beverages

Review

The Role of Functional Beverages in Mitigating Cardiovascular Disease Risk Factors: A Focus on Their Antidiabetic and Hypolipidemic Properties

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Abstract: The incidence and mortality rates of cardiovascular diseases (CVDs) are constantly increasing. Among the main risk factors, diabetes mellitus and hyperlipidaemia, which are equally widespread pathological conditions, stand out. Current preventive strategies are based on physical activity and a healthy, balanced diet. Primary therapies, on the other hand, are based on the administration of hypoglycaemic and cholesterol-lowering drugs. Given the increasing consumer demand for food products with healthy properties, functional beverages may represent a breakthrough in this field. Through a careful analysis of studies conducted over the past seven years, it has emerged that herbal teas, fruit and vegetable drinks, as well as milk- and plant-based beverages, can mitigate these two critical CVD risk factors, often linked to the presence of specific polyphenols or fermentation processes. The selection of in vivo, in vitro and clinical trials revealed the ability of such drinks to reduce the enzymatic activity of α-glucosidase and α-amylase, as well as to decrease circulating lipid levels, properties that were surprisingly also exhibited by beverages derived from food waste. Therefore, this review aims to highlight the possibility of employing these drinks as adjuvant therapy in the treatment of diabetes mellitus and hyperlipidaemia in order to reduce two potential CVD risk factors.

Keywords: diabetes mellitus; hyperlipidaemia; functional beverages; cardiovascular diseases

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1. Introduction

Cardiovascular diseases (CVDs) represent a primary contributor to the rising global mortality rates of about 31%, with approximately 17.9 million deaths annually [1]. Given the growing prevalence of CVDs, preventive measures and public health education are essential. Indeed, community-centred prevention programs have been shown to exert beneficial effects on modifiable risk factors associated with cardiovascular disease [2]. Cardiovascular risk signifies the probability of developing a CVD, which is modulated by specific predisposing factors. Numerous studies have examined the principal drivers of CVD risk [3]. Bays et al. [4] underscored the significance of the American Society for Preventive Cardiology's annual summary document, which identifies ten key CVD risk factors: physical inactivity, poor and unhealthy diet, dyslipidaemia, hyperglycaemia, hypertension, obesity, advanced age, ethnicity, gender, tobacco use, renal dysfunction, and hypercholesterolemia.

The presence of diabetes mellitus is associated with a twofold increase in CVD risk [5]. Diabetes mellitus is an endocrine disorder characterized by elevated blood glucose levels and the excretion of glucose in urine, typically due to insufficient insulin production. Over time, this condition can lead to both macrovascular and microvascular complications, including retinopathy, neuropathy, and renal impairment [6]. The global prevalence of diabetes mellitus continues to rise; according to the World Health Organization (WHO), it accounted for 1.5 million deaths in 2019, ranking as the ninth leading cause of death worldwide and projected to ascend to the seventh leading cause by 2030.

Another significant CVD risk factor is hyperlipidaemia, which is a condition characterized by elevated cholesterol and/or triglycerides blood levels. Hyperlipidaemia can be defined as the trigger for the formation of atherosclerotic plaques, the hallmark of atherosclerosis. This pathology is characterized by degeneration of the arterial walls, which is responsible for cerebrovascular disease and/or coronary artery disease [7]. With a prevalence of 1 out of 311 individuals, familial hypercholesterolemia is among the most common hereditary genetic disorders globally. It occurs more frequently in atherosclerotic cardiovascular disease sufferers [8].

Beyond education, prevention is critical to reduce the incidence of the above-mentioned metabolic conditions. Currently, prevention strategies emphasize lifestyle modification. Healthy eating and regular physical activity are correlated with a reduced risk of CVD onset [4]. Within this context, functional beverages and the rising consumer demand for nutraceutical food products represent new trends. Such foods offer health benefits beyond basic nutrition, contributing to reduce disease risk. Functional foods and beverages are enriched with bioactive compounds (probiotics, minerals, polyphenols and phytonutrients) that support human health. In particular, the functional beverage market is growing, with a compound annual growth rate (CAGR) of 7.5% [9]. This expansion is also driving scientific interest in new beverage formulations that may enhance the quality of life. In the context of metabolic disorders, high-value products with antidiabetic and hypolipidemic properties could make a significant difference through the possibility of reducing the dose and, as a result, the side effects of synthetic drugs (nausea, weight loss, abdominal discomfort, etc.) [10,11].

This review aims to evaluate recent studies conducted over the past seven years, investigating functional beverages with antidiabetic and lipid-lowering effects. These properties have been explored through in vivo and in vitro models, supporting the therapeutic potential of these beverages that act on two important CVD risk factors. The aim is to bring to light recent (2017–2024) and detailed data supporting the use of such beverages, selecting not only those with proven anti-diabetic properties [12] but also those with established hypolipidemic properties. In particular, the review focuses not only on the aforementioned properties of fruit- and vegetable-based beverages [13], but also on various recent scientific advances in beverages based on milk, tea, and various plant sources, highlighting the possibility of using food waste to improve these sources.

2. Diabetes Mellitus

2.1. Classification of Diabetes Mellitus

Diabetes mellitus is a metabolic disorder marked by abnormally elevated levels of glucose in the bloodstream. This condition is primarily defined by either a reduction or complete absence of insulin production. The contemporary classification of diabetes is based on aetiology and includes the following categories (Figure 1): Type 1 diabetes mellitus, type 2 diabetes mellitus, gestational diabetes mellitus, and diabetes resulting from specific pathophysiological conditions (such as idiopathic forms, genetic defects of beta-cells, certain endocrinopathies and diabetes induced by specific pharmacological agents) [14].

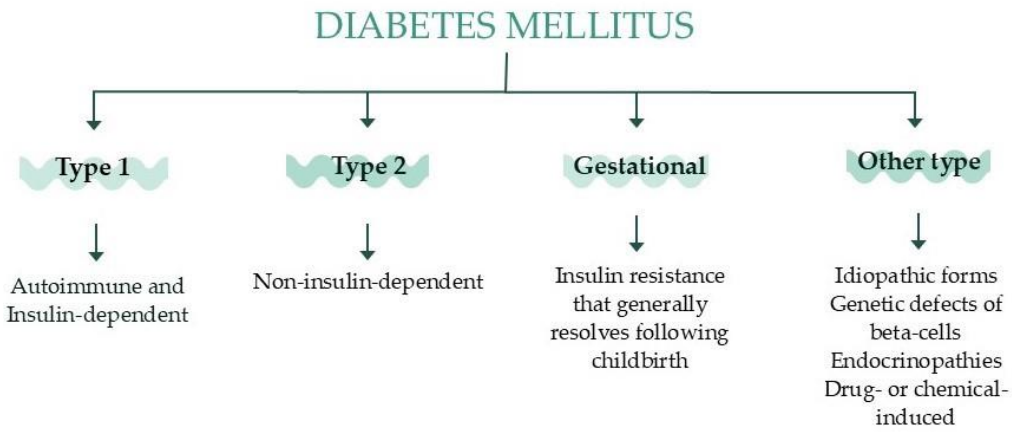

Figure 1. Classification of Diabetes Mellitus and main characteristics.

2.1.1. Type 1 Diabetes Mellitus

Type 1 diabetes mellitus, also referred to as insulin-dependent diabetes, typically manifests in childhood or adolescence. It is characterized by an autoimmune response in which autoantibodies target the ß-islet cells of the pancreas (including glutamic acid decarboxylase autoantibodies, islet cell autoantibodies, zinc transporter 8 autoantibodies, tyrosine phosphatase autoantibodies, and insulin autoantibodies) responsible for insulin production [14]. The rate of cellular destruction varies among affected individuals, potentially resulting in up to a 90% permanent loss of ß-cell functionality [15]. Type 1 diabetes represents a less prevalent form of the disorder, accounting for approximately 5–10% of cases, and is often associated with other autoimmune disorders (myasthenia gravis, Hashimoto's thyroiditis, etc.).

2.1.2. Type 2 Diabetes Mellitus

Type 2 diabetes mellitus, known as non-insulin-dependent diabetes, predominantly affects adults and comprises 90–95% of diabetes cases. Although the exact aetiology remains unclear, several risk factors are implicated, including obesity, dyslipidaemia, a history of gestational diabetes in women and genetic predisposition. Type 2 diabetes is characterized by a gradual decline in insulin sensitivity, eventually leading to reduced ß-cell functionality, a process referred to as insulin resistance. Insulin resistance impairs the body's capacity to maintain normal glycaemic levels over time [16].

2.1.3. Gestational Diabetes Mellitus

Gestational diabetes mellitus typically arises during the first trimester of pregnancy and is characterized by insulin resistance that generally resolves following childbirth. In rare cases, it may progress to type 2 diabetes mellitus later in the pregnancy or postpartum period [17].

2.2. Diagnosis, Symptoms and Treatment of Diabetes Mellitus

Several criteria are applied for the diagnosis of diabetes mellitus. A first diagnostic criterion is the measurement of fasting plasma glucose (FPG), with levels at or above 126 mg/dL considered indicative of diabetes. A further diagnostic criterion is the evaluation of a chronic blood glucose marker A1C, which reflects average blood glucose levels over a 2–3-month period. It must be at least 6.8% in order to make a correct diagnosis. When indicated, an oral glucose tolerance test (OGTT) may be conducted. For a diagnosis to be established, glucose levels must reach or exceed 200 mg/dL for at least two hours during the test [16].

Diabetes mellitus presents with symptoms that include increased urine output (polyuria), heightened thirst (polydipsia), excessive food intake (polyphagia) and weight loss [18]. Generally, an adult presenting with hyperglycaemic symptoms and a random plasma glucose level of at least 200 mg/dL can be classified as having diabetes.

Treatment for diabetes mellitus typically involves dietary management and regular physical activity. For type 1 diabetes, subcutaneous administration of insulin (produced via biotechnological methods) is essential. However, management of type 2 diabetes may involve oral hypoglycaemic agents (such as sulfonylureas), antihyperglycaemic agents (such as biguanides) and subcutaneous insulin administration when necessary [19].

3. Hyperlipidaemia

Hyperlipidaemia is a major risk factor in the development of atherosclerosis and cardiovascular diseases [20]. It is characterized by elevated blood levels of total cholesterol (TC), triglycerides (TG), low-density lipoprotein cholesterol (LDL-C) and reduced blood levels of high-density lipoprotein cholesterol (HDL-C). Kim et al. [21] reported that even modest elevations in blood lipid levels can significantly increase the risk of CVDs. A higher risk was identified in patients with TC level of $\geq$200 mg/dL, TG level of $\geq$60 mg/dL and LDL-cholesterol level of $\geq$130 mg/dL.

As lipids are deposited, they lead to the formation of plaques in the bloodstream, which accumulate over time and can lead to the obstruction of important arterial pathways. Obstruction in the cerebral arteries can result in cerebral stroke, while in the coronary arteries, it can lead to myocardial infarction. Therefore, prevention strategies combined with early diagnosis are essential.

3.1. Classification and Aetiology of Hyperlipidaemia

Hyperlipidaemia can be classified into three main types [22]:

1. Hypercholesterolaemia: elevated blood cholesterol levels;
2. Hypertriglyceridaemia: elevated blood triglyceride levels;
3. Mixed Hyperlipidaemia: elevated levels of both cholesterol and triglycerides.

The aetiology of hyperlipidaemia is generally divided into primary and secondary causes. Primary, or familial, hyperlipidaemia includes conditions such as familial defective Apo-B100, lipoprotein lipase deficiency, familial hypercholesterolaemia (FH), familial hypertriglyceridemia, familial combined hyperlipidaemia, remnant hyperlipoproteinemia and polygenic hypercholesterolaemia.

Secondary causes, on the other hand, may arise from external or acquired factors, including medication use (e.g., glucocorticoids, thiazide diuretics), alcohol abuse, obesity associated with poor dietary habits, diabetes mellitus, hypothyroidism and nephrotic syndrome [23].

3.2. Diagnosis, Symptoms and Treatment of Hyperlipidaemia

Hyperlipidaemia is diagnosed through blood sample analysis to quantify LDL-C, HDL-C, TC and TG levels [23]. The condition is often asymptomatic and lacks distinct clinical manifestations. However, in severe cases of dyslipidaemia, signs may include localized lipid deposits (xanthomas) [24], corneal arcus (lipid deposits around the iris) [25] and xanthelasma (yellowish plaques on the medial eyelids) [26].

Treatment primarily focuses on lifestyle modifications, including dietary adjustments and increased physical activity. In more severe cases, pharmacological interventions may be required, involving the use of statins (HMG-CoA reductase inhibitors), bile acid sequestrants, ezetimibe, fibrates or niacin. Additionally, supplements and nutraceuticals, such as monacolin K or fish oils, are frequently recommended [27].

This comprehensive approach underscores the importance of integrating prevention, early detection and targeted therapeutic strategies to alleviate the burden of hyperlipidaemia and its associated complications.

4. Beverages with Antidiabetic and Hypolipidemic Properties

The market for functional foods is experiencing rapid growth. According to the European Food Information Council (EUFIC), a food product qualifies as functional if it demonstrates positive effects on one or more physiological functions, beyond its basic nutritional value, in a manner that promotes health and well-being and/or reduces the risk of disease [28]. Currently, consumers are attentive to nutritional content and associated health benefits. Therefore, the safety of such products is another critical aspect to be considered. Different production, product and presentation requirements are outlined in both general and specific regulations in each country, in line with international Codex standards. In particular, all functional foods and beverages prevalent in EU markets are produced according to the principles of the Hazard Analysis and Critical Control Point (HACCP) system in order to meet the required safety standards [29].

Functional beverages are attractive mainly because they are easy to consume, transport and store [30]. However, various production process parameters and storage conditions can reduce product quality and efficiency. Therefore, in order to improve the stability of the bioactive molecules contained in these beverages, various studies are being conducted on encapsulation, emulsion and high-pressure homogenization techniques [9]. The goal remains to achieve high levels of product quality, safety and stability, especially in light of new trends such as functional beverages.

Significant research is currently focused on developing beverages with high nutritional and therapeutic benefits, and the exploration of the antidiabetic and hypolipidemic properties of such beverages is a promising area. These drinks could be a valid adjuvant to primary therapies for diabetes mellitus and hypercholesterolemia. As modern medicine emphasizes prevention, these beverages could be useful in reducing important cardiovascular risk factors, following the demonstration of their valid efficacy and safety.

The current classification of functional drink categories includes energy and weight management drinks and those with digestive, cardiovascular, cognitive or immune system benefits [9]. These drinks are typically based on tea, milk (cow's or plant-based), fruits, vegetables or other botanicals, often incorporating natural products with documented healthy properties.

4.1. Herbal Teas

Several studies focusing on the development of herbal teas with hypoglycemic and hypolipidemic properties were reviewed (Table 1). These properties have been assessed through in vitro and in vivo experiments, as well as clinical trials. Typically prepared by infusing or decocting leaves, rhizomes, tubers, or flowers in mineral water, these teas have shown promise as functional beverages with significant health benefits.

Dechakhamphu et al. [31] explored the development of Kombucha made from *Cyperus rotundus L.* (purple nutsedge), a plant commonly used in traditional Chinese medicine. This fermented and sweetened tea displayed notable α-glucosidase inhibitory activity (IC_{50} = 142.7 ± 5.2 μL/mL), a finding corroborated through an in vivo *Drosophila* model, which suggested its potential to regulate blood glucose levels by inhibiting sugar absorption. Similarly, studies on mint- and nettle-based Kombucha with varying sucrose levels found that a lower sucrose content enhanced their antidiabetic efficacy in vitro [32].

Table 1. A summary of studies on the antidiabetic and hypolipidemic properties of herbal teas.

Study Type	Herbal Tea	Model/Participants	Dosage and Duration of the Treatment	Bioactive Compounds in Matrices	Reference
In vitro & In vivo	*C. rotundus* kombucha	In vitro: anti-alpha glucosidase activity In vivo: *D. melanogaster* Oregon-R-C strain	In vivo: kombucha was diluted to concentrations of 400 and 100 µL/mL with water	Epicatechin, chlorogenic acid, stigmasterol and 3-deoxy-D-mannoic lactone	[31]
In vitro	Mint- and nettle-based kombucha	α-amylase and α-glucosidase inhibition assay	Not applicable	Fermentation increased the content of polyphenols, such as gallic acid, caffeic acid, luteolin-diglycoside and quercetin derivatives	[32]
In vitro	*Berberis microphylla* leaves	Lipase, α-amylase, α-glucosidase inhibition assay	Not applicable	3-caffeoylquinic acid and quercetin derivatives	[33]
In vitro	Rosehip (*Rosa canina L.*)-based tisanes enriched with hibiscus and saffron	α-amylase inhibition assay	Not applicable	Polyphenols	[34]
In vivo	White tea combined with *Gynostemma pentaphyllum* (Jiaogulan)	Male C57BL/6 mice	Free access to 2% (*w*/*v*) fresh infusions for 6 weeks	Polyphenols	[35]
In vivo	Mulberry leaf Fu brick tea	Male C57BL/6 mice	520 mg/kg of aqueous extracts daily for 4 weeks	1-deoxynojirimycin: reduces the absorption of carbohydrates in the small intestine Caffeine and GABA: protective and regenerative effects of islet beta cells Kaempferol: stimulates glycogen synthesis	[36]
Clinical trial	*Pluchea indica Less* tea	21 diabetic patients	2 g of tea with 100 cc of hot water (without sugar), twice a day for two months	Flavonoids	[37]
In vitro & In vivo	Green tea (*Camellia sinensis*) and okra seeds	In vitro: inhibition of cholesterol through a photometrical assay based on the Lieberman-Burchard reaction In vivo: rats	In vivo: 2 mL/200 g/day for 21 weeks	Flavonoids	[38]
In vivo	*Monascus purpureus*-fermented pu-erh tea water extract	SPF inbred Sprague Dawley rats	125 mg/kg.bw, 250 mg/kg.bw and 500 mg/kg.bw for 4 weeks	Caffeine, catechin, epicatechin, flavonoids, tea polyphenols and thearubigin	[39]
In vivo	*E. cristatum* (MF800948)-fermented loose tea	Zebrafish (AB strain)	They were exposed to different concentrations of aqueous extract: 100, 300, 500 and 700 µg/mL for 48 h	Fermentation increased the content of alkaloids and theabrownin	[40]
In vivo	Jinhua Xigyuan	Male SD rats	0.4 g/kg·bw, 0.8 g/kg·bw and 1.6 g/kg·bw for 10 weeks	Epigallocatechin	[41]

The *Berberis microphylla G. Forst* shrub, native to southern Chile and Argentina, was used to prepare an infusion that inhibited lipase (65%), α-glucosidase (52%), and α-amylase (76%) activity in vitro [33]. Further, Vasić et al. demonstrated that rosehip (*Rosa canina L.*)-based tisanes enriched with hibiscus and saffron effectively inhibited α-amylase by preventing the enzymatic release of 2-chloro-4-nitrophenol, a chromogenic by-product of

substrate degradation [34]. Additionally, white tea combined with *Gynostemma pentaphyllum* (Jiaogulan) significantly lowered blood glucose levels and improved glucose intolerance in diabetic mice by suppressing hepatic glucose-6-phosphatase expression, thereby reducing gluconeogenesis and hepatic lipid accumulation [35].

Mulberry leaves, widely consumed in South Korea and Japan for the content of potent antihyperglycemic compounds, have also shown to be promising. Indeed, Shao et al. developed a mulberry leaf Fu brick tea that restored normal glycemic levels and pancreatic cell function in hyperglycemic mouse models [36]. Similarly, a clinical trial involving 21 diabetic patients demonstrated that *Pluchea indica* Less tea reduced random blood glucose levels and alleviated physical fatigue [37].

Emerging evidence has also emphasized the hypolipidemic potential of teas. Cornelia et al. [38] formulated a beverage from green tea (*Camellia sinensis*) and okra seeds, both rich in polyphenols. Among the tested varieties, Jawa tea—a type of green tea—yielded the highest extraction efficiency (7.22 ± 0.16%) and demonstrated significant cholesterol-lowering activity in vitro, through the Lieberman-Burchard reaction. In vivo studies further revealed reductions in low-density lipoprotein (LDL), triglyceride and total cholesterol levels, alongside increased high-density lipoprotein (HDL) levels.

The effects of fermentation on tea's hypolipidemic properties have also been investigated. For instance, hyperlipidaemic rats treated with Monascus purpureus-fermented pu-erh tea extract (MPT) or sun-dried green tea extract (SGT) showed significant reductions in total cholesterol, LDL and triglycerides, with the MPT group also demonstrating anti-atherosclerotic effects [39]. Xiao et al. [40] reported an enhanced lipid-lowering activity in *E. cristatum* (MF800948)-fermented loose tea, in a high-fat zebrafish model. The same results were obtained through an in vivo test (high-sucrose, high-fat diet induced in rats), conducted to evaluate the properties of 'Jinhua Xiangyuan' tea infusion, a specific Chinese tea variety [41].

Collectively, these findings highlight the dual potential of herbal teas as both antidiabetic and hypolipidemic agents. Fermentation processes appear to amplify these beneficial effects, which are largely attributed to the high concentrations of polyphenolic compounds, including flavonoids and phenolic acids, present in the tea matrices (Table 1). These advancements position functional teas as promising candidates for addressing metabolic disorders.

4.2. Fruit and Vegetable Drinks

A variety of functional fruit- and vegetable-based beverages have been formulated and assessed through in vitro and in vivo studies. These beverages have demonstrated notable anti-diabetic and hypolipidemic properties, primarily attributed to the bioactive compounds present in their juices and extracts, particularly polyphenols, carotenoids and vitamins.

Widyawati et al. [42] prepared an extract of *Pluchea indica* less leaves in 100 mL of hot water and enriched it with varying concentrations of lemon juice (0%, 1%, 2%, 3%, 4%, and 5% v/v). This addition significantly enhanced α-amylase inhibition, increasing activity from 55.30 ± 2.90% to 84.85 ± 2.47%, and α-glucosidase inhibition from 67.86 ± 4.12% to 89.29 ± 7.14%, compared to the control (extract without lemon juice). Similarly, fermented bitter gourd (*Momordica charantia*), widely consumed in Asia and India, was analysed in comparison to grape juice and two fermented blends of bitter gourd and grape juices [43]. Using the 3,5-dinitrosalicylic acid (DNSA) method to measure sugar-reducing activity, the study demonstrated that fermentation significantly improved anti-diabetic efficacy. The fermentation process has also been utilized in the preparation of beverages made from lentils, brown rice and sorghum [44]. The variants exhibited

substantial α-amylase inhibition (74.67%, 59.25% and 51.23%, respectively), outperforming their non-fermented counterparts and further emphasizing the role of fermentation in enhancing anti-diabetic effects.

In a separate 2024 study, Gedik et al. [45] developed a sugar-free drink from gilaburu fruit (*Viburnum opulus* L.), which demonstrated a 77 ± 1.37% inhibition of α-glucosidase activity. This effect was attributed to polyphenolic compounds, including quercetin and caffeic acid. Such compounds, also found in berries, have been linked to improved diabetes management by reducing apoptosis, promoting pancreatic β-cell proliferation, stimulating insulin production and enhancing cellular sensitivity to insulin [46]. For instance, cranberry juice has shown potential in modulating postprandial glycemia [47].

Lastly, Fan et al. [48] created a probiotic fermented sea buckthorn juice (*Hippophae rhamnoides* Linn.), a fruit cultivated in Russia, Mongolia, and China. The beverage exhibited remarkable hypolipidemic properties, inhibiting cholesterol esterase (84.68%) and pancreatic lipase (86.18%), key enzymes in lipid metabolism.

Other fruit- and vegetable-based beverages were subjected to in vivo testing. A detailed summary of the studies conducted is provided in Table 2.

Table 2. A summary of in vivo studies, conducted on fruit and vegetable drinks, to evaluate their antidiabetic and hypolipidemic properties.

Fruit or Vegetable Drink	Animal Model	Dosage and Duration of the Treatment	Findings	Bioactive Compounds in Matrices	Reference
Pigeon pea beverage	Male Sprague Dawley rats	Beverage dissolved in distilled water at doses of 2.7 g/kg body weight for two weeks	Reduction in plasma cholesterol level; Reduction in plasma glucose level.	Antioxidant and dietary fiber compounds	[49]
Beverage with cranberry, apple and blueberry juices, water extract of ginger, Se, Zn, K, vitamin B6, arginine and taurine.	Male rats	0.5X, X and 2X (X = 700 mL) per day, for 40 days.	At 1X and 2X doses, there was a reduction in TC, non-HDL-C and triacylglycerol levels.	Quercetin-3-*O*-galactoside, quercetin-3-*O*-rutinoside, chlorogenic acid, 6-gingerol (known for anti-atherogenic effects) and 6-shogaol	[50]
1. *Aronia melanocarpa* and pectin beverage 2. *Aronia melanocarpa* with herbs beverage	Male Wistar rats	10 mL/kg for three months	The HDL-C value increased, while the TC/HDL index decreased. The LDL/HDL index increased.	Anthocyanins, proanthocyanidins, β-sitosterol, campesterol, quercetin, kaempferol, catechin	[51]
Fermented lemon juice	Male Syrian hamsters	Low-dose (3.1 mL/kg/day), medium-dose (6.2 mL/kg/day), and high-dose (9.3 mL/kg/day) groups. Every day for 6 weeks.	TC, TG and LDL-C values were significantly lower. The LDL/HDL index increased.	Bioflavonoid, specially naringenin	[52]
African walnut enriched-kunu beverage	Wistar male albino rats	2 mL three times a day for 14 days.	Decreased fasting blood glucose level.	Lignin, dietary fiber, L-arginine, folic acid	[53]

Various beverages were also evaluated in clinical trials to highlight their therapeutic potential. Cerrillo et al. [54] examined the effects of a low-alcohol orange beverage on the lipid profiles of 18 participants (8 men and 10 women) with moderately elevated total cholesterol and LDL-C levels. Participants had to consume 500 mL of the functional beverage daily for two weeks. A significant reduction in plasma total cholesterol and LDL-C levels has been found, compared to controls, indicating beneficial effects for hypercholesterolemic individuals.

Additionally, a double-blind randomized, two-arm parallel-group, placebo-controlled trial estimated the benefits of a jelly drink containing roselle calyces extract and passion

fruit juice [55]. The test involved 40 dyslipidemic participants that consumed 300 mL of the drink daily for eight weeks. Significant reductions in LDL-C (16%) and TG levels (17%) were observed. The activity was attributed to the presence of bioactive compounds such as gallic acid, ascorbic acid and quercetin.

Lastly, Razzaq et al. [56] investigated the antihypertensive effects of carrot and beetroot juices with different concentrations (20–40% for carrot; 60–80% for beetroot). Over 60 days, 24 hypertensive individuals, consuming 250 mL of these beverages every other day, showed significant reductions in systolic and diastolic blood pressure, pulse rate and plasma levels of total and LDL-C cholesterol, alongside increased HDL-C levels.

In all these studies, the total content of polyphenols and flavonoids in natural extracts as determined by spectrophotometric assays, is highlighted. In particular, the biological activity studied is associated with these natural molecules, as polyphenols have been shown to possess not only chelating capacity but also structural modification potential [32]. Furthermore, flavonoids are known for their protective effects against diabetic neuronal cell death and dysfunction [37] and for having mechanisms of action similar to those of statins (hydroxymethylglutaryl coenzyme A reductase inhibitors) [38]. Table 3 summarizes the main compounds identified in higher concentrations in some extracts used for the preparation of functional beverages, together with their known properties.

Table 3. The main compounds identified in higher concentrations in the extracts, together with their properties as reported in the conducted studies, are presented.

Identified Bioactive Compounds	Reported Biological Activities	Reference
Vicine, charantin and polypeptide-p	Vicine is an alkaloid glycoside with hypoglycaemic activity, like charantin Polypeptide-p is a hypoglycaemic peptide, often called plant insulin	[43]
Caffeic acid, quercetin	The interaction between oligosaccharide content and coating material chitosan increase the inhibition of α-glucosidase activity, while quercetin and caffeic acid may support this activity.	[45]
Rutin and epicatechin	They reduce blood lipid levels	[48]
Hesperidin, narirutin, vicenin-2 and auroxantin	Probably there is a synergistic effect of alcohol and the polyphenols and carotenoids present	[54]
Anthocyanins and β-carotene	β-carotene is able to reduce circulating cholesterol at high plasma concentrations	[56]

4.3. Milk-Based Beverages

Several milk-based beverages were developed and evaluated to assess their biological properties [57–60]. Specifically, a variety of milk types, both of animal and plant origin, was utilized. In fact, in recent years, consumers have increasingly opted for alternatives to cow's milk, either due to health concerns (e.g., lactose intolerance) or to align with specific dietary preferences (e.g., vegetarian and vegan diets). For instance, quinoa yogurt beverages have been produced by fermenting milk derived from germinated quinoa seeds [61,62]. These beverages demonstrated inhibitory activity against α-amylase and α -glucosidase, exhibiting IC_{50} values that were comparable to or lower than those of the positive control (acarbose). They have been found to be a source of fibre and protein as well as rich in saponins, such as oleanolic acid, which possess antioxidant and α-glucosidase inhibitory activity. Similar in vitro studies have been conducted on probiotic fermented whey-based beverages, highlighting excellent anti-diabetic properties [63].

Another popular plant-based milk alternative is soy milk. Jiang et al. [64] developed fermented soy milk using a novel strain of *Lactiplantibacillus plantarum* (X7021) and tested its effects on forty ICR mice. The fermentation process enhanced the beverage's inhibitory activity against hydroxymethylglutaryl-coenzyme A reductase (HMG-CoA reductase) and significantly reduced serum lipid levels. Comparable results were reported by Rendón-

Rosales et al. [65] in cow's milk fermented with specific strains of *Lactococcus lactis*, which effectively lowered total and non-HDL cholesterol levels. In these reported studies, biological activities are associated with the presence of bioactive peptides generated during the fermentation process.

Clinical trials have also shown that soymilk beverages exhibit significant hypolipidemic effects in hypercholesterolemic patients [66,67]. It is reported that this activity may be attributed to the presence of phytosterols in the beverages, that compete with cholesterol for intestinal absorption and also promote its excretion. Therefore, these beverages represent a promising and health-conscious alternative with the potential to appeal to a broad range of consumers.

4.4. Plant-Based and Food-Waste-Derived Functional Beverages

The growth of functional beverages, derived from natural matrices, plant-based ingredients and food industry by-products, has attracted significant attention in recent research. An example is the valorization of cocoa bean shells, a major by-product of the cocoa industry. Rojo-Poveda et al. [68] explored this resource by preparing 30 beverages using six different coffee-making methods. Among these, the beverage brewed with a Mocha coffee maker demonstrated a remarkable 52.0% reduction in α-glucosidase activity.

Similarly, Ayobamidele Badejo et al. [69] developed a functional drink by combining *Cyperus esculentus var. sativus* (Tiger nut), *Vernonia amygdalina Del.* (Asteraceae) and *Momordica charantia* (bitter melon) in varying concentrations. Beyond the inhibition of α-glucosidase, this formulation was also evaluated for its α-amylase inhibitory activity. The optimal composition, comprising 94% Tiger nut and 3% each of *Vernonia* and *Momordica*, exhibited the strongest inhibitory effects. Both studies [68,69] emphasize the high content of polyphenols, which, through the formation of lactones or quinones with the enzyme's nucleophilic groups, are able to modulate its activity. In particular, a high concentration of catechin, epicatechin and catechin-3-*O*-glucoside, which belong to the flavan-3-ol class, has been identified in coffee beverages. These compounds have been suggested to enhance both insulin secretion and sensitivity.

The idea of reusing broccoli by-products has also shown promise. Broccoli leaves, often discarded, were used to produce a fermented beverage rich in polyphenols [70]. Utilizing the probiotic strain *Lactiplantibacillus plantarum* and high-temperature short-time pasteurization, researchers achieved excellent enzyme inhibition rates for both α-amylase and α-glucosidase, ranging from 34 to 52%, linked to the higher content of 3-*O*-Caffeoylquinic acid and kaempferol di-glucoside. Another study focused on cashew apples, an agricultural by-product of the cashew nut industry. Kham et al. [71] repurposed these fruits to produce a low-alcohol, health-promoting beverage through fermentation with the yeast strain *C. rhodanensis DK*, isolated from fermented tea. Interestingly, the unfermented version of this beverage exhibited superior α-glucosidase inhibitory activity, probably explained by the reduced content of inhibitory compounds such as fructose (which exerts intrinsic inhibitory activity on the enzyme), compared to the fermented version.

A unique approach was taken by Demircan et al. [72], who formulated a beverage incorporating sweet basil extract, chlorophyll and hydrophilic vitamins. This drink achieved an IC_{50} value of 1.6 mg/mL for α-glucosidase inhibition, significantly outperforming metformin, a standard pharmaceutical control. The observed bioactivity was attributed to polyphenols, including rosmarinic and gallic acids and kaempferol, as well as essential oils, such as limonene and 1,8-cineole identified in sweet basil extract, also confirming results and hypotheses reported in other studies [73].

In vivo studies have further corroborated the potential of functional beverages in managing metabolic disorders. Swami et al. [74] produced a fermented alcoholic beverage

from *Syzygium cumini* stems, which significantly reduced fasting blood glucose levels in rats from 326 ± 21.8 mg/dL to 171 ± 8.6 mg/dL, again attributable to the presence of natural phenolic compounds (quercetin, gallic acid and myricetin). Additionally, the beverage was found to restore damaged islets of Langerhans and improve lipid profiles by lowering total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C) and atherogenic indices.

Finally, additional research into anti-diabetic functional beverages led to the development of a formulation based on okra, stevia and ginger extracts in a ratio of 75:22:3 [75]. Administered to Swiss male mice at a dose of 0.52 mL/day over 12 days, this beverage significantly reduced blood glucose levels (It is hypothesized that the rhamnogalacturonan polysaccharide present contributes to the observed activity), though no effect was observed on total serum cholesterol.

Together, these studies underscore the potential of plant-based and by-product-derived beverages as functional foods with promising applications in metabolic health management.

5. Conclusions

Functional beverages have resulted as an ideal response to contemporary consumer demands, which prioritize products that offer health benefits. These innovative beverages align with the public interest in addressing chronic health challenges, such as CVDs, through dietary interventions. Given the multifactorial nature of CVD pathogenesis, the development of beverages with anti-diabetic and hypolipidemic properties is really promising. These nutraceuticals may serve as adjuvant therapies when integrated alongside established pharmacological treatments. Recent advancements in fortifying drinks with bioactive compounds—achieved through the incorporation of plant extracts, fruit juices or the application of fermentation processes—have demonstrated efficacy in enhancing their health-promoting properties. These methods enable the enrichment of beverages with bioactive molecules, such as polyphenols, flavonoids and probiotics, which are known to exert beneficial effects on cardiovascular health. In vitro studies have demonstrated the inhibitory effects of functional beverages on enzymes such as α-glucosidase and α-amylase, as well as significant cholesterol- and glucose-lowering activities. At the same time, in vivo studies and clinical trials have confirmed excellent anti-diabetic and hypolipidaemic effects, such as lowering blood glucose levels and improving glucose tolerance; restoration of normal glycaemic levels and pancreatic cell function; reduction in LDL, triglyceride and total cholesterol levels, while increasing HDL levels; anti-atherosclerotic effects; inhibition of cholesterol esterase and pancreatic lipase; and significant inhibitory activity against hydroxymethylglutaryl-coenzyme A reductase.

However, while these initial findings are promising, further research is critical to facilitate the successful introduction of such products to the market. Indeed, it is essential to consider palatability and the sensory aspect that play a crucial role in influencing patients' compliance as future consumers. On the other hand, future directions should be based on large-scale development strategies according to regulatory and legislative aspects and including studies about: safety of such food products or influence of smoking, alcohol, stimulants, medication on the activity of the functional drink.

In conclusion, functional beverages represent a promising frontier in preventive health and therapeutic support, particularly in the context of CVDs. This may represent a novel nutritional strategy to increase patients' adherence to therapeutic treatment, considering their pathophysiological conditions that should not be underestimated.

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