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THERAPEUTIC POTENTIAL OF AMLA AND CINNAMON BARK IN DIABETES MELLITUS: A PHYTOCHEMICAL AND MECHANISTIC PERSPECTIVE

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ABSTRACT

Diabetes mellitus (DM) is a metabolic disorder characterized by high blood glucose levels due to insulin resistance or impaired insulin secretion. While conventional treatments help manage DM, natural remedies like amla (*Emblica officinalis*) and cinnamon (*Cinnamomum* spp.) have shown promising antidiabetic effects. Amla, rich in polyphenols and antioxidants, protects pancreatic β-cells, enhances insulin secretion and improves glucose metabolism. Cinnamon contains bioactive compounds like cinnamaldehyde, which mimics insulin action, enhances glucose uptake and lowers blood sugar levels. Studies suggest that both amla and cinnamon effectively reduce fasting blood glucose and cholesterol levels, making them potential adjunct therapies for diabetes management. Further research is needed to confirm their long-term safety and efficacy.

Key words : Antidiabetic, Cinnamon bark, Amla.

Introduction

Diabetes mellitus is a chronic, potentially debilitating disease that poses a significant global health burden. The prevalence of non-insulin dependent diabetes mellitus is increasing across all populations due to modern lifestyle changes, including sedentary behaviour and poor dietary habits. India has seen an alarming rise in diabetes cases, earning the title of the “diabetes capital of the world.” This chronic disorder affects carbohydrate, fat, and protein metabolism, leading to increased fasting and postprandial blood sugar levels (Tan *et al.*, 2019; Zekewos *et al.*, 2018; Subramaniyan *et al.*, 2014; Vijayaraghavan *et al.*, 2010). The number of people with diabetes is rising due to various factors, such as population growth, aging, urbanization, and increasing prevalence of obesity and physical inactivity. In 2021, the global prevalence of diabetes mellitus (DM) was estimated at 537 million adults, with projections suggesting a further increase to 643 million by 2030 and 783 million by 2045, making it a critical public health challenge that requires immediate attention.

Diabetes mellitus is primarily characterized by persistent hyperglycaemia, resulting from defects in insulin secretion, insulin action, or both (Vinik, 2016). The disease is broadly categorized into two major types: Type 1 diabetes mellitus (T1DM), which is caused by the autoimmune destruction of pancreatic β-cells, leading to absolute insulin deficiency (Thivolet, 2002) and Type 2 diabetes mellitus (T2DM), which is primarily driven by insulin resistance and progressive β-cell dysfunction (Narendran *et al.*, 2005). Additionally, other forms of diabetes include gestational diabetes mellitus (GDM) and rare monogenic types. The pathophysiology of diabetes is complex, involving multiple organ systems such as the pancreas, liver, muscles, adipose tissue and gut, all of

which contribute to impaired glucose metabolism and long-term complications. In healthy individuals, blood glucose levels are tightly regulated by the coordinated actions of insulin and glucagon, two hormones secreted by the pancreas. After food consumption, rising blood glucose levels stimulate pancreatic β-cells to release insulin, which facilitates glucose uptake in muscle and adipose tissue through glucose transporter-4 (GLUT4) while inhibiting hepatic glucose production. Insulin also suppresses glucagon secretion from pancreatic α-cells, thereby preventing excessive glucose release. However, in diabetes, this delicate balance is disrupted, leading to chronic hyperglycaemia and metabolic dysfunction.

In Type 1 diabetes, an autoimmune response results in the destruction of insulin-producing β-cells, largely due to autoreactive T-cells that mistakenly target these cells (Devendra *et al*., 2004). The immune attack is further exacerbated by proinflammatory cytokines such as interleukin-1β (IL-1β), tumour necrosis factor-alpha (TNF-α) and interferon-gamma (IFN-γ), which accelerate β-cell apoptosis. Genetic predisposition plays a crucial role in T1DM, with HLA genes (HLA-DR3 and HLA-DR4) being significant risk factors (Barrett *et al*., 2009). Environmental triggers, such as viral infections and toxins, may further initiate or accelerate the autoimmune destruction of β-cells. As β-cell mass declines, insulin production becomes insufficient, leading to severe hyperglycaemia. Without insulin, glucose cannot be effectively transported into cells, forcing the body to rely on alternative energy sources such as fat breakdown (lipolysis) and ketone body formation (ketogenesis), which can ultimately result in diabetic ketoacidosis (DKA), a life-threatening condition (Dunger *et al*., 2004). Conversely, Type 2 diabetes is primarily characterized by insulin resistance, where peripheral tissues, such as muscles and adipose tissue, fail to respond effectively to insulin. This results in compensatory hyperinsulinemia, as the pancreas attempts to produce more insulin to maintain glucose homeostasis. However, over time, pancreatic β-cells become exhausted, leading to progressive insulin deficiency. Several factors contribute to insulin resistance, including obesity, chronic inflammation, oxidative stress and lipid toxicity (Kay *et al*., 1997). Excess adipose tissue, particularly visceral fat, releases inflammatory cytokines like TNF-α and interleukin-6 (IL-6), which interfere with insulin signalling pathways. Furthermore, elevated levels of free fatty acids (FFAs) contribute to ectopic fat deposition in non-adipose tissues, such as the liver and muscles, exacerbating metabolic dysfunction (Scarim *et al*., 1997). Chronic hyperglycaemia also leads to glucotoxicity, which induces oxidative stress and mitochondrial damage, further impairing β-cell function. A hallmark feature of T2DM is hepatic insulin resistance, wherein insulin fails to suppress gluconeogenesis in the liver, leading to excessive glucose production and worsening hyperglycaemia. The gut plays a critical role in glucose metabolism through incretin hormones, particularly glucagon-like peptide-1 (GLP-1) and gastric inhibitory polypeptide (GIP), which enhance insulin secretion in response to food intake. In diabetes, GLP-1 secretion is reduced, leading to impaired insulin release and prolonged postprandial hyperglycaemia (Ehses *et al*., 2009).

Recent research highlights the gut microbiome's significant role in diabetes, as dysbiosis (an imbalance in gut bacteria) contributes to insulin resistance and chronic inflammation. Increased intestinal permeability allows lipopolysaccharides (LPS) from harmful bacteria to enter systemic circulation, triggering low-grade inflammation that further disrupts metabolic balance. Moreover, a decline in short-chain fatty acids (SCFAs), which are beneficial metabolites produced by gut bacteria, worsens glucose regulation and insulin sensitivity. If left uncontrolled, diabetes can lead to severe complications affecting multiple organ systems. Diabetic neuropathy, a common complication, results from chronic hyperglycaemia-induced nerve damage, leading to pain, numbness and loss of sensation, particularly in the extremities. Diabetic nephropathy, another serious consequence, involves progressive kidney damage characterized by proteinuria (excess protein in urine), which may eventually progress to end-stage renal disease (ESRD) (Borch-Johnsen *et al*., 1985). Diabetic retinopathy, caused by damage to the retinal blood vessels, is a leading cause of blindness worldwide (Fong *et al*., 2004). Cardiovascular disease (CVD) is one of the most prevalent and life-threatening complications of diabetes, as prolonged hyperglycemia contributes to atherosclerosis, hypertension and an increased risk of heart attacks and strokes (Alam *et al*., 2004). Given the rising burden of diabetes, there is an increasing interest in alternative and complementary therapies, particularly herbal medicines derived from medicinal plants. Traditional medicine is used by approximately 60% of the world's population, with India being a major contributor to herbal-based diabetes management (Gupta *et al*., 2017). Indian medicinal plants, such as *Emblica officinalis* (amla), *Momordica charantia* (bitter melon), *Gymnema sylvestre* and *Trigonella foenum-graecum* (fenugreek), have been extensively studied for their anti-diabetic properties. Amla is an integral part of Ayurveda, is rich in antioxidants, particularly vitamin C, polyphenols and

flavonoids, which help reduce oxidative stress and inflammation. Studies suggest that amla can enhance insulin sensitivity, improve β-cell function and lower fasting and postprandial glucose levels (Tirgar *et al*., 2010). Additionally, its role in preventing diabetic complications, such as neuropathy and nephropathy, highlights its therapeutic potential in diabetes management. Cinnamon bark is another best medicine to improve general health due to presence of bioactive compounds which treat various diseases such as DM2. In addition to its anti-diabetic properties, cinnamon is also efficient in its use as an anti-inflammatory, antibacterial and antioxidant (Sahib, 2016).

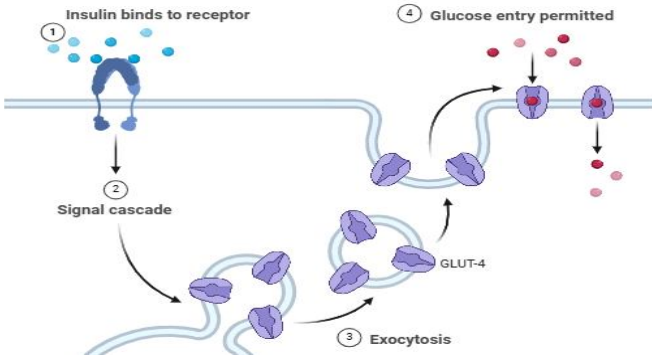

Fig. 1 : Insulin Signaling Pathway and Glucose uptake Mechanism.

The integration of traditional knowledge with modern scientific advancements can offer a holistic approach to diabetes prevention and management. While conventional anti-diabetic drugs like metformin, sulfonylureas, and GLP-1 receptor agonists play a crucial role in glycaemic control, incorporating dietary modifications, lifestyle changes, and evidence-based herbal medicine can provide comprehensive and sustainable diabetes management strategies. Further research and clinical trials are necessary to validate the efficacy and safety of traditional herbal medicines, ensuring their integration into mainstream diabetes care. Collaboration between modern medicine, traditional knowledge, and innovative research is essential in tackling the diabetes epidemic. A multidisciplinary approach that includes healthcare professionals, researchers, policymakers and traditional medicine practitioners can help develop effective interventions to reduce the global burden of diabetes. By fostering connections between various fields, we can work towards a future where diabetes management is more accessible, holistic, and patient-centric, ultimately improving the quality of life for millions of individuals worldwide.

Amla

Amla (*Phyllanthus emblica*), commonly known as Indian gooseberry, is a highly valued medicinal plant in Ayurvedic and traditional medicine. It is renowned for its exceptional nutritional profile, particularly its rich vitamin C content and potent antioxidant properties. Amla has been used for centuries in India and other parts of Asia for its diverse health benefits, ranging from improving immunity to promoting skin and hair health. In recent years, scientific research has further substantiated many of these traditional claims, leading to a growing interest in its pharmacological potential. Botanically, amla belongs to the Euphorbiaceae family and is a small to medium-sized deciduous tree found in tropical and subtropical regions. The fruit is spherical, light green to yellowish, with a characteristic sour and bitter taste (Scartezzini *et al*., 2006). It is widely consumed in various forms, including fresh fruit, dried powder, juice and extracts, making it a versatile ingredient in both food and medicine. The bioactive compounds present in amla, such as flavonoids, tannins, polyphenols and alkaloids, contribute to its wide range of therapeutic properties (Jain *et al*., 2016). Traditionally, amla has been a cornerstone of Ayurvedic medicine, where it is considered a "Rasayana" or rejuvenating herb. Ayurvedic texts describe its benefits in enhancing digestion, purifying blood, and promoting longevity (Parvez *et al*., 2018) It is also a key component of Triphala, a popular Ayurvedic formulation used for detoxification and digestive health. Additionally, amla has been used in home remedies for treating common ailments such as cough, cold and indigestion.

One of the most significant health benefits of amla is its powerful antioxidant activity. The fruit is one of the richest natural sources of vitamin C, which helps neutralize free radicals and reduce oxidative stress. Studies suggest that the antioxidant properties of amla can play a crucial role in preventing chronic diseases such as cardiovascular diseases, diabetes, and cancer. The presence of polyphenols and tannins further enhances its free radical-scavenging ability, making it a promising natural supplement for health and wellness. In addition to its antioxidant effects, amla has demonstrated potential in supporting metabolic health. Research indicates that amla extracts may help regulate blood glucose levels, improve insulin sensitivity (Zare *et al*., 2018) and reduce the risk of type 2 diabetes. Some studies have also highlighted its role in lowering cholesterol and improving lipid profiles, making it beneficial for cardiovascular health. These properties position amla as a valuable natural remedy for metabolic disorders. Amla is also recognized for its antimicrobial and anti-inflammatory properties. It has been found to exhibit antibacterial, antiviral and antifungal activities, making it effective against various pathogens.

Its anti-inflammatory effects contribute to its role in managing conditions such as arthritis, asthma and inflammatory bowel diseases. This anti-inflammatory action is largely attributed to the presence of bioactive compounds such as gallic acid and ellagic acid, which modulate inflammatory pathways. The benefits of amla extend to dermatology and hair care as well. Traditionally, amla has been used to promote hair growth, reduce hair fall, and prevent premature graying. It's high vitamin C content helps in collagen synthesis, which is essential for skin elasticity and anti-aging effects. Many cosmetic formulations, including shampoos, hair oils and skincare products, incorporate amla extracts to harness these benefits. Apart from its medicinal uses, amla is gaining popularity as a functional food due to its high nutritional value. It is commonly consumed as juice, pickles, candies, and dietary supplements. The growing interest in natural and plant-based health solutions has led to increased demand for amla-based products in the global market. Its inclusion in nutraceuticals and functional foods highlights its importance as a superfood with immense health-promoting potential.

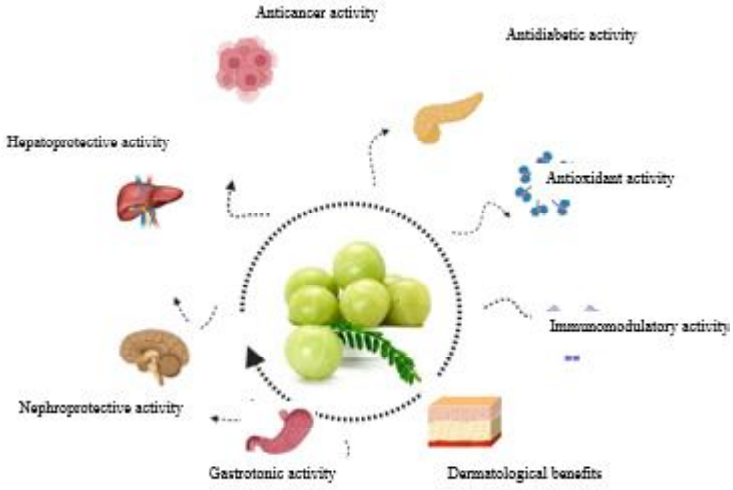

Fig. 2 : Medicinal properties of amla.

Chemical constituents of amla

Amla (*Phyllanthus emblica*), commonly known as Indian gooseberry, is a nutritionally rich fruit with a complex phytochemical profile. It contains a variety of bioactive compounds, including vitamin C, tannins, flavonoids, polyphenols, alkaloids, saponins, organic acids, dietary fiber and essential minerals. These constituents contribute to its extensive medicinal and therapeutic applications. The following sections provide a detailed description of each major chemical component found in amla.

Amla is one of the richest natural sources of vitamin C, containing approximately 600–700 mg per 100 g of fresh fruit. Vitamin C is a potent antioxidant that helps neutralize free radicals and prevent oxidative stress-induced damage to pancreatic β-cells. Studies suggest that vitamin C supplementation lowers fasting blood glucose levels, enhances insulin sensitivity and reduces diabetes-related complications such as neuropathy and nephropathy (Saini *et al*., 2022). Additionally, it improves endothelial function, reducing the risk of cardiovascular diseases commonly associated with diabetes (Priya and Islam, 2019). Tannins, including gallic acid, ellagic acid, emblicanin A, emblicanin B and punigluconin, contribute to amla's hypoglycaemic effects. These compounds inhibit carbohydrate-digesting enzymes such as α-glucosidase and α-amylase, delaying glucose absorption and preventing postprandial hyperglycaemia (Mirunalini *et al*., 2010). Tannins also exhibit anti-inflammatory properties, reducing chronic inflammation that contributes to insulin resistance. Their hepatoprotective effects further aid in maintaining normal glucose metabolism by protecting the liver from fatty degeneration, a common issue in diabetic patients (Malar *et al*., 2009). Flavonoids like quercetin, kaempferol, rutin, and myricetin present in amla are known for their insulin-sensitizing properties (Duan *et al*., 2005). These compounds improve glucose uptake by enhancing the translocation of glucose transporter 4 (GLUT4) to the cell membrane, facilitating glucose entry into muscle and adipose tissues. Additionally, flavonoids modulate key insulin signalling pathways, reducing insulin resistance. Studies have shown that quercetin can regenerate pancreatic β-cells, promoting endogenous insulin secretion and improving glycaemic control in diabetic individuals. Polyphenols such as pyrogallol, chebulzinic acid, chebulagic acid and corilagin exert strong antidiabetic effects through multiple mechanisms. These compounds inhibit oxidative stress, which plays a crucial role in the progression of diabetes and its complications. By modulating inflammatory pathways and reducing cytokine production, polyphenols protect pancreatic β-cells from damage and improve insulin function. Additionally, they influence lipid metabolism, reducing triglyceride and cholesterol levels, which are often dysregulated in diabetes. Amla contains alkaloids that contribute to its glucose-lowering effects. These bioactive compounds interact with cellular receptors involved in glucose metabolism, enhancing insulin sensitivity and reducing hepatic glucose production (Akanda and Hasan, 2021.) Alkaloids also influence the release of incretin hormones such as glucagon-like peptide-1 (GLP-1), which stimulate insulin secretion and suppress glucagon release. This helps maintain stable

blood sugar levels and prevents hyperglycaemia. Amla is a rich source of dietary fiber, which plays a significant role in diabetes management. Fiber slows down the digestion and absorption of carbohydrates, resulting in a gradual rise in blood glucose levels instead of sharp spikes. Soluble fiber in amla also improves gut microbiota composition, promoting the production of short-chain fatty acids (SCFAs) that enhance insulin sensitivity. Additionally, fiber aids in weight management, an essential factor in controlling type 2 diabetes. Oxidative stress is a major contributor to pancreatic β-cell dysfunction in diabetes (Padma *et al*., 2011). The bioactive compounds in amla, particularly vitamin C, tannins, flavonoids and polyphenols, exhibit strong antioxidant activity. These compounds neutralize reactive oxygen species (ROS), reducing oxidative damage to β-cells and preserving their insulin-secreting function (Riaz *et al*., 2016). By enhancing endogenous antioxidant defence mechanisms such as superoxide dismutase (SOD) and glutathione peroxidase, amla helps maintain pancreatic health and prevents diabetes progression (Xu *et al*., 2016). Chronic low-grade inflammation is closely linked to insulin resistance and the development of type diabetes. Amla's bioactive compounds suppress pro-inflammatory cytokines such as tumour necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6), which impair insulin signalling (Zhao *et al*., 2013). The anti-inflammatory effects of flavonoids and polyphenols help restore normal insulin function and improve metabolic homeostasis. This makes amla a valuable natural remedy for managing diabetes and reducing the risk of complications associated with chronic inflammation.

Role of amla in diabetes managements

Amla (*Phyllanthus emblica*), also known as Indian gooseberry, has been extensively studied for its potential benefits in managing diabetes. Its rich phytochemical composition, including polyphenols, tannins, flavonoids, and vitamin C, contributes to its hypoglycemic, antioxidant, and anti-inflammatory properties. These properties make amla a valuable natural remedy for improving blood glucose control, insulin sensitivity and reducing complications associated with diabetes.

Hypoglycaemic effects

One of the key benefits of amla in diabetes management is its ability to lower blood sugar levels. Studies have demonstrated that amla extracts significantly reduce fasting blood glucose and postprandial blood sugar levels in diabetic patients. Research conducted on diabetic animal models showed that amla extracts enhanced glucose uptake in muscle cells and improved insulin

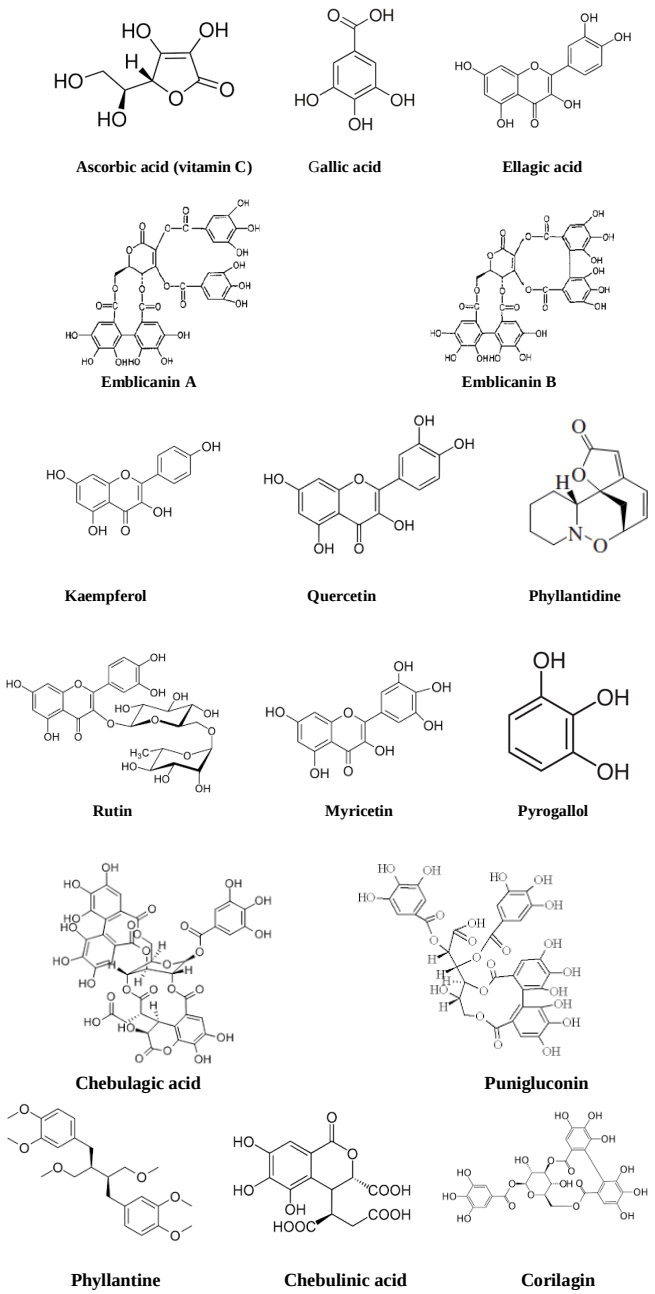

Fig. 3 : Chemical structures of constituents of amla.

secretion from pancreatic beta cells (Sundaram *et al*., 2018). A clinical study by Santhi Sri *et al*. (2013) found that consuming 35 grams of fresh amla daily for six months led to a significant decrease in blood glucose levels and improved glycaemic control in type 2 diabetes patients. The study confirms *Emblica officinalis* has anti-hyperglycaemic and lipid-lowering effects. In both normal and diabetic individuals, 1–3 g daily reduced blood glucose, while 2–3 g improved cholesterol profiles. In diabetic models, its seed extract showed significant anti-diabetic activity. (Muhammad Shoaib Akhtar *et al*., 2011). The hypoglycaemic effects of fermented Amla beverage are linked to its antioxidant activity, flavonoids, and bioactive

compounds from functional Lactobacillus bacteria. These compounds lower glucagon levels, enhance glucose utilization, and stimulate pancreatic cells to increase insulin secretion, like glibenclamide. (Modi *et al*., 2023). The *Emblica officinalis* fruit contains 3.2% fiber, 8.65% phytosterols, 0.05% saponins, 19.70% polyphenols, 0.342% flavonoids and 0.425% ascorbic acid. The observed anti-hyperglycaemic effects may be attributed to these bioactive compounds, particularly polyphenols and flavonoids, which are known to protect pancreatic islet β-cells, enhance insulin sensitivity, and exhibit antioxidative and anti-hyperlipidaemic properties (Vasant and Narasimhacharya, 2012).

Antioxidant properties and oxidative stress reduction

Diabetes is often associated with increased oxidative stress, which damages pancreatic beta cells and contributes to insulin resistance. Amla, being one of the richest natural sources of vitamin C, plays a crucial role in neutralizing free radicals and reducing oxidative stress. The presence of tannins and flavonoids further enhances antioxidant activity, thereby protecting pancreatic cells from damage. Studies have shown that regular consumption of amla helps in reducing malondialdehyde (MDA) levels, a biomarker of oxidative stress and increases superoxide dismutase (SOD) activity, an important antioxidant enzyme (Kumar *et al*., 2019). Amla in the form of either the commercial enzymatic extract SunAmla (20 or 40 mg/kg of body weight/day) or a polyphenol-rich fraction of ethyl acetate extract (10 or 20 mg/kg of body weight/day) was given orally for 20 days to the streptozotocin-induced diabetic rats. Amla extracts showed strong free radical scavenging activity. (Rao, 2005). Four weeks of aqueous *E. officinalis* extract administration improved oral glucose tolerance in type 2 diabetic rats and after eight weeks, it significantly reduced fasting serum glucose levels. Triglycerides decreased by 14%, while serum ALT, creatinine, cholesterol, and insulin levels showed no significant changes. Additionally, erythrocyte malondialdehyde levels remained unchanged, but reduced glutathione content increased significantly (Ansari, 2014). The combination therapy significantly improved lipid profiles and antioxidant activity, outperforming linagliptin and *Emblica officinalis* monotherapy (Khanam, 2023).

Improvement in insulin sensitivity

Amla has been found to improve insulin sensitivity, making it beneficial for individuals with insulin resistance and Type 2 diabetes. The polyphenols and flavonoids in amla help in modulating insulin signalling pathways, leading to improved glucose uptake by cells. Research indicates that amla reduces insulin resistance by enhancing GLUT-4 (glucose transporter) expression in muscle and adipose tissues, thereby facilitating better glucose utilization (Sabu and Kuttan, 2015). Additionally, amla's anti-inflammatory effects contribute to reducing low-grade chronic inflammation, which is a key factor in insulin resistance. Amla decreased low-density lipoprotein cholesterol and increased HDL cholesterol in ovariectomized rats fed chow or fructose. In ovariectomized and fructose-fed rats, it prevented insulin resistance aside from subduing the rise in triglycerides (Koshy *et al*., 2012). *E. officinalis* extract-treated groups significantly ($p \leq 0.001$) reduced blood glucose levels compared to the metformin-treated group when treated with extract doses (200 and 400 mg/kg) led to notable decreases in serum glucose, cholesterol and triglyceride levels.

Inhibition of carbohydrate digestion and absorption

Amla has been shown to slow down the digestion and absorption of carbohydrates, thereby preventing postprandial glucose spikes. This is attributed to its ability to inhibit carbohydrate-digesting enzymes, such as á-amylase and á-glucosidase, which break down starch and disaccharides into glucose. A study found that amla extract effectively inhibited these enzymes, reducing the rate of glucose absorption in the intestines and preventing sudden spikes in blood sugar levels after meals (Grover *et al*., 2016). *E. officinalis* aqueous extract significantly enhanced insulin secretion, glucose uptake, and insulin action. It also inhibited starch digestion (8–74%) and protein glycation (44–87%), demonstrating strong anti-diabetic potential (Kasabri *et al*., 2014). Nutritional therapy supports using specific foods to help manage diabetes by providing essential nutrients and antioxidants. Wheat and barley products can regulate blood glucose by inhibiting key enzymes (Arpita *et al*., 2022).

Lipid profile and cardiovascular benefits

Diabetes is often accompanied by dyslipidaemia, characterized by high triglycerides, LDL (bad cholesterol), and low HDL (good cholesterol) levels, increasing the risk of cardiovascular diseases. Amla has been shown to improve lipid profiles by lowering LDL and triglycerides while increasing HDL cholesterol levels. A clinical study demonstrated that daily consumption of 500 mg of amla extract for 12 weeks significantly improved lipid parameters and reduced atherosclerotic risk factors in diabetic patients (Baliga *et al*., 2019). This cardioprotective effect is attributed to amla's polyphenols and flavonoids, which help reduce lipid peroxidation and

enhance lipid metabolism. EOE (standardized for 10% BGG) at 1 g and 2 g per day is safe, well tolerated, and effective for diabetes and dyslipidaemia, with the 2 g dose outperforming metformin which was promising long-term supplement for T2DM management (Majeed *et al*., 2022).

Anti-inflammatory effects and diabetes-related complications

Chronic inflammation is a key contributor to diabetes-related complications, such as neuropathy, nephropathy, and retinopathy. Amla contains bioactive compounds with potent anti-inflammatory effects, helping in reducing inflammatory cytokines like TNF-α and IL-6, which are associated with diabetes progression (Reddy *et al*., 2018). Studies suggest that amla helps in protecting kidney function (nephroprotective effects) by reducing oxidative stress and inflammation in diabetic nephropathy models. Additionally, its neuroprotective effects help prevent diabetic neuropathy by reducing nerve damage and improving nerve conduction velocity.

Hepatoprotective effects

The liver plays a crucial role in glucose metabolism, and diabetes is often associated with fatty liver disease and liver dysfunction. Amla has been found to exert hepatoprotective effects by reducing liver enzyme levels (ALT, AST, ALP), improving liver function and preventing fat accumulation in the liver. A study reported that amla supplementation significantly reduced hepatic lipid accumulation and improved liver insulin sensitivity in diabetic rats (Ghosh *et al*., 2017; Thilakchand *et al*., 2013; Baliga *et al*., 2019)

Potential role in gut microbiota modulation

Recent studies suggest that gut microbiota imbalance plays a significant role in the development of insulin resistance and diabetes. Amla has been found to promote gut health by supporting the growth of beneficial gut bacteria while inhibiting pathogenic bacteria. This probiotic-like effect helps in maintaining gut barrier integrity, reducing inflammation and improving metabolic health in diabetic individuals (Patel *et al*., 2021).

Wound healing and diabetic ulcers

Diabetic patients often suffer from slow wound healing due to high blood sugar levels and oxidative stress. Amla's antimicrobial, anti-inflammatory, and collagen-boosting properties contribute to faster wound healing and improved tissue regeneration. Studies have shown that amla extracts help in reducing infection, promoting angiogenesis, and accelerating wound closure in diabetic foot ulcers (Chaudhary *et al*., 2020).

Cinnamon bark

Cinnamon bark, obtained from various species of the *Cinnamomum* genus, is renowned for its distinctive flavor, fragrance, and therapeutic properties (Shan *et al*., 2005; Jayaprakash and Rao, 2011). This ancient spice has been cherished since antiquity for its culinary uses and medicinal benefits (Kawatra and Rajagopalan, 2015). The two most common types are *Cinnamomum verum* (Ceylon cinnamon) and *Cinnamomum cassia* (Chinese cinnamon), each offering unique chemical compositions and biological activities (Singh *et al*, 2007; Rao and Gan, 2014). Chemically, cinnamon bark is rich in essential oils, primarily cinnamaldehyde, which gives it its characteristic aroma and flavor (Gruenwald *et al*, 2010). Other important constituents include eugenol, cinnamic acid and coumarin derivatives, all contributing to its diverse biological effects (Mathew and Abraham, 2006). These compounds have been extensively studied for their antioxidant, anti-inflammatory, antimicrobial and even anticancer properties (Kawatra and Rajagopalan, 2015; Sahib, 2016). The antioxidant properties of cinnamon bark are particularly notable, as they help combat oxidative stress by neutralizing free radicals and reducing cellular damage (Shan *et al*., 2005; Mathew and Abraham, 2006). This property is crucial in preventing various chronic diseases linked to oxidative stress, such as cardiovascular disorders, neurodegenerative diseases and aging-related conditions (Zhao *et al*., 2014). In addition to its antioxidant activity, cinnamon bark has demonstrated anti-inflammatory effects, attributed mainly to its ability to inhibit pro-inflammatory enzymes and cytokines (Hariri and Thibault, 2010). This makes it a potential therapeutic agent for conditions characterized by chronic inflammation, including arthritis and inflammatory bowel diseases (Ranasinghe *et al*., 2013). Cinnamon bark's antimicrobial properties have also attracted significant attention (Shan *et al*., 2005). Studies have shown its effectiveness against various pathogens, including bacteria and fungi (Ooi *et al*., 2006). This antimicrobial activity extends its potential applications beyond food preservation to the development of natural antimicrobial agents for pharmaceutical and personal care products (Gruenwald *et al*., 2010). Beyond its biological activities, cinnamon bark has been explored for its role in managing blood sugar levels and improving insulin sensitivity, which is promising for individuals with diabetes or those at risk of developing the disease (Cao *et al*., 2007). Compounds like cinnamaldehyde may enhance insulin signalling and glucose uptake in cells, contributing to improved metabolic health (Namazi *et al*., 2019; Jain *et al*., 2017). Furthermore, cinnamon bark has been investigated for

its cardiovascular benefits. It may help lower blood pressure and cholesterol levels, potentially reducing the risk of heart disease (Nyadjeu *et al.*, 2013; Mesripour and Hajialyani, 2016). These effects are thought to be mediated through its antioxidant and anti-inflammatory actions, as well as its ability to improve blood vessel function (Zhao *et al.*, 2014; Jayaprakasha and Rao, 2011). In the realm of food science, cinnamon bark is valued not only for its flavor enhancement but also for its preservative properties (Shan *et al.*, 2005; Ooi *et al.*, 2006). The antimicrobial compounds present can inhibit the growth of foodborne pathogens and spoilage organisms, thereby extending the shelf life of perishable foods naturally.

Chemical Constituents of cinnamon bark

Cinnamon bark has been widely used in traditional medicine to treat various ailments, including gastrointestinal disorders, respiratory infections and metabolic conditions. Recent scientific research has focused on its antidiabetic properties, identifying a range of bioactive compounds that contribute to blood glucose regulation, insulin sensitivity, and metabolic balance. These compounds include essential oils, polyphenols, flavonoids, coumarins, alkaloids, tannins and polysaccharides, each playing a critical role in diabetes management.

Cinnamaldehyde, the primary bioactive compound in cinnamon essential oil, constitutes 60–80% of its content and is responsible for its characteristic aroma and medicinal effects. Research indicates that cinnamaldehyde enhances insulin sensitivity by improving insulin receptor signalling pathways. It also promotes glucose uptake in muscle and adipose tissues, reducing insulin resistance (Guo *et al.*, 2017). Additionally, cinnamaldehyde exhibits anti-inflammatory properties that help mitigate chronic inflammation, a key contributor to

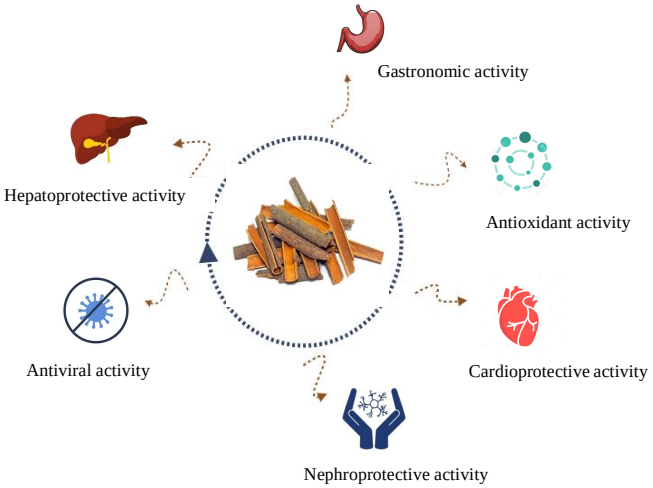

Fig. 4 : Medicinal properties of cinnamon bark.

Type 2 diabetes progression. Eugenol, another essential oil component found in higher concentrations in Ceylon cinnamon, has been recognized for its potential in managing diabetes. It possesses antioxidant properties that reduce oxidative stress, which can damage pancreatic β-cells responsible for insulin production. Studies suggest that eugenol enhances glucose metabolism and reduces hyperglycaemia by improving insulin function and protecting pancreatic cells from oxidative damage (Chaudhary *et al.*, 2024). Cinnamon bark is rich in polyphenolic compounds such as cinnamic acid, procyanidins, catechins, and quercetin, which contribute significantly to its antidiabetic effects (Sandaruwan *et al.*, 2024). These compounds exhibit strong antioxidant activity, neutralizing free radicals that cause cellular damage and impair insulin function (Das, 2011). Cinnamic acid has been shown to lower blood sugar levels by improving glucose uptake in peripheral tissues and reducing inflammation (Selim *et al.*, 2024). Flavonoids present in cinnamon, including quercetin and catechins, play a crucial role in modulating glucose metabolism. These compounds inhibit key carbohydrate-digesting enzymes such as á-glucosidase and á-amylase, slowing the absorption of sugars in the intestine and preventing postprandial glucose spikes (Eidenberger *et al.*, 2013). Additionally, flavonoids improve endothelial function and enhance blood circulation, reducing the risk of diabetes-occurring anticoagulants found in cinnamon bark, have been studied for their role in metabolic health. While excessive consumption may pose risks of hepatotoxicity, controlled intake has shown potential benefits in regulating blood sugar levels. (Sandaruwan *et al.*, 2024). Coumarins support vascular health, reducing the risk of diabetes-induced cardiovascular complications. However, Ceylon cinnamon, which contains lower levels of coumarins compared to Cassia cinnamon, is often recommended for long-term consumption (Machyna kova and Hrobonova, 2017; Lungarini, 2008). Cinnamon bark contains alkaloids that contribute to its pharmacological effects, particularly in regulating glucose metabolism. These compounds enhance insulin sensitivity by modulating key signalling pathways involved in glucose uptake and energy production. Alkaloids also exhibit anti-inflammatory and antioxidant properties, reducing metabolic stress that contributes to insulin resistance in diabetic individuals. Tannins, another class of bioactive compounds in cinnamon, possess astringent, antimicrobial, and anti-inflammatory properties (Semwal and Semwal, 2013; Simic *et al.*, 2004) Their role in diabetes management is linked to their ability to regulate gut microbiota, improve digestion, and reduce inflammation

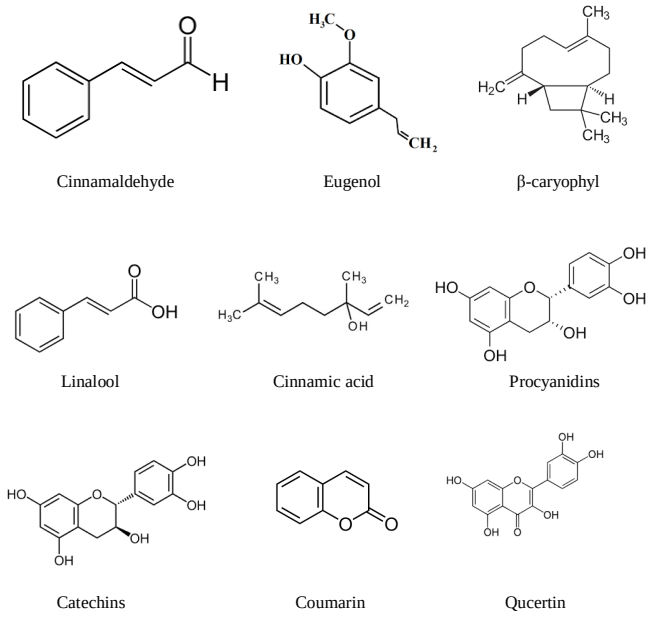

Fig. 5 : Chemical structures of constituents of cinnamon bark.

in the gastrointestinal tract. A balanced gut microbiome is essential for metabolic homeostasis, as it influences insulin signalling and glucose absorption. Additionally, tannins help prevent complications such as diabetic ulcers and infections. Polysaccharides found in cinnamon bark, particularly water-soluble ones, exhibit significant antidiabetic properties. These compounds enhance insulin secretion and improve glucose utilization, helping to regulate blood sugar levels (Ervina *et al*., 2016). Polysaccharides also play a role in modulating immune function and reducing oxidative stress, further supporting metabolic health in diabetic patients (Silva *et al*., 2024). Studies suggest that cinnamon polysaccharides may act as natural insulin mimetics, enhancing glucose uptake and utilization in cells.

Role of cinnamon bark in diabetes managements

Antioxidant uses

Its high antioxidant content also helps reduce oxidative stress, which plays a role in antidiabetic, aging and chronic diseases (Zhao *et al*., 2021). The polyphenolic polymers found in C. verum and C. aromaticum have antioxidant activity and have been shown to reduce oxidative stress in a dose-dependent manner through inhibition of 5-lipooxygenase enzyme (Anderson *et al*., 2004; Blomhoff, 2004; Ranjbar *et al*., 2006).

Role of cinnamon bark in diabetes management

Diabetes mellitus is a chronic metabolic disorder characterized by hyperglycaemia due to insulin resistance or deficiency. Cinnamon bark has gained prominence as a natural anti-diabetic agent due to its ability to regulate blood glucose levels, enhance insulin sensitivity and improve pancreatic function (Anderson *et al*., 2019). Methyl hydroxychalcone polymer (MHCP) in common and cassia cinnamon was found to be an effective mimetic of insulin (Jarvill-Taylor *et al*., 2001). MHCP demonstrated in vitro activation of glycogen synthase and inhibition of glycogen synthase kinase-3b as well as insulin receptor phosphorylation homologous to the effects of insulin in 3T3-LI adipocytes (Jarvill-Taylor *et al*., 2001). High doses of cinnamon, particularly *Cinnamomum aromaticum*, showed effectiveness in lowering fasting glucose, total cholesterol, and LDL while increasing HDL in DM2 patients (Silva *et al*., 2021).

Effects on blood glucose regulation

Cinnamon polyphenols have been shown to mimic insulin activity and enhance glucose uptake in cells. Studies indicate that cinnamon supplementation reduces fasting blood glucose levels and improves glycated haemoglobin (HbA1c) in diabetic patients (Khan *et al*., 2020). Cinnamaldehyde enhances insulin receptor activity, facilitating glucose metabolism (Zhou *et al*., 2022). *In vivo* studies show an increase in insulin-stimulated IR-b and the IRS1 tyrosine phosphorylation treated with cassia cinnamon (Qin *et al*., 2003). Cinnamon acts as a synergetic agonist with insulin in vivo to decrease blood glucose levels after a glucose tolerance test (Verspohl *et al*., 2005) and in chronically high fructose diets (Qin *et al*., 2004). Cassia cinnamon reduced blood glucose (10.3%–29%) (Dugoua *et al*., 2007).

Improvement in insulin sensitivity

Cinnamon influences insulin signalling pathways by upregulating glucose transporter 4 (GLUT4) expression, which enhances glucose absorption in muscle and adipose tissues (Singh and Verma, 2021). Additionally, it reduces insulin resistance by modulating oxidative stress and inflammation, two key factors in type 2 diabetes progression (Gupta *et al*., 2021). *Cinnamon zeylanicum* improved insulin action and reduced oxidative stress in diabetic male rats observed after 30 days, the cinnamon-treated group showed increased superoxide dismutase and glutathione peroxidase levels, while serum malondialdehyde decreased (Khaki *et al*., 2013).

Reduction of oxidative stress and inflammation

Chronic hyperglycaemia in diabetes leads to increased oxidative stress, which contributes to complications such as neuropathy, nephropathy, and retinopathy. The antioxidant properties of cinnamon, particularly from polyphenols and flavonoids, help in neutralizing free radicals and protecting pancreatic β-cells from oxidative damage (Ali *et al*., 2020).

Lipid metabolism and diabetes

Dyslipidaemia is a common complication in diabetes, characterized by elevated cholesterol and triglyceride levels. Cinnamon has been reported to lower total cholesterol, LDL (low-density lipoprotein) and triglycerides while increasing HDL (high-density lipoprotein) levels, thereby improving overall metabolic health (Rahman *et al*., 2022). *Cinnamomum zeylanicum* extract on LDL cholesterol and other lipid parameters in individuals with LDL levels of 100–190 mg/dL. It also examined effects on glucose, anthropometric measures, blood pressure, and safety outcomes (Muthukuda *et al*., 2025.). *Cinnamomum zeylanicum* lowered blood glucose, reduced food intake and improved lipid parameters in diabetes-induced rats.

Conclusion

Amla (*Emblica officinalis*) and cinnamon (*Cinnamomum* spp.) have demonstrated significant potential as natural remedies for managing diabetes mellitus. Their bioactive compounds aid in glucose metabolism, insulin secretion and oxidative stress reduction, making them valuable adjuncts to conventional treatments. While current studies highlight their effectiveness in lowering blood glucose and cholesterol levels, further clinical research is necessary to establish standardized dosages, long-term safety and efficacy. Incorporating these natural agents into diabetes management strategies may offer a complementary approach to improving patient outcomes.

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