabolic dysfunctions[2]. Diabetes is characterised by impaired insulin secretion, resistance to insulin action in peripheral tissues, or a combination of both. Persistent hyperglycemia, along with other metabolic disturbances, can damage multiple organs over time, leading to serious diseases and life-threatening complications. As one of the most pressing global public health challenges, diabetes contributes significantly to high mortality rates and reduced life expectancy worldwide[3]. The disease is accompanied by high medical expenses, mostly due to secondary chronic complications. Patients are at a higher risk and are predisposed to other fatal diseases, such as cardiovascular disease (CVD), kidney problems, chronic liver disease, hypertension, cancer, stroke, retinopathy, nephropathy, neuropathy, and foot ulcer development, among others[3,4].

Diabetes can be classified into the following major categories:

Type 1 diabetes (T1D): Nearly 5% of all cases of diabetes. It is an autoimmune disorder[5]

Type 2 diabetes (T2D): 95% of all diabetes cases. It is usually associated with obesity[5,6].

Gestational diabetes (GD): occurs during pregnancy[7].

Certain types of diabetes arise from specific causes, such as diseases affecting the exocrine pancreas (e.g., cystic fibrosis) or as a result of medication use, including immunosuppressive drugs administered after organ transplantation[8].

Type 2 diabetes is strongly linked to obesity, with adipose tissue functioning as an active endocrine organ that secretes various hormone-like substances capable of increasing insulin resistance[9]. Insulin resistance routinely precedes type 2 diabetes and is characterised by high insulin levels despite normal blood glucose levels. This condition is commonly prevalent in pre-pubertal children with obesity and women with polycystic ovarian syndrome or PCOS[10].

The number of patients suffering from diabetes is rising alarmingly all over the world. According to the International Diabetes Federation (IDF), the population affected by diabetes in 2019 was approximately 9.3% (463 million patients), while further predictions include an increase to 10.2% (578 million patients) by 2030 and to 10.9% (700 million patients) by 2045[11]. The World Health Organisation (WHO) has listed diabetes among the top 10 fatal diseases, and a nearly 70% increase in diabetes-related deaths was recorded between 2000 and 2019[11]. Therefore, finding safe, preventive, and therapeutic modalities to treat and cure diabetes is imperative to reduce the burden on the public health system.

1.1. Diabetes and obesity:

The diabetes epidemic is rapidly escalating, particularly in developing countries, driven largely by rising obesity rates across all age groups. This surge is primarily linked to sedentary lifestyles and unhealthy dietary habits[6]. Shortly, diabetes is projected to affect 9.3% of the global population. Currently, over 500 million people worldwide are living with type 2 diabetes (T2D), and an additional 500 million have impaired glucose tolerance—largely influenced by inadequate nutritional intake[11]. In Portugal, where the traditional Mediterranean diet is increasingly being replaced by poor eating habits and physical inactivity, diabetes is on the rise, and approximately 60% of the population is now overweight[12]. The prevalence of T2D in Portugal is one of the highest in Europe[13]. Conversely, the incidence of obesity is also rising steadily in India, where the predominantly vegetarian population relies heavily on cereals. By 2030, India is estimated to have approximately 80 million people living with diabetes, significantly surpassing China (approximately 45 million) and the USA (approximately 35 million)[14]. The Indian population is often described as “metabolically obese” despite having a normal body weight, placing them at a heightened risk for developing vascular diseases and type 2 diabetes[15]. Therefore, diets high in simple sugars (such as sucrose and fructose) and low in protein, along with certain nutraceuticals like phytochemicals, can adversely affect an individual’s metabolic and immune health[16, 17].

1.2. Diabetes mellitus and cardiovascular disease (CVD):

Diabetes mellitus is a well-recognised risk factor for cardiovascular disease (CVD), with type 2 diabetes mellitus (T2DM) significantly increasing the likelihood of cardiovascular complications. Furthermore, individuals with both diabetes and hypertension face nearly twice the risk of cardiovascular events compared with hypertensive patients without diabetes[18]. Multiple studies have demonstrated that obesity contributes to cardiovascular disease through various mechanisms, including subclinical inflammation, endothelial dysfunction, increased sympathetic activity, atherogenic lipid profiles, prothrombotic factors, and obstructive sleep apnea[19]. Excess visceral fat and central obesity are key contributors to insulin resistance, elevated triglyceride levels, alterations in low-density lipoprotein (LDL) particle size, and reduced high-density lipoprotein (HDL) levels. Complex mechanisms involving different pathophysiological pathways, such as those mediated by cytokines and other inflammatory mediators like leptin, result in excess fat causing insulin resistance. Insulin resistance leads to the development of type 2 diabetes mellitus and can initiate or accelerate the atherogenic process through various mechanisms, including persistent hyperglycemia[19]. In pathological conditions such as obesity and diabetes, impairment of the adiposity buffer reduces adipocytes' uptake of free fatty acids, leading to increased cardiolipotoxicity[20]. The volume of epicardial fat is an independent predictor of total coronary artery occlusion. When correlated with clinical and biochemical markers of metabolic syndrome, patients with type 2 diabetes mellitus possess a higher volume of epicardial adipose tissue compared to non-diabetics, contributing to more severe coronary atherosclerosis[20].

1.3 Nutritional Management in Diabetes:

Nutritional management in diabetes extends beyond meeting basic nutrient needs—it serves as a fundamental step in effective diabetes control. A well-balanced diet supports glycemic regulation by managing the amount, type, and timing of food intake alongside insulin therapy, while also positively impacting overall metabolism to slow disease progression and reduce the risk of complications. Caloric requirements for each diabetic patient vary based on factors such as age, weight, sex, and physical activity level. The distribution of macronutrients is tailored according to lipid profile, kidney function, meal timing, lifestyle, and the type of hypoglycemic medications used. Additionally, personal, familial, and cultural food preferences must be taken into account to ensure adherence and long-term success[21].

In individuals with diabetes, the most effective way to prevent hyperglycemia is by maintaining blood glucose levels within the normal range without triggering hypoglycemia. This is typically achieved through a combination of proper diet, regular physical activity, and appropriate medication. However, managing diabetes and its complications often requires more than just conventional medicine; alternative therapies may also play a supportive role. Observational studies suggest that diet is a key factor in the prevention and management of diabetes. The TOSCA-IT study (Trial on the influence of dietary fat and carbohydrates proportions on plasma lipids, glucose control, and low-grade inflammation in patients with type 2 diabetes) found that a diet rich in total polyphenols was linked to improved cardiovascular risk profiles and reduced levels of subclinical inflammation in individuals with type 2 diabetes mellitus[22].

2. Nutraceuticals

Nutraceutical is a term that refers to any substance that may be considered as food or a part of food having underlying properties that provide medical or health benefits, such as prevention or treatment of disease. This term was first coined by "The Foundation for Innovation in Medicine (New York, USA)" in 1989 for categorising food products involved in the rapid growth of biomedical research involving human health[23]. The wide expanse of nutraceuticals incorporates many food substances such as isolated nutrients, herbal products, processed products (cereals, milk products, beverages, etc.), designer foods, minerals, etc. It has been suggested that nutraceuticals play a central role in physiological functions and biological mechanisms[24].

Nutraceuticals act as biological defence agents and protect the body from harmful disease-causing toxins, ultimately improving health and promoting wellness. Nutraceuticals have been divided into various categories such as phytochemicals, nutrients (carbohydrates, vitamins, minerals, amino acids), herbs, probiotics, antioxidants, dietary supplements, etc. Nutraceuticals have manifold therapeutic effects on the human physiological systems. They protect against various diseases by acting as immune-boosters, anti-cancerous, anti-glycemic, and anti-inflammatory agents, etc.[25].

Nutraceuticals are food products with both nutritional and medicinal properties and can act as a promising alternative medicine, beneficial for regulating plasma glucose levels, thereby helping in both prevention and management of diabetes. Their bioactive compounds can modulate various metabolic pathways, improve glycemic control and reduce diabetes-related complications. They are rich sources of dietary fiber, carotenoids, collagen, etc and are functional foods with higher antioxidant and anti-inflammatory properties that can help reduce the cost of diabetes treatment and its related complications. They can also be an alternative option for people who may show adverse reactions to conventional antidiabetic medications[26].

2.1 Nutraceuticals in Diabetes Disease Management:

Type 2 diabetes, or adult-onset diabetes, is a complex metabolic disorder marked by impaired insulin function and regulation and pancreatic β-cell dysfunction, disruption in lipid and glucose metabolism, and higher oxidative stress markers. All these subclinical conditions give rise to a multiparametric complex situation that impairs vascular, neural, retinal, kidney, and cardiac tissues, ultimately reducing the quality of life of the patient and increasing the mortality rate[27]. Conventionally, Indians have relied on a variety of nutraceuticals to maintain their overall health and well-being. Moreover, Ayurveda also emphasises the possible benefits of some herbs in diabetes management. This study further explores some of the more commonly known nutraceuticals and their potential in diabetes control. A few of these are discussed below:

2.1.1 Docosahexaenoic acid (DHA)

DHA is an essential ω-3 fatty acid, found in adequate amounts in the bloodstream. As a nutraceutical, it can be obtained from seafood, fish and krill oils, and algal oils. DHA-fortified foods such as infant formula help formula-fed infants obtain DHA that is otherwise naturally present in breast milk[28]. DHA helps reduce insulin resistance, enhances cognitive function, and lowers the risk of preterm birth and cardiovascular diseases. It also plays a vital role in neuro-visual development[28]. This is particularly crucial for women with gestational diabetes mellitus, reinforcing the recommendation for adequate intake of essential fatty acids during pregnancy[29]**.** There is evidence to support the protective role played by DHA supplementation in diabetic retinopathy[30]. It also improves the functioning of macrophage progenitor cells, which are critical in wound healing since there is a decline in macrophage function in diabetic patients[31]. DHA also exhibits anti-inflammatory properties and reduces diabetes-induced CVD by decreasing blood triglyceride levels and improving high-density lipoprotein cholesterol levels[31].

2.1.2 Lipoic acid

Alpha lipoic acid or thioctic acid is a cofactor for mitochondrial energy-synthesising enzymes[32]. It is a universal antioxidant, with a capacity for metal chelation, revival of antioxidants, and oxidative damage repair. It helps in glucose uptake and improves the glycemic index in diabetics. It is therefore used to treat diabetic neuropathy since it diminishes pain and improves nerve conduction velocity[32]. Lipoic acid may be more effective as a long-term dietary supplement for the preventive management of diabetic symmetrical polyneuropathy (DSPN), primarily by enhancing microcirculation and reducing oxidative stress, thereby helping to protect diabetics from related complications[32,33].

2.1.3 Dietary fibers from Psyllium

Psyllium is a water-soluble dietary fiber used extensively as a pharmacological supplement. It also functions as an ingredient in processed foods to aid in weight loss and glucose control in diabetic patients, as it helps decrease lipid levels in hyperlipidemia. It significantly reduces fasting blood sugar levels and HbA1c parameters in diabetic patients[34]. Psyllium acts by abating nutrient absorption in the gut, lengthening satiety, and protecting against digestive enzymes. There is no consensus on the recommended dose of psyllium, but it is not known to cause any adverse reactions apart from rare allergies in some individuals[35].

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2.1.4 Minerals and Vitamins

Adequate magnesium levels are associated with a reduced risk of diabetes and enhanced insulin sensitivity. Supplements such as chromium picolinate, calcium, and vitamin D may also support insulin function and help improve glycemic control in certain individuals with diabetes. Additionally, extracts from bitter melon and cinnamon have shown potential in both the treatment and prevention of diabetes. It has been proposed that nutraceuticals containing effective combinations of these ingredients at meaningful doses could significantly aid in diabetes prevention and may be legally marketable.

In prediabetics, intake of moderate to high doses of vitamin D (≥1000 IU/day) reduced the risk of developing Type 2 Diabetes (T2DM) significantly[36]. Insulin resistance and impaired insulin secretion are also associated with vitamin D deficiency. Its low levels can also result in several diabetic complications such as retinopathy, diabetic kidney disease, erectile dysfunction, peripheral neuropathy, etc[36]. Apart from vitamin D, deficiency of vitamin B12 also seems to be associated with insulin resistance and an increased risk of pregnant women developing gestational diabetes mellitus or GDM37. A 5-year study done on a Japanese cohort showed that higher dietary intake of green leafy vegetables, meat, and fish, which are rich sources of fat-soluble vitamins E and K, lowered the risk of developing T2DM in the population[37,38]. Vitamin C (> 200 mg/day) has been shown to reduce the incidence of GDM in pregnant women[39]. Intake of vitamin C supplements is known to reduce hyperglycemia apart from its antioxidative properties; it also exhibits cytoprotective functions on the pancreatic cells by improving the synthesis of prostaglandin E1 (PGE1), endothelial nitric oxide, and prostacyclin (PGI2)[40].

Imbalances in dietary micronutrients such as selenium, cobalt, iodine, magnesium, chromium, zinc, calcium, boron, and iron can cause alterations in glucose homeostasis and insulin resistance. These micronutrients act in the body by activating insulin receptor sites and modifying oxidative stress influences[41]. Some of the common micronutrients that play a role in diabetes management are listed below in table 1.

Table1. Common micronutrients that play a role in diabetes management

S. No.	Micronutrient	Effect
	Boron	Its deficiency results in increased plasma insulin levels
	Calcium	Low levels cause increased metabolic disorders
	Cobalt	Deficiency causes type 2 diabetes
	Chromium	In required amounts, it improves the levels of blood glucose, insulin, and lipids
	Iodine	Deficiency alters blood glucose levels
	Iron	Its deficiency affects blood glucose metabolism
	Magnesium	Deficiency causes insulin resistance and type 2 diabetes
8.	Selenium	In adequate amounts, it reduces oxidative stress and the incidence of metabolic syndromes
	Zinc	Adequate amounts reduce oxidative stress, while high levels can cause hypertension

2.1.5 Cryptides or Bioactive peptides

Cryptides or bioactive peptides are oligopeptides ranging in length from 2–20 amino acids, found within larger protein molecules. These can be released via several mechanisms such as proteolytic digestion of peptide bonds by enzymes, acids, and alkalis or fermentation[2]. Several bioactive peptides have been recognised from various plant sources such as wheat, seeds, nuts, soybeans, and processed soybean products such as soymilk, tofu, soy sauce, buckwheat, highland barley seeds, lentils, rice, oats, Quinoa, pulses, flaxseeds, and numerous other plant products. Animal and marine sources include peptides derived from eggs, milk, meat, oysters, crabs, squids, and fish such as salmon, cod, and tuna that help boost glucose metabolism[2].

Milk and milk products such as yoghurt and cheese are rich sources of bioactive peptides with numerous beneficial properties. Milk proteins, whey, and casein are also important sources of peptides with anti-diabetic properties. Peptides have been identified and isolated from egg whites and meat by their digestion using pepsin and trypsin. The processing of meat in the form of drying, curing, ripening, and fermentation also releases bioactive peptides capable of multifunctional activities. Other food-derived bioactive peptides also assist in the regulation of carbohydrate metabolism, regulate insulin secretion, and reduce glucose absorption from the gut[42].

Cryptides exhibit various immunomodulatory, anti-inflammatory, anticancer, antioxidant, anti-lipidimic, and antimicrobial properties[2]. These are a better alternative to conventional drug therapies for the treatment of lifestyle disorders as they do not accumulate in body tissues and cause serious side effects. Employment of well-formulated delivery systems helps improve viability and overcome drawbacks such as unpalatable taste, low chemical stability, and easy GI digestion. An example of such a peptide drug is Nutripeptin, a peptide derived from cod fish fillets that helps reduce the glycemic index of food and aids in diabetes management[2].

The amino acid composition and sequence in the bioactive peptide play a major role in determining their anti-diabetic properties. The peptide's structure and subsequent function depend upon the enzymes used, substrate pre-treatment, and hydrolysis conditions. The presence of specific hydrophobic amino acids—such as alanine, glycine, isoleucine, leucine, phenylalanine, proline, methionine, tryptophan, and valine—supports the formation of peptides involved in glucose metabolism. Additionally, peptides that inhibit α-amylase activity often contain aromatic and high molecular weight amino acids like phenylalanine, tryptophan, tyrosine, and arginine[2]**.** Several studies have indicated that bioactive peptides are capable of managing diabetes, but there still exists a gap between these studies and the possibility of these peptides for commercial use. Further analysis is needed to improve their stability, availability, delivery, and half-life to ensure adequate safety and efficacy[2, 42].

2.1.6 β-sitosterol, a phytosterol

β-sitosterol or SIT has a structure similar to cholesterol but with an additional ethyl group at the C-24 position. It is an important component of plant cell membranes and helps regulate the membrane's permeability and fluidity. Studies have shown that SIT possesses antioxidant properties that may help in its role as an antidiabetic agent. A study on a high-fat diet and sucrose-induced type-2 diabetic rats, upon administration of SIT (20 mg/kg b.wt, orally for 30 days), exhibited a lowering of both blood glucose and serum insulin levels along with a normalization of lipid profile, oxidative stress markers, and antioxidant enzymes. The experimental rats also observed low levels of insulin receptor (IR) and glucose transporter 4 (GLUT4) proteins[43]. Additional experimental studies are needed to clarify the molecular mechanisms by which SIT influences oxidant and antioxidant pathways. This understanding could pave the way for the development of new drugs aimed at improving human health. Since SIT enhances antioxidant levels, it demonstrates effective antidiabetic, hypolipidemic, neuroprotective, and chemopreventive properties. Experimental studies suggest that SIT may serve as a valuable supplement in combating serious diseases. Due to its high therapeutic potential, it is considered a promising candidate for future drug development; however, further clinical research is necessary to confirm its efficacy in treating life-threatening conditions such as diabetes[43].

2.1.7 Polyphenols

Over 8,000 polyphenols have been identified across various plant species, classified as phenolic acids, flavonoids, stilbenes, and lignans. These secondary metabolites serve as a defence mechanism against UV radiation and pathogens. In the past couple of decades, studies have shown that some phytochemicals and polyphenolic compounds can be used as nutraceuticals in anti-diabetic therapy since they provide glycemic control and minimise metabolic complications[6]. Their consumption induces a hypoglycemic effect on the body possibly by increasing the efficacy of carbohydrate absorption in the intestine by blocking Na+-dependent glucose transporters present in the intestine (SGLT1, SGLT2), modulation of α-glucosidase and α-amylase (key enzymes in the digestion of dietary carbohydrates to glucose), anti-inflammatory response, increment in β- cell activity and insulin response, and disrupted secretion of glucose-dependent insulinotropic polypeptide (GIP) and glucagon-like polypeptide-1 (GIP-1)[44]. In the current scenario, clinical studies that signify the true potential of phenolic compounds are far from complete and need to be analysed further in humans before their use as anti-hyperglycemic agents[44].

2.1.9 n-3 long-chain polyunsaturated fatty acids (LCPUFAs)

Several clinical trials have shown that intake of n-3 fatty acids can lower fasting blood glucose, HbA1c levels, and insulin resistance[45]. Reduction was also seen in triglyceride, cholesterol, LDL and HDL levels but no statistically significant changes were observed in BMI, weight, TNF and c-reactive protein (CRP) levels. Therefore, supplementation with *n*-3 fatty acids exhibits some benefits on glucose and lipid profiles, but the dosage should be around 1000–2000 mg/d for a minimum of 8 weeks' duration. The protective role of fatty acids in cardiovascular diseases, glucose and lipid metabolism and inflammation has led to wide-scale use of fish oil products as nutraceuticals[46].

2.1.10 Curcumin

Curcumin reduces oxidative stress by scavenging free radicals and enhancing the activity of antioxidant enzymes, which is crucial for protecting pancreatic beta cells from damage caused by reactive oxygen species (ROS) in diabetes. Chronic inflammation plays a central role in the development of insulin resistance and diabetes-related complications. Curcumin inhibits pro-inflammatory cytokines such as TNF-α and IL-6, thereby improving insulin sensitivity[47]. Curcumin enhances insulin signalling and glucose uptake by activating AMP-activated protein kinase (AMPK) pathways[48]. Clinical trials have shown improved fasting blood glucose (FBG) and HbA1c levels in patients receiving curcumin supplements[49]. Curcumin reduces oxidative and inflammatory damage to peripheral nerves, alleviating diabetic neuropathy symptoms. It mitigates kidney damage by reducing fibrosis and oxidative stress[50]. Curcumin protects retinal cells from damage by reducing vascular endothelial growth factor (VEGF) expression[51]. Curcumin reduces LDL cholesterol, triglycerides and increases HDL cholesterol, mitigating cardiovascular risks associated with diabetes. Curcumin's poor bioavailability limits its therapeutic potential. However, advanced formulations like nanoparticle curcumin, liposomal curcumin, and combinations with piperine have significantly improved absorption and efficacy[52].

Mechanisms of Action in Diabetes:

- Activation of AMPK Pathway: Enhances glucose uptake and fatty acid oxidation.
- Inhibition of NF-κB and MAPK Pathways: Reduces inflammation and cellular stress.

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- Upregulation of PPAR-γ: Improves lipid metabolism and insulin sensitivity.
- Modulation of Adipokines: Balances leptin and adiponectin levels, improving metabolic health.
- Reduction of Advanced Glycation End-products (AGEs): Decreases glycation-mediated tissue damage.
- Curcumin has low bioavailability because of its rapid metabolism and limited absorption in the body. Strategies to enhance its effectiveness include:
- Formulations with Piperine: Black pepper extract increases absorption by up to 2000%[53].
- **Liposomal Curcumin:** Encapsulation in liposomes improves stability and delivery[54].
- **Curcumin Nanoparticles:** Enhance solubility and bioavailability[55].
- **Curcumin-Phospholipid Complexes (Meriva):** Increases bioavailability and cellular uptake[56].

Curcumin is generally safe at therapeutic doses; however, high doses may lead to gastrointestinal discomfort or interact with anticoagulants and antidiabetic medications. Research indicates that curcumin supplementation can reduce fasting blood glucose (FBG) and HbA1c levels, while also improving insulin resistance. Curcumin also demonstrates efficacy in reducing inflammatory markers (e.g., CRP) in diabetic patients. Curcumin is a promising nutraceutical for diabetes management due to its multi-targeted approach to improving insulin sensitivity, reducing oxidative stress, and preventing complications. While its bioavailability remains a challenge, advanced formulations make it a viable complementary therapy in diabetes care[52]. Consult a healthcare professional before beginning curcumin supplementation, particularly if you are taking any medications.

A brief list of commonly used nutraceuticals for the diabetes management is mentioned here (table 2).

Table 2. Examples of Commonly Used Nutraceuticals in Diabetes:

S. No.	Nutraceutical	Source Key	Benefits
	Omega-3 fatty acids	Fish oil, flaxseeds	Lowers inflammation and triglycerides
	Curcumin	Turmeric	Reduces inflammation and blood glucose
	Resveratrol	Grapes, red wine	Improves insulin sensitivity
	Fenugreek	Seeds	Lowers postprandial glucose
	Alpha-lipoic acid (ALA)	Spinach, supplements	Reduces oxidative stress, neuropathy symptoms
	Berberine	Barberry	Enhances insulin secretion
	Gymnema sylvestre	Leaves	Regenerates β-cells
	Chromium Picolinate	Broccoli, supplements	Enhances insulin action
	Cinnamon	Bark	Improves insulin sensitivity

	Probiotics	Yogurt, kefir	Modulates gut microbiota
	Bitter Melon	Fruit, seeds	Mimics insulin activity
	Magnesium	Nuts, greens	Reduces insulin resistance
	Vitamin D	Fortified foods, sunlight	Improves β-cell function
	Polyphenols	Green tea, Tea	Antioxidant, reduces blood glucose
	Cryptides	eggs, milk, meat, oysters, crabs, squids, and fish such as salmon, cod, and tuna	boost glucose metabolism
	Dietary fiber	Psyllium	weight loss and glucose control

Safety and Considerations:

- **Dosage:** Optimal doses need to be adhered to for efficacy without any harmful effects.
- **Interactions:** Some nutraceuticals may interact with antidiabetic drugs, requiring monitoring.
- **Standardisation:** Variability in preparation and bioavailability needs addressing for consistent results.

In summary, Nutraceuticals have emerged as a promising adjunct in the prevention and management of diabetes mellitus, offering a natural and holistic approach to controlling the disease. These bioactive compounds, derived from food sources, provide therapeutic benefits beyond basic nutrition, addressing key mechanisms involved in diabetes pathophysiology, such as insulin resistance, oxidative stress, inflammation, and β-cell dysfunction.

Key findings include:

- **Glycemic Control**: Nutraceuticals like cinnamon, fenugreek, and chromium improve insulin sensitivity and lower blood glucose levels.
- **Antioxidant Properties**: Polyphenols (e.g., resveratrol, curcumin) and vitamins (e.g., vitamin C, E) reduce oxidative stress, a major contributor to diabetes complications.
- **Anti-inflammatory Effects**: Omega-3 fatty acids and flavonoids help modulate inflammatory pathways, improving metabolic health.
- **Lipid Profile Improvement**: Certain nutraceuticals aid in lowering LDL cholesterol and triglycerides, reducing cardiovascular risks in diabetic patients.
- **Prevention of Complications**: Long-term use of specific nutraceuticals may help delay or prevent complications such as neuropathy, nephropathy, and retinopathy.

Despite their potential, nutraceuticals should supplement, not replace, conventional treatments. Their efficacy varies depending on individual factors such as genetic predisposition, disease severity, and lifestyle. Standardisation of dosages, long-term safety studies, and clinical trials are necessary to establish robust guidelines for their integration into diabetes care.

Moreover, nutraceuticals offer a vital, supportive strategy in diabetes management, emphasising the importance of dietary interventions alongside pharmacological and lifestyle modifications. However, they should be incorporated into a holistic treatment plan under professional guidance, considering the needs of individuals and their potential interactions.

3. Ayurveda in Diabetes Management

Ayurveda addresses diabetes as **"Madhumeha"**, a subtype of Prameha, emphasising holistic treatment involving herbal formulations, dietary alterations, and lifestyle modification. Nutraceuticals are food-derived products that provide health benefits beyond basic nutrition, and also offer antidiabetic effects through various bioactive compounds.

Ayurvedic Concept of Madhumeha

In Ayurvedic texts, diabetes is primarily discussed under the term "Madhumeha" (literally "sweet urine disease"). It is categorised as a **Kapha Prameha**, but over time can involve all three doshas: Vata, Pitta, and Kapha. According to *Charaka Samhita* and *Sushruta Samhita*, causative factors include a sedentary lifestyle, excessive intake of sweet and fatty foods, and genetic predisposition[57].

The treatment focuses on:

- Balancing the doshas
- Detoxification through Panchakarma
- Herbal therapy (Aushadhi)
- Diet (Ahara)
- Lifestyle (Vihara)

3.1.1 Common Ayurvedic Herbs for Diabetes

1. **Gudmar (*Gymnema sylvestre*)**
Known as *"sugar destroyer"*, Gymnema reduces intestinal absorption of glucose and stimulates pancreatic beta-cell regeneration[58].

2. **Neem (*Azadirachta indica*)**
Exhibits hypoglycemic effects by enhancing insulin sensitivity and reducing fasting glucose[59].

3. **Karela (*Momordica charantia*)**
Contains polypeptide-p, vicine, and charantin, which mimic insulin activity[60].

4. **Turmeric (*Curcuma longa*)**
Curcumin has anti-inflammatory, antioxidant, and insulin-sensitising effects[61].

5. **Triphala**
A blend of three fruits (Haritaki, Amalaki, and Bibhitaki), Triphala enhances digestion and improves insulin sensitivity[62].

6. **Fenugreek (*Trigonella foenum-graecum*)**

Rich in soluble fiber, it reduces glucose absorption, enhances insulin sensitivity[63]and demonstrated a significant reduction in fasting blood sugar and postprandial glucose in type 2 diabetes patients.

7. **Guduchi (*Tinospora cordifolia*)**

Acts as an immunomodulator and antioxidant, supports pancreatic function. Animal models have shown anti-diabetic potential[64, 65].

8. **Holy Basil/Tulsi (*Ocimum sanctum*)**

Enhances insulin secretion and acts as an adaptogen[66].

9. **Kothala himbatu (*Salacia reticulate*)**

Inhibits alpha-glucosidase and aldose reductase also known to reduce postprandial hyperglycemia[67].

3.1.2. Ayurvedic Formulations

- **Nishamalaki** (Turmeric + Amla): Antioxidant-rich combination supporting insulin action[68].
- **Chandraprabha Vati**: Used for urinary issues and diabetes-related complications[69].

3.1.3. Panchakarma Therapies

- **Vamana** (therapeutic emesis) and **Virechana** (purgation) are used to eliminate aggravated doshas.
- **Basti** (medicated enemas) helps in metabolic regulation.

3.1.4. Synergistic Use of Ayurveda and Nutraceuticals

The integration of Ayurvedic and nutraceutical approaches can be highly beneficial due to their complementary mechanisms.

- **Gymnema + Berberine**: Beta-cell regeneration and AMPK activation[70, 71].
- **Triphala + Probiotics**: Gut microbiome modulation and insulin sensitivity[72,73].
- **Turmeric + ALA**: Anti-inflammatory synergy for diabetic complications[74,75].

Such combinations offer multi-targeted action, reduced side effects, and a sustainable therapeutic approach.

3.1.5. Scientific Evidence and Clinical Studies

- A randomized clinical trial on ***Gymnema sylvestre*** showed significant reductions in fasting blood sugar and HbA1c over 18–20 months[76].
- **Curcumin supplementation** (300 mg/day) for 3 months showed improved insulin sensitivity in prediabetics[77].
- A double-blind experiment with **ALA (600 mg/day)** showed improvements in diabetic neuropathy[78].
- Meta-analysis confirmed **cinnamon** intake (≥1g/day) reduces fasting blood glucose and cholesterol[79].

Safety and Limitations

While generally safe, both Ayurvedic herbs and nutraceuticals can act together with conventional treatments.

- **Prudence** is opined in combining berberine with metformin[80].

- **Herbal quality control** is essential to avoid contamination[81].

Standardization, proper dosing, and practitioner guidance are crucial to safe usage.

Future Direction

- **Integrative medicine models** combine allopathy, Ayurveda, and nutraceuticals.
- **Personalised Ayurveda** using genetic and metabolic profiling.
- More **double-blind, placebo-controlled clinical trials** to validate efficacy.
- **AI-based formulations** tailor herbal-nutraceutical combinations to individual needs.

Conclusion

The growing prevalence of diabetes calls for innovative, holistic, and sustainable management strategies. Both Ayurvedic herbs and formulations, along with commonly known nutraceuticals, offer promising alternatives to conventional diabetic management and therapies. They are particularly beneficial in the initial onset stages of type 2 diabetes. Their ability to target multiple metabolic pathways, improve insulin sensitivity, and prevent complications makes them valuable in integrated diabetes care. However, standardised formulations, rigorous research, and regulatory oversight are needed to maximise their benefits and address potential safety concerns.

Conflict of Interest

The authors declare no Conflict of Interest.

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