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Innovations in Functional Food Development for Diabetes Management: A Narrative Review

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Abstract

This review explores advancements in the food industry for developing functional foods to manage diabetes. It evaluates the mechanisms and clinical evidence for eight bioactive components. Dietary fibers help control blood sugar levels and insulin sensitivity by slowing glucose absorption and promoting the production of short-chain fatty acids. Polyphenols reduce glucose spikes by inhibiting carbohydrate-digesting enzymes and activating signaling pathways like AMPK. Antioxidants protect pancreatic β-cells and insulin secretion by combating oxidative stress and inflammation. Probiotics and prebiotics improve metabolic balance by modulating gut microbiota and strengthening the intestinal barrier. Omega-3 and monounsaturated fatty acids reduce inflammation and enhance insulin receptor signaling. Fermented foods provide bioactive compounds with hypoglycemic effects, while alkaloids, flavonoids, and terpenoids have diverse anti-diabetic properties. Clinical trials have shown promising results in lowering fasting glucose, HbA1c and postprandial spikes, but limitations like small sample sizes and inconsistent formulations call for further validation through robust randomized controlled trials. Conflicting results across studies emphasize the need for cautious interpretation.

Keywords: Diabetes mellitus, Blood glucose, Functional foods

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Introduction

Diabetes mellitus is a major worldwide health issue, with its rising rapidly in different parts of the world. It is defined by high blood sugar levels due to the body's inability to produce or use insulin effectively (1). This condition affects approximately 537 million people worldwide and is a leading cause of morbidity and mortality (2). The rising prevalence of diabetes, particularly in low- and middle-income countries, imposes a considerable economic burden on individuals and healthcare systems. This is due to the chronic nature of the disease and its severe macrovascular and microvascular complications (3).

The challenges associated with diabetes management are multifaceted, encompassing socio-cultural, economic, and healthcare system-related barriers. Individuals diagnosed with diabetes often face difficulties adhering to complex self-management practices, which include dietary modifications, physical activity, medication adherence, and regular monitoring of blood glucose levels (4). Epidemiological evidence links elevated blood levels of pro-inflammatory markers to diets high in processed foods, full-fat dairy, refined grains, and sugar-sweetened beverages. Moreover, inflammation correlates not only with these overall eating patterns but also with the specific balance and intake levels of macronutrients and micronutrients (5). Functional foods are rich in bioactive compounds such as polyphenols, flavonoids, and fibers, which have demonstrated hypoglycemic properties (6,7). These foods influence glucose metabolism through multiple mechanisms, including enhancing gut health, modulating the gut microbiota, and improving gut barrier integrity. These effects can lead to improved insulin sensitivity and reduced inflammation, both of which are essential for effective diabetes management (8, 9).

Recent studies highlight the importance of incorporating innovative food technologies to improve glycemic control in individuals with diabetes. Kaur et al. (2021) emphasize that the development of low glycemic index foods and novel functional ingredients can significantly reduce postprandial blood sugar spikes (10). A systematic review and controlled clinical trial demonstrated that the use of soluble fibers (11,12) and low- or non-nutritive sweeteners (13) effectively lowers postprandial glucose and insulin responses, providing a complementary approach to traditional dietary management. Additionally, a systematic review and meta-analysis of randomized controlled trials showed improvements in markers of fasting and postprandial glycemic control with beta-glucan-rich foods (14). In a controlled trial, starch-restricted, fiber-rich functional bread with an increased beta-glucan-to-starch ratio improved long-term metabolic control in diabetic patients (15). Furthermore, a systematic review and meta-analysis of randomized controlled trials suggested that probiotics and synbiotics may be effective in managing diabetes (16). It appears that innovations in functional food development offer a transformative opportunity to optimize glycemic control and improve metabolic outcomes.

Definition of functional foods

Functional foods are defined as novel or conventional foods that provide health benefits beyond basic nutrition when consumed regularly at effective levels (17). These foods include whole foods, as well as fortified, enriched, or enhanced foods that may offer beneficial effects on health. However, the definition of the term remains complex, and scientific investigation is essential to prove the bioavailability and efficacy of these compounds at physiologically achievable levels within typical dietary patterns (18).

It is important to note that functional foods, dietary supplements, and nutraceuticals are

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distinct categories situated at the intersection of nutrition and pharmaceuticals, each regulated by unique frameworks (19). Functional foods are regular foods that provide specific health benefits beyond basic nutrition when consumed as part of a regular diet (20). Dietary supplements, including vitamins, and botanical extracts, are used to improve or maintain health (21). Nutraceuticals encompass both functional foods and dietary supplements, offering health benefits that include prevention and treatment. (20). Developing a framework that categorizes functional foods based on volume and quality of scholarly research could enhance public education, inform clinical guidance, and establish functional foods as a reliable strategy for promoting health and well-being (22).

Innovations in the food industry for functional foods

The food industry is increasingly focusing on functional foods, which offer health benefits beyond basic nutrition (23). This trend is driven by growing consumer awareness of the link between diet and health, as well as the potential of food industry by-products as valuable ingredients (24). These by-products are nutrient-rich, contain bioactive compounds, and have functional properties, making them ideal for creating innovative food products (25). However, to ensure a product qualifies as functional, companies must adhere to specific guidelines for development, efficacy testing, and safety assessment (26).

Recent advancements in technologies and production methods have significantly accelerated the development of functional foods for managing diabetes. Fermented products, a prominent class of functional foods, have shown antidiabetic effects in both in vitro and in vivo studies (27). Similarly, food-derived bioactive peptides produced through enzymatic hydrolysis (top-down) or assembled via synthetic routes (bottom-up) demonstrate promising glycemic regulatory properties. But their clinical benefits require confirmation through well-powered, large-scale trials (28). Biotechnology has been instrumental in incorporating targeted bioactive compounds and the enhancement of fermentation processes to improve the health-promoting qualities of functional food products (29). Despite these advancements, challenges such as high production costs, limited market access (30), the need for rigorous scientific validation of health claims, and the requirement to offer a variety of products for regular consumption (31) remain unresolved. Key formulation strategies include incorporating of bioactive ingredients, removing undesirable components, adjusting existing constituents to meet market demands, and emproving metabolic outcomes in diabetic patients (32).

Bioactive components and their role in diabetes management

Dietary Fibers

Dietary fiber is essential for managing diabetes, due to its bioactive components that impact metabolism. Soluble fiber, found in foods like oats, beans, and fruits, helps control blood sugar levels by slowing glucose absorption and enhancing insulin sensitivity. Insoluble fiber, present in whole grains and vegetables, promotes digestive health and can aid in weight management, which is crucial for diabetes control (33). Additionally, short-chain fatty acids (SCFAs), produced from fiber fermentation in the gut, can improve insulin secretion and β-cell function, benefiting those with type 2 diabetes (34). Phytochemicals and antioxidants in fiber-rich foods may also reduce inflammation and oxidative stress, supporting overall metabolic health (35). Research has shown that increasing dietary fiber intake can lead to significant reduction in HbA1c levels, fasting plasma glucose, and body weight (36).

Polyphenols

Polyphenols, a diverse group of bioactive compounds found in plant-based foods, have attracted significant attention for their

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potential role in managing of diabetes. These compounds enhance insulin sensitivity and glucose metabolism, both are crucial for effective diabetes management (37,38). Polyphenols decrease glucose absorption in the intestine and inhibit carbohydrate digestion, resulting in lower blood sugar levels (38,39). They also regulate intracellular signaling pathways, such as activating of AMP-activated protein kinase (AMPK), which plays a role in glucose transport and metabolism (39). Polyphenols complement conventional diabetes treatments, potentially reducing the side effects of pharmaceutical interventions (40). Despite, promising mechanisms like reducing oxidative stress, suppressing pro-inflammatory cytokines, and modulating key metabolic regulators like AMPK and peroxisome proliferator-activated receptors (PPARs) (41), findings from epidemiological and intervention studies are inconsistent (42). Variability in bioavailability and individual metabolic responses (41, 43, 44) likely contribute to this heterogeneity. Therefore, well-designed, standardized intervention trials are necessary to clarify conflicting findings and confirm the anti-diabetic effects of dietary polyphenols.

Antioxidants

The importance of antioxidants and bioactive compounds in managing diabetes is increasingly acknowledged for their ability to combat oxidative stress, a key factor in the development of the disease. These compounds can improve insulin secretion, protect β-cells, and reduce diabetes-related complications. Oxidative stress occur when there is an imbalance between reactive oxygen species (ROS) and antioxidants, leading to complications (45). Antioxidants work by scavenging free radicals, thereby reducing oxidative damage and enhancing metabolic function (46). Flavonoids and carotenoids, known for their antioxidant and anti-inflammatory properties, can boost β-cell function and insulin secretion. They may also prevent β-cell apoptosis and promote proliferation, offering protection effects against diabetes (47).

While some studies suggest that antioxidant supplements can benefit diabetes complications , other do not show a clear clinical advantage, resulting in conflicting evidence (48,49). A meta-analysis indicated that antioxidant treatment led to significant improvements in fasting glucose, HbA1c and oxidative stress biomarkers (49). However, other reviews highlight inconsistent findings among trials and question the ability of antioxidants to prevent atherosclerosis or reduce clinical complications in individuals with diabetes (50). The effectiveness of antioxidants likely varies based on the specific compound tested, dosage and formulation, study duration, patient characteristics, baseline antioxidant levels, and concurrent treatments (51). Therefore, well-designed randomized trials with sufficient power standardized interventions and relevant endpoints are needed to determine which antioxidants, at what doses and in which patient populations can effectively reducein diabetes related complications.

Probiotics

Probiotics are being explored as potential aids in managing diabetes management, primarily because they can help regulate gut microbiota and improve metabolic health. Probiotics play a role in restoring the balance of gut microbiota, which is often disrupted in individuals with diabetes, leading to better metabolic outcomes (52,53). Certain probiotics, like Clostridium butyricum, produce butyrate, which helps regulate blood sugar levels and reduces inflammation (54). Probiotics also strengthen the intestinal barrier, reducing the risk of metabolic endotoxemia, which can contribute to insulin resistance (55). Lactobacillus sporogenes has been linked to improved glycemic responses and overall metabolic health. Streptococcus faecalis has been shown to be effective in lowering postprandial glucose levels, particularly in experimental models. Bacillus

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mesentericus is known for its role in gut health and may contribute to better diabetes management through its probiotic effects (54). However, the evidence supporting the efficacy of probiotics varies significantly depending on the specific strains (56,57), doses, and treatment durations (58). Some show benefits for blood sugar control, while others have minimal effect. Meta-analyses indicate moderate variability in outcomes, suggesting that strain-specific effects play a significant role in the results. This variability underscores the importance of considering strain-specific effects and individual factors before drawing broad conclusions (56).

Prebiotic

Prebiotics, non-digestible carbohydrates, support the growth of beneficial gut bacteria, enhancing insulin sensitivity and glucose metabolism. They influence gut microbiota by promoting the growth of beneficial bacteria, such as butyrate producers, linked to improved glucose metabolism (59). Prebiotic consumption leads to the production of SCFAs, which help lower blood sugar levels and reduce inflammation (60). These effects can enhance insulin sensitivity and reduce insulin resistance,which is crucial in managing diabetes. Inulin, fructooligosaccharides, and galactooligosaccharides, are well-studied prebiotics with significant health benefits (61-62). Tailoring prebiotic intake to individual gut microbiota profiles may further optimize diabetes management strategies (59).

Beneficial fatty acids

Fatty acids are essential in the development of type 2 diabetes as they impact insulin receptor signaling and glucose transporter translocation. The specific composition of dietary fatty acids can worsen or improve insulin resistance, highlighting their significance in diabetes management. It is crucial to be aware that saturated and trans fats can increase insulin resistance and inflammation, which are detrimental to diabetes control (63). Saturated fatty acids (SFAs) are known to contribute to insulin resistance, a hallmark of type 2 diabetes mellitus. They can disrupt insulin signaling pathways and impair glucose transporter translocation (64). High consumption of SFAs is associated with higher levels of pro-inflammatory cytokines, exacerbating insulin resistance and β-cell dysfunction (63). Conversely, certain dietary fats, such as omega-3 fatty acids, are linked to a lower risk of type 2 diabetes. Research indicates that regular intake of these fats can reduce inflammation and improve insulin sensitivity, thereby reducing the risk of diabetes (65). Current guidelines recommend reducing SFA intake while increasing monounsaturated and polyunsaturated fatty acids consumption to lower the risk of diabetes and enhance the management of existing conditions (66).

Fermented foods

Fermented foods are known to boost antioxidant activity, which can help reduce oxidative stress linked to diabetes (67). Bioactive peptides created during fermentation have antidiabetic properties that can enhance insulin sensitivity and glycemic control (68,69). Additionally, organic acids, like lactic acid, can lower blood sugar levels and promote gut health, which is important for managing diabetes (70). Beneficial bacteria, such as Lactobacillus and Bifidobacterium species found in fermented foods, can influence the gut microbiota, improve metabolic functions, and potentially assist in weight management (68,71). In a randomized controlled trial, individuals with type 2 diabetes who consumed probiotic fermented milk (kefir) for 8 weeks experienced a notable decrease in fasting blood glucose and HbA1c levels compared to a control group (72). However, the overall health benefits of fermented foods are not yet fully backed by strong clinical evidence, and the effects can vary depending on the specific food, microbial strains, and preparation method (73).

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Functional Plant Compounds

These natural substances, derived from various medicinal plants, have different mechanisms that improve insulin sensitivity, decrease glucose absorption and reduce oxidative stress. Key bioactive compounds such as alkaloids, flavonoids, terpenoids, and polyphenols, have shown significant antidiabetic properties (74). They enhance insulin sensitivity, inhibit carbohydrate-digesting enzymes, and regulate glucose metabolism (74,75). While preclinical studies show promise for alkaloids and flavonoids, further clinical trials are needed to determine optimal dosages and potential interactions with other medications (76). Salleh (2021) points out the challenges of human clinical trials involving medicinal plants, and stresses the importance of standardized methodologies and reliable data collection (77). It is crucial to conduct rigorous clinical trials to confirm the efficacy and safety of these compounds (78). Caution is advised regarding, potential interactions between flavonoid-containing supplements and medications (79). Therefore, the therapeutic potential of these plant-derived compounds should be interpreted cautiously until supported by high-quality clinical trials.

Mechanisms of action in diabetes management

Reduce glucose absorption and improve insulin function

The impact of functional foods on blood glucose levels is significant, especially in reducing glucose absorption and improving insulin activity. Functional foods that are high in polysaccharides and dietary fiber can slow down glucose absorption in the intestines, resulting in lower postprandial blood sugar levels (7). Foods with a low glycemic index (GI), such as whole grains and legumes, are absorbed more gradually, helping to maintain stable blood glucose levels and reduce insulin spikes (80). Bioactive compounds, such as polyphenols and flavonoids, found in functional foods enhance insulin sensitivity, which is crucial for efficient glucose metabolism (7,79). The gut microbiota plays a key role in glucose regulation, and functional foods can positively influence gut health, thereby improving insulin function and reducing inflammation associated with diabetes (8). While functional foods show potential in managing blood glucose levels, their effectiveness may vary depending on individual responses and the specific characteristics of the foods consumed (81).

The role of functional foods in modulating inflammation and oxidative stress

Functional foods are in rich nutrients and bioactive compounds that help regulate inflammation and oxidative stress, contributing to overall health. Epidemiological studies indicate that diets high in fruits, vegetables, and fermented foods, such as the Mediterranean diet, are linked to lower inflammation levels and a decreased risk of chronic diseases (82). Certain bioactive compounds, such as polyphenols and flavonoids, can activate pathways like Nrf2, which controls responses to oxidative stress (83). These functional foods impact important key signaling pathways, including Nrf2 and NF-κB, which are crucial for managing oxidative stress and inflammation (84).

Changes in gut microbiota and cellular signaling pathways

Dysbiosis, an imbalance in the microbiota, is linked to chronic inflammation and plays a role in conditions such as obesity and inflammatory bowel disease. Short-chain fatty acids (SCFAs) produced by the microbiota can help reduce the production of pro-inflammatory cytokines, thus regulating immune responses (85). The gut microbiota also influences important signaling pathways, such as the Toll-like receptor (TLR) pathway, which is crucial for immune system function. Dysbiosis can activate TLR signaling, leading to inflammatory processes associated with metabolic disorders (86). Targeting the gut microbiota with probiotics, prebiotics, and fecal microbiota transplantation presents new

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therapeutic approaches for managing inflammatory diseases and metabolic disorders (87).
Table 1 outlines the main bioactive categories, their mechanisms of action, and the physiological effects relevant to diabetes management.

Conclusion

Research has shown that functional foods can improve glycemic control and insulin sensitivity, which are essential for managing diabetes (81). These foods have antioxidant and anti-inflammatory properties that can help reduce oxidative stress and inflammation linked to diabetes, potentially lowering the risk of complications (38). Modifying the gut microbiota through dietary changes has been found to impact glucose regulation, underscoring the importance of functional foods in supporting gut health and metabolic balance (8). However, the effectiveness of functional foods remains uncertain due to limitations in current research, such as small sample sizes, short study durations, and methodological differences. Individual factors like genetics and existing health conditions can significantly influence the impact of functional foods, making generalizations challenging (81). It's worth noting that much of the evidence supporting of functional foods comes from in vitro, animal, or preliminary human trials (88,89). Therefore, integrating functional foods into diabetes management should be done under professional supervision to ensure appropriate dietary modifications and prevent potential adverse effects. Future studies should prioritize robust trial designs and transparent reporting to strengthen the evidence base.

Table 1. Mechanisms of action of functional foods in diabetes management

Bioactive category	Mechanistic pathways	Physiological effects
Dietary fibers	SCFA production, delayed glucose absorption	improved insulin sensitivity, glycemic control
Polyphenols	enzyme inhibition, AMPK activation	reduced postprandial glucose, anti-inflammatory effects
Antioxidants	ROS scavenging, Nrf2 activation	β-cell protection, reduced oxidative stress
Probiotics	microbiota modulation, butyrate production	reduced inflammation, enhanced metabolic function
Prebiotics	growth of beneficial bacteria, SCFA production	improved insulin sensitivity, reduced insulin resistance
Beneficial fatty acids	anti-inflammatory cytokine reduction, insulin signaling enhancement	lower insulin resistance, systemic inflammation reduction
Fermented foods	bioactive peptide and organic acid production	improved glycemic control, microbiota regulation
Plant compounds	enzyme inhibition, metabolic pathway regulation	reduced glucose absorption, improved insulin function

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Conflict of Interest

The author declares no conflicts of interest.

Authors' contributions

The author was responsible for the conception, literature review, critical analysis, manuscript drafting, and final approval of the version to be published.

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