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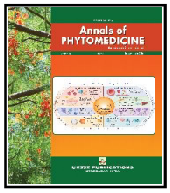

Review Article : Open Access

Therapeutic significance of *Momordica cymbalaria* (Hook. f.) as a traditional vegetable

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Abstract

Momordica cymbalaria (Hook. f.), a traditional wild vegetable of the family Cucurbitaceae, is widely consumed in South India and utilized in indigenous medicine for the management of metabolic and digestive disorders. Although, closely related to cultivated bitter gourd (*M. charantia*), this underutilized species has gained increasing scientific attention for its nutritional and therapeutic potential. The present review compiles and critically analyzes available literature on the botanical characteristics, nutritional composition, phytochemical constituents, and pharmacological properties of *M. cymbalaria*. The fruits are reported to be rich in vitamins, minerals, dietary fiber, and bioactive compounds such as flavonoids, phenolics, tannins, and saponins, which contribute to its antioxidant capacity. Experimental studies have demonstrated significant antidiabetic, hypolipidemic, hepatoprotective, anti-inflammatory, and antimicrobial activities in various *in vivo* and *in vitro* models. Emerging molecular evidence suggests modulation of insulin signaling pathways and oxidative stress mechanisms as key modes of action. Despite promising findings, limited clinical validation, lack of standardized phytochemical profiling, and insufficient agronomic development restrict its broader utilization. Overall, *M. cymbalaria* represents a valuable functional food and medicinal vegetable with considerable potential for enhancing human health and nutritional security.

1. Introduction

Traditional vegetables and wild edible plants have long played a critical role in human nutrition and healthcare across generations, particularly in tropical and subtropical regions (Fabricant and Farnsworth, 2001). These plant resources provide essential nutrients along with diverse bioactive compounds that modulate physiological processes and contribute to disease prevention. In many developing countries, plant-based foods and traditional remedies continue to serve as primary healthcare resources, emphasizing their importance in sustaining community health. In recent years, increasing awareness of the strong relationship between diet and chronic disease development has renewed scientific interest in underutilized crops as functional foods capable of delivering therapeutic benefits beyond basic nutrition (Jeyadevi *et al.*, 2012). Non-communicable diseases now constitute a major public health burden in India, with diabetes mellitus emerging as one of the most prevalent metabolic disorders. Recent estimates indicate that nearly 90 million adults in India are currently living with diabetes, and projections suggest this number may exceed 150 million by 2050. National surveys further demonstrate high prevalence particularly among middle-aged and elderly populations. In Karnataka, diabetes prevalence has been reported at approximately 13-15 per cent among adults, with several community-based studies indicating rapidly increasing trends in both urban and rural areas. In addition, prediabetes prevalence in certain populations of Karnataka has reached over 20 per cent, indicating a substantial future disease burden. Alongside metabolic disorders, India continues to face widespread micronutrient deficiencies, particularly involving iron, calcium, and vitamin C. These deficiencies contribute to anemia, reduced immunity, poor metabolic resilience, and impaired organ function. The coexistence of chronic metabolic diseases and nutritional deficiencies represents a dual burden that threatens long-term public health and economic productivity. At the biological level, diabetes and related metabolic disorders are driven by interconnected mechanisms including insulin resistance, oxidative stress, chronic inflammation, lipid dysregulation, and gastrointestinal dysfunction. Excessive generation of reactive oxygen species causes cellular damage to pancreatic β-cells and vascular tissues, worsening hyperglycemia and diabetic complications. Chronic inflammatory signaling further disrupts insulin sensitivity and accelerates metabolic deterioration. Dysregulated lipid metabolism increases the risk of cardiovascular and hepatic diseases, while impaired gut function affects glucose absorption and immune balance. Consequently, dietary interventions providing antioxidants, anti-inflammatory compounds,

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insulin-sensitizing agents, and dietary fiber are increasingly recognized as essential components of disease prevention and long-term health management (Patel *et al*., 2012).

Plant-based foods rich in phytochemicals have gained significant attention for their ability to influence these pathological pathways naturally. The genus *Momordica* within the Cucurbitaceae family is widely known for its medicinal value, particularly *Momordica charantia*, which has been extensively studied for its antidiabetic properties (Grover and Yadav, 2004; Joseph and Jini, 2013). However, several wild species within the genus remain underexplored despite long-standing traditional use. Among these, *M. cymbalaria* commonly known as Karchikai or Athalakkai, is a traditional vegetable widely consumed in South India. Indigenous communities have historically utilized this plant for regulating blood glucose levels, improving digestion, supporting liver function, and enhancing overall vitality (Rao *et al*., 1999; Jeyadevi *et al*., 2012). Scientific studies conducted over the past two decades have increasingly validated these ethnomedicinal claims. Experimental investigations reveal that *M. cymbalaria* fruit extracts significantly reduce blood glucose levels, improve insulin sensitivity, and modulate lipid metabolism in diabetic and obese animal models (Elangovan *et al.*, 2019; Kumar *et al.*, 2018). Mechanistic evidence suggests activation of glucose transporters such as GLUT4, regulation of peroxisome proliferator-activated receptor gamma (PPARγ), and enhancement of carbohydrate metabolizing enzymes, directly addressing the fundamental disturbances underlying type 2 diabetes. In addition to its metabolic effects, *M. cymbalaria* exhibits strong antioxidant activity due to its high content of phenolic compounds and flavonoids, which scavenge free radicals and reduce oxidative tissue damage. These antioxidant properties are critical in protecting organs such as the liver and pancreas from chronic metabolic stress. The plant has also demonstrated anti-inflammatory and antimicrobial activities, further supporting its broad therapeutic relevance. Nutritionally, the fruits are rich in vitamin C, dietary fiber, calcium, potassium and iron, contributing to immune function, digestive health and micronutrient balance. Regular dietary inclusion of such nutrient-dense traditional vegetables may help address both chronic disease risk and nutritional deficiencies prevalent in Indian populations. Despite its substantial therapeutic and nutritional potential, *M. cymbalaria* remains underutilized in formal agricultural and healthcare systems. Cultivation is largely limited to wild collection and small-scale traditional practices, resulting in inconsistent availability and potential genetic erosion. Furthermore, lack of standardized phytochemical profiling, dosage guidelines and clinical validation restricts its integration into modern nutritional and therapeutic frameworks. In the context of rising chronic disease burden, preventive healthcare strategies and sustainable nutrition, traditional vegetables such as *M. cymbalaria* represent valuable yet under recognized resources. Their capacity to address nutritional deficiencies and mechanistic drivers of metabolic disorders positions them as promising functional foods for contemporary health challenges. This review therefore aims to comprehensively synthesize existing scientific knowledge on the botanical characteristics, nutritional composition, phytochemical constituents, pharmacological activities and future prospects of *M. cymbalaria*, highlighting its therapeutic significance for improving human wellbeing.

2. Botanical description and taxonomy

M. cymbalaria is a member of the family Cucurbitaceae, which includes several economically and medicinally important vegetable crops. The genus *Momordica* comprises more than 50 species distributed predominantly in tropical regions of Asia and Africa, many of which possess therapeutic properties (Jeyadevi *et al.*, 2012). *M. cymbalaria* is an underutilized wild edible species traditionally valued for both nutritional and medicinal purposes in South India. The plant is a creeping or climbing perennial vine characterized by slender, pubescent stems and coiled tendrils that facilitate spreading growth over the ground or support structures. It exhibits vigorous vegetative development during warm and rainy seasons, reflecting strong adaptation to tropical climatic conditions. The root system is primarily fibrous, with occasional thickened structures that enable perennial regeneration and efficient nutrient uptake under semi-wild environments. Leaves are arranged alternately along the stem and are broadly ovate to palmately lobed with three to seven deep lobes and serrated margins. The leaf surface is rough and pubescent, which may aid in reducing water loss and enhancing tolerance to high temperatures. Long petioles allow optimal leaf orientation for effective photosynthesis. *M. cymbalaria* is monoecious, bearing separate male and female flowers on the same plant. The flowers are yellow in color and typically solitary. Male flowers occur on longer peduncles and possess prominent stamens producing abundant pollen, whereas female flowers are larger with a distinct inferior ovary that develops into fruit following pollination. Flowering generally coincides with the monsoon season, promoting insect-mediated pollination, particularly by bees. The fruits are small, oval to oblong, measuring approximately 3-6 cm in length. The immature fruits are green with a slightly rough surface and mild bitterness, making them suitable for culinary use. Upon maturity, the fruits turn yellowish-orange and split to release seeds. The pulp encloses several flattened seeds embedded within a spongy matrix. Compared to cultivated bitter gourd the fruits of *M. cymbalaria* are considerably smaller and less bitter. Seeds are flat, pale brown, and possess a hard seed coat with a slightly sculptured surface typical of cucurbits. They exhibit good viability under natural conditions, facilitating natural regeneration. The plant follows a seasonal growth cycle, with vegetative growth initiating during early monsoon, followed by flowering and fruiting throughout the rainy and post-rainy periods. Perennial root structures enable regrowth in subsequent seasons. Geographically, *M. cymbalaria* is predominantly distributed across South India, particularly in Karnataka, Tamil Nadu, Andhra Pradesh and Telangana. It commonly grows in forest margins, wastelands, hedgerows and home gardens, preferring well-drained soils and warm tropical climates (Jeyadevi *et al.*, 2012). Its ability to thrive under minimal agronomic inputs highlights its potential for sustainable cultivation and conservation. Morphologically, the species can be distinguished from cultivated bitter gourd by its smaller fruit size, milder bitterness and creeping growth habit. These characteristics contribute to its suitability as a traditional vegetable and underline its potential for domestication as a nutritionally and medicinally valuable crop. Overall, the botanical features of *M. cymbalaria* reflect strong ecological adaptability and resilience, supporting its traditional use and potential for broader agricultural and medicinal applications.

2.1 Plant authentication

Accurate taxonomic identification is essential for ensuring the scientific reliability and reproducibility of research involving medicinal

plants. The botanical identity of *M. cymbalaria* has been well documented in classical taxonomic literature and regional floristic records (Jeyadevi *et al*., 2012). The species is authenticated based on distinctive morphological characteristics including its perennial creeping or climbing growth habit, slender pubescent stems bearing coiled tendrils, alternately arranged palmately lobed leaves, yellow monoecious flowers, and small oval to oblong fruits measuring approximately 3-6 cm in length. These diagnostic features clearly differentiate *M. cymbalaria* from closely related species such as *M. charantia*, which typically possesses larger fruits and a predominantly climbing growth habit (Jeyadevi *et al*., 2012; Srinivasulu, 2017). Taxonomic validation of the species has been reported in standard botanical references including regional floras of South India and Cucurbitaceae taxonomic monographs (Jeyadevi *et al*., 2012). The plant is widely recognized under vernacular names such as Karchikai and Athalakkai in southern India, further supporting its ethnobotanical identity (Rao *et al*., 1999). Herbarium voucher specimens of *M. cymbalaria* are maintained in several recognized botanical repositories and institutional herbaria, ensuring permanent taxonomic documentation and reference for future studies (Srinivasulu, 2017).

3. Phytochemical composition of *Momordica cymbalaria*

Phytochemicals are biologically active compounds produced by plants that play crucial roles in defense mechanisms and therapeutic effects in humans. The medicinal properties of *M. cymbalaria* are largely attributed to its rich and diverse phytochemical profile, which includes primary metabolites essential for nutrition and secondary metabolites responsible for pharmacological activities. Numerous studies have investigated the chemical constituents of *M. cymbalaria* fruits, seeds and other plant parts, revealing the presence of several bioactive compounds (Jeyadevi *et al*., 2012).

3.1 Primary Metabolites

Primary metabolites contribute to the nutritional value of the plant and support fundamental metabolic functions. In *M. cymbalaria*, these include carbohydrates, proteins, lipids and amino acids. The fruit pulp contains appreciable carbohydrate content, serving as an energy source, while proteins and essential amino acids support tissue repair and enzymatic functions. Lipid fractions, particularly in seeds, contain fatty acids that contribute to cellular structure and metabolic regulation.

3.2 Secondary Metabolites

Secondary metabolites are chiefly responsible for the therapeutic properties of *M. cymbalaria*. Phytochemical screening has confirmed the presence of flavonoids, phenolic compounds, tannins, alkaloids, saponins and terpenoids (Jeyadevi *et al*., 2012; Srinivasulu, 2017). Flavonoids and phenolic compounds are among the most abundant constituents and play a significant role in antioxidant activity. These compounds scavenge free radicals, reduce oxidative stress and protect cellular components from damage. The high phenolic content of *M. cymbalaria* is strongly correlated with its observed antioxidant potential in various experimental studies. Tannins present in the fruit contribute to antimicrobial and anti-inflammatory effects by precipitating proteins and inhibiting microbial growth. Alkaloids are known to influence metabolic and neurological functions, while saponins exhibit cholesterol-lowering, immune-modulating, and antidiabetic properties. Terpenoids and triterpenes, characteristic of many cucurbit plants, have also been detected and are associated with anti-inflammatory, anticancer and hepatoprotective activities.

3.3 Bioactive proteins and bitter principles

In addition to classical phytochemicals, *M. cymbalaria* contains bioactive proteins and bitter principles similar to those found in *M. charantia*. Studies have isolated protein fractions exhibiting hypoglycemic effects, suggesting direct involvement in glucose metabolism regulation (Rao *et al*., 1999; Kumar *et al*., 2018). These proteins are believed to enhance insulin sensitivity and modulate carbohydrate metabolizing enzymes. Bitter compounds, including cucurbitane-type triterpenoids, contribute not only to the characteristic taste but also to therapeutic properties such as antidiabetic and anti-inflammatory effects.

3.4 Relationship between phytochemicals and therapeutic activity

The therapeutic efficacy of *M. cymbalaria* is primarily attributed to the synergistic interaction of its diverse phytochemical constituents, which collectively target multiple physiological and biochemical pathways involved in disease development. Unlike synthetic drugs that often act on a single molecular target, plant-derived compounds exert broad-spectrum biological effects, making them particularly effective in managing complex chronic disorders such as diabetes mellitus, oxidative stress-related diseases and inflammatory conditions. Phenolic compounds and flavonoids present in *M. cymbalaria* play a central role in antioxidant defense mechanisms. These compounds possess strong free radical scavenging activity, enabling them to neutralize reactive oxygen species generated during metabolic stress. Excessive oxidative stress damages cellular membranes, proteins and DNA, contributing to pancreatic â-cell dysfunction, insulin resistance and progression of diabetic complications. By reducing oxidative burden, phenolics and flavonoids protect pancreatic tissues, improve insulin signaling efficiency and prevent long-term tissue damage.

Anti-inflammatory constituents such as terpenoids, tannins and flavonoids suppress the production of pro-inflammatory cytokines including tumor necrosis factor-α (TNF-α), interleukins and cyclooxygenase enzymes. Chronic low-grade inflammation is a key factor underlying insulin resistance and metabolic syndrome. The anti-inflammatory activity of *M. cymbalaria* therefore contributes directly to improved insulin sensitivity and reduced progression of metabolic disorders. Bioactive proteins isolated from *M. cymbalaria* fruits have demonstrated hypoglycemic effects by enhancing glucose uptake in peripheral tissues and regulating carbohydrate metabolism enzymes. These proteins are believed to stimulate insulin secretion, increase glucose transporter expression and improve cellular responsiveness to insulin. Such actions facilitate efficient glucose utilization and help maintain blood glucose homeostasis. Saponins and alkaloids further contribute to metabolic regulation by influencing lipid metabolism and cholesterol absorption. Saponins are known to bind bile acids, promoting cholesterol excretion and reducing serum lipid levels, thereby lowering cardiovascular risk associated with diabetes. Alkaloids may modulate enzymatic activity involved in glucose breakdown and absorption in the gastrointestinal tract. Unsaturated fatty acids present in *M. cymbalaria* seed and fruit extracts help regulate inflammatory pathways and improve lipid profiles. These fatty acids enhance membrane fluidity and support

hormonal signaling processes critical for metabolic health. Importantly, the combined action of these phytochemicals produces a synergistic therapeutic effect, where antioxidant protection reduces cellular damage, anti-inflammatory agents suppress metabolic stress responses and glucose-regulating compounds restore normal metabolic function. This integrative mechanism is particularly valuable in diabetes mellitus, which involves oxidative stress, inflammation, impaired insulin signaling and lipid abnormalities simultaneously. Therefore, the phytochemical composition of *M. cymbalaria* enables a multi-targeted therapeutic approach that addresses both the underlying causes and complications of metabolic disorders. Such synergistic interactions highlight the plant's potential as a functional food and complementary therapeutic agent, offering advantages over single-target pharmacological interventions.

4. Nutritional composition of *Momordica cymbalaria*

Nutritional evaluation of traditional vegetables is essential for understanding their role in dietary health and functional food development. *M. cymbalaria* is recognized as a nutrient-dense vegetable providing essential macronutrients, micronutrients and dietary fiber, which collectively contribute to metabolic health, immune function and disease prevention. Several studies have analyzed the proximate composition and mineral content of the fruit, demonstrating its significant nutritional potential (Jeyadevi *et al.*, 2012).

4.1 Proximate composition

The proximate composition reflects the basic nutritional constituents of the fruit and is presented below on a fresh weight basis.

Table 1: Nutritional composition of *M. cymbalaria* fruit (per 100 g fresh weight)

Parameter	Value
Moisture (%)	85-88
Energy (kcal)	35-45
Carbohydrates (g)	6.5-8.2
Protein (g)	1.6-2.4
Fat (g)	0.3-0.6
Crude fiber (g)	1.8-2.9
Ash (g)	0.8-1.2
Vitamin C (mg)	28-45
Vitamin A (µg â-carotene)	220-360
Thiamine B1 (mg)	0.05-0.09
Riboflavin B2 (mg)	0.04-0.08
Niacin B3 (mg)	0.6-1.1
Calcium (mg)	24-38
Iron (mg)	1.4-2.3
Potassium (mg)	180-260
Phosphorus (mg)	32-48
Magnesium (mg)	18-27
Sodium (mg)	2-6

5. Pharmacological and therapeutic activities of *M. cymbalaria*

The medicinal value of *M. cymbalaria* is supported by extensive experimental evidence demonstrating its broad spectrum of pharmacological properties. These therapeutic effects are primarily attributed to the synergistic action of its phytochemical constituents, which target multiple metabolic and physiological pathways. Among the various biological activities reported, antidiabetic, antioxidant, hepatoprotective, anti-inflammatory, hypolipidemic and antimicrobial properties are the most prominent.

5.1 Antidiabetic activity

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from impaired insulin secretion, insulin resistance or both. Long-term hyperglycemia leads to severe complications including cardiovascular disease, nephropathy, neuropathy, retinopathy and hepatic dysfunction. The increasing prevalence of diabetes in India and globally has intensified the search for plant-based therapeutic agents capable of managing blood glucose levels with fewer side effects than conventional drugs (Patel *et al.*, 2012). In this context, *M. cymbalaria* has emerged as a promising traditional medicinal vegetable with scientifically validated antidiabetic properties. Early experimental investigations demonstrated significant hypoglycemic effects of *M. cymbalaria* fruit powder in alloxan-induced diabetic rat models, where treated animals exhibited marked reductions in fasting blood glucose levels compared to untreated controls (Rao *et al.*, 1999). In addition to glycemic control, these studies reported improvements in serum lipid profiles, indicating beneficial effects on associated metabolic disturbances.

Subsequent studies utilizing ethanolic and methanolic extracts of fruit pulp, skin and seeds further confirmed the antidiabetic efficacy of *M. cymbalaria*. Administration of these extracts resulted in significant decreases in blood glucose levels and enhanced insulin sensitivity in streptozotocin-induced diabetic animals (Elangovan *et al.*, 2019). Treated groups showed improved glucose tolerance and reduced insulin resistance, suggesting restoration of normal metabolic function. At the molecular level, mechanistic studies have revealed that bioactive compounds in *M. cymbalaria* influence key pathways involved in glucose homeostasis. Fruit extracts have been shown to upregulate glucose transporter type 4 (GLUT4) expression in muscle and adipose tissues, facilitating increased glucose uptake from the bloodstream (Kumar *et al.*, 2018). This action directly counters insulin resistance, a hallmark of type 2 diabetes mellitus. Furthermore, *M. cymbalaria* activates peroxisome proliferator-activated receptor gamma (PPARγ), a nuclear receptor that regulates lipid and glucose metabolism. Activation of PPARγ enhances insulin sensitivity, promotes adipocyte differentiation and improves metabolic balance. The modulation of this pathway by *M. cymbalaria* contributes significantly to its hypoglycemic and hypolipidemic effects.

The plant's antioxidant properties also play a crucial supportive role in its antidiabetic activity. Oxidative stress is known to damage pancreatic â-cells and impair insulin secretion. The high phenolic and flavonoid content of *M. cymbalaria* scavenges reactive oxygen species, protecting â-cells from oxidative injury and preserving insulin production capacity. This cytoprotective effect enhances long-term glycemic control. In addition, bioactive proteins isolated from *M.*

cymbalaria fruits have demonstrated insulin-like activity. These proteins stimulate glucose utilization and may enhance endogenous insulin secretion, further contributing to blood glucose regulation. Such protein-based hypoglycemic agents offer promising avenues for future therapeutic development. *M. cymbalaria* also influences carbohydrate digestion and absorption processes. Certain phytochemicals inhibit key digestive enzymes such as á-amylase and á-glucosidase, slowing the breakdown of complex carbohydrates into glucose and reducing postprandial blood glucose spikes. This mechanism is particularly beneficial in controlling post-meal hyperglycemia in diabetic patients. Collectively, these findings indicate that *M. cymbalaria* exerts antidiabetic effects through multiple complementary mechanisms including enhancement of insulin sensitivity, protection of pancreatic cells, regulation of glucose transport, modulation of metabolic gene expression, antioxidant defense and inhibition of carbohydrate-digesting enzymes. Such a multi-targeted therapeutic approach is especially advantageous in managing diabetes mellitus, a disease involving complex metabolic dysregulation. Despite strong preclinical evidence, clinical studies evaluating the antidiabetic efficacy of *M. cymbalaria* in human subjects remain limited. Future research should focus on controlled clinical trials, dose optimization, long-term safety assessment and standardization of bioactive compounds to facilitate its integration into modern diabetes management strategies.

Table 2: Antidiabetic effects of *M. cymbalaria*

Experimental model	Extract type	Dose (mg kg^{-1} bw)	Glycemic reduction (%)	Metabolic improvements	References
Alloxan-induced diabetic rats	Whole fruit powder	100-300	38-52	Decreased cholesterol and triglycerides; improved lipid profile	Rao *et al.* (1999)
Streptozotocin-induced diabetic rats	Ethanolic fruit skin and seed extract	200	45	Enhanced insulin sensitivity; normalized lipid levels	Elangovan *et al.* (2019)
High-fat diet induced diabetic mice	Methanolic fruit extract	100-250	40-48	Increased GLUT4 expression; reduced insulin resistance	Kumar *et al.* (2018)
Diabetic rats (metabolic study)	Whole fruit dietary supplementation	-	35	Restoration of hepatic glycogen; improved carbohydrate metabolism	Rao *et al.* (1999)
Oxidative stress diabetic model	Fruit extract	150	42	Reduced lipid peroxidation; pancreatic protection	Kumar *et al.* (2018)

Table 3: Antioxidant activity of *M. cymbalaria*

Experimental model/assay	Extract type	Dose/ concentration	Reduction in oxidative stress (%)	Antioxidant improvements	References
DPPH free radical scavenging assay	Methanolic fruit extract	50-200 µg ml^{-1}	60-85	Strong free radical neutralization capacity	Srinivasulu (2017)
FRAP antioxidant assay	Ethanolic fruit extract	100-250 µg ml^{-1}	55-78	Increased reducing power	Jeyadevi *et al.* (2012)
Diabetic rat oxidative model	Fruit extract	150 mg kg^{-1} bw	Decrease Lipid peroxidation 45-50	Increased SOD, CAT, GPx enzymes	Kumar *et al.* (2018)
High-fat diet induced oxidative stress	Methanolic fruit extract	150 mg kg^{-1} bw	Decrease MDA levels ~48	Restoration of antioxidant defense system	Kumar *et al.* (2018)
In vitro hydroxyl radical assay	Fruit extract	50-200 µg ml^{-1}	58-80	Protection against oxidative membrane damage	Srinivasulu (2017)

5.2 Antioxidant activity

Oxidative stress arises from an imbalance between the production of reactive oxygen species (ROS) and the body's antioxidant defense system, leading to cellular damage of lipids, proteins and nucleic acids. It plays a central role in the development and progression of chronic metabolic disorders including diabetes mellitus, cardiovascular diseases, hepatic dysfunction and inflammatory conditions. Persistent hyperglycemia significantly enhances ROS generation, contributing to pancreatic â-cell damage, insulin resistance and tissue degeneration. Consequently, antioxidant-rich plant foods are increasingly recognized as vital components in disease prevention and therapeutic management. *M. cymbalaria* exhibits strong antioxidant potential largely due to its high content of phenolic compounds, flavonoids and other redox-active phytochemicals. In vitro antioxidant assays such as DPPH free radical scavenging, ferric

reducing antioxidant power (FRAP) and hydroxyl radical inhibition tests have consistently demonstrated significant antioxidant activity of fruit extracts. These assays indicate the plant's ability to donate hydrogen atoms or electrons to neutralize free radicals, thereby interrupting oxidative chain reactions. In vivo studies further substantiate these findings by showing enhanced activity of endogenous antioxidant enzymes following administration of *M. cymbalaria* extracts. Treated experimental animals exhibited increased levels of superoxide dismutase, catalase and glutathione peroxidase enzymes responsible for detoxifying reactive oxygen species. Concurrently, lipid peroxidation markers such as malondialdehyde were significantly reduced, indicating decreased oxidative membrane damage.

The antioxidant properties of *M. cymbalaria* are particularly beneficial in protecting pancreatic â-cells, which possess inherently low antioxidant capacity and are highly susceptible to oxidative injury. By reducing oxidative stress, the plant helps preserve insulin secretion capacity and delays progression of diabetes-related complications. In hepatic tissues, antioxidant activity limits oxidative damage associated with fatty liver disease and metabolic stress, thereby complementing the hepatoprotective effects discussed earlier. Similarly, in vascular tissues, reduced oxidative stress contributes to improved endothelial function and decreased risk of cardiovascular complications. The presence of vitamin C further enhances the antioxidant profile of *M. cymbalaria*, as this vitamin plays a crucial role in scavenging free radicals, regenerating other antioxidants and supporting immune defense mechanisms. Importantly, the antioxidant effect of *M. cymbalaria* is not attributed to a single compound but rather to the synergistic interaction of multiple phytochemicals. This combined action provides broader and more sustained oxidative protection compared to isolated antioxidant molecules.

5.3 Hepatoprotective effects

The liver is a central metabolic organ responsible for glucose regulation, lipid metabolism, detoxification and protein synthesis. In metabolic disorders such as diabetes mellitus and obesity, hepatic tissues are exposed to excessive oxidative stress, lipid accumulation and inflammatory damage, leading to conditions such as non-alcoholic fatty liver disease and impaired liver function. Elevated liver enzymes including alanine aminotransferase (ALT), aspartate aminotransferase (AST) and alkaline phosphatase (ALP) are common indicators of hepatic injury. Experimental investigations have demonstrated that *M. cymbalaria* exhibits significant hepatoprotective activity against metabolic and oxidative stress-induced liver damage. Administration of fruit extracts has been shown to normalize elevated liver enzyme levels in diabetic and high-fat diet-induced animal models, indicating stabilization of hepatocyte membranes and restoration of liver function (Kumar *et al.*, 2018). Histopathological examinations further confirm these biochemical findings. Treated animals display reduced fatty degeneration, diminished inflammatory infiltration and near-normal hepatic architecture compared to untreated controls. This structural protection suggests effective prevention of liver cell necrosis and lipid accumulation. The hepatoprotective mechanism of *M. cymbalaria* is strongly linked to its antioxidant and hypolipidemic properties. Phenolic compounds and flavonoids scavenge reactive oxygen species, reducing lipid peroxidation and mitochondrial damage within hepatocytes. Simultaneously, regulation of lipid metabolism prevents excessive triglyceride accumulation that leads to fatty liver formation. Anti-inflammatory phytochemicals further suppress cytokine-mediated hepatic injury, while improved glycemic control reduces glucose-induced oxidative stress in liver tissues. Together, these multi-pathway effects provide comprehensive liver protection. Thus, *M. cymbalaria* acts not only as a glucose-regulating agent but also as a hepatic protective functional food, particularly beneficial in metabolic syndrome and diabetes-associated liver complications.

5.4 Anti-inflammatory activity

Inflammation is a natural physiological response to injury and infection; however, persistent low-grade inflammation is a key pathological factor underlying metabolic disorders such as diabetes mellitus, obesity, cardiovascular disease and hepatic dysfunction. Chronic activation of inflammatory pathways leads to increased production of pro-inflammatory cytokines, oxidative stress amplification, tissue damage and impaired insulin signaling. Therefore, plant-based anti-inflammatory agents are increasingly explored as complementary strategies for managing chronic inflammatory conditions. *M. cymbalaria* exhibits significant anti-inflammatory activity, largely attributed to its diverse phytochemical constituents including flavonoids, phenolic compounds, tannins, terpenoids, and saponins. Experimental studies have demonstrated that fruit extracts effectively suppress inflammatory responses in both *in vitro* and *in vivo* models. One of the primary mechanisms involves inhibition of pro-inflammatory enzymes such as cyclooxygenase (COX) and lipoxygenase (LOX), which are responsible for the synthesis of prostaglandins and leukotrienes that mediate inflammation and pain. By reducing the activity of these enzymes, *M. cymbalaria* decreases inflammatory mediator production and limits tissue swelling. Additionally, the plant suppresses inflammatory cytokines including tumor necrosis factor-alpha (TNF-á), interleukin-1â (IL-1â) and interleukin-6 (IL-6), which play central roles in sustaining chronic inflammatory states. Down regulation of these cytokines reduces immune cell infiltration and protects tissues from progressive damage. The antioxidant properties of *M. cymbalaria* further enhance its anti-inflammatory effects. Oxidative stress activates inflammatory transcription factors such as nuclear factor-kappa B (NF-êB), which stimulates cytokine release. By neutralizing reactive oxygen species, phytochemicals in *M. cymbalaria* indirectly suppress NF-êB activation, thereby reducing inflammation at the molecular level. Flavonoids contribute by stabilizing cellular membranes and inhibiting inflammatory mediator synthesis, while tannins exert protein-binding effects that reduce vascular permeability and inflammatory exudation. Terpenoids modulate immune signaling pathways and reduce leukocyte migration to inflamed tissues. In metabolic disorders, chronic inflammation disrupts insulin signaling pathways and accelerates tissue degeneration. The anti-inflammatory activity of *M. cymbalaria* therefore plays a critical role in restoring metabolic balance, improving insulin sensitivity and preventing diabetes-associated complications.

5.5 Hypolipidemic activity

Dyslipidemia is a major metabolic disorder associated with diabetes mellitus and cardiovascular diseases, characterized by elevated cholesterol, triglycerides and LDL levels with reduced HDL concentration (Sharma *et al*., 2008). Experimental studies have demonstrated that *M. cymbalaria* significantly improves lipid profiles in diabetic and metabolically stressed animal models by reducing total cholesterol, triglycerides and LDL while increasing HDL levels

(Rao *et al.*, 1999; Elangovan *et al.*, 2019). The lipid-lowering effects are attributed to the presence of saponins, flavonoids, phenolic compounds and unsaturated fatty acids. Saponins promote cholesterol excretion by binding bile acids, while flavonoids regulate lipid metabolism enzymes and prevent oxidative modification of lipoproteins. Improved glycemic control further contributes to normalization of lipid metabolism.

5.6 Antimicrobial activity

Microbial infections remain a major public health concern, particularly in individuals with metabolic disorders and weakened immune systems. The rapid emergence of antibiotic resistance has intensified interest in plant-derived antimicrobial agents as alternative therapeutic resources. Medicinal plants rich in phytochemicals are increasingly recognized for their ability to inhibit microbial growth through multi-targeted mechanisms. *M. cymbalaria* has demonstrated significant antimicrobial activity in several laboratory-based investigations. *In vitro* agar diffusion and broth dilution studies revealed that ethanolic and methanolic fruit extracts effectively inhibited the growth of pathogenic bacteria such as *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Bacillus subtilis* (Srinivasulu, 2017; Jeyadevi *et al.*, 2012). Minimum inhibitory concentration (MIC) values ranging from 50 to 150 µg ml{ ¹ were reported against *E. coli* and *S. aureus*, indicating strong bactericidal potential of the extracts (Srinivasulu, 2017). Antifungal activity against *Candida albicans* and other fungal strains has also been observed, suggesting broad-spectrum antimicrobial efficacy (Jeyadevi *et al.*, 2012).

Applied experimental case studies further support these findings. In laboratory wound infection models, topical application of *M. cymbalaria* extract significantly reduced microbial load and accelerated wound healing compared to untreated controls, accompanied by decreased inflammation and improved tissue regeneration (Kumar *et al.*, 2018). The antimicrobial effects are primarily attributed to flavonoids, tannins, alkaloids and phenolic compounds. These phytochemicals disrupt microbial cell membranes, inhibit protein and nucleic acid synthesis, interfere with enzymatic metabolism and cause leakage of intracellular components. Tannins precipitate microbial proteins, flavonoids destabilize membrane integrity and alkaloids inhibit microbial replication pathways. Recent studies have also explored nanoparticle formulations synthesized using *M. cymbalaria* extracts, such as silver and selenium nanoparticles, which exhibited enhanced antibacterial activity compared to crude extracts alone (Hemalatha *et al.*, 2021). This highlights the potential of advanced phytochemical-based biomedical applications.

5.7 Immune boosting potential

The immune system plays a crucial role in protecting the body against infections, oxidative stress and chronic diseases. Nutritional deficiencies, metabolic disorders and persistent inflammation can impair immune responses, increasing susceptibility to infections and delayed recovery. Plant-based foods rich in antioxidants, vitamins, minerals and bioactive phytochemicals are increasingly recognized for their ability to modulate immune function and enhance host defense mechanisms. *M. cymbalaria* possesses several constituents that contribute to immune enhancement, including vitamin C, flavonoids, phenolic compounds, saponins and essential minerals such as iron and zinc. Vitamin C is a key immunomodulatory nutrient that stimulates white blood cell activity, enhances antibody production and protects immune cells from oxidative damage (Jeyadevi *et al.*, 2012). Experimental studies indicate that antioxidant-rich extracts of *M. cymbalaria* reduce oxidative stress in immune tissues, thereby improving immune cell viability and function (Kumar *et al.*, 2018). By neutralizing reactive oxygen species, the plant prevents immune suppression caused by chronic oxidative stress. Saponins present in the plant are known to stimulate immune responses by enhancing macrophage activity and promoting cytokine production involved in pathogen defense. Flavonoids further contribute by modulating inflammatory pathways and improving communication between immune cells.

In laboratory models, administration of *M. cymbalaria* extracts has been associated with increased levels of endogenous antioxidant enzymes and improved resistance to experimentally induced infections, suggesting enhancement of innate immune defense mechanisms (Srinivasulu, 2017). Additionally, improved metabolic control achieved through the antidiabetic and anti-inflammatory actions of *M. cymbalaria* indirectly supports immune health, as stable blood glucose levels and reduced inflammation are critical for effective immune function.

Table 4: Immunomodulatory evidence of *M. cymbalaria*

Experimental model	Extract type	Dose	Immune response observed	References
Oxidative stress-induced rat model	Methanolic fruit extract	150 mg kg^{-1} bw	Increased antioxidant enzymes; improved immune cell viability	Kumar *et al.* (2018)
In vitro macrophage activation assay	Ethanolic fruit extract	50-200 µg ml^{-1}	Enhanced phagocytic activity and cytokine production	Srinivasulu (2017)
Infection resistance laboratory model	Fruit extract	100 mg kg^{-1} bw	Reduced microbial load; improved immune response	Kumar *et al.* (2018)
Antioxidant-linked immune protection assay	Fruit extract	50-150 µg ml^{-1}	Protection of lymphocytes from oxidative damage	Jeyadevi *et al.* (2012)
Inflammatory immune modulation model	Methanolic fruit extract	150 mg kg^{-1} bw	Suppressed excessive inflammatory cytokines; balanced immune signaling	Kumar *et al.* (2018)

6. Future scope and research perspectives

Although substantial experimental evidence supports the nutritional and therapeutic potential of *M. cymbalaria*, several research gaps remain that must be addressed to enable its wider utilization in healthcare, agriculture and nutraceutical development. Future investigations should adopt multidisciplinary approaches integrating phytochemistry, pharmacology, molecular biology, agronomy and clinical sciences.

6.1 Clinical validation and human trials

Most available evidence on the medicinal effects of *M. cymbalaria* is derived from *in vitro* and animal studies. Well-designed clinical trials are essential to confirm its efficacy in managing diabetes mellitus, dyslipidemia, hepatic disorders, immune modulation and inflammatory conditions in human populations. Standardized dosage forms, treatment duration and safety assessments should be prioritized to facilitate therapeutic acceptance.

6.2 Standardization of bioactive compounds

Variability in phytochemical composition due to environmental conditions, maturity stage and genetic diversity limits reproducibility of therapeutic outcomes. Future research should focus on isolating, characterizing and quantifying key bioactive compounds responsible for medicinal effects. Development of standardized extracts and quality control protocols will be critical for pharmaceutical and nutraceutical applications.

6.3 Molecular mechanism elucidation

Although several therapeutic pathways have been identified, deeper understanding of cellular and genetic mechanisms remains limited. Advanced studies involving transcriptomics, proteomics, metabolomics and signal transduction analysis can clarify how *M. cymbalaria* regulates insulin signaling, oxidative stress pathways, immune responses and lipid metabolism at molecular levels.

6.4 Nutraceutical and functional food development

Given its combined nutritional and medicinal properties, *M. cymbalaria* has strong potential for development into functional foods, dietary supplements, herbal formulations and therapeutic beverages. Processing technologies that preserve bioactivity while improving shelf life and consumer acceptability should be explored.

6.5 Safety, toxicology and drug interaction studies

Comprehensive toxicity evaluations including acute, sub-chronic and chronic exposure studies are required to establish safe consumption levels. Potential interactions with conventional antidiabetic or lipid-lowering drugs should also be investigated to ensure safe integrative therapy.

6.6 Conservation and biodiversity management

As a traditionally underutilized species, *M. cymbalaria* faces risks from habitat loss and genetic erosion. Conservation strategies including germplasm preservation, seed banks and community-based cultivation programs should be promoted to maintain biodiversity and traditional knowledge.

7. Conclusion

M. cymbalaria is a valuable traditional vegetable with substantial nutritional and therapeutic significance, yet remains underutilized in modern agricultural and healthcare systems. The present review highlights its rich phytochemical composition, notable nutritional profile and diverse pharmacological properties, reinforcing its role as a functional food with promising medicinal potential. Scientific evidence demonstrates that *M. cymbalaria* exhibits potent antidiabetic activity through multiple complementary mechanisms, including enhancement of insulin sensitivity, stimulation of glucose uptake, protection of pancreatic â-cells from oxidative damage and inhibition of carbohydrate-digesting enzymes. Its strong antioxidant capacity further contributes to the prevention of oxidative stress-related tissue damage, forming a fundamental basis for its therapeutic effects in metabolic disorders. The plant also displays significant hepatoprotective, anti-inflammatory, hypolipidemic, antimicrobial and immunomodulatory activities, indicating a broad-spectrum biological impact. These effects are largely attributed to the synergistic interaction of phytochemicals such as flavonoids, phenolic compounds, saponins, terpenoids and bioactive proteins. The combined nutritional and medicinal properties position *M. cymbalaria* as a holistic health-promoting vegetable capable of addressing both nutrient deficiencies and chronic disease burden. Despite encouraging experimental findings, the translation of this traditional vegetable into mainstream therapeutic and nutritional frameworks remains limited. Key challenges include insufficient clinical validation, lack of standardized phytochemical profiling, limited agronomic development and inadequate awareness of its health benefits. Addressing these gaps through multidisciplinary research will be essential for its sustainable utilization.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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