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# Cinnamon as a Natural Adjunct in Glycemic Control: A Review of Current Evidence and Underlying Mechanisms

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Type 2 diabetes mellitus (T2DM) represents one of the most significant public health issues of the twenty-first century. It is characterised by chronic hyperglycaemia resulting from insulin resistance, impaired insulin secretion, and progressive beta-cell dysfunction. Its prevalence continues to rise globally, driven by sedentary lifestyles, unbalanced diets, and an ageing population, imposing significant socioeconomic and healthcare burdens. Conventional treatment strategies based on pharmacological therapy, dietary modifications, and increased physical activity frequently fail to achieve sustained glycaemic targets, prompting growing interest in complementary and natural interventions. Among various plant-derived substances, cinnamon (*Cinnamomum verum* J. Presl) has emerged as a promising adjunctive agent in glycaemic control. It contains multiple bioactive constituents, such as cinnamaldehyde, eugenol, and polyphenolic proanthocyanidins, which exert a range of effects on glucose and lipid metabolism. These compounds enhance insulin receptor activity, facilitate glucose uptake in peripheral tissues, inhibit intestinal α-glucosidase and α-amylase enzymes, and reduce oxidative stress and inflammatory signalling. Through these mechanisms, cinnamon supplementation may improve insulin sensitivity, lower fasting blood glucose, and attenuate postprandial hyperglycaemia. Evidence from numerous clinical trials and meta-analyses provides evidence that daily supplementation with 1–6 g of cinnamon over several weeks can produce modest yet statistically significant reductions in fasting plasma glucose, HbA1c, triglycerides, and LDL cholesterol. Furthermore, experimental findings suggest beneficial effects on hepatic enzyme activity and oxidative balance in patients with T2DM. Nevertheless, inconsistencies in reported outcomes are attributed to differences in study design, cinnamon species (*C. verum* versus *C. cassia*), and formulation (powder, extract, or capsule). Safety considerations, particularly with regard to the coumarin content of *C. cassia*, support the preferential use of *C. verum* in clinical applications. From a therapeutic perspective, cinnamon supplementation is a safe, affordable, and easily accessible complementary strategy that could enhance conventional antidiabetic therapy, improve metabolic stability, and promote patient adherence. Therefore, integrating cinnamon into comprehensive diabetes management alongside pharmacotherapy, dietary regulation, and lifestyle modification may contribute to improved long-term clinical outcomes.

**Keywords:** Cinnamon, type 2 diabetes mellitus, glycaemic control, insulin sensitivity, polyphenols, cinnamaldehyde, complementary therapy

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## Introduction

Type 2 diabetes mellitus (T2DM) is a chronic metabolic disorder characterised by insulin resistance, impaired insulin secretion, and hyperglycaemia (Hameed et al., 2015). It represents a significant public health concern, affecting an estimated 537 million adults worldwide in 2021, a figure projected to increase in the coming decades (Hossain et al., 2024). T2DM is associated with serious complications, including cardiovascular disease, nephropathy, neuropathy, and retinopathy, which significantly reduce quality of life and increase mortality (Kulkarni et al., 2024).

Over the past three decades, the prevalence of T2DM has steadily increased globally and in Poland, reflecting lifestyle changes, dietary patterns, urbanisation, and an ageing population (Topor-Mądry et al., 2019). This upward trend is accompanied by a growing economic burden on healthcare systems due to the management of chronic diseases and the treatment of complications. Therefore, understanding the epidemiology of T2DM is crucial for developing effective prevention and intervention strategies (Hossain et al., 2024). Traditionally, efforts to manage T2DM have focused on pharmacological therapy and lifestyle interventions, including dietary modifications and increased physical activity (Młynarska et al., 2025). However, despite these measures, many patients struggle to achieve optimal glycemic control, highlighting the need for safe, accessible, and sustainable complementary and adjunctive therapeutic approaches.

Maintaining stable blood glucose levels is central to T2DM management, as chronic hyperglycaemia contributes to both microvascular and macrovascular complications (Zakir et al., 2023). Clinical studies indicate that even modest improvements in glycaemic control can significantly reduce the risk of retinopathy, nephropathy, and cardiovascular events (Poonoosamy et al., 2023). This highlights the importance of achieving target glucose levels in clinical practice. Moreover, glycaemic variability, rather than average glucose levels alone, is increasingly recognised as an independent risk factor for diabetic complications (Martinez et al., 2021). Episodes of postprandial and fasting hyperglycaemia promote oxidative stress, inflammation, and endothelial dysfunction, thereby exacerbating disease progression. Consequently, strategies that reduce chronic hyperglycaemia and glycaemic fluctuations are critical for the effective management of T2DM (Blaak et al., 2012). Furthermore, optimal glycemic control also improves patients' quality of life and reduces healthcare costs associated with diabetes-related hospitalisations and treatments (Banerji and Dunn, 2013). Despite advances in antidiabetic medications, many patients fail to achieve and maintain the recommended glycemic targets due to issues with adherence, side effects, or comorbidities, highlighting the need for complementary strategies (García-Pérez et al., 2013).

As healthcare costs continue to rise and interest in alternative medicine increases, it is essential to conduct rigorous evaluations of plant-based therapies that have demonstrated efficacy against various chronic diseases, including cardiovascular disorders, diabetes, and cancer (Hariri et al., 2016; Caserta et al., 2023; Chen et al., 2025). Within this context, natural therapies have attracted growing interest as adjuncts to conventional diabetes management (Pandey et al., 2011; Abeysekera et al., 2022; Nanda et al., 2023). Cinnamon (*Cinnamomum verum* J.Presl), for example, has a long history of traditional use for its hypoglycaemic properties, and modern scientific research is beginning to elucidate the mechanisms underlying these effects (Bibi et al., 2024). Bioactive constituents of cinnamon, such as polyphenols and cinnamaldehyde, have been shown to modulate glucose metabolism, insulin signalling, and pathways associated with oxidative stress (Mollazadeh and Hosseinzadeh, 2016). Evidence suggests that cinnamon supplementation may enhance insulin sensitivity, promote glucose uptake by peripheral tissues, and attenuate postprandial glucose spikes, making it a promising candidate for complementary therapy in type 2 diabetes mellitus (Qin et al., 2010; Moridpour et al., 2024). Its accessibility, affordability, and relatively low risk of adverse effects further support its potential integration into dietary strategies aimed at improving glycaemic control. Nevertheless, despite encouraging preclinical and clinical findings, the efficacy and optimal dosage of cinnamon remain under investigation (Akilen et al., 2012; Moridpour et al., 2024). Variations in study design, cinnamon species, and preparation methods have contributed to inconsistent results. Despite these challenges, cinnamon continues to attract interest as a natural adjunct in T2DM management, and highlighting the need for a comprehensive synthesis of the current research to clarify its therapeutic potential.

### Cinnamon: Botanical Profile and Chemical Composition

Cinnamon is one of the world's oldest known spices, widely utilised in the food processing, pharmaceutical, and cosmetics industries. It is derived from the dried inner bark of several tropical evergreen species belonging to the genus *Cinnamomum* Schaeff.

(a member of the Lauraceae family), which are primarily native to Southeast Asia (Blahová and Svobodová, 2012).

From antiquity, cinnamon has been esteemed not only as a spice and an incense but also for its antiseptic properties. The recorded use of cinnamon dates back to approximately 2800 B.C., when the ancient Egyptians employed it in the process of mummification owing to its antibacterial effects and distinctive aroma. By the fourteenth century, cinnamon had become valued in Europe as an additive for improving the preservation of meat. The pursuit of spices such as cinnamon was among the major incentives that drove European maritime exploration during the fifteenth century (Pathirana and Senaratne, 2020).

The discovery, trade, and cultivation of cinnamon are closely interwoven with the broader history of colonisation. Following the arrival of the Portuguese in Ceylon in the early sixteenth century, *C. verum* became one of the most prized commodities within European imperial trade networks, leading to repeated attempts to transport the species overseas and to establish its cultivation in other tropical regions (Pathirana and Senaratne, 2020; Costa, 2024).

Within the genus *Cinnamomum*, four species are of major economic importance. The first is *Cinnamomum verum* J. Presl, known as "true cinnamon" or *Ceylon cinnamon*. Historically, Sri Lanka was the main supplier of true cinnamon bark and leaf oils. The latter are particularly rich in eugenol (Mallavarapu et al., 1995; Thomas and Duethi, 2001). The older botanical name of this species, *Cinnamomum zeylanicum* Blume, derives from the island's former name, Ceylon (Spence, 2024).

The other three major species of cinnamon include *Cinnamomum cassia* Nees ex Blume (syn. *Cinnamomum aromaticum* Nees), commonly known as Chinese or 'bastard' cinnamon; *Cinnamomum burmanni* (Nees & T. Nees) Blume, often referred to as Korintje, Java, or Indonesian cinnamon; and *Cinnamomum loureiroi* Nees, widely recognised as Vietnamese or Saigon cinnamon (Thomas and Duethi, 2001). Among these, *C. cassia* is the second most widely recognised and commercially traded cinnamon species globally, surpassed only by *C. verum* J. Presl (Külkamp et al., 2025). Historically, *C. cassia* was used in China long before the introduction of true cinnamon, yet it is presently regarded as an inferior substitute in both flavour and quality (Thomas and Duethi, 2001; Kawatra and Rajagopalan, 2015).The species is believed to have originated in south-eastern China (Thomas and Duethi, 2001). Külkamp et al. (2025) proposed the conservation of the species name *C. cassia* Nees ex Blume against its earlier homonyms *C. cassia* (L.) J. Presl or D. Don to ensure taxonomic consistency. At present, cinnamon is primarily exported in the form of quills from four major producing countries: China, Indonesia, Vietnam, and Sri Lanka. Collectively, these four countries supply the overwhelming majority of the world's commercial cinnamon production (Kawatra and Rajagopalan, 2015). In both the United States and European markets, two primary types of cinnamon are commercially available – *Ceylon cinnamon* (*C. verum*) and cassia (*C. cassia*) (Blahová and Svobodová, 2012).

A key morphological distinction is that cassia tends to have darker, thicker bark than true cinnamon (Spence, 2024) (Figure 1).

*C. verum* is often regarded as possessing the most delicate and complex flavour profile among the major cinnamon species, with a characteristically sweet and mild taste, lacking the pronounced pungency of cassia. By contrast, consumers in North America are generally more accustomed to the stronger, spicy-sweet aroma and flavour of *C. cassia* and *C. loureiroi*. The latter exhibits a particularly robust flavour due to its high cinnamaldehyde and volatile oil content. In comparison, *C. burmanni*, although also rich in cinnamaldehyde, presents a smoother taste with less intensity than *C. cassia* or *C. loureiroi* (Spence, 2024). Notably, the differences in chemical composition between these species, particularly concerning the levels of cinnamaldehyde, eugenol and coumarin, are crucial for their sensory properties and their applications in the pharmaceutical, cosmetic, and food industries. The varying concentrations of these bioactive compounds influence both the safety and therapeutic potential of each type of cinnamon, underscoring the need for continued comparative studies on their composition and biological activity (Spence, 2024).

Cinnamon is a complex natural product containing a diverse array of bioactive and resinous compounds that contribute to its distinctive aroma and flavour, as well as its broad therapeutic potential (Figure 2). Depending on the part of the plant used, *Cinnamomum* species exhibit a broad spectrum of properties beneficial to human health. In particular, the dried bark and twigs are commonly employed to enhance glucose metabolism (Hariri et al., 2016; Abeysekera et al., 2022; Sarmadi et al., 2023), while the bark also demonstrates hepatoprotective effects against steatosis (Farmani et al., 2025). Moreover, cinnamon bark has been shown to possess antioxidant, anti-inflammatory, antimicrobial,

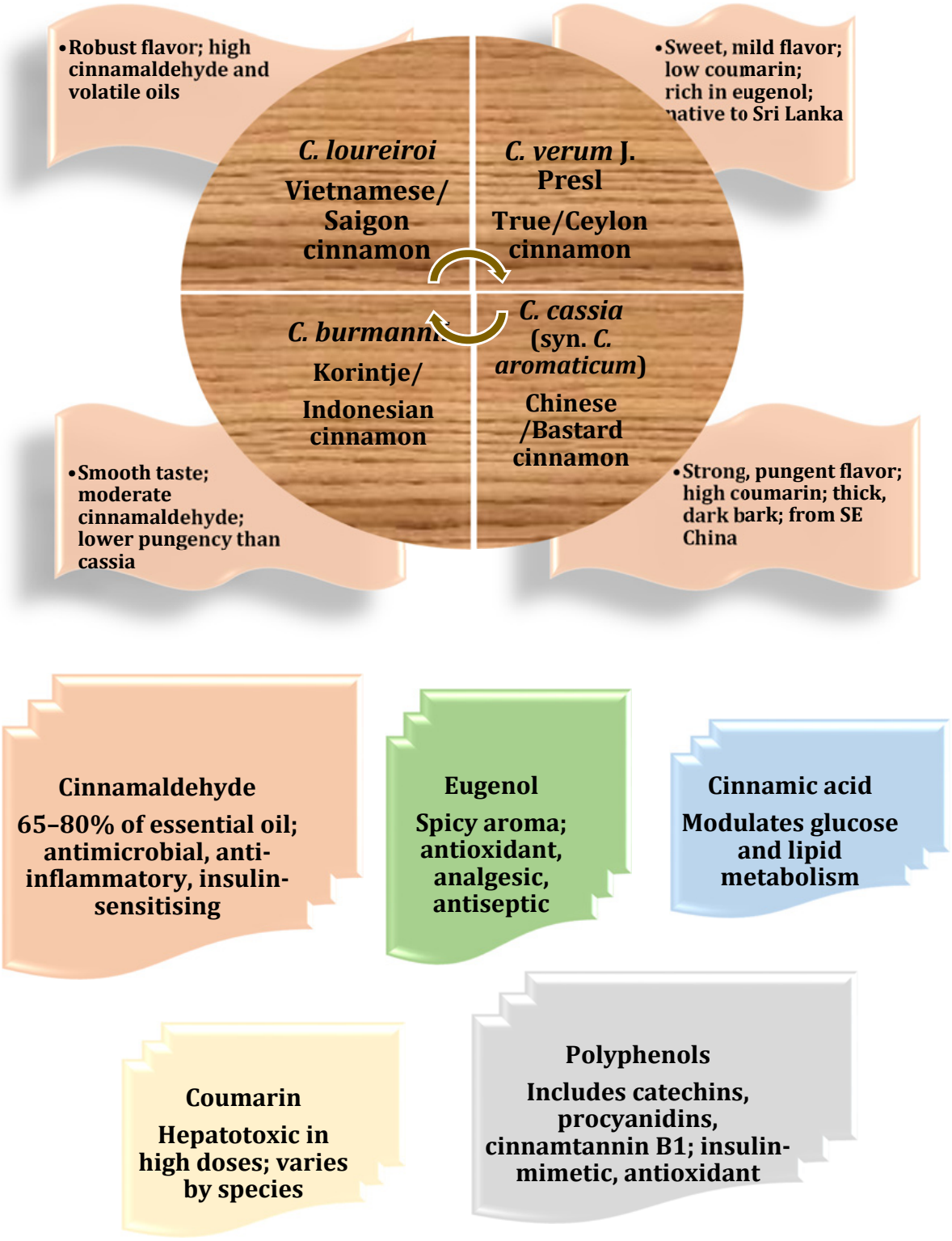


**Figure 1** Botanical profile,chemical composition, and key bioactive compounds in cinnamon

antihypertensive, antilipidemic, immunomodulatory, and anticancer effects (Hariri et al., 2016; Caserta et al., 2023; Živković et al., 2025), whereas the leaves display predominantly antimicrobial, antifungal, and anticancer properties (Abeysekera et al., 2022; Caserta et al., 2023; Datta et al., 2024). In addition, cinnamon has shown beneficial effects in mitigating neurological disorders, such as Alzheimer's and Parkinson's disease (Rao and Gan, 2014; Chen et al., 2025). These properties are largely attributed to the unique chemical composition of cinnamon essential oil, particularly the presence of bioactive constituents such as cinnamaldehyde, eugenol, cinnamyl alcohol, linalool, and various terpenoids. These compounds play crucial roles in inhibiting pathogenic microorganisms, neutralising oxidative stress, modulating the immune response, and suppressing tumour development (Caserta et al., 2023; Živković et al., 2025).

The volatile profile of *C. verum* has been extensively investigated and is well documented in the literature. The main constituents of cinnamon include cinnamaldehyde, eugenol, cinnamic acid, coumarin, and a diverse range of polyphenolic compounds, including catechins, procyanidins, and proanthocyanidins (Rao and Gan, 2014; Błaszczyk et al., 2021). The principal volatile component, cinnamaldehyde, typically accounts for approximately 65–80% of the essential oil derived from the bark (Rao and Gan, 2014). Cinnamaldehyde is primarily responsible for the characteristic scent and flavour of cinnamon. Beyond its sensory role, this compound exhibits pronounced antimicrobial, anti-inflammatory, and insulin-sensitising activities, thereby contributing significantly to the spice's therapeutic potential (Rao and Gan, 2014; Guo et al., 2024). Eugenol, on the other hand, imparts the spicy aroma typical of cinnamon and possesses well-documented antioxidant, analgesic, and antiseptic properties (Nisar et al., 2021). Cinnamic acid and its derivatives have been reported to modulate glucose metabolism and lipid profiles, whereas polyphenols – particularly cinnamtannin B1 – mimic insulin action by promoting glucose uptake in adipocytes and muscle cells (Adisakwattana, 2017; Mohsin et al., 2023). Furthermore, these polyphenolic compounds function as potent free radical scavengers, protecting pancreatic β-cells from oxidative damage, a key mechanism underlying insulin resistance and the progression of T2DM (Adisakwattana, 2017).

In addition to its principal bioactive constituents, cinnamon contains a broad spectrum of resinous and volatile components, including cinnamate, cinnamyl acetate, l-borneol, caryophyllene oxide, β-caryophyllene, l-bornyl acetate, E-nerolidol, α-cubebene, α-terpineol, terpinolene, and α-thujene (Sangal, 2011; Vangalapati et al., 2012; Rao and Gan, 2014). The composition and relative abundance of these constituents vary markedly across different plant organs. For example, the essential oil of *C. zeylanicum* leaves contains 70–95% eugenol, while the bark comprises 65–80% cinnamaldehyde, and the root bark contains approximately 60% camphor (Vangalapati et al., 2012). The fruits are characterized by elevated levels of trans-cinnamyl acetate (42–54%) and caryophyllene (9–14%), whereas the buds and flowers are particularly rich in terpene hydrocarbons, including α-bergamotene,


**Figure 2** The main chemical compounds of *Cinnamomum verum*
Photo by Zbigniew Mazur

α-copaene, and caryophyllene oxide. This pronounced variability in phytochemical composition is influenced by multiple factors, including the plant organ analysed, species type, harvest season, geographic origin, and post-harvest processing conditions. Collectively, these variables exert a significant impact on the bioactivity and commercial quality of cinnamon essential oils (Rao and Gan, 2014).

The synergistic interaction between volatile oils and polyphenolic compounds is thought to enhance the overall therapeutic efficacy of cinnamon. Experimental evidence indicates that this complex phytochemical interplay contributes to a range of metabolic benefits, including improved insulin sensitivity, attenuation of lipid peroxidation, and modulation of key digestive enzymes involved in carbohydrate metabolism (Qin et al., 2010; Stevens and Allred, 2022). Taken together, these findings emphasise the distinctive biochemical complexity of cinnamon and endorse its potential as a multifunctional natural agent with broad applications in the food, cosmetics, and pharmaceutical industries.

Environmental factors such as soil type, temperature, humidity, and altitude significantly affect the biosynthesis of secondary metabolites, particularly essential oils and polyphenols (Kowalska et al., 2021; Sun et al., 2024). For example, *C. verum* cultivated in Sri Lanka typically contains higher concentrations of eugenol and cinnamaldehyde, whereas *C. cassia* from China and Indonesia tends to exhibit elevated levels of coumarin and cinnamic acid derivatives (Senevirathne et al., 2022).

Harvesting time and bark maturity also affect the chemical profile, as younger bark generally possesses greater amounts of volatile compounds compared to mature bark (Geng et al., 2011; Fajara et al., 2019). Furthermore, extraction methodologies such as steam distillation, ethanol extraction, and supercritical $CO_2$ techniques can selectively enrich specific constituents while reducing others, thereby modulating the pharmacological potential of the final product. Recognizing these sources of compositional variability is essential for ensuring the reproducibility and interpretability of experimental findings as well as the efficacy of dietary interventions (Sun et al., 2025). Consequently, standardisation of cinnamon extracts based on defined chemical markers is imperative to validate their biological activity and to support the development of reliable clinical recommendations for glycaemic control.

## Molecular Mechanisms Underlying the Antidiabetic Effects of Cinnamon

Approximately three decades ago, cinnamon (*Cinnamomum* spp.) was proposed as a potential antidiabetic agent due to its ability to mimic insulin activity and facilitate glucose transport into cells (Khan et al., 1990). Subsequent *in vitro* and *in vivo* studies have corroborated its hypoglycaemic and insulin-sensitising properties, establishing cinnamon as a promising natural adjunct for the prevention and treatment of T2DM and metabolic syndrome (Qin et al., 2003; Medagama, 2015; Silva et al., 2022).

Cinnamon and its bioactive constituents, particularly polyphenolic compounds, procyanidin type-A polymers, methylhydroxychalcone polymer, cinnamaldehyde, catechin, rutin, quercetin and kaempferol, exhibit potent insulin-mimetic and insulin-sensitising effects (Figure 3). These compounds stimulate the phosphorylation of insulin receptor (IR) and insulin receptor substrate (IRS) proteins, activating downstream signalling cascades such as PI3K/PDK1/Akt1, PKC and AMP-activated protein kinase (AMPK). Collectively, these pathways promote glucose uptake into adipocytes and skeletal muscle cells, enhancing glycogen synthesis (Qin et al., 2003; Anderson et al., 2004; Sheng et al., 2008; Silva et al., 2022). Moreover, cinnamon constituents modulate peroxisome proliferator-activated receptors (PPARs), thereby improving insulin sensitivity, glucose utilisation and lipid metabolism (Qin et al., 2010; Mollazadeh and Hosseinzadeh, 2016).

*In vitro* studies have demonstrated that aqueous-alcoholic extracts of cinnamon enhance the translocation of the glucose transporter GLUT4 from the intracellular compartment to the plasma membrane, thereby increasing the amount of membrane-bound GLUT4 within three hours of administration (Absalan et al., 2012). This effect is associated with the activation of AMP-activated protein kinase and acetyl-CoA carboxylase, improving cellular energy metabolism (Shen et al., 2014). *In vivo* experiments on diabetic animals have shown that cinnamon's bioactive compounds, especially cinnamaldehyde and polyphenols, reduce fasting glucose and glycated haemoglobin (HbA1c) levels by 0.27–0.83% following long-term supplementation (Silva et al., 2022).

Cinnamon modulates genes involved in glucose metabolism, such as GLUT1, GLUT4, glycogen synthase and glycogen synthase kinase 3β, by inhibiting intestinal α-glucosidase and ATPase activity, enhancing glucose disposal in hepatic and muscle


**Figure 3** Antidiabetic and metabolic effects of cinnamon and its bioactive compounds

tissues (Absalan et al., 2012; Beejmohun et al., 2014). Furthermore, the administration of cinnamaldehyde (5–20 mg·kg$^{-1}$ for 45 days) to rats with streptozotocin (STZ)-induced diabetes significantly reduced plasma glucose, HbA1c, total cholesterol and triglyceride levels, while increasing insulin, hepatic glycogen and HDL cholesterol levels with effects comparable to glibenclamide (Subash et al., 2007). Similarly, an aqueous cinnamon extract (30 mg·kg$^{-1}$·day$^{-1}$ for 22 days) prevented hyperglycaemia and nephropathy in diabetic rats by increasing the expression of uncoupling protein-1 (UCP-1) and GLUT4 in brown adipose tissue and skeletal muscle (Shen et al., 2010).

In addition to its insulinotropic effects, cinnamon exhibits notable antioxidant and anti-inflammatory properties that enhance its antidiabetic efficacy (Sahib, 2016; Pagliari et al., 2023). Its polyphenolic compounds scavenge reactive oxygen species (ROS), inhibit lipid peroxidation, and upregulate endogenous antioxidant enzymes such as superoxide dismutase (SOD) and glutathione peroxidase (GPx). They also suppress pro-inflammatory mediators including nuclear factor kappa-B (NF-κB), tumour necrosis factor alpha (TNF-α) and interleukin 6 (IL-6), thereby protecting pancreatic beta cells and preserving insulin receptor functionality (Wang et al., 2025). Furthermore, cinnamon regulates insulin-like growth factor 1 (IGF1) signalling, mitochondrial bioenergetics, and autophagy, thereby improving insulin sensitivity, glycaemic control, and metabolic homeostasis (Couturier et al., 2010; Mollazadeh and Hosseinzadeh, 2016).

Systemic inflammation is increasingly recognised as a key contributor to insulin resistance in T2DM (Berbudi et al., 2025). Tristetraprolin (TTP), an anti-inflammatory protein downregulated in the adipose tissue of obese individuals (Al-Daghri et al., 2021), protects against insulin resistance (Cao et al., 2008). Cinnamon extract has been shown to rapidly upregulate TTP mRNA in 3T3-L1 adipocytes, highlighting its potential to counteract inflammation and metabolic dysregulation in obesity and T2DM (Cao et al., 2007).

The effects of cinnamon extend to lipid metabolism. The cytokine TNF-α, a key mediator linking obesity to insulin resistance, stimulates the overproduction of intestinal apoB48-containing lipoproteins (Qin et al., 2007). Oral supplementation with Cinnulin PF® reduces postprandial apoB48 secretion and serum triglycerides in animal models, while *ex vivo* studies demonstrate suppression of TNF-α-induced apoB48 oversecretion in enterocytes (Qin et al., 2009). Cinnamon decreases the expression of inflammatory cytokines (IL-1β, IL-6 and TNF-α) and enhances the expression of genes involved in insulin signalling (IR, IRS1, IRS2, PI3K and Akt1), improving intestinal insulin sensitivity and lipid homeostasis (Qin et al., 2009).

High-fat and high-fructose diets exacerbate insulin resistance, inflammation, and atherogenic lipoprotein production (Tan and Norhaizan, 2019; Abbasi and Khodadadi, 2025). In fructose-fed, insulin-resistant rats, the acute administration of Cinnulin PF® normalised postprandial triglycerides, restored intestinal insulin signalling, and reduced the expression of microsomal triglyceride transfer protein (MTP) and sterol regulatory element-binding protein-1c (SREBP-1c) (Qin et al., 2009). These findings suggest that cinnamon enhances intestinal insulin sensitivity while reducing dyslipidaemia and cardiovascular risk.

Cinnamon also exhibits strong antiglycation activity. Phenolic compounds, such as catechin, epicatechin, procyanidin B2, and polymeric phenols, inhibit advanced glycation end-products (AGEs) formation through antioxidant capacity and by trapping reactive carbonyl species, such as methylglyoxal (MGO) (Peng et al., 2008; Ranasinghe et al., 2012; Beejmohun et al., 2014). This mechanism may prevent or alleviate diabetic complications associated with oxidative and carbonyl stress.

Clinical evidence further supports the metabolic benefits of cinnamon (Table 1). Randomised trials have shown that cinnamon supplementation (1–6 g per day for three months) significantly lowers fasting blood glucose levels (by 12.9–52.2 mg·dL$^{-1}$) and HbA1c in individuals with T2DM (Khan et al., 2003; Gruenwald et al., 2010; Akilen et al., 2010; Lu et al., 2012; Santos et al., 2018). Nonetheless, despite these encouraging findings, most evidence derives from *in vitro* and animal studies. Further large-scale, standardised clinical trials are needed to confirm the efficacy and optimal dosage of cinnamon in humans (Ranasinghe et al., 2013; Silva et al., 2022).

Taken together, these multifaceted mechanisms suggest that cinnamon exerts insulin-mimetic effects, enhances insulin sensitivity, reduces oxidative and inflammatory stress, improves lipid and glucose metabolism. Moreover, it may inhibit the formation of advanced glycation end products, thereby mitigating one of the key pathogenic pathways in metabolic dysfunction. Owing to the combined antioxidant, anti-inflammatory, anti-glycation, and insulin-sensitising properties of its bioactive constituents, cinnamon represents

**Table 1** Studies on the antidiabetic effects of cinnamon

| Research area | Model/method | Dose/extract | Effects | References |
|---|---|---|---|---|
| **Cinnamon essential oil** | alloxan-induced diabetic rats | 5, 10, 20 mg·kg$^{-1}$ (intraperitoneal) | decrease in fasting glucose; nephroprotective effect | Mishra et al., 2010 |
| **Cinnamon extract (various species)** | *in vitro* – intestinal α-glucosidase and pancreatic α-amylase | Different species and concentrations | inhibition of digestive enzymes; delayed carbohydrate absorption | Adisakwattana et al., 2011; Mohamed et al., 2011 |
| **Methanolic extract** | *in vitro* and *in vivo* (STZ-induced diabetic rats) | 300 mg·kg$^{-1}$ | inhibition of yeast and mammalian α-glucosidase; reduction of postprandial hyperglycaemia | Mohamed et al., 2011 |
| **Cinnamaldehyde** | STZ-diabetic rats; isolated pancreatic islets (*in vitro*) | 20 mg·kg$^{-1}$ orally | increased hepatic and muscular glycogen; enhanced insulin secretion; GLUT4 translocation | Anand et al., 2010 |
| **Cinnamon extract** | 3T3-L1 adipocytes (*in vitro*) | 0.2–0.4 mg·mL$^{-1}$ | increased glucose uptake (insulin-mimetic effect); modulation of adiponectin secretion | Roffey et al., 2006 |
| **Aqueous extract** | STZ-diabetic rats | 30 mg·kg$^{-1}$·day$^{-1}$ for 22 days | reduced hyperglycaemia and nephropathy; increased UCP-1 and GLUT4 expression | Shen et al., 2010 |
| **Aqueous cinnamon extract (*Cinnamomum cassia*)** | Fructose-fed insulin-resistant rats | Cinnulin PF®, 10–20 mg·kg$^{-1}$ | improved intestinal insulin sensitivity; reduced postprandial triglycerides; downregulation of MTP and SREBP-1c | Qin et al., 2009 |
| **Cinnamaldehyde** | STZ-diabetic rats | 5–20 mg·kg$^{-1}$ for 45 days | reduced plasma glucose, HbA1c, total cholesterol, TG; increased insulin and HDL; restored hepatic enzymes | Subash et al., 2007 |
| **Polyphenolic fraction** | *in vitro* and *in vivo* | - | stimulation of IR phosphorylation, activation of PI3K/Akt pathway, increased GLUT4 translocation | Silva et al., 2022 |
| **Clinical study (human)** | patients with T2DM | 1–6 g cinnamon·day$^{-1}$ for 3 months | decreased fasting glucose and HbA1c levels | Khan et al., 2003; Akilen et al., 2010; Lu et al., 2012 |
| **Clinical study (human)** | healthy subjects | 3 g cinnamon | no significant effect on glucose, gastric emptying, or oxidative stress | Markey et al., 2011 |

a promising and well-tolerated natural adjunct for the long-term management of type 2 diabetes mellitus and related metabolic disorders.

## Clinical Evidence and Mechanistic Insights Into the Antidiabetic Effects of Cinnamon

Over the past decade, numerous systematic reviews and meta-analyses have investigated whether cinnamon supplementation improves glycaemic control in patients with T2DM (Table 2). Taken together, these analyses suggest that cinnamon can modestly yet significantly reduce fasting blood glucose (FBG), glycated haemoglobin (HbA1c) and insulin resistance indices compared to placebo or baseline values (Costello et al., 2016; Moridpour et al., 2024). However, the magnitude of these effects varies across studies, likely reflecting differences in cinnamon species, dosage, formulation, and study duration. The variable ratio of cinnamaldehyde, eugenol, and procyanidins between *C. cassia* and *C. verum* may account for the inconsistency in glycaemic outcomes, suggesting a species-dependent response.

A comprehensive meta-analysis by Costello et al. (2016) encompassing 11 randomised controlled trials with 694 participants found consistent reductions in fasting plasma glucose and modest decreases in HbA1c. Nevertheless, only four studies achieved the treatment goals set by the American Diabetes Association. The authors concluded that, while cinnamon may provide mild benefits as an adjunct to standard therapies, current dietary and pharmacological guidelines should remain the primary approach. They further highlighted the need for chemically standardised cinnamon preparations and longer intervention periods to ensure reproducibility and clinical relevance.

**Table 2** Clinical studies on the antidiabetic effects of cinnamon

| Country/study | Number of participants | Dose | Effects | References |
|---|---|---|---|---|
| | diabetes, aged 52.2 ± 6.32 years | | | |
| **USA** | 60 patients with type 2 | 1, 3, or 6 g of cinnamon daily for 40 days | decrease in fasting blood glucose by 18–29%; improvement in triglycerides and LDL cholesterol levels | Khan et al., 2003 |
| **Germany** | 79 patients with type 2 diabetes | 3 g cinnamon daily for 4 months | moderate reduction in fasting blood glucose (~10%) compared to the control group | Mang et al., 2006 |
| **USA** | 543 adults with T2DM (meta-analysis of 10 RCTs) | 120 mg–6 g·day$^{-1}$ for 4–18 weeks | reduction in fasting plasma glucose; no significant effect on HbA1c | Allen et al., 2013 |
| **Meta-analysis** | 6 randomized clinical trials (435 participants) | 1–6 g·day$^{-1}$ for 40 days–4 months | decrease in fasting blood glucose; positive effect on HbA1c | Akilen et al., 2012 |
| **Meta-analysis** | 24 randomized controlled trials | – | significant improvement in fasting glucose and insulin resistance (HOMA-IR); no change in serum insulin levels | Moridpour et al., 2024 |
| **Meta-analysis** | 7 studies (256 participants) | 1,500 mg·day$^{-1}$ for 12 weeks | improvement in hepatic enzyme activity in T2DM patients | Mousavi et al., 2021 |
| **Iran** | 140 patients with T2DM | 500 mg twice daily for 3 months | reduction in fasting blood glucose and HbA1c; improved insulin sensitivity in overweight participants | Zare et al., 2019 |
| **Mexico** | 18 patients with poorly controlled T2DM | 1000 mg three times daily for 12 weeks (*C. cassia*) | significant decrease in fasting glucose and HbA1c; improved lipid metabolism | Delgadillo-Centeno et al., 2023 |
| **Sri Lanka** | 150 adults with type 2 diabetes | 1,000 mg·day$^{-1}$ for 12 weeks | decrease in fasting blood glucose; improved antioxidant status | Muthukuda et al., 2025 |
| **China** | 69 patients with T2DM treated with gliclazide | 120 mg or 360 mg cinnamon extract per day for 3 months | reduction in fasting plasma glucose and HbA1c in both dosage groups | Lu et al., 2012 |
| **UK** | 58 patients with T2DM | 2 g·day$^{-1}$ *C. cassia* for 12 weeks | significant decrease in HbA1c and fasting plasma glucose vs. placebo | Akilen et al., 2010 |

Subsequent meta-analyses have expanded upon these findings. For example, Zhou et al. (2022), analysing 16 randomised clinical trials with 1,020 patients, reported significant improvements in glycolipid profiles, particularly among participants with baseline HbA1c levels of approximately 8%, and noted minimal adverse events. Similarly, Moridpour et al. (2024) reviewed 24 randomised controlled trials and confirmed significant reductions in fasting glucose, HOMA-IR, and HbA1c levels, though serum insulin concentrations remained unchanged. These insulin-sensitising effects are believed to be mediated by the activation of AMP-activated protein kinase (AMPK) and the increased expression of glucose transporter type 4 (GLUT4).

Comparable outcomes were observed by Allen et al. (2013) in a meta-analysis of ten randomised controlled trials involving 543 patients. Cinnamon supplementation (120 mg to 6 g daily for 4–18 weeks) significantly lowered fasting plasma glucose, total cholesterol, LDL-C, and triglyceride levels while modestly increasing HDL-C. However, HbA1c remained unaffected, likely due to the relatively short duration of most trials (<12 weeks), insufficient to capture changes in HbA1c, considering the lifespan of erythrocytes.

Medagama (2015) summarised the molecular pathways through which *C. cassia* may improve glycaemic control. These include the stimulation of insulin receptor phosphorylation, the enhancement of GLUT-4 translocation, the modulation of hepatic enzymes such as pyruvate kinase (PK) and phosphoenolpyruvate carboxykinase (PEPCK), and the inhibition of intestinal glucosidases. Clinical trials involving daily doses ranging from 500 mg to 6 g for up to four months have demonstrated significant improvements in fasting glucose and HbA1c levels, particularly among individuals with poorly controlled diabetes or impaired glucose tolerance.

Zarezadeh et al. (2023) conducted an umbrella meta-analysis of eleven systematic reviews and confirmed that cinnamon supplementation significantly improves glycaemic control in patients with T2DM and in women with polycystic ovary syndrome (PCOS). These findings suggest that cinnamon's metabolic effects extend beyond glucose regulation, potentially involving modulation of adipokine signalling and inflammatory pathways associated with insulin resistance.

Several randomised controlled trials (RCTs) have provided direct clinical evidence supporting these findings. For example, Khan et al. (2003) observed significant reductions in fasting plasma glucose in 60 patients with T2DM receiving 1–6 g·day$^{-1}$ of *C. cassia* for 40 days. Akilen et al. (2010) and Vafa et al. (2012) reported comparable decreases in HbA1c and fasting glucose after 8–12 weeks of supplementation with 2–3 g·day$^{-1}$ of *C. cassia* or *C. zeylanicum*. Similarly, Lu et al. (2012) found dose-dependent improvements in fasting glucose and HbA1c following three months of *C. cassia* extract (120–360 mg·day$^{-1}$), while Anderson et al. (2015) observed reductions in postprandial glucose and insulin resistance after eight weeks of *C. cassia* water extract (CinSulin®, 500 mg·day$^{-1}$).

However, not all clinical studies have confirmed favourable outcomes. Markey et al. (2011) found no significant changes in glycaemic parameters or oxidative stress after administering 3 g·day$^{-1}$ of cinnamon to healthy individuals. Furthermore, Roffey et al. (2006) reported that high extract concentrations disrupted adiponectin secretion in adipocytes, implying a dose threshold beyond which the metabolic benefits of cinnamon may diminish or even reverse. Similarly, Deyno et al. (2019), in a meta-analysis of 16 RCTs, found significant reductions in fasting blood glucose (FBG) and homeostatic model assessment of insulin resistance (HOMA-IR) but no significant effect on HbA1c or lipid profiles, underscoring the need for experimental standardisation.

Beyond its direct glycaemic effects, cinnamon modulates the gut microbiota, which plays a crucial role in insulin sensitivity and systemic inflammation. Wang et al. (2025) demonstrated that quercetin derived from cinnamon improves insulin signalling and glucose metabolism by increasing *Akkermansia* and *Ligilactobacillus* abundance, while reducing the *Firmicutes*/*Bacteroidetes* ratio. These microbial shifts correlated with lower levels of inflammatory markers (LPS, IL-6, and TNF-α) and enhanced intestinal barrier integrity, as evidenced by increased expression of ZO-1 and occludin.

Animal studies further corroborate these findings. In mice fed a high-fat diet, administration of cinnamon extract for eight weeks reduced hepatic steatosis, plasma non-esterified fatty acids, and insulin resistance, associated with modulation of the microbiota – specifically, a decrease in *Desulfovibrio* and *Lactococcus* populations and an increase in *Allobaculum* and *Roseburia* populations (Van Hul et al., 2028). Additionally, the antioxidants cinnamic acid and procyanidins found in cinnamon protect pancreatic β-cells by upregulating nuclear factor erythroid 2-related factor 2 (NRF-2), heme oxygenase-1, and γ-glutamylcysteine synthetase, thus preventing oxidative stress-induced apoptosis and improving insulin secretion (Li et al., 2023; Bai et al., 2025).

Sarmadi et al. (2023) reported that cinnamon supplementation significantly increased total antioxidant capacity (TAC) in patients with T2DM and PCOS. In animal models, the oral administration of cinnamon extract (at doses of 100–400 mg·kg$^{-1}$ over a period of 42 days) reduced oxidative stress by decreasing malondialdehyde (MDA) levels and restoring superoxide dismutase (SOD) and catalase activities in the liver and kidneys (Niazmand et al., 2021). Advanced formulations, such as cinnamon-silver nanoparticles (C-Ag-NPs), demonstrated superior efficacy compared with aqueous extracts in reducing hyperglycaemia, hyperlipidaemia, and oxidative liver damage in diabetic rats (El-Baz et al., 2023).

Additionally, cinnamon may inhibit digestive enzymes such as α-amylase and α-glucosidase, thereby attenuating postprandial hyperglycaemia. Computational and *in vitro* studies have identified *C. zeylanicum* phytocompounds, including 1HE (1,2,4a,5,6,8a-hexahydro-1-isopropyl-4,7-dimethylnaphthalene) and C4B (cis-4-benzyl-2,6-diphenyltetrahydropyran), as potent inhibitors of α-amylase (Rao and Shanti, 2025). Experimental data confirmed that cinnamon markedly suppressed starch digestion in both the oral and gastric phases ($p < 0.05$) (Hayward et al., 2019).

Comparative clinical trials have revealed notable differences between *C. verum* (*Ceylon cinnamon*) and *C. cassia* (Chinese cinnamon). Both species reduce fasting glucose and HbA1c levels, but *C. cassia*, though more potent, contains higher concentrations of coumarin, a hepatotoxic compound (Shinjyo et al., 2020). This raises safety concerns for long-term use; therefore, *C. verum* is generally preferred for chronic

supplementation, particularly in patients with liver impairment.

Finally, a recent comprehensive review by Debnath et al. (2025) further supports the antidiabetic potential of *C. cassia*, particularly when combined with traditional Chinese medicinal herbs such as *Panax ginseng* Author and *Astragalus membranaceus* Author. These synergistic formulations enhance glycaemic control and lipid metabolism while maintaining safety. However, future investigations should prioritise dose–response optimisation, the development of coumarin-free extracts, and pharmacokinetic standardisation to maximise efficacy and minimise toxicity.

Thus, preclinical and clinical evidence indicate that cinnamon exerts multifactorial antidiabetic effects through insulin-mimetic actions, antioxidant protection, modulation of the gut microbiota, and inhibition of carbohydrate-hydrolysing enzymes. Nevertheless, further large-scale, standardised, and long-duration clinical trials are required to substantiate its therapeutic efficacy, establish optimal dosing regimens, and ensure its safety for long-term metabolic management.

## Therapeutic Dosing and Safety Profile of Cinnamon in Glycaemic Management

A major safety concern regarding cinnamon supplementation is its coumarin content, particularly in *C. cassia* (Figure 4). Coumarin is a naturally occurring aromatic compound that can cause hepatotoxicity and hepatocellular damage when consumed in excessive amounts (Gu et al., 2022). Although adverse effects in humans following coumarin exposure are rare and typically associated with high doses used in clinical treatments, recent studies have reported a link between coumarin administration and the development of liver tumours in rats and mice, as well as Clara cell toxicity and lung tumours in mice (Felter et al., 2006). Initially, coumarin was suspected to possess genotoxic and carcinogenic properties in humans; however, recent toxicological evidence indicates that it is non-genotoxic agent and has enabled the establishment of a tolerable daily intake (Pitaro et al., 2022).

The European Food Safety Authority has established a tolerable daily intake (TDI) for coumarin of 0.1 mg per kilogram of body weight (European Food Safety Authority, 2004), a level that can be readily exceeded through regular consumption of *C. cassia* (cassia cinnamon) supplements. In contrast, *C. verum* contains significantly lower levels of coumarin, often less than 0.004% of its dry weight compared with 0.3–0.8% in *C. cassia* (Jose et al., 2019). This compositional difference renders *C. verum* a safer option for long-term therapeutic use, especially among patients with chronic conditions such as type 2 diabetes. Excessive coumarin intake has been associated with elevated hepatic enzyme levels and, in rare cases, mild hepatotoxicity or hepatitis. However, these effects are generally reversible following discontinuation of supplementation (Shekarchizadeh-Esfahani et al., 2021; Pitaro et al., 2022). Therefore, individuals seeking the glycemic benefits of cinnamon are advised to use *Ceylon cinnamon* or chemically standardised extracts explicitly labelled as 'coumarin-free'. Regular monitoring of hepatic function may also be prudent for patients consuming high doses or undergoing prolonged supplementation (Pitaro et al., 2022).

Clinical studies and meta-analyses suggest that cinnamon can effectively improve glycemic control at daily doses ranging from 0.5 to 6 grams, depending on the form and duration of supplementation and population studied (Kleefstra et al., 2012; Kizilaslan and Erdem, 2019; Zelicha et al., 2024). Lower doses (0.5–2.0 g·day$^{-1}$) are generally sufficient for preventive or adjunctive purposes, whereas higher doses (3–6 g·day$^{-1}$) have been linked to associated with more significant reductions in fasting glucose and HbA1c levels in individuals with type 2 diabetes mellitus. The optimal duration of supplementation appears to range between eight and twelve weeks, with sustained use beyond this period requiring medical supervision (Banaszak et al., 2024). Cinnamon can be administered in various forms, including ground powder, aqueous or ethanolic extracts, and encapsulated preparations. Standardised extracts containing defined concentrations of key bioactive compounds, such as cinnamaldehyde and polyphenols, are preferred to ensure dose precision, reproducibility of effects, and pharmacological consistency (Rao and Gan, 2014). Individual variability in metabolism, dietary intake, and concurrent medication use should be carefully considered, as these factors may influence both efficacy and safety of cinnamon. Gradual titration of dosage and periodic monitoring of glucose and hepatic biomarkers are recommended to optimise therapeutic outcomes while minimising potential adverse effects (Allen et al., 2013; Wang et al., 2025).

Overall, cinnamon is considered well-tolerated when consumed within the recommended dosage ranges. Reported adverse effects are generally mild and transient, including gastrointestinal discomfort, nausea, and oral irritation (Shekarchizadeh-Esfahani et al., 2021; Gu et al., 2022). Hypersensitivity reactions,

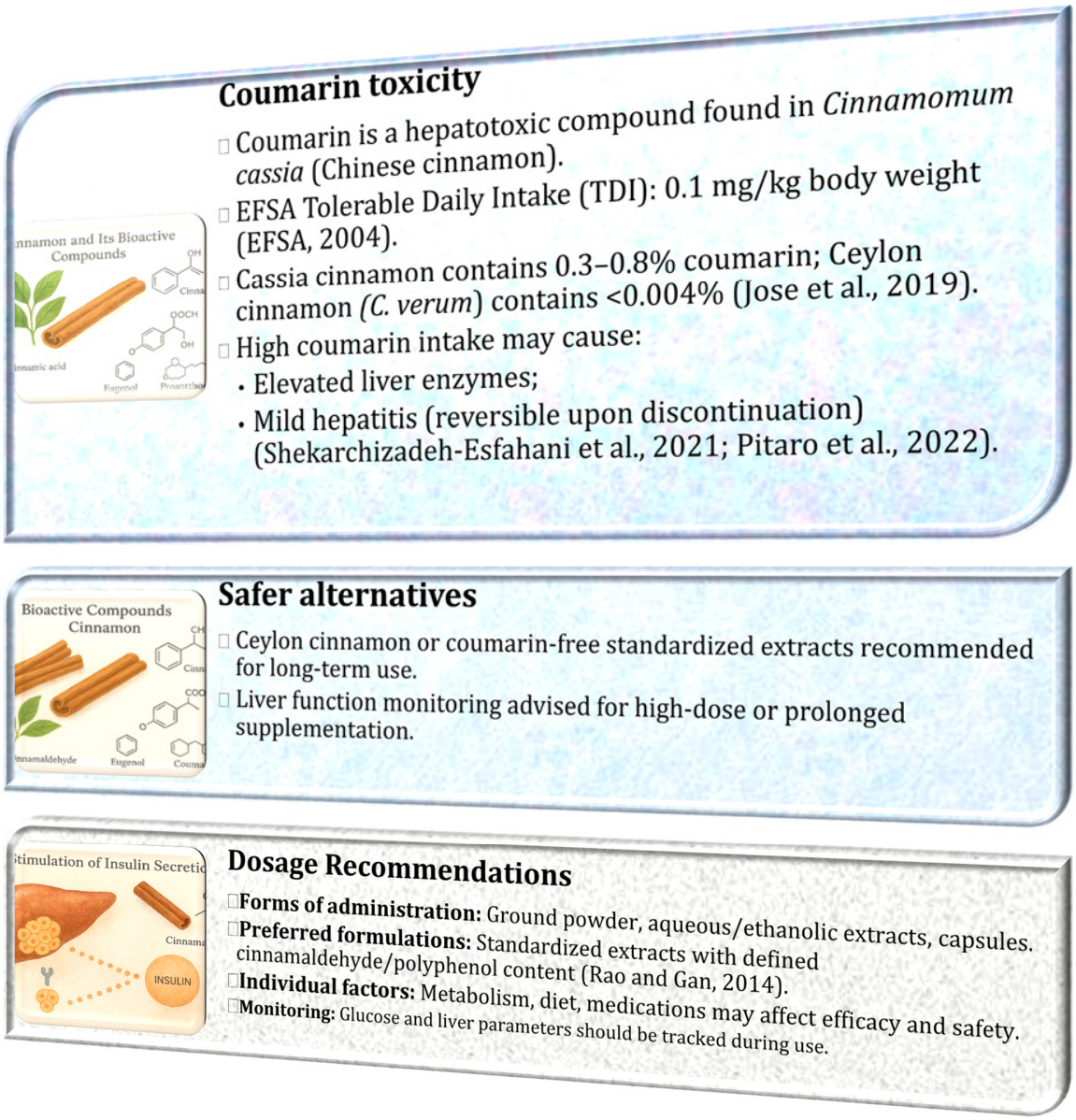


**Figure 4** Safety considerations and dosage recommendations for cinnamon supplementation

such as contact dermatitis or allergic responses to cinnamon oil, are uncommon but may occur, particularly in individuals with pre-existing sensitivities to aromatic spices (Tremblay and Avon, 2008; Isaac-Renton et al., 2015). Potential drug-herb interactions should also be considered, particularly among patients receiving antidiabetic, anticoagulant, or hepatically metabolised medications, as cinnamon may potentiate or interfere with their pharmacodynamics (Gupta et al., 2017). While rare, excessive consumption of cassia cinnamon has been associated with hepatotoxicity due to coumarin accumulation, underlining the importance of species identification and adherence to established dosage limits (Iwata et al., 2016). In clinical practice, *C. verum* is widely regarded as the safer alternative for long-term metabolic support, providing glycaemic benefits without significant adverse outcomes (Qin et al., 2010; Bibi et al., 2024). Continuous post-market surveillance and standardised labelling of cinnamon products are essential to ensure consumer safety and product transparency, and informed decision-making by healthcare professionals (De Silva et al., 2021).

In conclusion, while cinnamon supplementation may offer benefits in managing T2DM, its safety is contingent upon the type of cinnamon used, dosage, and potential interactions with other medications. Individuals considering cinnamon as an adjunct therapy should do so under medical supervision to ensure safety and efficacy.

## Analytical Approaches for Detecting Adulteration and Ensuring the Safety of *Cinnamomum* – Based Medicinal Products

Spices are highly vulnerable to adulteration due to their considerable economic value and extensive global culinary demand (Morin and Lees, 2018; Velázquez et al., 2023). Among these, cinnamon represents one of the most widely traded spices worldwide, serving as a key ingredient in diverse culinary traditions, traditional medicinal practices, and modern scientific research.

Although *C. verum* is regarded as "true cinnamon," other species, most notably *C. cassia*, are also traded commercially. The higher market price of *C. verum* makes it especially vulnerable to adulteration, commonly through substitution or blending with *C. cassia*. This practice not only compromises product authenticity but also raises health concerns, as *C. cassia* contains substantially greater amounts of coumarin, a hepatotoxic compound associated with liver injury upon chronic exposure (Blahová and Svobodová, 2012; Abraham et al., 2020; Pages-Rebull et al., 2024). Mislabeling or intentional blending of *C. cassia* with *C. verum* compromises product authenticity and can thus result in excessive coumarin intake, posing toxicological risks to consumers (Kawatra and Rajagopalan, 2015). Given the widespread use of cinnamon in dietary supplements and medicinal formulations, ensuring its botanical authenticity and chemical safety is of critical importance for public health protection.

Recent advances in analytical chemistry have provided powerful tools for detecting adulteration and assessing the compositional integrity of *Cinnamomum* species. Beyond traditional chromatographic and DNA-based assays (Grazina et al., 2020; Yang et al., 2020), researchers have turned to multi-parametric analytical strategies that integrate several experimental techniques to achieve reliable authentication and quality control (Farag et al., 2022; Ghidotti et al., 2023; Li et al., 2024; Pages-Rebull et al., 2024; Primožič et al., 2025). Analytical metabolite fingerprinting has emerged as a crucial tool for authenticity, quality control, and *Cinnamomum* species discrimination (Farag et al., 2022; Primožič et al., 2025).

One such approach involves reversed-phase high-performance liquid chromatography, which has been employed to quantify four major bioactive compounds – cinnamaldehyde, cinnamic acid, cinnamyl alcohol, and coumarin (He et al., 2005). Based on chromatographic profiles, a five-marker chemical fingerprint was established, enabling reliable differentiation between genuine *C. cassia* and its adulterants. Quantitative analyses revealed that authentic Cassia bark contains notably high levels of cinnamaldehyde (13.01–56.93 $mg \cdot g^{-1}$), with the highest concentrations (up to 93.83 $mg \cdot g^{-1}$) found in the debarked cortex, traditionally regarded as premium quality. In contrast, bark samples from related species such as *C. wilsonii*, *C. japonicum*, *C. mairei*, and *C. burmanni* exhibited significantly lower cinnamaldehyde levels (<2.00 $mg \cdot g^{-1}$), confirming their status as adulterants. In this study, only *C. loureiroi* displayed comparable cinnamaldehyde content to *C. cassia*. These findings demonstrate that HPLC-based chemical fingerprinting represents a robust and reproducible method for quality control and authentication of Cassia bark in both the herbal medicine and spice markets, allowing effective discrimination between authentic products and economically motivated substitutions.

Complementing chromatographic analyses, the study by Primožič et al. (2025) highlighted the effectiveness of an integrated analytical approach that combines isotopic, elemental, spectroscopic, and antioxidant profiling with advanced chemometric modeling. This comprehensive strategy enabled not only species authentication but also the compositional and functional assessment of cinnamon. Significant interspecific differences were observed, with *C. verum* (Sri Lankan cinnamon) exhibiting markedly higher antioxidant activity (AA) and total phenolic content (TPC) compared to *C. cassia*. A strong positive correlation between AA and TPC underscored the influence of species on bioactive compound composition, directly impacting the pharmacological safety and efficacy of cinnamon-derived preparations. Furthermore, stable isotope and elemental profiling facilitated robust classification of geographical origin and agricultural production methods, achieving 89% accuracy for origin differentiation and 95% for cultivation type. Key discriminant markers included Rb, Cu, Ca, Se, $\delta^{13}C$, Na, $\delta^{34}S$, Cs, Mn, $\delta^{15}N$, Al, V, Cd, Fe, Ba, and P, highlighting the analytical depth and precision of the approach. A novel approach employing DNA barcoding coupled with high-resolution melting analysis (Bar-HRM) for the authentication of cinnamon species, specifically to distinguish *C. verum* from its common adulterants, was proposed by Peiris et al. (2025).

Thus, these experimental methodologies, ranging from chromatographic fingerprinting to multi-marker isotopic and elemental analyses, demonstrate the significant role of integrated analytical strategies in detecting adulteration, assessing bioactive composition, and ensuring the chemical safety of *Cinnamomum* – based medicinal formulations. By providing reliable authentication and toxicological evaluation, such approaches contribute to the production of safe, effective, and scientifically validated plant-based therapeutics.

## Integrative Applications of Cinnamon in Glycemic Control and Diabetes Management

Cinnamon can be easily incorporated into the daily diet as a functional food that supports glycemic regulation and overall metabolic health. Common approaches include adding ground cinnamon to beverages such as tea, coffee, and smoothies, as well as using it as a natural flavouring in porridge, yoghurt, and baked goods. These practices not only improve the sensory qualities of food and drink, but also provide a convenient and sustainable means of achieving beneficial intake levels of cinnamon, thereby reducing the need for pharmaceutical supplementation (Santos and da Silva, 2018). In culinary contexts, *C. verum* is recommended due to its low coumarin content and mild flavour profile, making it suitable for regular dietary use (Spence, 2024). To maximise bioavailability, cinnamon may be consumed alongside foods containing healthy fats or proteins, which facilitate the absorption of lipophilic compounds such as cinnamaldehyde (Mohammadabadi and Jain, 2024). Additionally, the preparation of cinnamon-infused teas or decoctions represents a traditional and widely accepted practice that enables controlled intake of water-soluble bioactives with minimal risk of toxicity (Spence, 2024). Regular, moderate dietary consumption can serve as a preventive measure against glucose dysregulation, particularly in individuals at risk of developing metabolic syndrome or prediabetes. Such integrative use aligns with contemporary nutritional strategies that emphasise the preventive role of natural bioactive compounds in chronic disease management (Castro-Barquero et al., 2020).

Beyond its use in the diet, cinnamon is also available in various supplemental forms, including powdered capsules, aqueous and ethanolic extracts, essential oils, and standardised tablets (Nabavi et al., 2015). Standardised extracts of *Ceylon cinnamon* are the most frequently used in clinical trials, as they ensure consistent concentrations of active constituents such as cinnamaldehyde and polyphenols. This standardisation is crucial for maintaining reproducible therapeutic effects while minimising coumarin-related toxicity (Rao and Gan, 2014). Capsules and tablets are particularly suitable for individuals requiring precise dosing who are unable to achieve therapeutic levels through diet alone. Aqueous extracts may offer better gastrointestinal tolerance and more rapid absorption (Silva et al., 2022). Conversely, essential oils are generally not recommended for oral administration due to their high concentration and potential to cause mucosal irritation (Vivas and Migliari, 2015). To ensure both safety and efficacy, consumers should select certified products with transparent labelling of the botanical source, extraction method, and coumarin content. Furthermore, professional guidance from healthcare providers is advised, particularly for individuals already undergoing pharmacological treatment for diabetes.

Integrating cinnamon supplementation into conventional diabetes management represents a promising complementary approach that can improve the efficacy of standard therapies and promote holistic patient care (Allen et al., 2013;

Costello et al., 2016; Silva et al., 2022). Cinnamon can be safely co-administered with oral hypoglycaemic agents such as metformin or sulfonylureas, provided that patients are closely monitored to prevent the risk of hypoglycaemia. Evidence suggests that combining cinnamon with pharmacotherapy yields greater reductions in fasting glucose and HbA1c levels than drug therapy alone (Zhou et al., 2022; Zarezadeh et al., 2023). Furthermore, cinnamon supplementation complements lifestyle modification programmes, focused on dietary regulation and increased physical activity – both of which are cornerstone interventions in type 2 diabetes management (Silva et al., 2022). Its antioxidant and anti-inflammatory properties may also contribute to improved cardiovascular outcomes and mitigation of oxidative stress associated with chronic hyperglycaemia (Mirmiranpour et al., 2019; Silva et al., 2022; Mohammadabadi and Jain, 2024). Successful integration, however, requires clearly defined clinical guidance regarding dosage, treatment duration, and potential contraindications. Therefore, interdisciplinary collaboration among endocrinologists, dietitians, and primary care physicians is essential to establish evidence-based protocols for the use of cinnamon as an adjunctive therapy in diabetes management.

### Limitations and Research Gaps in the Clinical Evaluation of Cinnamon for Diabetes Management

Despite growing scientific interest, the existing body of research on cinnamon's antidiabetic potential is characterised by substantial methodological variability (Zarezadeh et al., 2023; Yu et al., 2023). Studies differ widely in terms of participant characteristics, diabetes severity, intervention duration, and the species or preparation of cinnamon employed (Sithamparapillai et al., 2025). This heterogeneity complicates cross-study comparisons and limits the generalisability of findings, leading to inconsistent conclusions regarding efficacy. Additionally, many studies are constrained by small sample sizes and short intervention periods, reducing statistical power and the capacity to detect subtle metabolic changes (Zelicha et al., 2024; Sithamparapillai et al., 2025). Therefore, to strengthen future evidence, research should adopt standardised experimental protocols incorporating well-defined inclusion criteria, consistent dosage regimens, and validated biomarkers of glycemic control, to ensure methodological rigour and reproducibility.

Although short-term trials have demonstrated significant reductions in fasting glucose and HbA1c levels, the long-term efficacy and safety of cinnamon supplementation remain insufficiently explored. Given that few trials have extended beyond 12–16 weeks, it is unclear whether the observed benefits are sustainable over prolonged use (Zhou et al., 2022; Zarezadeh et al., 2023). Furthermore, chronic exposure to coumarin-containing species raises legitimate concerns regarding cumulative hepatotoxicity and potential pharmacological interactions with concomitant medications (Garrard, 2014; Iwata et al., 2016; Pitaro et al., 2022). To address these uncertainties, large-scale, multicentre, and long-term clinical trials are required to evaluate the durability of metabolic improvements, the potential development of tolerance, and the impact on diabetes-related complications such as neuropathy, nephropathy, and cardiovascular diseases. Generating such data is essential for validating cinnamon as a credible adjunct in chronic diabetes care.

A critical limitation within the current literature is the lack of standardised dosages of cinnamon. Existing studies employ diverse cinnamon types (powders, extracts, and essential oils) at doses ranging from 0.5 to 6 g per day, often without clearly quantifying the bioactive compounds, such as cinnamaldehyde and proanthocyanidins (Pandey et al., 2020; Sharifi-Rad et al., 2021). This inconsistency impedes efforts to identify optimal therapeutic dosages and to evaluate safety thresholds. To address this issue, future investigations should prioritise chemically characterised and standardised preparations with clearly defined phytochemical profiles (Sharifi-Rad et al., 2021; Silva et al., 2022). Establishing consensus on dosage, treatment duration, and relevant bioactive markers will improve reproducibility, enable of cross-trial comparability, and facilitate clinical translation. Such standardisation will also support the development of regulatory frameworks governing the safe and effective use of cinnamon-based supplements in the management of metabolic diseases (Sharifi-Rad et al., 2021).

## Conclusions

Cinnamon has emerged as a promising natural adjunctive therapy in the management of type 2 diabetes mellitus, with a growing body of experimental and clinical evidence supporting its therapeutic use. Its bioactive compounds – primarily cinnamaldehyde, polyphenols, and proanthocyanidins – exert multifaceted mechanisms of action, including the enhancement of insulin sensitivity, stimulation of glucose uptake, inhibition of intestinal glucose absorption, and modulation of oxidative stress and inflammation pathways. Although clinical studies vary in design and methodology, their findings consistently

indicate moderate but significant improvements in fasting blood glucose, HbA1c, and lipid profiles among individuals receiving cinnamon supplementation. Collectively, this evidence suggests that cinnamon may serve as a valuable adjunct in glycaemic regulation, particularly when incorporated into a balanced diet and combined with conventional therapeutic strategies.

From a clinical perspective, cinnamon represents a safe, accessible and cost-effective complementary option for patients seeking to optimise glycaemic control. Integrating it into dietary regimens or supplementation protocols may enhance patient adherence and contribute to improved metabolic outcomes. However, appropriate species selection and dosing are critical to minimising potential adverse effects, particularly those related to coumarin exposure from *Cinnamomum cassia*. For this reason, *Cinnamomum verum* is generally preferred in clinical and nutritional applications due to its lower coumarin content and superior safety profile.

In clinical practice, healthcare professionals are encouraged to incorporate cinnamon supplementation into a comprehensive diabetes management plan alongside pharmacological therapy, dietary, and lifestyle modification. Regular monitoring of blood glucose and hepatic function is advisable during long-term use to ensure safety and therapeutic efficacy. Effective implementation further requires interdisciplinary collaboration among clinicians, dietitians, and researchers to develop evidence-based clinical guidelines for the safe and standardised use of cinnamon in diabetic care.

Despite the encouraging evidence, further investigation is required to consolidate cinnamon's role in diabetes management. A rigorous, interdisciplinary approach integrating clinical pharmacology, nutrition science, and molecular biology is essential to validate its efficacy, elucidate underlying mechanisms, and establish its position as a scientifically substantiated adjunct in the prevention and management of type 2 diabetes.

### Conflicts of Interest

The authors have no competing interests to declare.

### Ethical Statement

This article does not include any studies that would require an ethical statement.

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## References

Abbasi, E., & Khodadadi, I. (2025). High-fat diet may increase the risk of insulin resistance by inducing dysbiosis. *Metabolism Open*, 27, 100381. https://doi.org/10.1016/j.metop.2025.100381

Abeysekera, W. P. K. M., Pemakumara, G. A. S., Ratnasooriya, W. D., & Abeysekera, W. K. S. M. (2022). Anti-inflammatory, cytotoxicity and antilipidemic properties: novel bioactivities of true cinnamon (*Cinnamomum zeylanicum* Blume) leaf. *BMC Complementary Medicine and Therapies*, 22(1), 259. https://doi.org/10.1186/s12906-022-03728-5

Absalan, A., Mohiti-Ardakani, J., Hadinedoushan, H., & Khalili, M. A. (2012). Hydro-alcoholic cinnamon extract, enhances glucose transporter isotype-4 translocation from intracellular compartments into the cytoplasmic cembrane of C2C12 myotubes. *Indian Journal of Clinical Biochemistry: IJCB*, 27(4), 351–356. https://doi.org/10.1007/s12291-012-0214-y

Adisakwattana S. (2017). Cinnamic acid and its derivatives: mechanisms for prevention and management of diabetes and its complications. *Nutrients*, 9(2), 163. https://doi.org/10.3390/nu9020163

Adisakwattana, S., Lerdsuwankij, O., Poputtachai, U., Minipun, A., & Suparpprom, C. (2011). Inhibitory activity of cinnamon bark species and their combination effect with acarbose against intestinal α-glucosidase and pancreatic α-amylase. *Plant Foods for Human Nutrition,* 66(2), 143–148. https://doi.org/10.1007/s11130-011-0226-4

Akilen, R., Tsiami, A., Devendra, D., & Robinson, N. (2010). Glycated haemoglobin and blood pressure-lowering effect of cinnamon in multi-ethnic type 2 diabetic patients in the UK: A randomized, placebo-controlled, double-blind clinical trial. *Diabetic Medicine*, 27(10), 1159–1167. https://doi.org/10.1111/j.1464-5491.2010.03079.x

Akilen, R., Tsiami, A., Devendra, D., & Robinson, N. (2012). Cinnamon in glycaemic control: systematic review and meta analysis. *Clinical Nutrition* (Edinburgh, Scotland), 31(5), 609–615. https://doi.org/10.1016/j.clnu.2012.04.003

Al-Daghri, N. M., Al-Shuwaie, A. Y. A., Alghamdi, A., Amer, O. E., Khattak, M. N. K., Ansari, M. G. A., Alnaami, A. M., & Sabico, S. (2021). Tristetraprolin, inflammation, and metabolic syndrome in Arab adults: A case control study. *Biology*, 10(6), 550. https://doi.org/10.3390/biology10060550

Allen, R. W., Schwartzman, E., Baker, W. L., Coleman, C. I., & Phung, O. J. (2013). Cinnamon use in type 2 diabetes: An

updated systematic review and meta-analysis. *Annals of Family Medicine*, 11(5), 452–459. https://doi.org/10.1370/afm.1517

Anand, P., Murali, K. Y., Tandon, V., Murthy, P. S., & Chandra, R. (2010). Insulinotropic effect of cinnamaldehyde on transcriptional regulation of pyruvate kinase, phosphoenolpyruvate carboxykinase, and GLUT4 translocation in experimental diabetic rats. *Chemico-Biological Interactions,* 186(1), 72–81. https://doi.org/10.1016/j.cbi.2010.03.044

Anderson, R. A., Broadhurst, C. L., Polansky, M. M., Schmidt, W. F., Khan, A., Flanagan, V. P., Schoene, N. W., & Graves, D. J. (2004). Isolation and characterization of polyphenol type-A polymers from cinnamon with insulin-like biological activity. *Journal of Agricultural and Food Chemistry*, 52(1), 65–70. https://doi.org/10.1021/jf034916b

Anderson, R. A., Zhan, Z., Luo, R., Guo, X., Guo, Q., Zhou, J., Kong, J., Davis, P. A., & Stoecker, B. J. (2015). Cinnamon extract lowers glucose, insulin and cholesterol in people with elevated serum glucose. *Journal of Traditional and Complementary Medicine*, 6(4), 332–336. https://doi.org/10.1016/j.jtcme.2015.03.005

Babu, P. V., Liu, D., & Gilbert, E. R. (2013). Recent advances in understanding the anti-diabetic actions of dietary flavonoids. *Journal of Nutritional Biochemistry*, 24(11), 1777–1789. https://doi.org/10.1016/j.jnutbio.2013.06.003

Bai, Y., Tan, D., Deng, Q., Miao, L., Wang, Y., Zhou, Y., Yang, Y., Wang, S., Vong, C. T., & Cheang, W. S. (2025). Cinnamic acid alleviates endothelial dysfunction and oxidative stress by targeting PPARδ in obesity and diabetes. *Chinese Medicine*, 20(1), 13. https://doi.org/10.1186/s13020-025-01064-7

Banaszak, M., Górna, I., Woźniak, D., Przysławski, J., & Drzymała-Czyż, S. (2024). The impact of curcumin, resveratrol, and cinnamon on modulating oxidative stress and antioxidant activity in type 2 diabetes: moving beyond an anti-hyperglycaemic evaluation. *Antioxidants*, 13(5), 510. https://doi.org/10.3390/antiox13050510

Banerji, M. A., & Dunn, J. D. (2013). Impact of glycemic control on healthcare resource utilization and costs of type 2 diabetes: current and future pharmacologic approaches to improving outcomes. *American Health & Drug Benefits*, 6(7), 382–392.

Beejmohun, V., Peytavy-Izard, M., Mignon, C., Muscente-Paque, D., Deplanque, X., Ripoll, C., & Chapal, N. (2014). Acute effect of *Ceylon cinnamon* extract on postprandial glycemia: alpha-amylase inhibition, starch tolerance test in rats, and randomized crossover clinical trial in healthy volunteers. *BMC Complementary and Alternative Medicine*, 14, 351. https://doi.org/10.1186/1472-6882-14-351

Berbudi, A., Khairani, S., & Tjahjadi, A. I. (2025). Interplay between insulin resistance and immune dysregulation in type 2 diabetes mellitus: implications for therapeutic interventions. *ImmunoTargets and Therapy*, 14, 359–382. https://doi.org/10.2147/ITT.S499605

Bibi, T., Altemimi, A. B., Rabail, R., Munir, S., Shahbaz, M. U., Rizvi, M. K., Manzoor, M. F., Abdi, G., Ul Haq, A., & Aadil, R. M. (2024). The therapeutic perspective of cinnamon (*Cinnamomum verum*) consumption against metabolic syndrome. *Journal of Functional Foods,* 122, 106545. https://doi.org/10.1016/j.jff.2024.106545

Blaak, E. E., Antoine, J. M., Benton, D., Björck, I., Bozzetto, L., Brouns, F., Diamant, M., Dye, L., Hulshof, T., Holst, J. J., Lamport, D. J., Laville, M., Lawton, C. L., Meheust, A., Nilson, A., Normand, S., Rivellese, A. A., Theis, S., Torekov, S. S., & Vinoy, S. (2012). Impact of postprandial glycaemia on health and prevention of disease. *Obesity Reviews*, 13(10), 923–984. https://doi.org/10.1111/j.1467-789X.2012.01011.x

Blahová, J., & Svobodová, Z. (2012). Assessment of coumarin levels in ground cinnamon available in the Czech retail market. *The Scientific World Journal*, 2012, 263851. https://doi.org/10.1100/2012/263851

Błaszczyk, N., Rosiak, A., & Kałużna-Czaplińska, J. (2021). The potential role of cinnamon in human health. *Forests*, 12(5), 648. https://doi.org/10.3390/f12050648

Cao, H., Polansky, M. M., & Anderson, R. A. (2007). Cinnamon extract and polyphenols affect the expression of tristetraprolin, insulin receptor, and glucose transporter 4 in mouse 3T3-L1 adipocytes. *Archives of Biochemistry and Biophysics,* 459(2), 214–222. https://doi.org/10.1016/j.abb.2006.12.034

Cao, H., Urban, J. F., Jr, & Anderson, R. A. (2008). Cinnamon polyphenol extract affects immune responses by regulating anti- and proinflammatory and glucose transporter gene expression in mouse macrophages. *The Journal of Nutrition*, 138(5), 833–840. https://doi.org/10.1093/jn/138.5.833

Caserta, S., Genovese, C., Cicero, N., Gangemi, S., & Allegra, A. (2023). The anti-cancer effect of cinnamon aqueous extract: a focus on hematological malignancies. *Life* (Basel, Switzerland), 13(5), 1176. https://doi.org/10.3390/life13051176

Castro-Barquero, S., Ruiz-León, A. M., Sierra-Pérez, M., Estruch, R., & Casas, R. (2020). Dietary strategies for metabolic syndrome: a comprehensive review. *Nutrients*, 12(10), 2983. https://doi.org/10.3390/nu12102983

Chen, B. H., Jen, C. T., Wang, C. C., & Pan, M. H. (2025). Improving Alzheimer's disease and Parkinson's disease in rats with nanoemulsion and byproducts prepared from cinnamon leaves. *Pharmaceutics*, 17(9), 1200. https://doi.org/10.3390/pharmaceutics17091200

Costello, R. B., Dwyer, J. T., Saldanha, L., Bailey, R. L., Merkel, J., & Wambogo, E. (2016). Do cinnamon supplements have a role in glycemic control in type 2 diabetes? A narrative review. *Journal of the Academy of Nutrition and Dietetics*, 116(11), 1794–1802. https://doi.org/10.1016/j.jand.2016.07.015

Couturier, K., Batandier, C., Awada, M., Hininger-Favier, I., Canini, F., Anderson, R. A., Leverve, X., & Roussel, A. M. (2010). Cinnamon improves insulin sensitivity and alters the body composition in an animal model of the metabolic syndrome. *Archives of Biochemistry and Biophysics,* 501(1), 158–161. https://doi.org/10.1016/j.abb.2010.05.032

Crawford P. (2009). Effectiveness of cinnamon for lowering hemoglobin A1C in patients with type 2 diabetes: A randomized, controlled trial. *Journal of the American Board of Family Medicine: JABFM*, 22(5), 507–512. https://doi.org/10.3122/jabfm.2009.05.080093

Datta, T., Chaudhuri, B. N., Guchhait, P., Dawn, A. K., & Das, S. (2024). Antimicrobial effect of *Cinnamomum verum* leaf extract on fungus and MDR bacteria. *East African Scholars Journal of Medical Sciences*, 7(7), 259–265. https://doi.org/10.36349/easms.2024.v07i07.001

De Silva, D. A. M., Jeewanthi, R. K. C., Rajapaksha, R. H. N., Weddagala, W. M. T. B., Hirotsu, N., Shimizu, B. I., & Munasinghe, M. A. J. P. (2021). Clean vs dirty labels: Transparency and authenticity of the labels of *Ceylon cinnamon*. *PloS One*, 16(11), e0260474. https://doi.org/10.1371/journal.pone.0260474

Debnath, I., Ghosh, S., Bhunia, S., Nayak, A., Nandi, S., & Bhattacharjee, S. (2025). Mechanistic and clinical insights into the antidiabetic potential of *Cinnamomum cassia*: A review. *Pharmacological Research – Natural Products*, 8, 100340. https://doi.org/10.1016/j.prenap.2025.100340

Delgadillo-Centeno, J. S., Grover-Páez, F., Hernández-González, S. O., Ramos-Zavala, M. G., Cardona-Müller, D., López-Castro, A., & Pascoe-González, S. (2023). *Cinnamomum cassia* on arterial stiffness and endothelial dysfunction in type 2 diabetes mellitus: Outcomes of a randomized, double-blind, placebo-controlled clinical trial. *Journal of Medicinal Food*, 26(6), 428–434. https://doi.org/10.1089/jmf.2022.0089

Deyno, S., Eneyew, K., Seyfe, S., Tuyiringire, N., Peter, E. L., Muluye, R. A., Tolo, C. U., & Ogwang, P. E. (2019). Efficacy and safety of cinnamon in type 2 diabetes mellitus and pre-diabetes patients: A meta-analysis and meta-regression. *Diabetes Research and Clinical Practice*, 156, 107815. https://doi.org/10.1016/j.diabres.2019.107815

El-Baz, Y. G., Moustafa, A., Ali, M. A., El-Desoky, G. E., Wabaidur, S. M., & Iqbal, A. (2023). Green synthesized silver nanoparticles for the treatment of diabetes and the related complications of hyperlipidemia and oxidative stress in diabetic rats. *Experimental Biology and Medicine*, 248(23), 2237–2248. https://doi.org/10.1177/15353702231214258

European Food Safety Authority (2004). Opinion of the scientific panel on food additives, flavourings, processing aids and materials in contact with food (AFC) on a request from the Commission related to coumarin (Question No. EFSA-Q-2003-118). *The EFSA Journal*, 104, 1–36. https://doi.org/10.2903/j.efsa.2004.104

Fajara, A., Ammara, G. A., Hamzah, M., Manurung, R., & Abduh, M. Y. (2019). Effect of tree age on the yield, productivity, and chemical composition of essential oil from *Cinnamomum burmanni*i. *Current Research on Biosciences and Biotechnology,* 1(1), 17–22.

Farag, M. A., Kabbash, E. M., Mediani, A., Döll, S., Esatbeyoglu, T., & Afifi, S. M. (2022). Comparative metabolite fingerprinting of four different cinnamon species analyzed via UPLC-MS and GC-MS and chemometric tools. *Molecules* (Basel, Switzerland), 27(9), 2935. https://doi.org/10.3390/molecules27092935

Farmani, R., Hosseini, M., Nakhaee, S., Ataie, Z., & Farrokhfall, K. (2025). Hepatoprotective effects of cinnamaldehyde against high-fat diet-induced liver damage. *Avicenna Journal of Phytomedicine*. Advance online publication. https://doi.org/10.22038/AJP.2025.26648

Felter, S. P., Vassallo, J. D., Carlton, B. D., & Daston, G. P. (2006). A safety assessment of coumarin taking into account species-specificity of toxicokinetics. *Food and Chemical Toxicology*, 44(4), 462–475. https://doi.org/10.1016/j.fct.2005.08.019

Gannon, N. P., Schnuck, J. K., Mermier, C. M., Conn, C. A., & Vaughan, R. A. (2015). trans-Cinnamaldehyde stimulates mitochondrial biogenesis through PGC-1α and PPARβ/δ leading to enhanced GLUT4 expression. *Biochimie*, 119, 45–51. https://doi.org/10.1016/j.biochi.2015.10.001

García-Pérez, L. E., Alvarez, M., Dilla, T., Gil-Guillén, V., & Orozco-Beltrán, D. (2013). Adherence to therapies in patients with type 2 diabetes. *Diabetes Therapy,* 4(2), 175–194. https://doi.org/10.1007/s13300-013-0034-y

Garrard, A. (2014). Coumarins. In P. Wexler (Ed.). *Encyclopedia of Toxicology* (3rd ed., pp. 1052–1054). Elsevier. https://doi.org/10.1016/B978-0-12-386454-3.00798-3

Geng, S., Cui, Z., Huang, X., Chen, Y., Xu, D., & Xiong, P. (2011). Variations in essential oil yield and composition during *Cinnamomum cassia* bark growth. *Industrial Crops and Products*, 33(1), 248–252. https://doi.org/10.1016/j.indcrop.2010.10.018

Ghidotti, M., Papoci, S., Pietretti, D., Ždiniaková, T., & de la Calle Guntiñas, M. B. (2023). Use of elemental profiles determined by energy-dispersive X-ray fluorescence and multivariate analyses to detect adulteration in *Ceylon cinnamon*. *Analytical and Bioanalytical Chemistry,* 415(22), 5437–5449. https://doi.org/10.1007/s00216-023-04817-1

Grazina, L., Amaral, J. S., & Mafra, I. (2020). Botanical origin authentication of dietary supplements by DNA-based approaches. *Comprehensive Reviews in Food Science and Food Safety*, 19(3), 1080–1109. https://doi.org/10.1111/1541-4337.12551

Gruenwald, J., Freder, J., & Armbruester, N. (2010). Cinnamon and health. *Critical Reviews in Food Science and Nutrition*, 50(9), 822–834. https://doi.org/10.1080/10408390902773052

Gu, D. T., Tung, T. H., Jiesisibieke, Z. L., Chien, C. W., & Liu, W. Y. (2022). Safety of cinnamon: an umbrella review of meta-analyses and systematic reviews of randomized clinical trials. *Frontiers in Pharmacology*, 12, 790901. https://doi.org/10.3389/fphar.2021.790901

Guariguata, L., Whiting, D. R., Hambleton, I., Beagley, J., Linnenkamp, U., & Shaw, J. E. (2014). Global estimates of diabetes prevalence for 2013 and projections for 2035. *Diabetes Research and Clinical Practice*, 103(2), 137–149. https://doi.org/10.1016/j.diabres.2013.11.002

Guo, J., Jiang, X., Tian, Y., Yan, S., Liu, J., Xie, J., Zhang, F., Yao, C., & Hao, E. (2024). Therapeutic potential of cinnamon oil: chemical composition, pharmacological actions, and applications. *Pharmaceuticals* (Basel, Switzerland), 17(12), 1700. https://doi.org/10.3390/ph17121700

Gupta, R. C., Chang, D., Nammi, S., Bensoussan, A., Bilinski, K., & Roufogalis, B. D. (2017). Interactions between antidiabetic drugs and herbs: an overview of mechanisms of action and clinical implications. *Diabetology & Metabolic Syndrome*, 9, 59. https://doi.org/10.1186/s13098-017-0254-9

Hafizur, R. M., Hameed, A., Shukrana, M., Raza, S. A., Chishti, S., Kabir, N., & Siddiqui, R. A. (2015). Cinnamic acid exerts anti-diabetic activity by improving glucose tolerance in vivo and by stimulating insulin secretion *in vitro*. *Phytomedicine*, 22(2), 297–300. https://doi.org/10.1016/j.phymed.2015.01.003

Hameed, I., Masoodi, S. R., Mir, S. A., Nabi, M., Ghazanfar, K., & Ganai, B. A. (2015). Type 2 diabetes mellitus: From a metabolic disorder to an inflammatory condition. *World Journal of Diabetes*, 6(4), 598–612. https://doi.org/10.4239/wjd.v6.i4.598

Hariri, M., & Ghiasvand, R. (2016). Cinnamon and Chronic Diseases. In: Gupta, S., Prasad, S., Aggarwal, B. (eds). Drug discovery from mother nature. *Advances in Experimental Medicine and Biology,* 929. Springer, Cham. https://doi.org/10.1007/978-3-319-41342-6_1

Hayward, N. J., McDougall, G. J., Farag, S., Allwood, J. W., Austin, C., Campbell, F., Horgan, G., & Ranawana, V. (2019). Cinnamon shows antidiabetic properties that are species-specific: Effects on enzyme activity inhibition and starch digestion. *Plant Foods for Human Nutrition,* 74(4), 544–552. https://doi.org/10.1007/s11130-019-00760-8

He, Z. D., Qiao, C. F., Han, Q. B., Cheng, C. L., Xu, H. X., Jiang, R. W., But, P. P., & Shaw, P. C. (2005). Authentication and quantitative analysis on the chemical profile of cassia bark (*Cortex cinnamomi*) by high-pressure liquid chromatography. *Journal of Agricultural and Food Chemistry*, 53(7), 2424–2428. https://doi.org/10.1021/jf048116s

Hossain, M. J., Al-Mamun, M., & Islam, M. R. (2024). Diabetes mellitus, the fastest growing global public health concern: Early detection should be focused. *Health Science Reports*, 7(3), e2004. https://doi.org/10.1002/hsr2.2004

Huang, B., Yuan, H. D., Kim, D. Y., Quan, H. Y., & Chung, S. H. (2011). Cinnamaldehyde prevents adipocyte differentiation and adipogenesis via regulation of peroxisome proliferator-activated receptor-γ (PPARγ) and AMP-activated protein kinase (AMPK) pathways. *Journal of Agricultural and Food Chemistry*, 59(8), 3666–3673. https://doi.org/10.1021/jf104814t

Huang, H., Chen, R., Ma, H., & Yuan, Z. (2019). Quality attributes and chemical composition of commercial cinnamon oils. *Quality Assurance and Safety of Crops & Foods*, 11(1), 89–94. https://doi.org/10.3920/QAS2018.1348

Isaac-Renton, M., Li, M. K., & Parsons, L. M. (2015). Cinnamon spice and everything not nice: many features of intraoral allergy to cinnamic aldehyde. *Dermatitis: Contact, Atopic, Occupational, Drug,* 26(3), 116–121. https://doi.org/10.1097/DER.0000000000000112

Iwata, N., Kainuma, M., Kobayashi, D., Kubota, T., Sugawara, N., Uchida, A., Ozono, S., Yamamuro, Y., Furusyo, N., Ueda, K., Tahara, E., & Shimazoe, T. (2016). The relation between hepatotoxicity and the total coumarin intake from traditional Japanese medicines containing cinnamon bark. *Frontiers in Pharmacology*, 7, 174. https://doi.org/10.3389/fphar.2016.00174

Jarvill-Taylor, K. J., Anderson, R. A., & Graves, D. J. (2001). A hydroxychalcone derived from cinnamon functions as a mimetic for insulin in 3T3-L1 adipocytes. *Journal of the American College of Nutrition*, 20(4), 327–336. https://doi.org/10.1080/07315724.2001.10719053

Jayaprakasha, G. K., & Rao, L. J. (2011). Chemistry, biogenesis, and biological activities of *Cinnamomum zeylanicum*. *Critical Reviews in Food Science and Nutrition*, 51(6), 547–562. https://doi.org/10.1080/10408391003699550

Jayaprakasha, G. K., Rao, L. J., & Sakariah, K. K. (2002). Chemical composition of volatile oil from *Cinnamomum zeylanicum* buds. *Zeitschrift für Naturforschung C*, 57(11–12), 990–993. https://doi.org/10.1515/znc-2002-11-1206

Jose, A. J., Leela, N. K., Zachariah, T. J., & Rema, J. (2019). Evaluation of coumarin content and essential oil constituents in *Cinnamomum cassia* (Nees & T. Nees) J. Presl. *Journal of Spices and Aromatic Crops,* 28(1), 43–51. https://doi.org/10.25081/josac.2019.v28.i1.5743

Kawatra, P., & Rajagopalan, R. (2015). Cinnamon: mystic powers of a minute ingredient. *Pharmacognosy Research*, 7(1), S1–S6. https://doi.org/10.4103/0974-8490.157990

Khan, A., Bryden, N. A., Polansky, M. M., & Anderson, R. A. (1990). Insulin potentiating factor and chromium content of selected foods and spices. *Biological Trace Element Research*, 24(3), 183–188. https://doi.org/10.1007/BF02917206

Khan, A., Safdar, M., Ali Khan, M. M., Khattak, K. N., & Anderson, R. A. (2003). Cinnamon improves glucose and lipids of people with type 2 diabetes. *Diabetes Care*, 26(12), 3215–3218. https://doi.org/10.2337/diacare.26.12.3215

Khan, R., Khan, Z., & Shah, S. H. (2010). Cinnamon may reduce glucose, lipid and cholesterol level in type 2 diabetic individuals. *Pakistan Journal of Nutrition*, 9(5), 430–433. https://doi.org/10.3923/pjn.2010.430.433

Khare, P., Jagtap, S., Jain, Y., Baboota, R. K., Mangal, P., & Boparai, R. K. (2016). Cinnamaldehyde supplementation prevents fasting-induced hyperphagia, lipid accumulation, and

inflammation in high-fat diet-fed mice. *Biofactors*, 42(2), 201–211. https://doi.org/10.1002/biof.1265

Kizilaslan, N., & Erdem, N. Z. (2019). The effect of different amounts of cinnamon consumption on blood glucose in healthy adult individuals. *International Journal of Food Science*, 2019, 4138534. https://doi.org/10.1155/2019/4138534

Kleefstra, N., Logtenberg, S. J., Groenier, K. H., & Bilo, H. J. (2012). Cinnamon in glycaemic control: systematic review and meta analysis. *Clinical Nutrition* (Edinburgh, Scotland), 31(5), 776–777. https://doi.org/10.1016/j.clnu.2012.06.007

Kouzi, S. A., Yang, S., Nuzum, D. S., & Dirks-Naylor, A. J. (2015). Natural supplements for improving insulin sensitivity and glucose uptake in skeletal muscle. *Frontiers in Bioscience*, 7(1), 94–106. https://doi.org/10.2741/E720

Kowalska, J., Tyburski, J., Matysiak, K., Jakubowska, M., Łukaszyk, J., & Krzymińska, J. (2021). Cinnamon as a useful preventive substance for the care of human and plant health. *Molecules* (Basel, Switzerland), 26(17), 5299. https://doi.org/10.3390/molecules26175299

Kreydiyyeh, S. I., Usta, J., & Copti, R. (2000). Effect of cinnamon, clove and some of their constituents on the $Na^+$-$K^+$-ATPase activity and alanine absorption in the rat jejunum. *Food and Chemical Toxicology*, 38(9), 755–762. https://doi.org/10.1016/S0278-6915(00)00073-9

Külkamp, J., Amar, G., Chittiboyina, A. G., Osman, A. G., & Khan, I. (2025). Proposal to conserve the name *Cinnamomum cassia* Nees ex Blume against *C. cassia* (L.) J. Presl/D. Don (Lauraceae). *Taxon*, 74(5), 1271–1272. https://doi.org/10.1002/tax.70047

Kulkarni, A., Thool, A. R., & Daigavane, S. (2024). Understanding the clinical relationship between diabetic retinopathy, nephropathy, and neuropathy: a comprehensive review. *Cureus*, 16(3), e56674. https://doi.org/10.7759/cureus.56674

Lee, S. C., Xu, W. X., Lin, L. Y., Yang, J. J., & Liu, C. T. (2013). Chemical composition and hypoglycemic and pancreas-protective effect of leaf essential oil from indigenous cinnamon (*Cinnamomum osmophloeum* Kanehira). *Journal of Agricultural and Food Chemistry*, 61(20), 4905–4913. https://doi.org/10.1021/jf401039z

Li, W., Qiao, J., Lin, K., Sun, P., Wang, Y., Peng, Q., Ye, X., Liu, W., & Sun, B. (2023). Ethyl-acetate fraction from a cinnamon-cortex extract protects pancreatic β-cells from oxidative stress damage. *Frontiers in Pharmacology*, 14, 1111860. https://doi.org/10.3389/fphar.2023.1111860

Li, Y., Yang, Y., Gu, D., Cheng, Y., Lv, X., Huang, Y., Ye, P., Zhang, X., Zhang, J., Jian, W., Liu, Y., Guo, Y., Bai, M., Huang, R., & Wu, H. (2024). Investigation of the impact of diverse climate conditions on the cultivation suitability of *Cinnamomum cassia* using the MaxEnt model, HPLC and chemometric methods in China. *Scientific Reports,* 14(1), 25686. https://doi.org/10.1038/s41598-024-75189-4

Lin, X., Xu, Y., Pan, X., Xu, J., Ding, Y., Sun, X., Song, X., Ren, Y., & Shan, P. F. (2020). Global, regional, and national burden and trend of diabetes in 195 countries and territories: An analysis from 1990 to 2025. *Scientific Reports,* 10(1), 14790. https://doi.org/10.1038/s41598-020-71908-9

Liyanage, N. M. N., Bandusekara, B. S., Kanchanamala, R. W. M. K., Hathurusinghe, H. A. B. M., Rathnayaka, A. M. R. W. S. D., Pushpakumara, D. K. N. G., Samita, S., Wijesinghe, K. G. G., Jayasinghe, G. G., Liyanage, W. K., & Bandaranayake, P. C. G. (2021). Identification of superior *Cinnamomum zeylanicum* Blume germplasm for future true cinnamon breeding in the world. *Journal of Food Composition and Analysis*, 96, 103747. https://doi.org/10.1016/j.jfca.2020.103747

Lu, T., Sheng, H., Wu, J., Cheng, Y., Zhu, J., & Chen, Y. (2012). Cinnamon extract improves fasting blood glucose and glycosylated hemoglobin level in Chinese patients with type 2 diabetes. *Nutrition Research* (New York, N.Y.), 32(6), 408–412. https://doi.org/10.1016/j.nutres.2012.05.003

Mallavarapu, G. R., Ramesh, S., Chandrasekhara, R. S., Rajeswara Rao, B. R., Kaul, P. N., & Bhattacharya, A. K. (1995). Investigation of the essential oil of cinnamon leaf grown at Bangalore and Hyderabad. *Flavour and Fragrance Journal*, 10(4), 239–242. https://doi.org/10.1002/ffj.2730100403

Mang, B., Wolters, M., Schmitt, B., Kelb, K., Lichtinghagen, R., Stichtenoth, D. O., & Hahn, A. (2006). Effects of a cinnamon extract on plasma glucose, HbA, and serum lipids in diabetes mellitus type 2. *European Journal of Clinical Investigation*, 36(5), 340–344. https://doi.org/10.1111/j.1365-2362.2006.01629.x

Markey, O., McClean, C. M., Medlow, P., Davison, G. W., Trinick, T. R., Duly, E., & Shafat, A. (2011). Effect of cinnamon on gastric emptying, arterial stiffness, postprandial lipemia, glycemia, and appetite responses to high-fat breakfast. *Cardiovascular Diabetology*, 10, 78. https://doi.org/10.1186/1475-2840-10-78

Martinez, M., Santamarina, J., Pavesi, A., Musso, C., & Umpierrez, G. E. (2021). Glycemic variability and cardiovascular disease in patients with type 2 diabetes. *BMJ Open Diabetes Research & Care*, 9(1), e002032. https://doi.org/10.1136/bmjdrc-2020-002032

Medagama A. B. (2015). The glycaemic outcomes of Cinnamon, a review of the experimental evidence and clinical trials. Nutrition Journal, 14, 108. https://doi.org/10.1186/s12937-015-0098-9

Mirmiranpour, H., Huseini, H. F., Derakhshanian, H., Khodaii, Z., & Tavakoli-Far, B. (2019). Effects of probiotic, cinnamon, and synbiotic supplementation on glycemic control and antioxidant status in people with type 2 diabetes; a randomized, double-blind, placebo-controlled study. *Journal of Diabetes and Metabolic Disorders*, 19(1), 53–60. https://doi.org/10.1007/s40200-019-00474-3

Mishra, A., Bhatti, R., Singh, A., & Singh Ishar, M. P. (2010). Ameliorative effect of the cinnamon oil from *Cinnamomum zeylanicum* upon early stage diabetic nephropathy. *Planta Medica*, 76(5), 412–417. https://doi.org/10.1055/s-0029-1186237

Młynarska, E., Czarnik, W., Dzieża, N., Jędraszak, W., Majchrowicz, G., Prusinowski, F., Stabrawa, M., Rysz, J., & Franczyk, B. (2025). Type 2 diabetes mellitus: new pathogenetic mechanisms, treatment and the most important complications. *International Journal of Molecular Sciences*, 26(3), 1094. https://doi.org/10.3390/ijms26031094

Mohamed Sham Shihabudeen, H., Hansi Priscilla, D., & Thirumurugan, K. (2011). Cinnamon extract inhibits α-glucosidase activity and dampens postprandial glucose excursion in diabetic rats. *Nutrition & Metabolism*, 8(1), 46. https://doi.org/10.1186/1743-7075-8-46

Mohammadabadi, T., & Jain, R. (2024). Cinnamon: a nutraceutical supplement for the cardiovascular system. *Archives of Medical Sciences – Atherosclerotic Diseases*, 9, e72–e81. https://doi.org/10.5114/amsad/184245

Mohsin, S. N., Saleem, F., Humayun, A., Tanweer, A., & Muddassir, A. (2023). Prospective nutraceutical effects of cinnamon derivatives against insulin resistance in type II diabetes mellitus-evidence from the literature. *Dose-Response*, 21(3), 15593258231200527. https://doi.org/10.1177/15593258231200527

Mollazadeh, H., & Hosseinzadeh, H. (2016). Cinnamon effects on metabolic syndrome: a review based on its mechanisms. *Iranian Journal of Basic Medical Sciences*, 19(12), 1258–1270. https://doi.org/10.22038/ijbms.2016.7906

Moridpour, A. H., Kavyani, Z., Khosravi, S., Farmani, E., Daneshvar, M., *Musa*zadeh, V., & Faghfouri, A. H. (2024). The effect of cinnamon supplementation on glycemic control in patients with type 2 diabetes mellitus: An updated systematic review and dose-response meta-analysis of randomized controlled trials. *Phytotherapy Research: PTR*, 38(1), 117–130. https://doi.org/10.1002/ptr.8026

Mousavi, S. M., Jayedi, A., Bagheri, A., Zargarzadeh, N., Wong, A., Persad, E., Akhgarjand, C., & Koohdani, F. (2021). What is the influence of cinnamon supplementation on liver enzymes? A systematic review and meta-analysis of randomized controlled trials. *Phytotherapy Research*, 35(10), 5634–5646. https://doi.org/10.1002/ptr.7200

Muthukuda, D., de Silva, C. K., Ajanthan, S., Wijesinghe, N., Dahanayaka, A., & Pathmeswaran, A. (2025). Effects of *Cinnamomum zeylanicum* (*Ceylon cinnamon*) extract on lipid profile, glucose levels and its safety in adults: A randomized, double-blind, controlled trial. *PLoS ONE*, 20(1), e0317904. https://doi.org/10.1371/journal.pone.0317904

Mutlu, M., Bingol, Z., Uc, E. M., Köksal, E., Goren, A. C., Alwasel, S. H., & Gulcin, İ. (2023). Comprehensive metabolite profiling of cinnamon (*Cinnamomum zeylanicum*) leaf oil using LC-HR/MS, GC/MS, and GC-FID: Determination of antiglaucoma, antioxidant, anticholinergic, and antidiabetic profiles. *Life*, 13(1), 136. https://doi.org/10.3390/life13010136

Nabavi, S. F., Di Lorenzo, A., Izadi, M., Sobarzo-Sánchez, E., Daglia, M., & Nabavi, S. M. (2015). Antibacterial effects of cinnamon: from farm to food, cosmetic and pharmaceutical industries. *Nutrients*, 7(9), 7729–7748. https://doi.org/10.3390/nu7095359

Nanda, J., Verma, N., & Mani, M. (2023). A mechanistic review on phytomedicine and natural products in the treatment of diabetes. *Current Diabetes Reviews*, 19(7), e221222212125. https://doi.org/10.2174/1573399819666221222155055

Niazmand, S., Mirzaei, M., Hosseinian, S., Khazdair, M. R., Gowhari Shabgah, A., Baghcheghi, Y., & Hedayati-Moghadam, M. (2021). The effect of *Cinnamomum cassia* extract on oxidative stress in the liver and kidney of STZ-induced diabetic rats. *Journal of Complementary & Integrative Medicine*, 19(2), 311–321. https://doi.org/10.1515/jcim-2021-0142

Nisar, M. F., Khadim, M., Rafiq, M., Chen, J., Yang, Y., & Wan, C. C. (2021). Pharmacological properties and health benefits of eugenol: a comprehensive review. *Oxidative Medicine and Cellular Longevity*, 2021, 2497354. https://doi.org/10.1155/2021/2497354

Pagliari, S., Forcella, M., Lonati, E., Sacco, G., Romaniello, F., Rovellini, P., Fusi, P., Palestini, P., Campone, L., Labra, M., Bulbarelli, A., & Bruni, I. (2023). Antioxidant and anti-inflammatory effect of cinnamon (*Cinnamomum verum* J. Presl) bark extract after *in vitro* digestion simulation. *Foods* (Basel, Switzerland), 12(3), 452. https://doi.org/10.3390/foods12030452

Pages-Rebull, J., Pérez-Ràfols, C., Serrano, N., & Díaz-Cruz, J. M. (2024). Analytical methods for cinnamon authentication. *Trends in Food Science & Technology*, 146, 104388. https://doi.org/10.1016/j.tifs.2024.104388

Pandey, A., Tripathi, P., Pandey, R., Srivatava, R., & Goswami, S. (2011). Alternative therapies useful in the management of diabetes: A systematic review. *Journal of Pharmacy & Bioallied Sciences*, 3(4), 504–512. https://doi.org/10.4103/0975-7406.90103

Pandey, D. K., Chaudhary, R., Dey, A., Nandy, S., Banik, R. M., Malik, T., & Dwivedi, P. (2020). Current knowledge of *Cinnamomum* species: A review on the bioactive components, pharmacological properties, analytical and biotechnological studies. In: J. Singh, V. Meshram, & M. Gupta (Eds.). *Bioactive Natural products in Drug Discovery* (pp. 127–164). Springer. https://doi.org/10.1007/978-981-15-1394-7_3

Paranagama, P. A., Wimalasena, S., Jayatilake, G. S., Jayawardena, A. L., Senanayake, U. M., & Mubarak, A. M. (2001). A comparison of essential oil constituents of bark, leaf, root and fruit of cinnamon (*Cinnamomum zeylanicum* Blum) grown in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, 29(3–4), 147–153. https://doi.org/10.4038/jnsfsr.v29i3-4.2613

Pathirana, R., & Senaratne, R. (2020). An introduction to Sri Lanka and its cinnamon industry. In: R. Senaratne & R. Pathirana (Eds.). *Cinnamon: Botany, Agronomy, Chemistry and Industrial Applications* (pp. 1–38). Cham, Switzerland: Springer.

Peiris, M. A. L. M., Nanayakkara, D., Silva, C., Abeysundara, S. P., & Wijesinghe, P. (2025). Barcode high-resolution

melting (Bar-HRM) analysis to authenticate true cinnamon (*Cinnamomum verum*) from its adulterants and contaminants. *PloS One*, 20(9), e0328808. https://doi.org/10.1371/journal.pone.0328808

Peng, X., Cheng, K. W., Ma, J., Chen, B., Ho, C. T., Lo, C., Chen, F., & Wang, M. (2008). Cinnamon bark proanthocyanidins as reactive carbonyl scavengers to prevent the formation of advanced glycation endproducts. *Journal of Agricultural and Food Chemistry*, 56(6), 1907–1911. https://doi.org/10.1021/jf073065v

Pitaro, M., Croce, N., Gallo, V., Arienzo, A., Salvatore, G., & Antonini, G. (2022). Coumarin-induced hepatotoxicity: a narrative review. *Molecules* (Basel, Switzerland), 27(24), 9063. https://doi.org/10.3390/molecules27249063

Poonoosamy, J., Lopes, P., Huret, P., Dardari, R., Penfornis, A., Thomas, C., & Dardari, D. (2023). Impact of intensive glycemic treatment on diabetes complications – a systematic review. *Pharmaceutics*, 15(7), 1791. https://doi.org/10.3390/pharmaceutics15071791

Primožič, S., Terro, C., Strojnik, L., Šegatin, N., Poklar Ulrih, N., & Ogrinc, N. (2025). Assessing the authenticity and quality of paprika (*Capsicum annuum*) and cinnamon (*Cinnamomum* spp.) in the Slovenian market: a multi-analytical and chemometric approach. *Foods*, 14(13), 2323. https://doi.org/10.3390/foods14132323

Qin, B., Dawson, H., Polansky, M. M., & Anderson, R. A. (2009). Cinnamon extract attenuates TNF-alpha-induced intestinal lipoprotein ApoB48 overproduction by regulating inflammatory, insulin, and lipoprotein pathways in enterocytes. *Hormone and Metabolic Research*, 41(7), 516–522. https://doi.org/10.1055/s-0029-1202813

Qin, B., Nagasaki, M., Ren, M., Bajotto, G., Oshida, Y., & Sato, Y. (2003). Cinnamon extract (traditional herb) potentiates in vivo insulin-regulated glucose utilization via enhancing insulin signaling in rats. *Diabetes Research and Clinical Practice*, 62(3), 139–148. https://doi.org/10.1016/s0168-8227(03)00173-6

Qin, B., Nagasaki, M., Ren, M., Bajotto, G., Oshida, Y., & Sato, Y. (2004). Cinnamon extract prevents the insulin resistance induced by a high-fructose diet. *Hormone and Metabolic*, 36(2), 119–125. https://doi.org/10.1055/s-2004-814223

Qin, B., Panickar, K. S., & Anderson, R. A. (2010). Cinnamon: potential role in the prevention of insulin resistance, metabolic syndrome, and type 2 diabetes. *Journal of Diabetes Science and Technology*, 4(3), 685–693. https://doi.org/10.1177/193229681000400324

Qin, B., Qiu, W., Avramoglu, R. K., & Adeli, K. (2007). Tumor necrosis factor-alpha induces intestinal insulin resistance and stimulates the overproduction of intestinal apolipoprotein B48-containing lipoproteins. *Diabetes*, 56(2), 450–461. https://doi.org/10.2337/db06-0518

Ranasinghe, P., Jayawardana, R., Galappaththy, P., Constantine, G. R., de Vas Gunawardana, N., & Katulanda, P. (2012). Efficacy and safety of 'true' cinnamon (*Cinnamomum zeylanicum*) as a pharmaceutical agent in diabetes: a systematic review and meta-analysis. *Diabetic Medicine*, 29(12), 1480–1492. https://doi.org/10.1111/j.1464-5491.2012.03718.x

Ranasinghe, P., Pigera, S., Premakumara, G. A., Galappaththy, P., Constantine, G. R., & Katulanda, P. (2013). Medicinal properties of 'true' cinnamon (*Cinnamomum zeylanicum*): A systematic review. *BMC Complementary and Alternative Medicine*, 13, 275. https://doi.org/10.1186/1472-6882-13-275

Rao, P. V., & Gan, S. H. (2014). Cinnamon: a multifaceted medicinal plant. *Evidence-Based Complementary and Alternative Medicine: eCAM*, 2014, 642942. https://doi.org/10.1155/2014/642942

Rao, V. V., & Shanti, K. N. (2025). Molecular interaction profiling and binding dynamics of *Cinnamomum zeylanicum* phytochemicals with human pancreatic amylase. *Journal of Molecular Graphics & Modelling*, 136, 108938. https://doi.org/10.1016/j.jmgm.2024.108938

Roffey, B., Atwal, A., & Kubow, S. (2006). Cinnamon water extracts increase glucose uptake but inhibit adiponectin secretion in 3T3-L1 adipose cells. *Molecular Nutrition & Food Research,* 50(8), 739–745. https://doi.org/10.1002/mnfr.200500253

Safdar, M., Khan, A., Khan-Khattak, M. M. A., & Siddique, M. (2004). Effect of various doses of cinnamon on blood glucose in diabetic individuals. *Pakistan Journal of Nutrition*, 3(5), 268–272. https://doi.org/10.3923/pjn.2004.268.272

Sahib A. S. (2016). Anti-diabetic and antioxidant effect of cinnamon in poorly controlled type-2 diabetic Iraqi patients: A randomized, placebo-controlled clinical trial. *Journal of Intercultural Ethnopharmacology*, 5(2), 108–113. https://doi.org/10.5455/jice.20160217044511

Sangal, A. (2011). Role of cinnamon as a beneficial antidiabetic food adjunct: A review. *Advances in Applied Science Research*, 2(4), 440–450.

Santos, H. O., & da Silva, G. A. R. (2018). To what extent does cinnamon administration improve the glycemic and lipid profiles? *Clinical Nutrition* ESPEN, 27, 1–9. https://doi.org/10.1016/j.clnesp.2018.07.011

Sarmadi, B., *Musa*zadeh, V., Dehghan, P., & Karimi, E. (2023). The effect of cinnamon consumption on lipid profile, oxidative stress, and inflammation biomarkers in adults: An umbrella meta-analysis of randomized controlled trials. *Nutrition, Metabolism and Cardiovascular Diseases*, 33(10), 1821–1835. https://doi.org/10.1016/j.numecd.2023.03.010

Senevirathne, B. S., Jayasinghe, M. A., Pavalakumar, D., & Siriwardhana, C. G. (2022). *Ceylon cinnamon*: A versatile ingredient for futuristic diabetes management. *Journal of Future Foods*, 2(2), 125–142. https://doi.org/10.1016/j.jfutfo.2022.03.010

Sharifi-Rad, J., Dey, A., Koirala, N., Shaheen, S., El Omari, N., Salehi, B., Goloshvili, T., Cirone Silva, N. C., Bouyahya, A., Vitalini, S., Varoni, E. M., Martorell, M., Abdolshahi, A., Docea, A. O., Iriti, M., Calina, D., Les, F., López, V., & Caruntu, C. (2021). *Cinnamomum* species: bridging

phytochemistry knowledge, pharmacological properties and toxicological safety for health benefits. *Frontiers in Pharmacology*, 12, 600139. https://doi.org/10.3389/fphar.2021.600139

Shekarchizadeh-Esfahani, P., Heydarpour, F., Izadi, F., & Jalili, C. (2021). The effect of cinnamon supplementation on liver enzymes in adults: A systematic review and meta-analysis of randomized controlled trials. *Complementary Therapies in Medicine*, 58, 102699. https://doi.org/10.1016/j.ctim.2021.102699

Shen, Y., Fukushima, M., Ito, Y., Muraki, E., Hosono, T., Seki, T., & Ariga, T. (2010). Verification of the antidiabetic effects of cinnamon (*Cinnamomum zeylanicum*) using insulin-uncontrolled type 1 diabetic rats and cultured adipocytes. *Bioscience, Biotechnology, and Biochemistry*, 74(12), 2418–2425. https://doi.org/10.1271/bbb.100453

Shen, Y., Honma, N., Kobayashi, K., Jia, L. N., Hosono, T., Shindo, K., Ariga, T., & Seki, T. (2014). Cinnamon extract enhances glucose uptake in 3T3-L1 adipocytes and C2C12 myocytes by inducing LKB1-AMP-activated protein kinase signaling. *PloS One*, 9(2), e87894. https://doi.org/10.1371/journal.pone.0087894

Sheng, X., Zhang, Y., Gong, Z., Huang, C., & Zang, Y. Q. (2008). Improved insulin resistance and lipid metabolism by cinnamon extract through activation of peroxisome proliferator-activated receptors. *PPAR Research*, 2008, 581348. https://doi.org/10.1155/2008/581348

Shinjyo, N., Waddell, G., & Green, J. (2020). A tale of two cinnamons: A comparative review of the clinical evidence of *Cinnamomum verum* and *C. cassia* as diabetes interventions. *Journal of Herbal Medicine*, 21, 100342. https://doi.org/10.1016/j.hermed.2020.100342

Silva, M. L., Bernardo, M. A., Singh, J., & de Mesquita, M. F. (2022). Cinnamon as a complementary therapeutic approach for dysglycemia and dyslipidemia control in type 2 diabetes mellitus and its molecular mechanism of action: A review. *Nutrients*, 14(13), 2773. https://doi.org/10.3390/nu14132773

Sithamparapillai, K., Shanmuganathan, R., & Rajaratnam, S. (2025). Efficacy of cinnamon in treating individuals with diabetes: An updated systematic review and meta-analysis. *Jaffna Medical Journal*, 37(1), 13–22. https://doi.org/10.4038/jmj.v37i1.232

Spence, C. (2024). Cinnamon: The historic spice, medicinal uses, and flavour chemistry. *International Journal of Gastronomy and Food Science*, 35, 100858. https://doi.org/10.1016/j.ijgfs.2023.100858

Stevens, N., & Allred, K. (2022). Antidiabetic potential of volatile cinnamon oil: A review and exploration of mechanisms using *in silico* molecular docking simulations. *Molecules* (Basel, Switzerland), 27(3), 853. https://doi.org/10.3390/molecules27030853

Subash Babu, P., Prabuseenivasan, S., & Ignacimuthu, S. (2007). Cinnamaldehyde – a potential antidiabetic agent. *Phytomedicine*, 14(1), 15–22. https://doi.org/10.1016/j.phymed.2006.11.005

Sun, S., Yu, Y., Jo, Y., Han, J. H., Xue, Y., Cho, M., Bae, S. J., Ryu, D., Park, W., Ha, K. T., & Zhuang, S. (2025). Impact of extraction techniques on phytochemical composition and bioactivity of natural product mixtures. *Frontiers in Pharmacology*, 16, 1615338. https://doi.org/10.3389/fphar.2025.1615338

Sun, X.-D., Zhang, M., Liang, H., Zhang, S., Wang, P.-J., & Gao, X.-L. (2024). Geographical origin identification of cinnamon using HPLC-DAD fingerprints and chemometrics. *Microchemical Journal*, 207, 111768. https://doi.org/10.1016/j.microc.2024.111768

Talaei, B., Amouzegar, A., Sahranavard, S., Hedayati, M., Mirmiran, P., & Azizi, F. (2017). Effects of cinnamon consumption on glycemic indicators, advanced glycation end products, and antioxidant status in type 2 diabetic patients. *Nutrients*, 9(9), 991. https://doi.org/10.3390/nu9090991

Tan, B. L., & Norhaizan, M. E. (2019). Effect of high-fat diets on oxidative stress, cellular inflammatory response and cognitive function. *Nutrients*, 11(11), 2579. https://doi.org/10.3390/nu11112579

Thomas, J., & Duethi, P. P. (2001). Cinnamon. In: K. V. Peter (Ed.). *Handbook of Herbs and Spices* (pp. 143–153). Woodhead Publishing.

Topor-Mądry, R., Wojtyniak, B., Strojek, K., Rutkowski, D., Bogusławski, S., Ignaszewska-Wyrzykowska, A., Jarosz-Chobot, P., Czech, M., Kozierkiewicz, A., Chlebus, K., Jędrzejczyk, T., Myśliwiec, M., Polańska, J., Wysocki, M. J., & Zdrojewski, T. (2019). Prevalence of diabetes in Poland: A combined analysis of national databases. *Diabetic Medicine*, 36(8), 1009–1016. https://doi.org/10.1111/dme.13949

Tremblay, S., & Avon, S. L. (2008). Contact allergy to cinnamon: case report. *Journal* (*Canadian Dental Association*), 74(5), 445–461.

Vafa, M., Mohammadi, F., Shidfar, F., Sormaghi, M. S., Heidari, I., Golestan, B., & Amiri, F. (2012). Effects of cinnamon consumption on glycemic status, lipid profile and body composition in type 2 diabetic patients. *International Journal of Preventive Medicin*e, 3(8), 531–536.

Van Hul, M., Geurts, L., Plovier, H., Druart, C., Everard, A., Ståhlman, M., Rhimi, M., Chira, K., Teissedre, P. L., Delzenne, N. M., Maguin, E., Guilbot, A., Brochot, A., Gérard, P., Bäckhed, F., & Cani, P. D. (2018). Reduced obesity, diabetes, and steatosis upon cinnamon and grape pomace are associated with changes in gut microbiota and markers of gut barrier. *American Journal of Physiology. Endocrinology and Metabolism*, 314(4), E334–E352. https://doi.org/10.1152/ajpendo.00107.2017

Vangalapati, M., Sree Satya, N., Surya Prakash, D., & Avanigadda, S. (2012). A review on pharmacological activities and clinical effects of Cinnamon species. *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, 3(1), 653–663.

Velázquez, R., Rodríguez, A., Hernández, A., Casquete, R., Benito, M. J., & Martín, A. (2023). Spice and herb frauds:

types, incidence, and detection: the state of the art. *Foods* (Basel, Switzerland), 12(18), 3373. https://doi.org/10.3390/foods12183373

Vivas, A. P., & Migliari, D. A. (2015). Cinnamon-induced oral mucosal contact reaction. *The Open Dentistry Journal*, 9, 257–259. https://doi.org/10.2174/1874210601509010257

Wang, R., Yang, K., Liu, X., Zhang, Y., Chen, Y., Wang, N., Yu, L., Liu, S., Hu, Y., & Qin, B. (2025). The antidiabetic mechanisms of cinnamon extract: Insights from network pharmacology, gut microbiota, and metabolites. *Current Issues in Molecular Biology*, 47(7), 543. https://doi.org/10.3390/cimb47070543

Yanakiev, S. (2020). Effects of cinnamon (*Cinnamomum* spp.) in dentistry: A review. *Molecules*, 25(18), 4184. https://doi.org/10.3390/molecules25184184

Yang, B.-C., Lee, M.-S., Sun, F.-C., Chao, H.-H., Chang, W.-T., Lin, M.-K., Chen, H.-J., & Lee, M.-S. (2020). Rapid identification of the indigenous medicinal crop *Cinnamomum osmophloeum* from various adulterant *Cinnamomum* species by DNA polymorphism analysis. *Pharmacognosy Magazine*, 16(68), 64–68. https://doi.org/10.4103/pm.pm_267_19

Yu, T., Lu, K., Cao, X., Xia, H., Wang, S., Sun, G., Chen, L., & Liao, W. (2023). The effect of cinnamon on lycolipid metabolism: A dose-response meta-analysis of randomized controlled trials. *Nutrients*, 15(13), 2983. https://doi.org/10.3390/nu15132983

Zainal-Abidin, Z., Mohd-Said, S., Abdul Majid, F. A., Wan Mustapha, W. A., & Jantan, I. (2013). Anti-bacterial activity of cinnamon oil on oral pathogens. *The Open Conference Proceedings Journal*, 4(Suppl. 2, M4), 12–16. https://doi.org/10.2174/2210289201304010237

Zakir, M., Ahuja, N., Surksha, M. A., Sachdev, R., Kalariya, Y., Nasir, M., Kashif, M., Shahzeen, F., Tayyab, A., Khan, M. S. M., Junejo, M., Manoj Kumar, F., Varrassi, G., Kumar, S., Khatri, M., & Mohamad, T. (2023). Cardiovascular complications of diabetes: from microvascular to macrovascular pathways. *Cureus*, 15(9), e45835. https://doi.org/10.7759/cureus.45835

Zare, R., Nadjarzadeh, A., Zarshenas, M. M., Shams, M., & Heydari, M. (2019). Efficacy of cinnamon in patients with type II diabetes mellitus: A randomized controlled clinical trial. *Clinical Nutrition* (Edinburgh, Scotland), 38(2), 549–556. https://doi.org/10.1016/j.clnu.2018.03.003

Zarezadeh, M., *Musa*zadeh, V., Foroumandi, E., Keramati, M., Ostadrahimi, A., & Mekary, R. A. (2023). The effect of cinnamon supplementation on glycemic control in patients with type 2 diabetes or with polycystic ovary syndrome: an umbrella meta-analysis on interventional meta-analyses. *Diabetology & Metabolic Syndrome*, 15(1), 127. https://doi.org/10.1186/s13098-023-01057-2

Zelicha, H., Yang, J., Henning, S. M., Huang, J., Lee, R. P., Thames, G., Livingston, E. H., Heber, D., & Li, Z. (2024). Effect of cinnamon spice on continuously monitored glycemic response in adults with prediabetes: a 4-week randomized controlled crossover trial. *The American Journal of Clinical Nutrition*, 119(3), 649–657. https://doi.org/10.1016/j.ajcnut.2024.01.008

Zhou, Q., Lei, X., Fu, S., Li, Z., Chen, Y., Long, C., Li, S., & Chen, Q. (2022). Efficacy of cinnamon supplementation on glycolipid metabolism in T2DM diabetes: A meta-analysis and systematic review. *Frontiers in Physiology*, 13, 960580. https://doi.org/10.3389/fphys.2022.960580

Živković, M., Stanisavljević, I., Gajović, N., Pavlović, S., Simović Marković, B., Jovanović, I. P., Cupara, S., Tadić, V., Žugić, A., Milenković, M. T., & Barjaktarević, A. (2025). Comprehensive phytochemical analysis and evaluation of antioxidant, antimicrobial, cytotoxic, and Immunomodulatory Activities of Commercial Cinnamon Bark Essential Oil (*Cinnamomum zeylanicum* L.). *International Journal of Molecular Sciences*, 26(13), 6482. https://doi.org/10.3390/ijms26136482