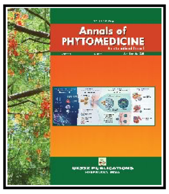
Annals of Phytomedicine 14(2): 105-118, 2025

DOI: http://dx.doi.org/10.54085/ap.2025.14.2.11

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Review Article : Open Access

A comprehensive review on nutritional, pharmacological and functional potential of an emerging cucurbit, *Momordica cymbalaria* Hook. Fenzl. with therapeutic promise

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Article Info

Article history

Received 29 August 2025

Revised 28 September 2025

Accepted 29 September 2025

Published Online 30 December 2025

Keywords

Momordica cymbalaria Hook. Fenzl.

Phytochemicals

Pharmacology

Nutraceuticals

Antimicrobial

Functional food

Abstract

Momordica cymbalaria Hook. Fenzl (syn. *Momordica tuberosa* Roxb., *Luffa tuberosa* Roxb.), a neglected cucurbit, native to semi-arid regions of India, has long been utilized in traditional medicine and consumed as a seasonal vegetable. The plant is increasingly recognized as a hidden nutritional treasure with immense pharmacological promise. Comparative studies have revealed that *M. cymbalaria* possesses superior levels of vitamin C, calcium, potassium, and dietary fiber compared to its better-known relative, *M. charantia* (bitter gourd). Its diverse phytochemical profile includes cucurbitacins, momordicosides, flavonoids, phenolics, saponins, alkaloids, tannins, sterols, and essential fatty acids, which collectively contribute to a wide pharmacological spectrum. Preclinical studies confirm its antidiabetic, antioxidant, hepatoprotective, nephroprotective, cardioprotective, anticancer, antimicrobial, anti-inflammatory, antiulcer, antifertility, and neuroprotective activities.

Despite these promising attributes, *M. cymbalaria* remains underutilized due to challenges in large-scale cultivation, limited awareness, and lack of clinical validation. This review critically evaluating ethnobotanical traditions, nutritional and phytochemical composition, pharmacological effects, nutraceutical potential, conservation strategies, and future prospects. By integrating traditional wisdom with modern scientific findings, this work positions *M. cymbalaria* as a valuable functional food and nutraceutical candidate with implications for human healthcare, nutritional security and in semi-arid ecosystems.

1. Introduction

The Cucurbitaceae family, with over 800 species, represents one of the most diverse groups of flowering plants. It includes globally important food crops such as cucumber (*Cucumis sativus*), pumpkin (*Cucurbita pepo*), watermelon (*Citrullus lanatus*), and bitter gourd (*Momordica charantia*). Beyond their culinary uses, cucurbits are known for their medicinal and nutritional value, particularly due to their abundance of bioactive compounds such as cucurbitacins, flavonoids, and terpenoids (Lee and Tan, 2015).

Among cucurbits, *M. charantia* has achieved global recognition for its hypoglycemic activity and is widely incorporated into herbal medicines, functional foods, and dietary supplements for diabetes management (Joseph and Jini, 2013). However, *M. cymbalaria* a closely related but underutilized species, has received far less attention despite its remarkable nutritional and pharmacological potential.

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Traditional medical systems such as Ayurveda, Siddha, and folk medicine attribute multiple therapeutic uses to *M. cymbalaria*. Fruits, roots, and leaves are used to treat ailments ranging from diabetes and rheumatism to liver and spleen disorders (Jeyadevi *et al.*, 2012; Mohammed *et al.*, 2024a). Tribal communities have historically consumed the fruits as a vegetable and administered root decoction as abortifacients and contraceptives (Jha *et al.*, 2018).

M. cymbalaria is a prostrate perennial climber distributed in semi-arid regions of peninsular India, particularly in Andhra Pradesh, Karnataka, Tamil Nadu, Madhya Pradesh, and Maharashtra (Anusha *et al.*, 2025). The fruits are small, spiny, and bitter, closely resembling those of *M. charantia*, though they are less widely cultivated and primarily gathered from wild or semi-wild habitats. The morphological characteristics of *M. cymbalaria*-including its flowers, fruits, leaves, and roots are illustrated in Figure 1.

The plant is a perennial, creeping or climbing herb, arising from a persistent tuberous rootstock. The tuber is small, perennial, and serves both as a vegetative propagule and a survival organ during adverse seasons (Ravikumar and Bhakshu, 2010). This geophytic habit distinguishes it from the annual *M. charantia* and other congeners. The stems are slender, angular, herbaceous, and covered with fine pubescence (Joseph and Jini, 2013).

The stems are prostrate or weakly climbing, usually spreading over surrounding vegetation or soil. They are angular in cross-section with longitudinal ridges and fine hairs. Tendrils are axillary, simple, unbranched, and coiled, enabling the plant to anchor onto supports (Patil *et al.,* 2014). Leaves are highly variable in shape, usually reniform to orbicular in outline, with 3-5 shallow lobes. Margins are serrated or crenate, and both surfaces are sparsely pubescent. Petioles are long, slender, and pubescent. Leaf lamina size ranges from 2-6 cm across depending on environmental conditions (Sudhakar and Rao, 2016). This variability has been exploited in germplasm characterization studies (Sharma *et al.,* 2019).

The species is monoecious, bearing separate male (staminate) and female (pistillate) flowers on the same plant (Naidu and Swamy, 2017). Produced in axillary clusters of 2-4, borne on slender pedicels. Calyx is small and green; corolla yellow, campanulate, with five free petals. Stamens are three, with filaments connate at the base. Corolla diameter ranges from 1.0-1.5 cm. Usually solitary, larger than male flowers, borne on shorter peduncles. The ovary is inferior, ellipsoid, and trilocular. Styles are short with three bifid stigmas. Corolla bright yellow, similar in form to staminate flowers but slightly larger (Rajyalakshmi and Prasad, 2014).

The fruit is a small, fleshy berry, oblong to ovoid, usually ribbed or angular (6-8 prominent ridges), measuring 2-5 cm in length and 1-2 cm in diameter (Jain *et al.,* 2018). The immature fruit is green, turning yellow to orange at maturity. Unlike the larger and warty fruits of *M. charantia*, and *M. cymbalaria* fruits are smooth or faintly pubescent and distinctly ridged, resembling miniature gourds. The pericarp is thin and encloses numerous seeds embedded in pulp.

Seeds are ovoid to round, flattened, with a hard testa. Average seed size ranges between 4-6 mm in length. They are embedded in a mucilaginous aril that turns reddish-orange on ripening, attracting dispersal agents (Mohammed *et al.,* 2024b). Germination is epigeal, and seedling emergence is rapid under favorable soil moisture conditions. In addition to seeds, propagation through tubers is also common in native habitats.

Flowering occurs during the monsoon and post-monsoon seasons (July-October), followed by fruiting in August-November. Seasonal variation is influenced by rainfall and soil type. Pollination is mainly by insects, especially bees, which are attracted to the bright yellow corolla (Kumari and Rao, 2020).

Figure 1: Morphological feature of *M. cymbalaria* (a) Tuber, (b) Flowering vine, (c) Fruits and (d) Seeds.

2. Ethnobotanical and traditional application

The ethnomedicinal significance of *M. cymbalaria* has been well recognized in Ayurvedic, Siddha, and tribal medicine systems. Historical accounts trace its use back several centuries in peninsular India, particularly among rural communities where the fruits are consumed as seasonal vegetables (Reddy and Prakash, 2013). Unlike the widely cultivated *M. charantia*, and *M. cymbalaria* has remained a semi-wild species, largely collected from local habitats, earning it the reputation of a "poor man's vegetable" and a household remedy for diverse ailments.

Different plant parts of *M. cymbalaria* are traditionally employed in distinct therapeutic contexts:

- **Fruits:** The most commonly consumed part, often prepared as curries or stir-fry. Fruit juice is administered as a tonic, stomachic, and mild laxative (Jeyadevi *et al.,* 2012). Folk medicine also reports their use against gout, rheumatism, malaria, and liver disorders (Fernandes *et al.,* 2007).
- **Roots:** Root decoctions are described as abortifacient, contraceptive, and aphrodisiac (Osinubi *et al.,* 2008). In tribal practices of Andhra Pradesh and Karnataka, roots are additionally used for digestive complaints such as diarrhea and indigestion (Jha *et al.,* 2018).
- **Leaves:** Fresh leaves are applied externally on wounds, ulcers, and fevers, while infusions are taken for intestinal parasites and febrile conditions (Shaika *et al.,* 2024).
- **Tubers:** Though less studied, tubers are occasionally employed in folk medicine as galactagogues and general tonics for stamina.

Ethnobotanical surveys confirm the plant's diverse applications. In Karnataka, fruits are commonly used against diabetes and as a household remedy for stomach ailments (Mohammed *et al.,* 2024a). In Tamil Nadu, decoctions of leaves and fruits are used in rural villages for fevers and infections. Reddy and Prakash (2013) documented its frequent mention in folk traditions of Andhra Pradesh, where roots are valued as contraceptives.

These practices provide a basis for the pharmacological claims validated in modern studies. For example, the antidiabetic use aligns with evidence of α-amylase inhibition (Jeyadevi *et al.,* 2012), while wound-healing applications correspond with antimicrobial activity (Mohammed *et al.,* 2024a).

While *M. charantia* is globally renowned for diabetes management, *M. cymbalaria* is unique for its dual reputation as both a food and contraceptive herb. Such contrasting ethnomedicinal uses highlight differences in phytochemistry. Comparative analysis is crucial for understanding its unique identity within Cucurbitaceae (Gupta *et al.,* 2013).

3. Nutritional composition

Nutritional profiling of *M. cymbalaria* provides valuable insights into its dietary significance and potential as a functional food. Jeyadevi *et al.* (2012) reported that the fruits contain vitamin C levels as high as 290 mg/100 g, nearly threefold greater than those of *M. charantia* (96 mg/100 g). This exceptional concentration of ascorbic acid places *M. cymbalaria* among the richest natural sources of vitamin C within cucurbits, comparable to vitamin-rich fruits such as guava and amla. In addition, the fruit exhibits higher calcium (72 mg/100 g) and potassium (500 mg/100 g) content, which highlights its importance in maintaining bone health and electrolyte balance (Table 1).

From a proximate perspective, the fruits contain approximately 12.6% carbohydrate, contributing moderately to caloric intake (Jeyadevi *et al.,* 2012). Protein content is around 2.15%, similar to *M. charantia*, while the leaves are enriched with essential amino acids such as valine, leucine, and lysine (Shaika *et al.,* 2024). A particularly striking feature of *M. cymbalaria* is its high dietary fiber content (6.42%), which is substantially greater than that of *M. charantia* and strongly suggests benefits for digestive health, cholesterol regulation, and weight management. In line with the present results, similar observations have been reported earlier by Parvathi and Kumar (2002), Bharathi *et al.* (2013), Chinthan *et al.* (2021), and more recently by Adaikkan and Thirunavukkarasu (2024).

Although, *M. cymbalaria* is comparatively poor in â-carotene (0.01 µg/100 g) relative to *M. charantia* (126 µg/100 g), the overall mineral profile is more favourable. Calcium and potassium dominate in the fruits, while leaves are particularly rich in micronutrients such as magnesium, manganese, and zinc (Shaika *et al.,* 2024). The distribution of nutrients across plant parts also varies considerably: fruits are the richest source of vitamins, phenolic compounds, and antioxidants; leaves are valuable for their amino acid and mineral content but also contain significant levels of antinutritional factors such as phytates and tannins; and tubers, although less nutrient-dense, contribute carbohydrates and bioactive saponins.

The presence of oxalates, tannins, and phytates in leaves is noteworthy, as these compounds chelate essential minerals and reduce their bioavailability (Shaika *et al.,* 2024). However, traditional processing methods-including boiling, fermentation, soaking, and roasting-are effective in lowering the concentration of these antinutritional factors. Such practices not only enhance palatability but also improve micronutrient bioavailability, thereby optimizing the nutritional benefits of the leaves. This is especially relevant in communities where green leafy vegetables form a dietary staple.

The comparative analysis of *M. cymbalaria* and *M. charantia* highlights significant nutritional variations that may influence their therapeutic potential and dietary applications. *M. cymbalaria* demonstrates higher levels of fibre, calcium, sodium, potassium, zinc, manganese, and vitamin C, which are essential for promoting digestive health, maintaining electrolyte balance, enhancing bone strength, and boosting antioxidant defense mechanisms. Particularly, its exceptionally high vitamin C content (290 mg/100 g) suggests a strong role in immunity enhancement and free radical scavenging activity. Conversely, *M. charantia* exhibits higher concentrations of beta-carotene, phosphorus, and energy content, reflecting its value as a rich source of provitamin A for vision and skin health, alongside providing greater caloric contribution. The presence of comparable protein and copper levels in both species further indicates their shared potential as functional foods. Overall, these compositional differences signify that while *M. cymbalaria* could be more beneficial for mineral supplementation and antioxidant protection, *M. charantia* may serve as a superior source of energy and vitamin A precursors, thereby complementing each other in human nutrition and healthcare.

Table 1: Comparative nutritional composition of *M. cymbalaria* and *M. charantia* (Jeyadevi *et al.*, 2012; Jha *et al.*, 2018)

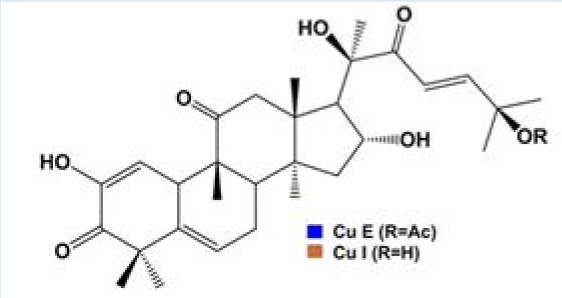
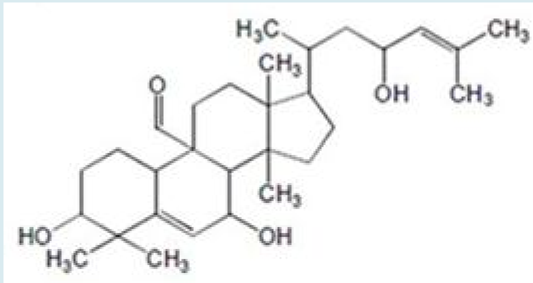
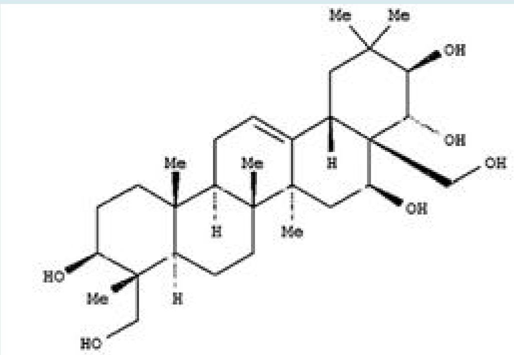
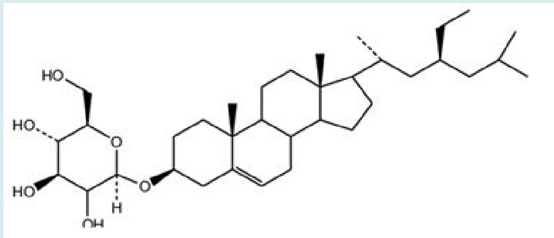
Composition	*M. cymbalaria*	*M. charantia*
Moisture %	84.30	83.20
Fibre %	6.42	1.70
Beta carotene %	0.01	126.00
Protein %	2.15	2.10
Carbohydrate %	12.60	10.60
Energy k cal/100 g	3.00	60.00
Calcium mg/100 g	72.00	23.00
Sodium mg/100 g	40.00	2.40
Potassium mg/100 g	500.00	171.00
Iron mg/100 g	1.70	2.00
Zinc mg/100 g	2.82	0.46
Manganese mg/100 g	0.32	0.08
Copper mg/100 g	0.18	0.19
Phosphorus mg/100 g	0.46	38.00
Vitamin C mg/100 g	290.00	96.00

A comparative assessment of *M. cymbalaria* and *M. charantia* reveals distinct nutritional strengths that highlight their complementary roles in human nutrition. Table 2 summarizes this comparison. While both species are rich in health-promoting phytochemicals, the nutrient superiority of *M. cymbalaria* is evident in its elevated vitamin C and calcium content, making it a valuable dietary source for enhancing immunity and bone health. Conversely, *M. charantia* is distinguished by its higher β-carotene content, which contributes significantly to provitamin A activity, thereby supporting vision and overall antioxidant defence (Jha *et al.*, 2018). This comparative insight emphasizes the potential for dietary diversification, where incorporating both species into the diet could provide synergistic nutritional benefits by balancing their respective strengths in micronutrient and phytochemical composition.

Table 2: Comparative phytochemical and pharmacological attributes of *M. cymbalaria* and *M. charantia*

Attribute	*M. cymbalaria*	*M. charantia*	References
Major phytochemicals	Cucurbitacins B, D, E, I; flavonoids; phenolics; saponins; alkaloids; sterols	Charantin, momordicosides, cucurbitacins, flavonoids	Mohammed *et al.*, 2024b; Gupta *et al.*, 2013
Antidiabetic	Strong α-amylase inhibition, β-cell protection	Well established, multiple clinical studies	Jeyadevi *et al.*, 2012; Joseph and Jini, 2013
Antioxidant	High due to vitamin C + phenolics	Moderate, mainly carotenoids	Shaika *et al.*, 2024
Hepatoprotective	Validated in animal models	Validated in animal and some human trials	Jha *et al.*, 2018
Anticancer	Cucurbitacins inhibit STAT3 pathways	Similar, more studied	Shaika *et al.*, 2024
Antifertility	Root extracts reduce fertility	Not widely reported	Osinubi *et al.*, 2008

Momordica cymbalaria	*Momordica charantia*
Therapeutic targets • Nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB) • Peroxisome proliferator activated receptor gamma (PPARγ)	**Therapeutic targets** • Adenosine monophosphate-activated protein kinase (AMPK) • Glucose transporter type 4 (GLUT4)
Key pathways • Inflammatory response • Glucose metabolism	**Key pathways** • Oxidative stress regulation • Lipid regulation

Bioactive compounds	Bioactive compounds
Cucurbitacin E 	Momordicin 
Gymnemagenin 	Charantin 

Comparative pharmacological pathways

4. Phytochemical composition

The phytochemical repertoire of *M. cymbalaria* is both diverse and pharmacologically important, underpinning its nutritional and therapeutic value. Unlike its close relative *M. charantia*, where investigations have predominantly focused on well-characterized bioactives such as charantin and momordicosides (Grover and Yadav, 2004; Joseph and Jini, 2013), *M. cymbalaria* demonstrates a wider array of metabolites. These include cucurbitacins, flavonoids, saponins, alkaloids, sterols, tannins, fatty acids, and vitamins, all of which synergistically contribute to its broad medicinal potential (Jeyadevi *et al.,* 2012; Mohammed *et al.,* 2024b) (Figure 3).

4.1 Cucurbitacin and triterpenoids

Cucurbitacins are highly oxygenated tetracyclic triterpenoids that impart a characteristic bitterness to cucurbitaceous plants. In *M. cymbalaria*, cucurbitacins B, D, E, and I have been detected, in addition to several structurally related momordicosides (Mohammed *et al.,* 2024b). These compounds exhibit pronounced anticancer, hepatoprotective, and anti-inflammatory activities, often mediated through modulation of NF-kB and JAK/STAT signalling pathways (Lee and Tan, 2015). Such mechanisms highlight their potential as lead molecules for drug development, particularly in cancer and chronic inflammatory disorders.

4.2 Flavonoids and phenolics

The fruits and leaves of *M. cymbalaria* are rich in flavonoids such as quercetin, kaempferol, and rutin, along with a wide spectrum of phenolic acids including gallic acid, ferulic acid, and caffeic acid (Shaika *et al.,* 2024). These compounds are recognized for their ability to scavenge free radicals, chelate pro-oxidant metal ions, and modulate oxidative stress pathways. Such antioxidant properties not only contribute to the plant's protective role against degenerative diseases but also enhance its nutritional value as a functional food.

4.3 Saponins and alkaloids

Saponins are predominantly localized in the tubers and roots of *M. cymbalaria*, correlating with their traditional use as contraceptives in indigenous medicine (Jha *et al.,* 2018). Beyond their antifertility role, saponins are known for their hypocholesterolemic, immunomodulatory, and anticarcinogenic effects. The plant also harbors a range of alkaloids, including momordicine-type alkaloids, which exhibit antidiabetic activity through modulation of glucose metabolism and antimicrobial activity by disrupting microbial cell integrity.

4.4 Sterols and fatty acids

Phytosterols, particularly β-sitosterol and stigmasterol, have been successfully isolated from ethanolic extracts of *M. cymbalaria* (Gupta *et al.,* 2013). These sterols are well documented for their cholesterol-lowering effects and potential to support cardiovascular health. In addition, fatty acid profiling of seeds has revealed the presence of palmitic, oleic, stearic, α-eleostearic, and γ-linolenic acids (Mohammed *et al.,* 2024a). These fatty acids collectively exert cardioprotective, anti-inflammatory, and lipid-modulating effects, underscoring the plant's value as a source of nutraceutical lipids.

4.5 Vitamin C and tannins

Fruits of *M. cymbalaria* are a particularly rich source of vitamin C, conferring strong antioxidant potential and supporting immune function (Jeyadevi *et al.,* 2012). In parallel, the plant also contains tannins, which, despite being considered antinutritional factors due to their capacity to bind proteins and minerals, play beneficial roles at moderate concentrations. Tannins contribute antimicrobial activity by inhibiting microbial enzymes and disrupting bacterial cell walls, thereby extending the spectrum of biological benefits attributed to the species (Shaika *et al.,* 2024).

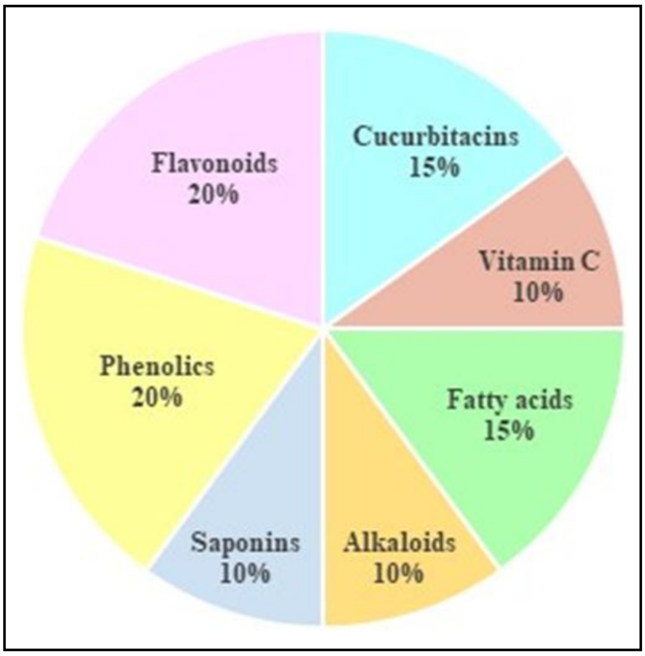


Figure 3: Major phytochemical groups in *M. cymbalaria.*

5. Pharmacological activities and therapeutic potential

The broad spectrum of pharmacological properties attributed to *M. cymbalaria* underscores its potential as a multipurpose medicinal herb. Its rich phytochemical reservoir, including cucurbitacins, flavonoids, phenolics, saponins, alkaloids, and sterols, confers diverse therapeutic benefits ranging from metabolic regulation to organ protection. The following subsections summarize the major bioactivities reported in preclinical and experimental studies.

5.1 Antidiabetic activity

Among its many pharmacological attributes, the antidiabetic potential of *M. cymbalaria* has received the most attention. Jeyadevi *et al.* (2012) demonstrated that methanolic fruit extracts significantly reduced blood glucose levels in alloxan-induced diabetic rats. The underlying mechanisms are multifaceted:

- Inhibition of carbohydrate-digesting enzymes (α-amylase and α-glucosidase), leading to delayed starch breakdown and attenuated postprandial glucose spikes.
- Protection of pancreatic β-cells *via* antioxidant activity, preventing oxidative damage caused by hyperglycemia.
- Enhancement of insulin sensitivity and signaling, particularly through modulation of cucurbitacins and flavonoids.
- Upregulation of GLUT4 expression in skeletal muscle, improving peripheral glucose uptake and utilization (Patel *et al.,* 2012; Mohammed *et al.,* 2024b).

Collectively, these effects provide both symptomatic relief of hyperglycemia and protection against diabetic complications, making *M. cymbalaria* a promising candidate for natural diabetes management.

5.2 Antioxidant activity

The antioxidant potential of *M. cymbalaria* has been extensively investigated through a variety of *in-vitro* assays. Hydroalcoholic extracts of the aerial parts, fruits, and roots were evaluated using ferric ion-reducing power, ABTS radical scavenging, nitric oxide (NO) scavenging, and total antioxidant capacity assays. Among these, the aerial part extracts exhibited the strongest ferric ion-reducing power, while fruit extracts demonstrated superior ABTS and NO radical scavenging activity. The total antioxidant activity of the fruit extract was quantified at 95.27 mg ascorbic acid equivalents per gram of extract, highlighting its strong reducing potential (Prashanth *et al.,* 2013).

Methanolic extracts of the fruits further showed significant DPPH (2,2-Diphenyl-1-picrylhydrazyl) is) free radical, superoxide anion, hydroxyl radical, and NO scavenging activities, along with inhibition of *in vitro* lipid peroxidation, supporting their role in oxidative stress management (Vrushabendra Swamy and Jayaveera, 2007). Similarly, hydroalcoholic extracts of the tubers demonstrated marked reducing power and scavenging of superoxide and hydroxyl radicals, reinforcing the antioxidant contribution of underground plant parts (Pramod *et al.,* 2008).

Phytochemical investigations revealed that the methanolic fruit extract contained 272.00 ± 2.20 mg gallic acid equivalents (GAE) per gram, as determined by the Folin-Ciocalteu assay, confirming its phenolic abundance. Since flavonoids and phenolic compounds are widely recognized as key contributors to natural antioxidant activity, these compounds are considered the primary drivers of *M. cymbalaria*'s antioxidant effects.

The fruits of *M. cymbalaria* are particularly rich in vitamin C, flavonoids, and phenolic compounds, which contribute to their strong antioxidant potential. This has been confirmed by Shaika *et al.* (2024), who reported significant free radical scavenging and metal-chelating activities using DPPH, FRAP (ferric ion reducing antioxidant potential), and ABTS (2,22 -azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) assays. Among plant parts, the fruits exhibited the highest antioxidant activity, recording maximum DPPH scavenging capacity (14.36 AAE mg/100 g), ABTS activity (0.53 TE mg/100 g), and reducing power (10.86 EC_{50}). By reducing oxidative stress, these antioxidants contribute to protection against chronic disorders, including diabetes, cardiovascular diseases, neurodegeneration, and cancer (Singh *et al.,* 2021).

5.3 Hepatoprotective activity

Jha *et al.* (2018) reported significant hepatoprotective effects of *M. cymbalaria* against carbon tetrachloride (CCl_2)-induced liver damage. Extract administration restored serum markers (AST, ALT, and bilirubin) to near-normal levels and enhanced antioxidant defense enzymes (SOD, CAT, and GSH). Mechanistically, hepatoprotection appears to result from:

- Stabilization of hepatocyte membranes, preventing cellular leakage of enzymes.
- Suppression of lipid peroxidation, reducing free radical-induced liver injury.

Vrushabendra Swamy and Jayaveera (2008) assessed the hepatoprotective effect of methanolic extract of *M. cymbalaria* against paracetamol-induced hepatic toxicity in rats. Pre-treatment with the extract resulted in a significant decrease in serum markers such as SGPT, SGOT, ALP, bilirubin, and cholesterol, while enhancing HDL and glutathione (GSH) levels in a dose-dependent manner, confirming its hepatoprotective efficacy. Vrushabendra Swamy *et al.* (2009) evaluated the hepatoprotective activity of methanolic extract of *M. cymbalaria* against thioacetamide-induced liver damage in rats. The study revealed that administration of the extract significantly improved liver function markers, including serum transaminases, and mitigated histopathological damage, indicating strong hepatoprotective potential. The hepatoprotective effects of ethanolic root extract of *M. cymbalaria* in rats with carbon tetrachloride-induced liver injury. The results demonstrated notable reductions in serum hepatic enzymes and improved antioxidant status, highlighting the plant's free radical scavenging ability as a potential mechanism for liver protection (Koneri *et al.,* 2008).

5.4 Nephroprotective activity

Drug induced nephrotoxicity remains a major clinical problem, with agents such as cisplatin, gentamicin, and paracetamol being well known to compromise renal function through mechanisms involving oxidative stress, mitochondrial dysfunction, and lipid peroxidation. Recent investigations have highlighted the protective role of *M. cymbalaria*, particularly the 70% ethanolic extract of its tubers, in mitigating renal damage in experimental animals. Pramod *et al.* (2011) evaluated the nephroprotective efficacy of 70% ethanolic extract of *M. cymbalaria* tubers in Wistar rats exposed to cisplatin, gentamicin, and paracetamol. The extract was administered orally at doses of 20 mg/kg and 40 mg/kg body weight, and nephroprotective activity was assessed through biochemical markers, oxidative stress parameters, and general health indicators. Cisplatin and gentamicin-induced nephrotoxicity. Cisplatin and gentamicin administration significantly elevated serum urea and creatinine levels, reflecting impaired renal clearance. Pre-treatment with *M. cymbalaria* extract markedly reduced these levels, with the 40 mg/kg dose showing near-normalization of renal biomarkers. Improvement in body weight was also noted, suggesting an overall protective effect against systemic toxicity. In paracetamol-treated rats, nephrotoxicity was characterized by elevated renal markers, depletion of reduced glutathione (GSH), and increased lipid peroxidation (LPO). Administration of *M. cymbalaria* extract at 40 mg/kg significantly restored GSH content and reduced LPO activity, thereby preventing oxidative damage.

Protective effects against gentamicin-induced nephrotoxicity have been reported in animal models (Mohammed *et al.,* 2024b). Extract treatment significantly decreased serum creatinine and urea levels, restored normal renal histoarchitecture, and improved kidney antioxidant status. This nephroprotection likely arises from a combination of free radical scavenging, anti-inflammatory activity, and tubular membrane stabilization.

5.5 Cardioprotective and hypolipidemic activity

M. cymbalaria has gained considerable attention for its antidiabetic and hypolipidemic effects, with emerging evidence also highlighting its cardioprotective role. Initial studies using fruit powder supplementation in alloxan-induced diabetic rats revealed significant reductions in serum cholesterol and triglyceride levels, along with improved hepatic glycogen content, indicating a lipid-lowering effect complementary to its antihyperglycemic activity (Bopanna *et al.,* 1997). Subsequent investigations by Sudarshana Deepa *et al.* (2019) demonstrated that skin and seed extracts of *M. cymbalaria* administered to diabetic rats produced dose-dependent decreases in serum lipid levels, restoration of antioxidant defense systems, and marked improvements in histopathological features. Likewise, a purified protein fraction termed "Mcy protein" isolated from the fruits of *M. cymbalaria*, exhibited potent antihyperlipidemic activity in streptozotocin-induced diabetic rats by reducing serum and tissue lipid concentrations, improving liver and kidney biomarkers, lowering blood glucose, and promoting pancreatic islet regeneration (Patel *et al.,* 2007).

In high-fat diet-induced obese and diabetic C57BL/6 mice, methanolic extracts of *M. cymbalaria* fruits (25 and 50 mg/kg) significantly alleviated dyslipidemia, reduced circulating cholesterol and free fatty acids, enhanced insulin sensitivity, and suppressed adiposity, thereby confirming its metabolic and lipid-regulatory potential (Ravikumar *et al.,* 2018). These lipid-lowering and metabolic regulatory actions are directly associated with its cardioprotective efficacy, as they reduce cardiovascular risk factors through improved antioxidant status and stabilization of metabolic homeostasis. Although, experimental studies specifically targeting myocardial injury and cardiac biomarkers are limited, pharmacological evaluations consistently support the plant's cardioprotective activity, primarily mediated by its hypolipidemic, antioxidant, and free radical scavenging mechanisms (Gopalasatheeskumar, 2018). Furthermore, methanolic extracts have been shown to decrease total cholesterol, triglycerides, and LDL cholesterol while elevating HDL cholesterol, reinforcing both lipid-lowering and cardioprotective benefits (Jha *et al.,* 2018). Bioactive constituents such as phytosterols (β-sitosterol, stigmasterol) and unsaturated fatty acids (oleic acid, γ-linolenic acid) are believed to underpin these effects by modulating lipid metabolism through inhibition of intestinal cholesterol absorption, preventing atherogenic plaque development, enhancing endothelial function, and mitigating oxidative stress in cardiac tissue. Collectively, these findings establish *M. cymbalaria* as a promising natural agent for hypolipidemic and cardioprotective interventions.

5.6 Analgesic

The ethanolic extract of *M. cymbalaria* leaves (250 and 500 mg/kg) has been evaluated for its analgesic potential using 0.7% v/v glacial acetic acid-induced writhing and radiant heat tail-flick models in Swiss albino mice (Ramanath and Burte, 2012). At 500 mg/kg, the extract significantly reduced the number of writhes in the acetic acid-induced model and increased the mean reaction time in the tail-flick test. In the writhing model, nociception is mediated by the release of endogenous substances such as histamine, serotonin, bradykinin, prostaglandins, and leukotrienes that stimulate sensory nerve endings, whereas the tail-flick response involves central modulation of pain *via* complex pathways, including opiate, dopaminergic, and serotonergic mechanisms. Thus, the analgesic activity of *M. cymbalaria* extract appears to operate through both peripheral mechanisms (inhibition of prostaglandin and leukotriene synthesis) and central pathways of pain regulation. Furthermore, flavonoids are known to inhibit prostaglandin synthesis and cyclooxygenase-2 expression (Hämäläinen *et al.,* 2011), suggesting that the flavonoid content in *M. cymbalaria* may be responsible for its analgesic effects.

5.7 Anthelmintic

The anthelmintic activity of petroleum ether, chloroform, ethanolic, and aqueous fruit extracts of *M. cymbalaria* (20 mg/ml) was evaluated using Indian adult earthworms (*Pheretima posthuma*) as an *in-vitro* model. Among the tested extracts, the chloroform fraction exhibited the most potent effect, inducing paralysis and death in the shortest duration, followed by petroleum ether, ethanolic, and aqueous extracts (Srinivas *et al.,* 2008). The results, summarized in Table 3, highlight that the chloroform extract achieved mean paralysis and death times of 5.8 ± 0.3 min and 10.2 ± 0.6 min, respectively, markedly outperforming the other solvent fractions.

This activity is largely attributed to the presence of tannins, alkaloids, and flavonoids, which are known to exert neuromuscular and metabolic inhibitory effects on helminths (Da Silva *et al.,* 2008; Wang *et al.,* 2010; Athanasiadou *et al.,* 2001). Specifically, tannins disrupt oxidative phosphorylation by inhibiting ATP synthesis in helminths (Martin, 1997) and bind to the worm's cuticular proteins, causing structural damage and paralysis (Williams *et al.,* 2014).

When compared with standard anthelmintics such as albendazole and piperazine citrate, the extracts - particularly the chloroform fraction-demonstrated comparable efficacy at the tested concentration. Albendazole acts by inhibiting microtubule synthesis, while piperazine citrate induces flaccid paralysis by blocking acetylcholine response in helminths. The faster action of the chloroform extract suggests a tannin-mediated cuticle binding mechanism that may complement the modes of action of these synthetic drugs. This observation underscores the therapeutic promise of *M. cymbalaria* fruit extracts as plant-based alternatives or adjuvants to conventional anthelmintics.

Table 3: Anthelmintic activity of *M. cymbalaria* fruit extracts against *P. posthuman* (Srinivas *et al.,* 2008)

Extract type	Concentration (mg/ml)	Time to paralysis (min)	Time to death (min)	Major phytochemicals responsible
Chloroform extract	20	5.8 ± 0.3	10.2 ± 0.6	Tannins, alkaloids, flavonoids
Petroleum ether	20	7.6 ± 0.4	13.5 ± 0.8	Tannins, alkaloids
Ethanolic extract	20	9.2 ± 0.5	16.8 ± 1.0	Flavonoids, alkaloids
Aqueous extract	20	12.4 ± 0.7	21.3 ± 1.2	Tannins, glycosides

5.8 Anticancer and antiangiogenic

Cancer remains a major global health challenge, and the search for plant-based therapeutics with fewer side effects has intensified in recent years. *M. cymbalaria* has emerged as a promising candidate owing to its rich phytoconstituents such as saponins and cucurbitacins, which exhibit both anticancer and antiangiogenic properties. Preclinical investigations across different animal models and cancer types provide compelling evidence of its therapeutic potential.

The methanolic extract of aerial parts (100 and 200 mg/kg) demonstrated potent anticancer activity in Ehrlich ascites carcinoma (EAC)-bearing Swiss albino mice by reducing tumor burden, viable cell counts, and body weight, while simultaneously normalizing hematological parameters (Jeevanantham *et al.,* 2011). Similarly, saponins isolated from roots (175 mg/kg) showed significant suppression of tumor growth in EAC-bearing mice, reducing viable tumor cell counts and prolonging survival (Koneri *et al.,* 2014).

In chemically induced cancer models, saponins have been equally effective. In DMBA-induced breast cancer in Wistar rats, oral administration of saponins (100 mg/kg) markedly reduced tumor burden, minimized necrosis and hemorrhage, and improved mammary gland histoarchitecture. These protective effects were accompanied by elevated antioxidant defenses such as glutathione (GSH), superoxide dismutase (SOD), and catalase (CAT) (Kaskurthy *et al.,* 2015). Similarly, in diethylnitrosamine-induced hepatocellular carcinoma, saponin treatment (175 mg/kg) reduced serum markers of hepatic injury (AST, ALT, ALP, bilirubin) and improved hepatic antioxidant enzyme activity (Nagarathana *et al.,* 2016).

The antiangiogenic activity of *M. cymbalaria* saponins has been validated in both rat air sac and chick chorioallantoic membrane (CAM) assays. In carrageenan-induced angiogenesis, saponins (175 mg/kg) significantly reduced vascular proliferation and pouch volume, while in CAM assays, saponins (32 µg) inhibited erythropoietin-induced vessel formation (Koneri *et al.,* 2014). Since angiogenesis is a key driver of tumor progression and metastasis, these findings provide a mechanistic link between antiangiogenic effects and tumor suppression.

Beyond saponins, cucurbitacins isolated from *M. cymbalaria* have shown strong cytotoxicity against breast and colon cancer cell lines, acting through inhibition of STAT3 phosphorylation, induction of caspase-mediated apoptosis, and modulation of ROS pathways (Zhang *et al.,* 2020).

Collectively, the findings summarized in Table 4 highlight the anticancer and antiangiogenic efficacy of *M. cymbalaria* across multiple models, establishing its potential as a natural chemopre-ventive and therapeutic agent.

Table 4: Anticancer and antiangiogenic studies of *M. cymbalaria*

Model used	Extract/Compound	Dose (mg/kg)	Key findings	References
Ehrlich ascites carcinoma (EAC), mice	Methanolic extract	100-200	↓ body weight, ↓ tumor volume, normalization of hematological parameters	Jeevanantham *et al.*, 2011
EAC, mice	Saponin (root)	175	↓ viable tumor cell count, ↓ survival time	Koneri *et al.*, 2014
DMBA-induced breast cancer, rats	Saponin (root)	100	↓ tumor size, improved histoarchitecture, ↓ necrosis and hemorrhage, ↓ antioxidants	Kaskurthy *et al.*, 2015
Diethylnitrosamine -induced liver cancer	Saponin (root)	175	↓ AST, ALT, ALP, bilirubin, cholesterol, TG; ↓ protein, SOD, CAT, GSH	Nagarathana *et al.*, 2016
Rat air sac angiogenesis model	Saponin (root)	175	↓ pouch volume, ↓ granulation tissue weight, ↓ dye uptake	Koneri *et al.*, 2014
Chick CAM assay	Saponin (root)	32 µg	↓ erythropoietin-induced vascular formation	Koneri *et al.*, 2014

5.9 Antimicrobial activity

Methanolic extracts exhibited broad-spectrum antimicrobial effects, with notable activity against *Escherichia coli, Staphylococcus aureus,* and *Candida albicans* (Mohammed *et al.,* 2024a). Tannins and flavonoids exert antimicrobial effects primarily by disrupting microbial cell membranes and inhibiting essential microbial enzymes (Pandey and Singh, 2016). These mechanisms underscore the potential of *M. cymbalaria* as a promising source of plant-derived antimicrobial agents, particularly relevant in the context of escalating antibiotic resistance.

5.10 Anti-inflammatory activity

Research has demonstrated that *M. cymbalaria* extracts exert strong anti-inflammatory effects, significantly reducing carrageenan-induced paw edema in rats (Mohammed *et al.,* 2024a). The underlying mechanism is attributed to the presence of bioactive constituents such as flavonoids and saponins, which suppress cyclooxygenase (COX) and lipoxygenase (LOX) pathways, thereby decreasing the production of pro-inflammatory mediators like prostaglandins and leukotrienes. This positions the plant as a promising natural therapeutic agent for arthritis and other chronic inflammatory conditions.

Specifically, the methanolic extract of the aerial parts (100 and 200 mg/kg) produced 53.11% and 44.43% inhibition of carrageenan-induced paw edema in Wistar rats at 4 h post-induction (Jeevanantham *et al.,* 2011). Likewise, ethanolic and aqueous fruit extracts (200 and 400 mg/kg) significantly reduced paw edema in formaldehyde, Freund's adjuvant, and collagen-induced arthritis models. Phytochemical studies further confirm the presence of flavonoids such as rutin and quercetin (Dhasan *et al.,* 2008; Kale and Laddha, 2012), which are well recognized for their ability to attenuate inflammation through modulation of COX, LOX, and cytokine-mediated pathways.

5.11 Neuroprotective and anticonvulsant effects

Experimental studies suggest neuroprotective benefits of *M. cymbalaria*, particularly in seizure models. Extracts reduced seizure onset and duration in PTZ-induced convulsions (Jha *et al.,* 2018). These effects are attributed to:

- GABAergic modulation by alkaloids and flavonoids, enhancing inhibitory neurotransmission.
- Antioxidant protection of neuronal cells, mitigating oxidative damage.

Such properties indicate promise in the management of epilepsy and neurodegenerative disorders.

5.12 Antifertility activity

Roots and tubers of *M. cymbalaria* have long been used in traditional medicine as contraceptives. Experimental validation revealed reduction in implantation rates and sperm motility following extract administration (Osinubi *et al.,* 2008). The activity is largely attributed to saponins, which exert antifertility effects through hormonal modulation and interference with gamete viability.

5.13 Other activities

Beyond its major pharmacological roles, *M. cymbalaria* demonstrates additional therapeutic benefits:

- **Antiulcer activity:** Extracts reduced gastric ulceration by enhancing mucosal defense and lowering gastric acid secretion (Natarajan and Muthusamy, 2014).
- **Antidepressant effect:** Alkaloids modulated serotonergic pathways, alleviating behavioural symptoms in stress-induced animal models (Mohammed *et al.,* 2024a).
- **Immunomodulatory activity:** Saponins stimulated immune cell proliferation, thereby enhancing host defense responses (Choudhury *et al.,* 2019).

The plant exhibits a wide range of therapeutic effects, including:

1. **Antidiabetic activity** - mediated by cucurbitacins, flavonoids, and saponins that inhibit α-amylase and α-glucosidase, enhance insulin secretion, and protect pancreatic β-cells.
2. **Antioxidant potential** - primarily due to its high vitamin C, phenolics, and flavonoids, which neutralize free radicals and reduce oxidative stress.
3. **Hepatoprotective effects** - saponins and triterpenoids regulate liver enzymes (AST, ALT, ALP), improve antioxidant enzyme activity, and protect against chemically induced hepatotoxicity.
4. **Anticancer and antiangiogenic activity** - saponins and cucurbitacins suppress tumor growth by inducing apoptosis, inhibiting STAT3 signaling, and blocking angiogenesis.
5. **Anthelmintic activity** - attributed to tannins, alkaloids, and flavonoids that paralyze and kill helminths by interfering with oxidative phosphorylation and cuticle integrity.
6. **Antifertility effect** - root extracts disrupt reproductive hormones and ovarian cycles, suggesting contraceptive potential.
7. **Cardioprotective and antiobesity roles** - *via* lipid-lowering, antihyperlipidemic, and antiadipogenic mechanisms.
8. **Immunomodulatory actions** - enhanced by phenolic compounds that strengthen host defense mechanisms.

6. Functional and nutraceutical potential

6.1 Nutraceutical significance

The nutritional richness of *M. cymbalaria* places it among promising underutilized species with nutraceutical relevance. Its fruits and leaves are particularly high in vitamin C, calcium, potassium, dietary fiber, and bioactive phytochemicals, which collectively support human health. Jeyadevi *et al.* (2012) highlighted that the vitamin C concentration in *M. cymbalaria* surpasses that of many citrus fruits, underscoring its role in strengthening immune function and preventing micronutrient deficiencies. In addition, Shaika *et al.* (2024) linked the abundance of phenolics and flavonoids in its fruits and leaves to robust antioxidant capacity, suggesting applications in anti-aging formulations, oxidative stress management, and chronic disease prevention. Taken together, these attributes establish *M. cymbalaria* as a valuable nutraceutical resource capable of contributing to dietary interventions for health maintenance and disease risk reduction.

6.2 Functional food applications

The ethnogastronomic use of *M. cymbalaria* in rural India provides a strong foundation for its integration into the modern functional food sector. Traditionally, its fruits are consumed as curries, chutneys, and stir-fried dishes, highlighting their cultural acceptance in local diets. Such practices can be adapted for value-added food development at a commercial scale. According to Bara *et al.* (2025), consumer perception and palatability are critical for the success of cucurbit-based functional foods. The relatively smaller size and bitter taste of *M. cymbalaria* fruits present challenges, but these can be mitigated through processing innovations such as blanching, fermentation, enzymatic debittering, and incorporation into composite food matrices.

Potential avenues for functional food and nutraceutical product development, including:

- **Fortified health beverages and juices** enriched with *M. cymbalaria* extracts for glycemic control in diabetic individuals.
- **Functional bakery products** such as bread, cookies, and biscuits incorporating dried fruit or leaf powder as a source of fiber, minerals, and antioxidants.
- **Dietary supplements (capsules or tablets)** standardized to contain bioactive compounds like cucurbitacins, flavonoids, or saponins.
- **Herbal teas, nutraceutical tonics, or adaptogenic blends** combining *M. cymbalaria* with other cucurbits or medicinal plants to enhance therapeutic efficacy.

These applications would not only diversify its consumption forms but also expand its reach to urban and global health-conscious consumers.

6.3 Mechanistic basis for nutraceutical value

The nutraceutical potential of *M. cymbalaria* is underpinned by well-established biological mechanisms of its phytochemicals:

- **Antidiabetic activity:** mediated by inhibition of digestive enzymes (α-amylase and β-glucosidase), delayed glucose absorption, enhanced insulin sensitivity, and stimulation of glucose transporter (GLUT4) activity.
- **Antioxidant action:** flavonoids, vitamin C, and phenolics neutralize free radicals, thereby reducing oxidative stress, delaying cellular ageing, and mitigating risks of cancer and cardiovascular disease.
- **Cardioprotective role:** phytosterols and fatty acids modulate lipid metabolism, reduce LDL cholesterol, elevate HDL, and suppress atherosclerotic plaque formation.
- **Bone and skeletal health:** high calcium and magnesium concentrations improve mineralization and strength, supporting applications in osteoporosis prevention.

These mechanisms highlight the translational value of *M. cymbalaria* bioactives for preventive nutrition and therapeutic supplementation.

6.4 Market and innovation potential

Despite its promising profile, *M. cymbalaria* remains largely underutilized in both domestic and international markets. Its cultural validation in traditional medicine provides a strong narrative for consumer trust, while its scientifically validated phytochemistry and pharmacological activities align with modern nutraceutical industry standards. With rising demand for plant-based nutraceuticals, particularly in regions facing micronutrient deficiencies, *M. cymbalaria* can be positioned as a functional food crop with high innovation potential.

Opportunities exist for:

- **Product diversification**, including powders, extracts, nutraceutical beverages, and functional snack foods.
- **Phytopharmaceutical exploration**, particularly in the standardization of cucurbitacins, flavonoids, and sterols.

- **Agro-industrial development**, encouraging cultivation of this underexploited species for nutraceutical processing.

Harnessing these opportunities would require collaborative efforts between agricultural scientists, food technologists, and pharmaceutical industries, thereby promoting *M. cymbalaria* from a folk medicinal plant to a mainstream functional food and nutraceutical resource.

7. Toxicological evaluation

M. cymbalaria have been performed to establish its safety profile for pharmacological applications. Acute oral toxicity studies carried out in mice following OECD (Organisation for Economic Co-operation and Development) guideline 425 revealed that the methanolic fruit extract is safe up to 2000 mg/kg body weight, with no signs of morbidity or mortality, thereby supporting its potential therapeutic use (Kumar *et al.,* 2018). Similarly, hepatoprotective studies in rats demonstrated that oral administration of *M. cymbalaria* fruit extract at 250-500 mg/kg not only protected against carbon tetrachloride-induced liver damage but also did not produce any detectable toxic effects when administered alone (Koneri *et al.,* 2008).

Subchronic exposure studies further confirm its tolerability. Elangovan *et al.* (2021) reported that oral administration of seed and skin extracts (250 and 500 mg/kg for 28 days) in diabetic rats improved reproductive function without adverse changes in organ weight, serum biochemistry, or histopathology. In another investigation, hydroalcoholic fruit extract of *M. cymbalaria* significantly mitigated sodium fluoride-induced hepatotoxicity in Wistar rats, with no evidence of intrinsic toxicity at the tested doses (Mitta *et al.,* 2021).

A recent comprehensive review has summarized these safety data, emphasizing that *M. cymbalaria* extracts are generally well-tolerated, with acute toxicity studies consistently reporting safety margins up to 2000 mg/kg (Firdous *et al.,* 2024). Collectively, these findings suggest that *M. cymbalaria* possesses a favorable safety profile in both acute and subchronic studies, thereby supporting its continued investigation as a nutraceutical and pharmacological agent.

8. Cultivation and conservation

8.1 Cultivation

M. cymbalaria remains an underutilized and poorly domesticated species, largely confined to wild collection rather than organized cultivation. This dependence on natural populations has contributed to its vulnerability to overexploitation. Overharvesting for food and medicinal use, along with habitat loss and fragmentation, are key threats to its persistence (Jeyadevi *et al.,* 2012). Furthermore, the species exhibits low seed viability and germination rates, which exacerbate its natural population decline. Ramesha *et al.* (2025) documented alarming reductions in *M. cymbalaria* populations across semi-arid tracts of Karnataka, primarily attributed to land-use conversion for agriculture and urbanization. Unless proactive conservation strategies are employed, there is a risk of genetic erosion and potential local extinction.

Despite these challenges, *M. cymbalaria* shows strong agronomic promise as a hardy crop for marginal lands. Anusha *et al.* (2025) reported that it grows well in semi-arid vertisols with minimal agronomic inputs, indicating suitability for climate-resilient agriculture. Its physiological adaptations - including drought tolerance, deep-rooted tubers, and efficient water use mechanisms - make it capable of surviving under water-limited conditions. These traits align with the urgent need for crops adapted to climate variability. With proper agronomic research, *M. cymbalaria* could be integrated into diversified dryland farming systems, contributing to food and nutritional security.

Propagation of *M. cymbalaria* remains a major bottleneck for domestication and large-scale cultivation. Seeds exhibit physical dormancy due to hard seed coats, coupled with short viability periods, resulting in poor germination rates. Vegetative propagation through tubers, while feasible, is inefficient and resource-intensive. Jeyadevi *et al.* (2012) emphasized the role of biotechnological interventions, including tissue culture, micropropagation, and embryo rescue, as promising alternatives for mass multiplication. These advanced methods not only facilitate rapid plantlet production but also support the conservation of elite genotypes with desirable traits such as higher nutrient density and reduced bitterness.

8.2 Conservation strategies

To safeguard *M. cymbalaria*, a multi-pronged approach is essential:

- **In situ conservation:** Protecting wild populations in natural habitats through biodiversity reserves and involving local communities in sustainable harvesting practices.
- **Ex situ conservation:** Establishing germplasm banks, botanical gardens, and seed repositories, along with advanced methods like cryopreservation and tissue culture.
- **Domestication and crop improvement:** Initiating selective breeding programs to develop varieties with improved yield, reduced bitterness, higher phytochemical content, and disease resistance.

A coordinated conservation program combining traditional ecological knowledge with modern biotechnology can ensure the long-term sustainability of this species.

9. Future prospects

9.1 Research gaps

Although research on *M. cymbalaria* has expanded in recent years, significant knowledge gaps remain:

- Lack of clinical trials validating preclinical pharmacological claims in humans.
- Limited genomic, transcriptomic, and metabolomic studies to elucidate biosynthetic pathways of cucurbitacins, flavonoids, and saponins.
- Absence of standardized extraction protocols ensuring reproducibility and quantification of bioactive compounds.
- Inadequate data on long-term toxicity, dosage safety, and pharmacokinetics in human populations.

Bridging these gaps would elevate *M. cymbalaria* from an ethnobotanical resource to a scientifically validated nutraceutical crop.

9.2 Opportunities in agriculture and industry

The unique blend of nutritional richness, pharmacological efficacy, and environmental adaptability makes *M. cymbalaria* an ideal candidate for multisectoral utilization:

- **Agricultural integration:** Introduction into dryland and climate-stressed farming systems as a resilient vegetable and tuber crop.
- **Nutraceutical development:** Formulation of value-added products targeting diabetes, cardiovascular health, bone strengthening, and immunity enhancement.
- **Functional food innovation:** Incorporation into fortified foods and beverages addressing micronutrient deficiencies in vulnerable populations.
- **Pharmaceutical exploration:** Discovery of novel bioactive leads from cucurbitacins, saponins, and phenolics for drug development pipelines.

These opportunities underscore the dual role of *M. cymbalaria* in addressing human health needs while also promoting agricultural sustainability.

9.3 Policy and awareness

The mainstreaming of underutilized crops like *M. cymbalaria* requires enabling policies and public awareness initiatives. Government support through research funding, crop improvement programs, and subsidies for cultivation can encourage farmers to adopt this species. Awareness campaigns in rural communities can promote sustainable use, reducing pressure on wild populations. Furthermore, public–private partnerships with nutraceutical and food industries can incentivize value addition, creating economic opportunities along the supply chain. Such measures would not only ensure the conservation and utilization of *M. cymbalaria* but also position it as a strategic crop for nutrition security and health innovation in the future.

10. Conclusion

Momordica cymbalaria is an underutilized cucurbit with exceptional nutritional and pharmacological potential. Rich in vitamin C, calcium, potassium, and diverse bioactive compounds such as cucurbitacins, flavonoids, and saponins, it demonstrates a wide range of therapeutic effects, including antidiabetic, antioxidant, hepatoprotective, nephroprotective, cardioprotective, and anticancer activities. Its ethnobotanical relevance and nutritional richness further underscore its value for improving human health and nutrition, offering complementary advantages to the well-known *M. charantia*. These attributes position *M. cymbalaria* as a promising candidate for development as a functional food and nutraceutical resource.

Despite these promising findings, its clinical validation, extract standardization, dosage optimization, and large-scale cultivation remain limited. Future research should focus on bridging preclinical evidence with human trials, implementing regulatory evaluation, and employing biotechnological strategies such as metabolic engineering and omics-guided improvement to enhance bioactive yield. Integrating traditional knowledge with modern scientific approaches and sustainable cultivation practices can unlock the full potential of *M. cymbalaria*, advancing its role in healthcare, nutraceutical applications, and global nutritional security.

Acknowledgements

The authors express their gratitude and credit to the researchers behind the original studies whose works are referenced in this review.

Conflict of interest

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

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Citation **G. Porkodi, G. Anand, P. Madhana Kumari, P. Ramamoorthy and R. Abirami (2025). A comprehensive review on nutritional, pharmacological and functional potential of an emerging cucurbit, *Momordica cymbalaria* Hook. Fenzl. with therapeutic promise. Ann. Phytomed., 14(2):105-118. http://dx.doi.org/10.54085/ap.2025.14.2.11.**