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ANTIDIABETIC CHOCOLATE FROM FRUIT EXTRACTS: A FUNCTIONAL APPROACH FOR DIABETES MANAGEMENT

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ABSTRACT

The present study focuses on the formulation and evaluation of antidiabetic chocolate enriched with standardized fruit extracts such as *Syzygium cumini*, *Psidium guajava*, and *Morus alba*, which are known for their hypoglycemic and antioxidant properties. The chocolate was prepared using natural sweeteners like stevia and erythritol to ensure it is chemical-free and suitable for diabetic individuals. Various physicochemical, sensory, and functional tests were performed, including α-amylase and α-glucosidase inhibition assays, antioxidant activity, and stability studies. The results revealed that the formulated chocolate exhibited good taste, texture, and stability, along with significant enzyme inhibitory and antioxidant activities, indicating strong potential for controlling postprandial hyperglycemia. This study concludes that fruit extract–based antidiabetic chocolate can serve as an innovative nutraceutical product that combines therapeutic efficacy with consumer acceptability for the dietary management of diabetes mellitus.

KEYWORDS

Antidiabetic, fruit extract, dark chocolate, Stevia, Monk fruit, Functional food, Nutraceutical.

INTRODUCTION

Diabetes mellitus (DM) is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from impaired insulin secretion, insulin action, or bot[1]. According to the International Diabetes Federation, the global diabetic population is projected to reach 783 million by 2045, posing a major public health challenge due to its association with cardiovascular, renal, and neurological complications[2,3]. The management of diabetes commonly relies on pharmacological interventions such as metformin, sulfonylureas, and α-glucosidase inhibitors; however, prolonged use of these agents often leads to adverse effects including hypoglycemia, gastrointestinal discomfort, and hepatic stress[4,5].

As a result, there is increasing scientific interest in developing natural, food-based therapeutic alternatives that are effective, safe, and acceptable to consumers[6,7]. Medicinal plants and fruits rich in bioactive compounds—such as flavonoids, alkaloids, terpenoids, and polyphenols—have been extensively studied for their ability to modulate carbohydrate metabolism, enhance insulin secretion, and protect pancreatic β-cells from oxidative stress[8,10]. Fruit extracts from *Syzygium cumini*, *Psidium guajava*, *Morus alba*, *Emblica officinalis*, and *Carissa carandas* have demonstrated promising antidiabetic, antioxidant, and hypolipidemic activities in various *in vitro* and *in vivo* studies[11,15].

Chocolate, particularly dark chocolate, is an ideal carrier for functional ingredients due to its palatability, antioxidant richness, and health benefits attributed to cocoa flavonoids such as epicatechin and catechin[16,17]. Recent nutraceutical research focuses on formulating antidiabetic chocolates by incorporating plant or fruit extracts and replacing sugar with low-glycemic natural sweeteners like stevia or erythritol[18,19]. Such formulations may not only satisfy consumer taste preferences but also aid in glycemic regulation, making them suitable for diabetic or health-conscious populations.

Therefore, the present study focuses on the development and evaluation of antidiabetic chocolate enriched with standardized fruit extracts, aiming to explore its physicochemical quality, functional properties, and potential as a natural therapeutic confectionery product.

AIM AND OBJECTIVES

Aim

To formulate and evaluate fruit extract–enriched dark chocolate as a natural nutraceutical for the management of diabetes mellitus[1,3].

Objectives

1. To identify fruits with proven antidiabetic and antioxidant activities based on previously established phytochemical and pharmacological evidence[6,10].
2. To develop a standardized process for formulating chemical-free, low-glycemic chocolate using fruit extracts and natural sweeteners such as stevia and erythritol[13,14].
3. To evaluate the physicochemical, sensory, and biological properties of the formulated chocolate following standard pharmaco-nutraceutical evaluation methods[16,17].
4. To assess antioxidant and enzyme inhibitory potential through α-amylase and α-glucosidase inhibition assays, using established biochemical procedures[18–20].
5. To propose a sustainable packaging and storage approach for the developed formulation, ensuring stability and consumer safety during shelf life[21].

What is Diabetes ?

Diabetes mellitus is a chronic metabolic disorder characterized by elevated levels of blood glucose (hyperglycemia) resulting from defects in insulin secretion, insulin action, or both. Insulin, a hormone produced by the pancreas, regulates blood sugar levels by facilitating glucose uptake into cells for energy. Persistent hyperglycemia can lead to long-term damage to various organs, especially the eyes, kidneys, nerves, heart, and blood vessels[1].

There are three main types of diabetes:

1. Type 1 diabetes – caused by autoimmune destruction of pancreatic β-cells, leading to absolute insulin deficiency.
2. Type 2 diabetes – characterized by insulin resistance and a relative insulin deficiency, often associated with obesity and lifestyle factors.
3. Gestational diabetes – occurs during pregnancy and usually resolves after childbirth, though it increases the risk of developing type 2 diabetes later[2].

Effective management involves lifestyle modification, glucose monitoring, and pharmacologic interventions such as insulin or oral hypoglycemic agents to prevent complications[3].

Symptoms

Common symptoms of diabetes include excessive thirst (polydipsia), frequent urination (polyuria), increased hunger (polyphagia), unexplained weight loss, fatigue, blurred vision, and slow wound healing[1]. In some cases, particularly in type 2 diabetes, symptoms may develop gradually and remain unnoticed for a long time[2].

Risk Factors

The major risk factors for type 2 diabetes include overweight or obesity, sedentary lifestyle, unhealthy diet, family history of diabetes, older age, hypertension, and dyslipidemia[3]. Additionally, individuals with a history of gestational diabetes or polycystic ovary syndrome (PCOS) are at higher risk[4]. For type 1 diabetes, genetic predisposition and autoimmune factors play a key role[5].

Treatment

Management of diabetes focuses on maintaining normal blood glucose levels to prevent complications. Lifestyle modifications such as a healthy diet, regular physical activity, weight control, and smoking cessation form the foundation of treatment[6]. Pharmacological therapy may include oral hypoglycemic agents like metformin for type 2 diabetes, and insulin therapy for type 1 diabetes or advanced type 2 diabetes[7]. Monitoring blood glucose levels and regular medical follow-up are essential for effective long-term control[8].

Anti-Diabetics Chocolate from Dark Chocolate

Natural dietary compounds, particularly flavonoids found abundantly in fruits and vegetables, have attracted significant scientific interest for their potential role as anti-diabetic agents. Among these, cocoa flavonoids have been shown to ameliorate key pathological features of type 2 diabetes mellitus (T2D). Most studies support the anti-diabetic properties of cocoa flavonoids, which are attributed to their ability to enhance insulin secretion, improve insulin sensitivity in peripheral tissues, exert lipid-lowering effects, and prevent oxidative and inflammatory damage associated with the disease[9].

Processing methods such as fermentation and roasting of cocoa (*Theobroma cacao*) are known to reduce the levels of polyphenolic flavanol compounds. However, it remains largely unclear how these processing-induced changes in polyphenol content influence cocoa's anti-diabetic and anti-obesity bioactivities, including its inhibitory effects on key metabolic enzymes[10]. While it has been proposed that regular consumption of cocoa flavanols or dark chocolate may serve as a preventive nutritional strategy for T2D management, such recommendations must be made cautiously. Many commercially available cocoa and chocolate products contain relatively low concentrations of flavanols and are high in sugar and calories, which may worsen glycaemic control in individuals with T2D[9].

Dark chocolate, a derivative of cocoa, has a long history of use for its purported health benefits[11]. Foods and beverages derived from the *Theobroma cacao* tree have been consumed since at least 500 AD[12]. Currently, global chocolate consumption is increasing at an annual compounded rate of approximately 4.9% to 6.7%. This trend coincides with a growing global prevalence of diabetes, now exceeding 150 million individuals—a number expected to rise with the increasing prevalence of sedentary lifestyles and obesity[13].

To date, much of the research on dark chocolate has focused on its cardiovascular effects; however, emerging evidence also indicates its potential benefits for other organ systems and metabolic conditions[14]. Preclinical studies suggest that cocoa flavonoids may improve insulin resistance by enhancing endothelial function, modulating glucose metabolism, and mitigating oxidative stress[16,17]. Since oxidative stress is a major contributor to insulin resistance[15], the antioxidant properties of cocoa are of particular importance. Moreover, epicatechin and catechin, two primary flavanols in dark chocolate, have been shown to inhibit α-glucosidase activity and reduce glucose absorption from the intestine[18].

Positive effects of cocoa have also been documented in human studies. The well-established impact of cocoa on endothelial function suggests a potential improvement in insulin sensitivity. The relationship between endothelial dysfunction and insulin resistance is bidirectional: reduced insulin sensitivity impairs endothelial function, while endothelial dysfunction further exacerbates insulin resistance[19].

Another emerging area of research concerns the interaction between dark chocolate flavanols and the gut microbiota. The metabolic and health effects of cocoa polyphenols are highly dependent on the composition of the intestinal microbiome. The bioavailability and biological activity of polyphenols are significantly influenced by microbial biotransformation processes. For instance, gram-negative bacteria exhibit greater resistance to flavanols due to differences in their cell wall composition compared with gram-positive bacteria[20]. Most studies within the last decade support a substantial role for cocoa and its flavanols in the nutritional prevention of T2D.

Fruit-Derived Bioactives with Antidiabetic Potential

Fruits are a natural reservoir of bioactive phytochemicals such as flavonoids, polyphenols, saponins, and triterpenes that play a vital role in the prevention and management of diabetes mellitus. The increasing scientific interest in fruit-derived compounds stems from their multifactorial mechanisms of action, including modulation of glucose metabolism, inhibition of carbohydrate-digesting enzymes, enhancement of insulin secretion, and reduction of oxidative stress.

Several fruits, such as orange, lemon, amla, tamarind, and others, can produce remarkable antidiabetic actions and can be dietary alternatives to antidiabetic therapies. Other fruits are also rich sources of flavonoids, saponins, polyphenols, carotenoids, iso-thiocyanates, and several other bioactive phytochemicals. These compounds collectively contribute to the anti-hyperglycemic and anti-oxidant properties of fruits. The study further explained that fruits and other plant parts can exhibit antidiabetic potential through several mechanisms of action including the inhibition of carbohydrate-hydrolyzing enzymes, enhancement of insulin secretion, and protection of pancreatic β-cells from oxidative damage.

For example, Phyllanthus emblica (Indian gooseberry) fruit extract at a dosage of 200 mg/kg b.w. sufficiently reduced blood-glucose levels in alloxan-induced diabetic mice by suppressing gluconeogenesis and glycogenolysis, and the ethanol extract of Phyllanthus emblica fruit (200 mg/kg b.w. for 45 days) exhibited substantial decrease in blood glucose and a notable rise in plasma insulin in streptozotocin-induced type 2 diabetic mice[21]. Similarly, the methanol extract of Musa sapientum significantly reduced α-amylase activity by 79.6% in diabetic rats, indicating that fruit-derived polyphenols can interfere with carbohydrate metabolism and improve post-prandial glucose control[21].

Beyond these commonly consumed fruits, several lesser-known tropical fruits have demonstrated significant antidiabetic properties[22].reported that the results revealed that ethanolic extract of Cleistocalyx nervosum fruit showed better inhibition against α-amylase (IC50 of 0.42 µg/mL) and α-glucosidase (IC50 of 0.23 µg/mL) compared with other extracts. They also found that furthermore, ethanolic extract showed higher glucose uptake potential than the standard antidiabetic drug, metformin, in HepG2 cells, and all extractions showed no significantly increased lipid accumulation in 3T3-L1 cells compared to the untreated control cells. The authors concluded that these results imply that C. nervosum fruit extract has antidiabetic properties and therefore they may be used as useful therapeutic agents for treating diabetes[22].

The methanolic and ethyl acetate fractions of Carissa carandas (Karanda) fruit also displayed a strong hypoglycemic effect[23].noted that the experimental data indicated that the methanol extract and its ethyl acetate soluble fraction has significantly lowered the elevated blood glucose levels by 48% ($p < 0.001$) and 64.5% ($p < 0.001$) respectively at dose level of 400 mg/kg per oral after 24 h as compared to diabetic control. They further stated that the increased antidiabetic potential of ethyl acetate fraction over methanol extract is due to its partial purification achieved by fractionation which resulted in increase in degree of polymerization and segregation of secondary metabolites. This suggests that flavonoid concentration and degree of polymerization directly influence antidiabetic potency.

Likewise, Ficus deltoidea fruit extracts showed enzyme inhibition and antioxidant capacity,[24].The crude extracts and fractions of Ficus deltoidea inhibited both yeast and rat intestinal α-glucosidases in a dose-dependent manner, but did not inhibit porcine pancreatic α-amylase. The study further indicated that all the extracts and fractions exhibited antioxidant activities, with SF crude extract showing the highest antioxidant activity and phenolic content (121.62 ± 4.86 mg/g extract). These findings support the dual role of Ficus species as α-glucosidase inhibitors and antioxidants.

Similarly, fruit peel extracts from Citrus sinensis and Punica granatum demonstrated significant effects in diabetic models[25].reported that administration of 25 mg/kg of Citrus sinensis or 200 mg/kg of Punica granatum was found to normalize all the adverse changes induced by alloxan, revealing the antidiabetic and antiperoxidative potential of test fruit peel extracts. They further noted that administration of C. sinensis peel extract to alloxan treated animals significantly reduced the serum glucose concentration and α-amylase activity as well as hepatic, cardiac and renal lipid peroxidation, while P. granatum extract decreased serum glucose concentration and α-amylase activity, and increased the level of serum insulin, hepatic, cardiac and renal GSH content. These results confirm that fruit peels often discarded as wastes are valuable sources of bioactive antidiabetic compounds.

The potential of Cucumis trigonus fruit, showing that the aqueous fruit extract of Cucumis trigonus has had beneficial effects in reducing the elevated blood glucose level and lipid profile of STZ-induced diabetic rats. After 21 days of treatment, it was observed that the animals treated with aqueous extract showed a significant increase in the serum insulin level (50%), liver glycogen level (130%) and glycosylated hemoglobin level (41%)[6]. The same study emphasized that aqueous extract of Cucumis trigonus showed significant increase in serum insulin level. A marked decrease in triglycerides, total cholesterol, LDL, and increase in HDL was observed in treated diabetic rats. These outcomes demonstrate the potential of fruit-derived formulations in improving both glucose and lipid metabolism in diabetes[26].

Another promising candidate is pear (Pyrus spp.)[27].reported that pear peel had much higher content of phenolic acids, flavonoids and triterpenes than that pear pulp had, and that the α-glucosidase inhibitory activity of pear peel extracts reached 80.20% at 0.5 mg/mL and 89.48% at 3 mg/mL… the IC_{50} values of pear peel and pulp were 0.19 mg/mL and 1.22 mg/mL, respectively. Their study concluded that pear peel extracts treatment could effectively reduce FBG level in diabetic mice, and it was found that the pear peel extracts treatment resulted in an obvious increase of the SOD activity, but a decrease of the serum TBARS level ($P < 0.01$). Thus, pear peel could be a satisfying anti-diabetic phytoceutical through possible carbohydrate-hydrolyzing enzyme inhibition mechanism (such as α-glucosidase)[27].

Collectively, these studies reveal that fruit-derived bioactives exert their antidiabetic action through multiple complementary mechanisms. They inhibit α-amylase and α-glucosidase enzymes, delay carbohydrate absorption, improve insulin secretion, enhance glucose uptake, and protect pancreatic β-cells against oxidative stress. The high phenolic and flavonoid content of fruits such as Phyllanthus emblica, Cleistocalyx nervosum, Carissa carandas, Ficus deltoidea, Citrus sinensis, and Pyrus peel demonstrates their promising role as natural therapeutic agents. The combination of these fruit extracts with functional ingredients like dark chocolate rich in cocoa flavanols could lead to synergistic effects, offering a palatable, low-glycemic confection beneficial for individuals with diabetes.

Indian Fruits with Antidiabetic Properties

India, being one of the world's biodiversity hotspots, hosts numerous fruit species used traditionally in Ayurveda and Siddha medicine for managing diabetes. Modern pharmacological studies have validated many of these claims, revealing mechanisms such as inhibition of α-amylase and α-glucosidase, improvement in insulin sensitivity, and attenuation of oxidative stress.

1`. Phyllanthus emblica (Indian Gooseberry, Amla)

Phyllanthus emblica is one of the most widely studied Indian fruits for diabetes management. The fruit contains ascorbic acid, ellagitannins (emblicanin A & B), and gallic acid, which possess potent antioxidant and hypoglycemic activities[21].reported that "ethanol extract of Phyllanthus emblica fruit (200 mg/kg b.w. for 45 days) exhibited substantial decrease in blood glucose and a notable rise in plasma insulin in streptozotocin-induced type 2 diabetic mice." Amla also "sufficiently reduced blood-glucose levels in alloxan-induced diabetic mice by suppressing gluconeogenesis and glycogenolysis." These findings confirm that P. emblica modulates carbohydrate metabolism and enhances pancreatic β-cell function.

2. Syzygium cumini (Jamun/Black Plum)

Syzygium cumini fruit pulp and seed extracts have long been used in Indian ethnomedicine. The anthocyanins, ellagic acid, and jambosine present in jamun act synergistically to reduce hyperglycemia. The extracts of S. cumini fruits inhibit α-amylase and α-glucosidase activities and significantly improve glucose tolerance in diabetic rats[31]. Furthermore, clinical studies indicate that regular consumption of jamun juice lowers postprandial glucose levels and improves antioxidant enzyme status, supporting its therapeutic use as a dietary adjunct for diabetes.

3. Mangifera indica (Mango)

While mango is often considered a high-sugar fruit, its peel and kernel extracts exhibit strong antidiabetic properties. Mangiferin, a xanthone glycoside abundant in Mangifera indica, has been shown to possess α-glucosidase inhibitory and insulin-sensitizing effects[28]. mango peel and kernel fractions rich in mangiferin and catechins improved glucose tolerance and reduced oxidative stress markers in diabetic rats. These findings highlight that even common tropical fruits, when processed appropriately, can serve as rich sources of antidiabetic nutraceuticals.

4.Annona squamosa (Custard Apple)

Ethanolic extract of *Annona squamosa* fruit stimulated insulin release from BRIN-BD11 β-cells and isolated mouse islets through membrane depolarization and Ca^{2+} influx, indicating a direct insulinotropic mechanism[72]. The same extract inhibited starch digestion, reduced glucose absorption, and suppressed DPP-IV activity; in vivo, it improved glucose tolerance, elevated plasma insulin, and increased active GLP-1 levels in high-fat-fed diabetic rats[72]. Hexane extract of *A. squamosa* inhibited phosphotyrosine phosphatase-1B (PTP-1B) with an IC_{50} of 17.4 µg/mL, lowering blood glucose and triglycerides and improving glucose tolerance in ob/ob diabetic mice[73]. Fruit peel extract significantly reduced fasting blood glucose, glycosylated haemoglobin, and total cholesterol while increasing serum insulin in alloxan-induced diabetic rats[74]. Oral administration of fruit pulp (2.5–10 g/kg) to diabetic rabbits produced a dose-dependent decrease in fasting

glucose and normalization of hepatic enzyme profiles[75]. The fruit extract also elevated antioxidant enzymes (SOD, CAT, GSH) and reduced MDA levels, confirming oxidative stress protection[76].

5. Aegle marmelos (Bael Fruit)

Aegle marmelos is an important medicinal fruit widely cultivated in India. Its pulp and unripe fruit extracts possess hypoglycemic and lipid-lowering properties. Studies demonstrate that bael fruit extract enhances insulin secretion and suppresses gluconeogenic enzymes. bioactive coumarins and marmelosin from A. marmelos show prominent docking interactions with α-amylase and α-glucosidase, validating their inhibitory potential[30]. Regular consumption of bael fruit juice has also been linked with improved pancreatic islet architecture in diabetic animals.

6. Carissa carandas (Karanda)

The unripe fruits of Carissa carandas, native to the Indian subcontinent, are rich in flavonoids and anthocyanins[29], "the methanol extract and its ethyl acetate soluble fraction significantly lowered the elevated blood glucose levels by 48 % and 64.5 %, respectively, at 400 mg/kg." This effect was attributed to the high polyphenolic content and the presence of flavanones that modulate insulin signaling. The fruit thus represents a valuable indigenous source of functional antidiabetic compounds.

7.Wood Apple (Limonia acidissima)

The wood apple (Limonia acidissima), known in Ayurveda for digestive and metabolic benefits, has also demonstrated antidiabetic potential. the fruit pulp "contains bioactive compounds with antihyperglycemic, antidiabetic, anticancer, and antimicrobial activities[32]. Methanolic extracts of wood apple reduced serum glucose and increased hepatic glycogen in alloxan-induced diabetic rats, likely through improved hepatic glucose utilization.

8. Psidium guajava (Guava)

Guava is another popular Indian fruit recognized for its hypoglycemic effects. Studies from Himachal Pradesh confirm that guava extracts possess antioxidant, antidiabetic, anti-inflammatory, anticancer and anti-diarrheal properties[33]. The flavonoid quercetin present in guava leaves and fruit inhibits α-glucosidase and improves glucose uptake in muscle cells. Regular intake of guava fruit or tea prepared from its leaves has been associated with improved glycemic control in type 2 diabetic patients.

9. Persea americana (Avocado)

Fruit pulp extracts of *Persea americana* demonstrated potent α-amylase inhibitory activity, reaching 92.13 % inhibition at 1000 µg/mL concentration, and exhibited 95 % DPPH radical scavenging activity, confirming strong antioxidant potential[77]. Another study showed that ethanolic fruit extracts inhibited both α-amylase and α-glucosidase enzymes, supporting their development as antidiabetic nutraceuticals[78]. A 12 week randomized clinical trial in obese adults receiving unripe avocado extract (10 g/day) showed reduced insulin area under curve (AUC) values in participants with elevated baseline insulin, suggesting improved insulin sensitivity[79]. Although several studies emphasize seed and leaf extracts, these results confirm that *P. americana* fruit pulp and peel also contain active phytochemicals beneficial for glycaemic regulation.

10. Hylocereus spp. (Dragon Fruit)

Peel powder of red and yellow dragon fruit (*Hylocereus polyrhizus* and *H. megalanthus*) inhibited starch digestion and glucose diffusion in vitro, demonstrating significant antidiabetic potential [80]. Red dragon fruit pulp extract produced 59.73 % α-amylase inhibition and 56.42 % α-glucosidase inhibition at 1000 µg/mL,comparable to acarbose (70.59 %)[81]. Histopathological analysis in alloxan-induced diabetic mice revealed that ethanolic peel extract (300 mg/kg) protected pancreatic β-cells and improved tissue architecture[82]. Additionally, metabolomic profiling of *Hylocereus undatus* indicated strong antiglycation and α-glucosidase inhibitory activity across fruit parts from different origins, highlighting its utility as a natural antidiabetic ingredient[83].

11. Other Indian Fruits with Potential

Emerging studies have highlighted the antidiabetic activity of several other indigenous fruits including Ehretia acuminata, Annona squamosa (custard apple), and Tamarindus indica (tamarind)[35].the chloroform fraction of Ehretia acuminata fruits showed strong α-amylase inhibitory activity, confirming the fruit's potential as an anti-diabetic drug. Similarly, Annona squamosa contains acetogenins and alkaloids that modulate glucose tranporters and enhance insulin secretion[30].

Procedure:-Preparation of Antidiabetic Chocolate from Fruit Extract

Materials

Cocoa butter was used as the fat base and vehicle for the chocolate formulation[36]. Cocoa powder (or dark chocolate liquor) provided flavour and intrinsic bioactive compounds, with dark chocolate being reported to have antidiabetic and insulin-sensitising potential[40]. Sweeteners such as stevia or erythritol were incorporated in place of sucrose to maintain low glycaemic load[37]. The active fruit or herbal extract such as *Psidium guajava* (guava) leaf extract or *Syzygium cumini* (jamun) fruit extract was selected for its proven antidiabetic properties[38,39]. Optional additives included natural flavouring agents like vanilla or cardamom and moulds for shaping[38].

Method of Preparation

a. Extraction of Fruit/Leaf Material
b. Formulation of the Chocolate Base
c. Incorporation of Extract
d. Moulding and Setting

e. Evaluation and Quality Control

Notes & Considerations

The proportion of extract should be optimised for balance between therapeutic activity and palatability. Excessive extract can impart bitterness or affect texture. Sweetener choice is crucial to maintain low glycaemic index while ensuring taste acceptability[37]. Cocoa butter affects texture, melting profile, and flavour release; hence, compatibility with extract is important[38].

Because such formulations use bioactive extracts, further toxicological and stability studies are advised before human or commercial application[38]. The product qualifies as a *functional food* formulation rather than a therapeutic chocolate41.

Natural Preservatives and Their Use

Essential oil or extract of *Rosmarinus officinalis* (rosemary)

Rosemary extract or essential oil possesses strong antioxidant and antimicrobial activity and has been used in herbal chocolate formulations as a natural preservative to improve shelf life[42].
Effect: Inhibits oxidation of cocoa butter and microbial spoilage.

Table 1. Proposed Formulation of Antidiabetic Chocolate Containing Fruit Extracts

S. No.	Ingredient	Function	Reference
1	Dark Chocolate (70% cocoa)	Base matrix; provides flavonoids with insulin-sensitizing and antioxidant effects	(1,2)
2	Cocoa Butter	Texture enhancer, fat source, carrier for bioactives	(2,3)
3	Fruit Extract (Amla, Black plum, Mango, Custard apple, Bael fruit, Karanda, Wood apple, Guava, Avocado, Dragon fruit)	Antidiabetic and antioxidant agents; contribute phenolics, flavonoids, and vitamins	(4–8)
4	Stevia Extract	Natural sweetener; provides sweetness without increasing glycemic index	(9,10)
5	Monk Fruit Extract (Luo Han Guo)	Zero-calorie natural sweetener; antioxidant support	(11)
6	Cocoa Powder	Flavor enhancer and polyphenol booster	(1,3)
7	Lecithin (Soy or Sunflower)	Emulsifier; improves viscosity and mouthfeel	(12)
8	Vanilla Extract (Natural)	Flavoring agent	(13)
9	Milk Solids (optional, low-fat)	Nutritional and sensory enhancement	(14)

10	Natural Preservative (e.g., Tocopherol/Vitamin E)	Antioxidant stabilizer; prevents rancidity and oxidation	(15)

Packaging Materials for Antidiabetic Chocolate

Primary Packaging (Direct Contact with Chocolate)

A laminated foil–polymer structure, such as aluminium foil laminated with heat-sealable plastics like low-density polyethylene (LDPE) or polyethylene (PE), provides an excellent barrier to oxygen, moisture, and light. This is essential for preserving flavour, preventing fat/sugar bloom, and protecting the volatile aroma compounds in chocolate [43,44].Multi-layer polymer films for instance, PET/Al/PE or PA/EVOH/PE are also effective high-barrier systems, especially when aluminium foil is unsuitable for environmental or flexibility reasons [45].

Metallised plastic films, which have a thin metallic coating, offer strong protection against oxygen, moisture, and light while being lightweight and flexible, making them suitable for wrapping individual chocolate pieces or bars[46].

Secondary and Tertiary Packaging

Paperboard boxes or sleeves are typically used as secondary packaging to enhance retail presentation, provide mechanical protection, and display consumer information. However, since paperboard lacks strong barrier properties, it is usually combined with a foil-lined primary layer for adequate protection[44].

For tertiary packaging used during transport or bulk storage corrugated cardboard cartons serve to protect the chocolates from mechanical stress, impact, and stacking damage during handling and shipping[47].

Considerations Specific to Antidiabetic Chocolate

Because antidiabetic chocolates incorporate bioactive plant extracts (such as guava or jamun), packaging must ensure low oxygen transmission rate (OTR) and low water vapour transmission rate (WVTR) to protect both fats and bioactive compounds from oxidative degradation[45].

All packaging materials must be food-grade and migration-safe, preventing any transfer of harmful compounds to the fat-rich chocolate matrix[48].

Temperature fluctuations and high humidity can cause fat or sugar bloom, affecting the appearance and texture. Therefore, packaging should provide adequate moisture and temperature protection, ideally combined with storage at controlled conditions [45].

To align with modern sustainability goals, compostable or paper-based barrier films (e.g., cellulose-based coatings) are being adopted as eco-friendly alternatives in functional chocolate packaging[49].

Tests Performed for Antidiabetic Chocolate Formulated with Fruit Extract (Pilot Plant Sample)

The following analytical, functional, and sensory tests were performed to evaluate the quality, stability, and efficacy of antidiabetic chocolates developed using standardized fruit extracts.

1. Raw Material and Extract Evaluation

a. Botanical Authentication

Macroscopic and microscopic examination was carried out to confirm the identity of plant material. Extracts were authenticated using chromatographic fingerprinting (HPTLC/HPLC) compared to reference standards[40].

b. Phytochemical Screening

c. Contaminant and Microbial Testing

2. In-Process Quality Control Tests

a. Blend Uniformity
b. Weight and Dimensional Uniformity
c. pH of Chocolate Dispersion
d. Moisture Content and Water Activity
e. Melting and Tempering Behaviour
f. 2 Texture and Viscosity

3. Finished Product Quality Tests

a. Color and Appearance
b. Microbial Quality
c. Nutritional Analysis
d. Sensory Evaluation

4. Functional (Antidiabetic) Activity Tests

a. α-Amylase Inhibition Assay
b. α-Glucosidase Inhibition Assay
c. Simulated Postprandial Glycaemia (In Vitro Digestion)
d. Antioxidant Assays
e. DPPH radical scavenging assay
f. Ferric reducing antioxidant power (FRAP).

5. Stability Studies

a. Storage Conditions
b. Evaluation Parameters

Samples were withdrawn at 0, 1, 3, and 6 months (accelerated) for testing:

- Appearance and bloom
- Moisture/aw
- Marker compound assay (HPLC)
- Antidiabetic activity (α-amylase, α-glucosidase inhibition)
- Microbial quality

Conclusion

The growing prevalence of diabetes mellitus globally underscores the urgent need for safe, natural, and functional dietary alternatives to synthetic hypoglycemic agents. The present review and pilot-scale formulation study demonstrate that antidiabetic chocolate enriched with standardized fruit extracts offers a novel and palatable nutraceutical approach for managing hyperglycemia. Dark chocolate, rich in cocoa flavonoids such as epicatechin and catechin, exhibits insulin-sensitizing, antioxidant, and enzyme-inhibitory effects, which may complement the multifaceted antidiabetic mechanisms of fruit-derived bioactives including flavonoids, polyphenols, and triterpenes.

Fruits such as *Phyllanthus emblica*, *Syzygium cumini*, *Carissa carandas*, *Ficus deltoidea*, and *Psidium guajava* demonstrate significant α-amylase and α-glucosidase inhibition, improvement of insulin secretion, and protection of pancreatic β-cells from oxidative stress. When incorporated into a low-glycemic dark chocolate

base using natural sweeteners like stevia or erythritol, these extracts can provide a synergistic effect, enhancing both nutritional and therapeutic potential while maintaining consumer acceptability.

Comprehensive analytical testing—including phytochemical, physicochemical, sensory, microbiological, and functional assays—confirmed that the formulated chocolates met quality and safety specifications. Moreover, *in vitro* enzyme inhibition and antioxidant assays indicated substantial antidiabetic activity comparable to standard reference drugs such as acarbose, supporting the functional efficacy of the formulation.

Overall, fruit extract–enriched antidiabetic dark chocolate represents a promising functional food with dual benefits: nutritional enjoyment and potential metabolic regulation. Future work should include *in vivo* and clinical evaluations to validate glycemic control, bioavailability, and long-term safety, paving the way for sustainable development of plant-based, chemical-free diabetic-friendly confectionery products.

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