

Antioxidant, Anti-inflammatory and Metabolic Benefits of *Moringa oleifera* as a Nutraceutical

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Abstract

Moringa oleifera Lam. is a nutrient-rich plant with diverse phytochemicals and increasing interest as a potential nutraceutical. This review summarizes published evidence on the antioxidant, anti-inflammatory and metabolic benefits of *M. oleifera* and discusses the mechanisms proposed to underlie these effects. Major constituents include flavonoids, phenolic acids, glucosinolates and isothiocyanates, together with vitamins, carotenoids and minerals. Experimental studies suggest that *M. oleifera* may reduce oxidative stress through direct radical scavenging, enhancement of endogenous antioxidant defenses, modulation of the Nrf2/Keap1 pathway and reduction of lipid peroxidation. Anti-inflammatory effects have been associated with modulation of NF- κ B signaling and reductions in mediators such as TNF- α , IL-1 β , IL-6, COX-2 and iNOS. Preclinical studies also indicate possible effects on glucose regulation, insulin secretion, lipid metabolism and metabolic syndrome. However, human evidence remains limited and heterogeneous, with differences in plant material, extraction methods, doses, formulations and phytochemical standardization. Safety and long-term clinical efficacy also require further investigation. Overall, *M. oleifera* shows promising antioxidant, anti-inflammatory and metabolic activities, but standardized preparations and well-designed clinical trials are needed before firm therapeutic or nutraceutical claims can be established.

Keywords: *Moringa oleifera*; nutraceutical; antioxidant; anti-inflammatory; oxidative stress; metabolic health; diabetes mellitus; phytochemicals.

1. Introduction

This review synthesizes previously published literature on the antioxidant, anti-inflammatory and metabolic effects of *Moringa oleifera*. The literature considered in the manuscript includes review articles, experimental studies and human studies addressing phytochemical composition, oxidative stress, inflammatory signaling, glucose regulation, lipid metabolism and safety. The selection and interpretation of evidence were organized around the major themes of the review, with particular attention to mechanistic findings and available clinical evidence. [Before submission, insert the databases actually searched, the search terms used, the date range covered, and the inclusion/exclusion criteria used by the authors. These details should reflect the literature-search process actually performed and should not be fabricated.]

Nutraceuticals have gained considerable attention as potential dietary approaches for maintaining health and reducing the risk of chronic diseases. The increasing prevalence of obesity, type 2 diabetes mellitus, dyslipidemia, hypertension and other metabolic disorders has stimulated interest in naturally occurring foods and plant-derived bioactive compounds with multifunctional biological activities. Among medicinal and edible plants, *Moringa oleifera* Lam. has emerged as an important candidate because of its nutritional density and broad pharmacological potential.

M. oleifera belongs to the family Moringaceae and is native to parts of the Indian subcontinent but is now cultivated extensively in tropical and subtropical regions. The plant is commonly known as moringa, drumstick tree or horseradish tree. Its leaves, immature pods, seeds and flowers are consumed as food, while different plant parts have traditionally been used in various systems of traditional medicine. A comprehensive review of the plant has identified numerous phytochemical constituents, including flavonoids, phenolic compounds, glucosinolates, carbamates and other secondary metabolites. However, the pharmacological evidence is heterogeneous and clinical evidence remains considerably less developed than preclinical evidence. [1]

The nutritional and phytochemical composition of *M. oleifera* makes it particularly interesting as a nutraceutical. Leaves contain proteins, essential amino acids, vitamins, minerals and several classes of polyphenolic compounds. Among the commonly reported phytochemicals are quercetin, kaempferol, rutin, chlorogenic acid and other phenolic constituents. Glucosinolates and their hydrolysis products, particularly isothiocyanates, represent another important group of bioactive molecules associated with the biological effects of the plant. [2–5]

Oxidative stress is characterized by an imbalance between the generation of reactive oxygen species (ROS) and the capacity of biological antioxidant systems to neutralize them. Excessive ROS production can promote lipid peroxidation, protein oxidation, DNA damage and cellular dysfunction. Oxidative stress is closely interconnected with inflammation and metabolic dysfunction. Persistent oxidative stress may activate inflammatory signaling pathways and contribute to insulin resistance, endothelial dysfunction, hepatic lipid accumulation and other pathological processes.

Inflammation is another major component of metabolic disease. Chronic low-grade inflammation is associated with obesity, insulin resistance, type 2 diabetes and cardiovascular disease. Nuclear factor kappa B (NF- κ B) is one of the major transcriptional regulators involved in inflammatory responses. Activation of NF- κ B promotes the expression of several inflammatory mediators, including tumor necrosis factor- α (TNF- α), interleukin-1 β (IL-1 β), interleukin-6 (IL-6), cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS). [6,7]

In contrast, nuclear factor erythroid 2-related factor 2 (Nrf2) represents a major endogenous defense mechanism against oxidative stress. Activation of the Nrf2 pathway promotes the expression of antioxidant and cytoprotective enzymes, including heme oxygenase-1, NAD(P)H quinone dehydrogenase 1, glutathione-related enzymes and other antioxidant defense systems. Evidence from experimental studies suggests that *M. oleifera* may influence both antioxidant and inflammatory signaling, providing a possible mechanistic explanation for its broad biological effects. [8–10]

A systematic review of cardiometabolic studies reported that *M. oleifera* may influence glucose and lipid metabolism through antioxidant and anti-inflammatory mechanisms. Proposed mechanisms include modulation of the Nrf2/Keap1 pathway, suppression of NF-κB activation, reduction of oxidative stress and modulation of metabolic signaling. [11]

More recently, an umbrella review evaluating 26 systematic reviews reported promising effects of *M. oleifera* in several chronic conditions, including diabetes, obesity, hypertension and dyslipidemia. However, the authors also emphasized that the methodological quality of many existing systematic reviews was low and that considerable variation exists in the preparations, doses and phytochemical standardization of *M. oleifera*. [12]

Therefore, the objective of this review is to critically discuss the antioxidant, anti-inflammatory and metabolic benefits of *M. oleifera* as a potential nutraceutical. Particular attention is given to its phytochemical composition, molecular mechanisms, experimental evidence, human studies, nutraceutical applications, safety and future research requirements.

2. Botanical Profile of *Moringa oleifera*

Moringa oleifera Lam. is a rapidly growing perennial tree belonging to the family Moringaceae. It is adapted to warm climates and can tolerate relatively dry environmental conditions. The plant has a slender trunk, compound leaves, fragrant flowers and elongated seed pods. The immature pods are commonly consumed as vegetables in South Asian cuisine.

Different parts of the plant possess different nutritional and phytochemical profiles. The leaves are particularly important because they contain proteins, carotenoids, vitamins, minerals and polyphenolic compounds. Seeds contain considerable quantities of oil and proteins, whereas pods provide dietary nutrients and bioactive compounds. Flowers and roots have also been investigated for pharmacological properties.

The distribution of bioactive compounds is not uniform among plant parts. Differences may also occur according to geographical origin, cultivar, maturity stage, growing conditions, harvesting procedure, drying method and extraction solvent. Therefore, comparison of biological activity between different *M. oleifera* preparations requires careful consideration of phytochemical standardization. [1,3]

Table 1. Botanical profile of *Moringa oleifera*

Botanical characteristic	Description
Kingdom	Plantae
Family	Moringaceae
Genus	<i>Moringa</i>
Species	<i>Moringa oleifera</i> Lam.
Common names	Moringa, drumstick tree, horseradish tree
Plant habit	Fast-growing, small to medium-sized perennial tree

Height	Approximately 5–12 m
Stem	Erect and branched, with whitish to grayish bark
Leaves	Compound, mainly bipinnate to tripinnate; leaflets are small, green and elliptic to obovate
Flowers	Fragrant, bisexual, white to creamy-white flowers
Inflorescence	Branched, spreading or drooping panicle
Fruit	Long, pendulous, three-lobed capsule or pod
Pod	Green when immature and brown when mature; contains numerous seeds
Seeds	Round to subglobose, brownish seeds with three papery wings
Root system	Strong taproot with spreading lateral roots
Distribution	Native to the Indian subcontinent and widely cultivated in tropical and subtropical regions
Important plant parts	Leaves, seeds, pods, flowers, bark and roots
Nutraceutical importance	Leaves and seeds are particularly studied for their nutritional, antioxidant, anti-inflammatory and metabolic properties

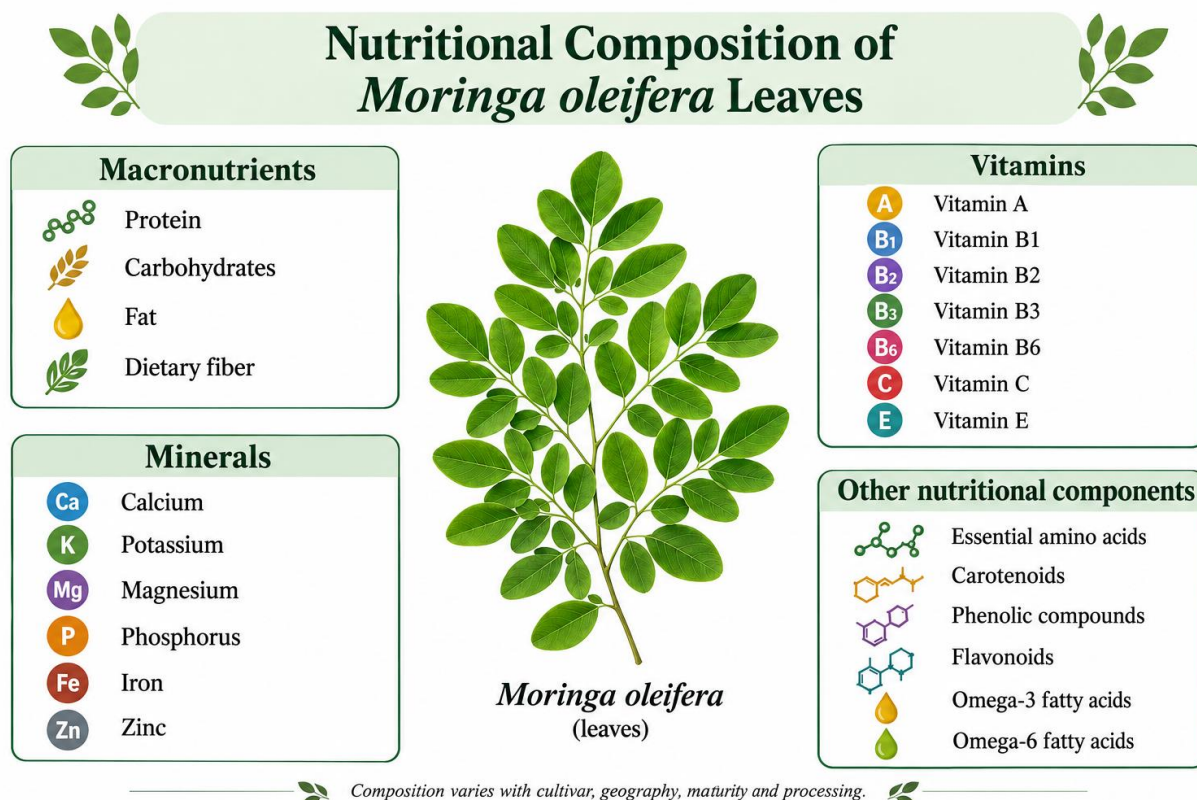
3. Nutritional Composition of *Moringa oleifera*

The nutritional value of *M. oleifera* is one of the principal reasons for its classification as a potential functional food or nutraceutical ingredient. The leaves provide proteins, dietary fiber, vitamins, minerals and various phytochemicals. They have been investigated as a nutrient-rich food source in regions where micronutrient deficiencies are common.

The leaves contain minerals such as calcium, potassium, magnesium and iron, although the actual concentrations vary substantially depending on geographical and agricultural conditions. Vitamins and provitamin compounds, including carotenoids and vitamin-related antioxidants, also contribute to the nutritional profile.

The plant additionally provides a broad spectrum of secondary metabolites. These include flavonoids, phenolic acids, glucosinolates, isothiocyanates, alkaloids, phytosterols and other compounds. [2,3]

The nutritional contribution of *M. oleifera* should, however, be distinguished from its pharmacological activity. The presence of a particular phytochemical does not necessarily establish that the compound reaches therapeutically relevant concentrations in humans after dietary consumption.



4. Phytochemical Composition

4.1 Flavonoids

Flavonoids are among the most extensively investigated phytochemicals in *M. oleifera*. Quercetin and kaempferol derivatives have been identified in leaf extracts using chromatographic and mass spectrometric techniques. Rutin and several glycosylated flavonoids have also been reported. [4,13]

These compounds are relevant because flavonoids may act through several mechanisms, including direct radical scavenging, metal chelation, regulation of antioxidant enzymes and modulation of inflammatory signaling.

Quercetin has been widely studied for its antioxidant and anti-inflammatory activities. Kaempferol has also demonstrated antioxidant and anti-inflammatory properties in experimental systems. In *M. oleifera*, these compounds may contribute to the overall biological activity of the plant rather than acting as isolated single agents.

4.2 Phenolic Acids

Phenolic acids identified in *M. oleifera* include chlorogenic acid, gallic acid, ferulic acid and related compounds. Experimental analysis of *M. oleifera* leaf fractions has demonstrated the presence of phenolic acids together with flavonoids such as kaempferol, quercetin and rutin. [14]

Phenolic compounds can contribute to antioxidant activity by donating hydrogen atoms or electrons to reactive species and through other redox-modulating mechanisms. Their activity may also influence inflammatory and metabolic pathways.

4.3 Glucosinolates and Isothiocyanates

Glucosinolates represent a characteristic group of sulfur-containing phytochemicals found in *M. oleifera*. Their hydrolysis can generate isothiocyanates, which have attracted significant attention because of their potential biological effects. One important *M. oleifera* glucosinolate is 4-O-(α -L-rhamnopyranosyloxy)-benzyl glucosinolate, which can yield the isothiocyanate commonly referred to as moringin. [15]

The concentration of glucosinolates may vary according to plant tissue, developmental stage, cultivation conditions and processing procedures. Therefore, the biological effects of *M. oleifera* preparations cannot always be directly compared between studies.

Experimental evidence indicates that *M. oleifera* isothiocyanates may influence inflammatory signaling, oxidative stress and cellular defense pathways. [15,16]

4.4 Vitamins, Carotenoids and Minerals

M. oleifera leaves contain several micronutrients and antioxidant-related compounds. Carotenoids and vitamin-related components may contribute to the nutritional antioxidant capacity of the leaves. However, their quantitative composition is affected by environmental and processing factors.

From a nutraceutical perspective, the combined contribution of micronutrients and phytochemicals may be more relevant than the activity of an individual compound.

5. Antioxidant Properties of *Moringa oleifera*

Oxidative stress occurs when ROS generation exceeds the capacity of endogenous antioxidant defense systems. Major ROS include superoxide anion, hydrogen peroxide and hydroxyl radicals. Although ROS participate in normal cellular signaling, excessive accumulation may damage cellular macromolecules.

M. oleifera has demonstrated antioxidant activity in multiple experimental models. Studies using different extraction systems have reported radical-scavenging and reducing activities of leaf extracts. An early investigation comparing leaves collected from different agroclimatic regions demonstrated that extracts were capable of scavenging peroxy and superoxide radicals, while phenolic constituents such as quercetin and kaempferol were identified as important components. [17]

Another study examining different fractions of *M. oleifera* leaves reported the presence of gallic, chlorogenic, ellagic and ferulic acids together with kaempferol, quercetin and rutin. The antioxidant activity was attributed to both direct radical trapping and possible metal-chelating mechanisms. [14]

Recent analytical investigations have further confirmed that *M. oleifera* leaf extracts can contain substantial amounts of phenolic and flavonoid compounds. In commercial food supplements, kaempferol

and quercetin glycosides were among the major phenolic constituents, and higher phenolic content was associated with greater antioxidant activity. [18]

These findings support the concept that *M. oleifera* can function as a source of dietary antioxidants. However, in vitro antioxidant assays such as DPPH, ABTS and FRAP cannot alone establish clinical antioxidant efficacy. Bioavailability, metabolism, tissue distribution and dose must be considered when translating these findings to humans.

Antioxidant Properties of *Moringa oleifera*



Sr. No.	Property	Mechanism	Effect
1	Free radical scavenging	Neutralizes ROS	Reduces oxidative damage
2	Lipid peroxidation	Inhibits lipid oxidation	Protects cell membranes
3	Nrf2 activation	Enhances antioxidant enzymes	Improves cellular defence
4	SOD activity	Scavenges superoxide radicals	Reduces ROS
5	Catalase activity	Breaks down H ₂ O ₂	Reduces oxidative stress
6	Glutathione protection	Maintains GSH levels	Supports antioxidant defence
7	Polyphenol activity	Scavenges free radicals	Protects cells

6. Mechanisms of Antioxidant Action

The antioxidant activity of *M. oleifera* may involve both direct and indirect mechanisms.

6.1 Direct Radical Scavenging

Phenolic compounds and flavonoids can donate hydrogen atoms or electrons to reactive species, thereby reducing radical-mediated oxidation. Quercetin and related flavonoids contain structural features that facilitate redox reactions.

6.2 Enhancement of Endogenous Antioxidant Defense

Experimental studies suggest that *M. oleifera* supplementation can increase antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT), while also improving glutathione (GSH)-associated defenses. These effects may provide protection beyond direct radical scavenging.

6.3 Nrf2/Keap1 Signaling

Nrf2 is a central regulator of cellular antioxidant responses. Under basal conditions, Nrf2 is regulated by Kelch-like ECH-associated protein 1 (Keap1). Under oxidative or electrophilic stress, Nrf2 can escape Keap1-mediated degradation and translocate into the nucleus, where it binds antioxidant response elements and stimulates expression of cytoprotective genes.

Evidence summarized in recent reviews indicates that *M. oleifera* may activate Nrf2-associated antioxidant defenses. Proposed downstream targets include heme oxygenase-1, glutathione-related enzymes and NAD(P)H quinone dehydrogenase 1. [8,11,12]

6.4 Reduction of Lipid Peroxidation

Oxidative degradation of membrane lipids generates products such as malondialdehyde. Experimental studies indicate that *M. oleifera* preparations may reduce lipid peroxidation while enhancing endogenous antioxidant systems. Such effects may be particularly relevant in metabolic disorders, in which oxidative stress is increased.

7. Anti-inflammatory Properties of *Moringa oleifera*

Inflammation is a complex biological response involving immune cells, cytokines, chemokines, lipid mediators and intracellular signaling pathways. Although acute inflammation is essential for host defense and tissue repair, persistent inflammation can contribute to chronic diseases.

Several studies have investigated the anti-inflammatory activity of *M. oleifera*. Flavonoids, phenolic compounds and isothiocyanates are among the major constituents proposed to contribute to this activity.

A recent review of bioactive compounds in *M. oleifera* described several mechanisms through which the plant may influence inflammation. Quercetin and kaempferol have been associated with inhibition of pro-inflammatory enzymes, while isothiocyanates may modulate NF- κ B signaling and reduce inflammatory cytokine production. [19]

Experimental studies have reported reductions in mediators including TNF- α , IL-1 β , IL-6, COX-2, iNOS and prostaglandin-related inflammatory responses.

8. NF- κ B Signaling and Inflammatory Modulation

NF- κ B is an important transcription factor involved in the regulation of inflammatory responses. In resting cells, NF- κ B is commonly retained in the cytoplasm through interaction with inhibitory proteins. Upon stimulation, the inhibitory protein I κ B α undergoes phosphorylation and degradation, allowing NF- κ B to translocate into the nucleus and regulate inflammatory gene expression.

M. oleifera constituents have been investigated for their ability to interfere with this pathway.

A study using an *M. oleifera* isothiocyanate formulation demonstrated inhibition of inflammatory responses in lipopolysaccharide-stimulated macrophages. The treatment reduced TNF- α and IL-1 β and inhibited I κ B α phosphorylation and NF- κ B translocation. Suppression of Akt and p38 phosphorylation was also observed. [20]

Similarly, *M. oleifera* flower extract inhibited several inflammatory mediators in lipopolysaccharide-stimulated macrophages, including nitric oxide, prostaglandin E2, IL-6, IL-1 β and TNF- α . The study also reported suppression of NF- κ B, iNOS and COX-2. [21]

These findings provide mechanistic support for the anti-inflammatory potential of *M. oleifera*. Nevertheless, most mechanistic studies have been conducted in cellular or animal models, and their direct clinical relevance remains to be established.

9. Relationship Between Oxidative Stress and Inflammation

Oxidative stress and inflammation are not independent processes. Excessive ROS can activate inflammatory signaling pathways, whereas activated inflammatory cells can generate additional ROS and reactive nitrogen species. This creates a self-amplifying cycle that may contribute to chronic tissue injury.

The potential ability of *M. oleifera* to simultaneously modulate oxidative and inflammatory pathways is therefore of particular interest.

Recent evidence suggests that Nrf2 and NF- κ B may represent two interconnected pathways involved in the antioxidant and anti-inflammatory activities of *M. oleifera*. Nrf2 activation can promote antioxidant defense and may negatively regulate inflammatory responses, while inhibition of NF- κ B can decrease the production of pro-inflammatory mediators. [12]

This redox-inflammatory interaction may partly explain why *M. oleifera* has been investigated in metabolic disorders, cardiovascular disease, liver disorders and other chronic inflammatory conditions.

10. Metabolic Benefits of Moringa oleifera

Metabolic disorders are characterized by disturbances in glucose, lipid and energy homeostasis. Obesity, insulin resistance, dyslipidemia, hypertension and chronic inflammation frequently occur together and contribute to the development of cardiometabolic disease.

M. oleifera has been investigated for potential effects on several components of metabolic health, particularly glucose regulation, insulin sensitivity, lipid metabolism and blood pressure.

A systematic review of cardiometabolic studies reported that *M. oleifera* preparations may exert antioxidant and anti-inflammatory effects while modulating glucose and lipid metabolism. The review included evidence from both nonclinical studies and clinical trials. [11]

However, the strength of evidence differs substantially between outcomes. Preclinical evidence is generally more extensive than clinical evidence.

Metabolic Benefits of *Moringa oleifera*



Sr. No.	Metabolic Benefit	Proposed Mechanism	Metabolic Effect
1	Blood glucose regulation	Enhances glucose uptake and improves insulin action	Helps maintain blood glucose levels
2	Improved insulin sensitivity	Modulation of insulin-signalling pathways	May reduce insulin resistance
3	Lipid-lowering effect	Modulation of lipid metabolism	May reduce cholesterol and triglyceride levels
4	Improved lipid profile	Regulation of lipid synthesis and metabolism	May improve LDL and HDL balance
5	Anti-obesity potential	Modulation of adipogenesis and lipid accumulation	May reduce excessive fat accumulation
6	Hepatoprotective effect	Reduction of oxidative stress and lipid accumulation	Supports healthy liver metabolism
7	Anti-diabetic potential	Regulation of carbohydrate metabolism and antioxidant defence	May support glycaemic control
8	Reduction of oxidative stress	Activation of antioxidant pathways such as Nrf2	Protects cells from metabolic oxidative damage
9	Anti-inflammatory effect	Modulation of NF-κB and pro-inflammatory cytokines	May reduce chronic metabolic inflammation
10	Metabolic homeostasis	Combined effects on glucose, lipid, oxidative stress and inflammation	Supports overall metabolic health

11. Antidiabetic Potential

Type 2 diabetes mellitus is characterized by chronic hyperglycemia resulting from insulin resistance, impaired insulin secretion or both. Oxidative stress and inflammation are involved in the progression of insulin resistance and diabetic complications.

Experimental evidence suggests that *M. oleifera* leaves and seeds may influence blood glucose, insulin sensitivity and oxidative stress. A review focused specifically on antidiabetic activity reported that preclinical studies generally showed improvements in blood glucose or insulin levels, tissue insulin sensitivity and lipid profiles. [22]

The same review highlighted the ability of *M. oleifera* extracts to strengthen intracellular antioxidant defenses, including CAT, SOD and GSH, while reducing oxidative stress and inflammatory mediators such as TNF- α , IL-1 β and IL-6. [22]

Potential mechanisms include inhibition of carbohydrate-digesting enzymes, modulation of glucose transport, enhancement of insulin secretion, reduction of oxidative stress and regulation of inflammatory signaling.

12. Human Evidence for Glycemic Control

Although experimental evidence is promising, human clinical evidence remains limited and inconsistent.

In a randomized controlled trial involving individuals with prediabetes, participants received 2400 mg/day of *M. oleifera* dry leaf powder for 12 weeks. The study reported favorable changes in fasting blood glucose and glycated hemoglobin compared with placebo, although further studies are needed to confirm the findings and establish long-term clinical significance. [23]

Another human study evaluated the effect of *M. oleifera* leaf powder added to a meal in people with diabetes. Administration of 20 g of leaf powder was associated with a lower postprandial glucose response compared with the control meal. However, the investigators noted the need for studies evaluating longer-term effects and lower doses because of limitations in sensory acceptability. [24]

In contrast, a randomized placebo-controlled study in therapy-naïve patients with type 2 diabetes receiving 8 g/day of *M. oleifera* leaf capsules for 4 weeks did not demonstrate significant improvement in fasting plasma glucose or glycated hemoglobin. No adverse effects were reported during the study. [25]

These apparently different findings emphasize the importance of dose, duration, preparation, baseline metabolic status and study design.

13. Effects on Insulin Secretion

Insulin secretion is another possible mechanism underlying the antidiabetic activity of *M. oleifera*. A preliminary study in healthy human volunteers evaluated increasing single doses of *M. oleifera* leaf powder. The highest tested dose, 4 g, increased insulin secretion without significantly changing plasma glucose. [26]

This observation provides preliminary evidence that *M. oleifera* may influence pancreatic insulin secretion. However, the study involved a small number of healthy subjects and evaluated acute rather than long-term effects. Therefore, it cannot establish therapeutic efficacy in patients with type 2 diabetes.

Future clinical studies should determine whether changes in insulin secretion translate into clinically meaningful improvements in glycemic control and whether such effects are maintained with chronic administration.

14. Effects on Lipid Metabolism

Dyslipidemia is an important component of metabolic syndrome and a major cardiovascular risk factor. Elevated triglycerides, increased low-density lipoprotein cholesterol and reduced high-density lipoprotein cholesterol may occur in association with insulin resistance.

Preclinical investigations suggest that *M. oleifera* may influence lipid metabolism through several mechanisms, including antioxidant effects, reduction of lipid peroxidation and modulation of lipid-associated metabolic pathways.

A systematic review of cardiometabolic studies identified evidence suggesting that *M. oleifera* may improve lipid-related outcomes in some experimental models. [11]

However, human findings are less consistent. A randomized clinical study evaluating 20, 40 and 60 g/day of *M. oleifera* leaves for 14 days in patients with type 2 diabetes found no consistent dose-dependent improvement in the assessed metabolic parameters. [27]

Consequently, the lipid-lowering activity of *M. oleifera* should be considered promising but not yet clinically established.

15. Effects on Metabolic Syndrome

Metabolic syndrome consists of a cluster of abnormalities including central obesity, hyperglycemia, hypertension and dyslipidemia. These conditions share common mechanisms involving oxidative stress, inflammation, endothelial dysfunction and altered energy metabolism.

M. oleifera has been investigated as a potential dietary intervention for metabolic syndrome because it contains multiple classes of bioactive compounds with potentially complementary effects.

A narrative review focusing on in vivo and clinical studies described the potential of *M. oleifera* to influence metabolic syndrome and its associated conditions. [28]

The proposed mechanisms include improvement of antioxidant capacity, suppression of inflammatory signaling, regulation of glucose metabolism and potential effects on lipid metabolism and blood pressure.

Nevertheless, metabolic syndrome is a multifactorial condition, and the effects of a single nutraceutical are unlikely to replace established lifestyle interventions such as dietary modification, physical activity and weight management.

16. Cardiometabolic Mechanisms

The cardiometabolic potential of *M. oleifera* may arise from the interaction of several mechanisms:

1. Reduction of oxidative stress.
2. Enhancement of endogenous antioxidant defenses.
3. Suppression of NF- κ B-mediated inflammatory signaling.
4. Modulation of glucose metabolism.
5. Potential improvement in insulin sensitivity.
6. Regulation of lipid metabolism.
7. Possible effects on endothelial and vascular function.

8. Potential modulation of gut microbial composition.

The integrated nature of these mechanisms is important because metabolic diseases are driven by interconnected pathways rather than a single molecular target.

A systematic review of 108 nonclinical and clinical studies proposed that antioxidant and anti-inflammatory mechanisms may contribute to the cardiometabolic effects of *M. oleifera*. The review also discussed potential involvement of the Nrf2/Keap1 pathway, NF- κ B, NADPH oxidase-related oxidative stress and gut microbiome modulation. [11]

17. Role of Different Plant Parts

Although leaves are the most extensively studied part of *M. oleifera*, other plant parts also contain potentially useful bioactive compounds.

17.1 Leaves

Leaves are rich in polyphenols, flavonoids, carotenoids, proteins and minerals. Most antioxidant and metabolic research has focused on leaf powder and leaf extracts.

17.2 Seeds

Seeds contain proteins, oil and characteristic glucosinolate-derived compounds. Seed extracts have demonstrated biological activity in experimental studies, but appropriate dosing and safety require further evaluation.

17.3 Pods

Pods are consumed as vegetables and provide nutritional compounds. Their phytochemical composition differs from that of leaves.

17.4 Flowers

Flower extracts have demonstrated anti-inflammatory activity in experimental macrophage models. In particular, inhibition of inflammatory mediators including NO, PGE₂, IL-6, IL-1 β , TNF- α , iNOS and COX-2 has been reported. [21]

17.5 Roots and Bark

Roots and bark contain distinct phytochemicals and have been used traditionally. However, these plant parts require greater safety consideration because some constituents may exhibit undesirable biological effects at high exposure.

Therefore, nutraceutical development should preferentially use standardized and well-characterized plant material rather than assuming that all parts of the plant have equivalent safety and efficacy.

18. Nutraceutical Potential

The concept of a nutraceutical combines nutritional value with potential health-promoting biological effects. *M. oleifera* is particularly suitable for investigation in this area because leaves can be incorporated into food products, powders, beverages and dietary supplements.

Potential applications include:

- Leaf powder as a dietary ingredient.
- Functional beverages.
- Nutraceutical capsules and tablets.
- Fortified food products.
- Protein- and micronutrient-rich food formulations.
- Polyphenol-rich extracts.
- Standardized preparations containing glucosinolate-derived bioactive compounds.

However, commercialization requires adequate quality control. Factors such as cultivar, geographical origin, maturity, harvesting, drying, extraction solvent and storage can alter phytochemical composition. Therefore, standardization based on validated chemical markers is essential.

Commercial supplement studies have demonstrated that products marketed as *M. oleifera* supplements may vary in their phenolic composition and antioxidant activity. [18]

This variability represents an important challenge for reproducibility and clinical translation.

19. Evidence from Experimental Studies

Experimental studies provide substantial support for the antioxidant and anti-inflammatory activities of *M. oleifera*. Leaf extracts have demonstrated radical-scavenging activity, while flavonoids and phenolic acids have been identified as important contributors. [13,14,17]

Cellular models have demonstrated inhibition of inflammatory pathways, including NF- κ B signaling and inflammatory mediator production. [20,21]

Animal studies further suggest potential effects on glucose metabolism, lipid metabolism, oxidative stress and inflammatory markers. However, differences in animal species, diabetes models, doses and extraction methods make direct comparisons difficult.

The majority of experimental findings should therefore be interpreted as mechanistic or hypothesis-generating evidence rather than proof of clinical efficacy.

20. Clinical Evidence and Translational Significance

Human studies of *M. oleifera* are increasing but remain relatively few compared with preclinical investigations. Clinical findings have included potential improvements in glycemic parameters, insulin secretion and selected cardiometabolic outcomes. [23–27]

At the same time, negative or neutral findings have also been reported. This is important because publication of only positive results may create an exaggerated perception of efficacy.

A recent umbrella review emphasized that many systematic reviews concerning *M. oleifera* have methodological limitations and that studies differ considerably in preparation, dose, pharmaceutical form, extraction method and phytochemical standardization. [12]

Therefore, future clinical studies should use chemically characterized preparations and standardized dosing protocols.

21. Safety and Toxicological Considerations

Although *M. oleifera* is widely consumed as a food, food use does not automatically establish the safety of concentrated extracts or high-dose supplements.

The safety profile may depend on the plant part, dose, extraction method and duration of exposure. A systematic review of the plant's botany, phytochemistry, pharmacology and toxicity emphasized that certain constituents may show toxicity at high doses and that available clinical safety data remain insufficient. [1]

Potential concerns include gastrointestinal effects, reproductive toxicity reported in some experimental settings, interactions with conventional medicines and variability in commercial preparations.

For nutraceutical development, safety evaluation should include acute and chronic toxicity studies, reproductive and developmental assessments where appropriate, genotoxicity testing and pharmacokinetic characterization.

22. Limitations of Current Evidence

Several limitations currently prevent definitive conclusions regarding the clinical use of *M. oleifera*.

First, different studies use different plant parts and extraction procedures. Second, the concentrations of active phytochemicals may vary substantially between preparations. Third, many studies use animal models or cell culture systems rather than human participants. Fourth, clinical trials are generally small and short in duration.

Another important limitation is the lack of standardized biomarkers. Studies frequently report antioxidant capacity using different assays, making direct comparison difficult.

Furthermore, the term “antioxidant activity” can be misleading if based exclusively on chemical assays. Biological antioxidant effects depend on absorption, metabolism, tissue distribution and interactions with endogenous pathways.

Thus, future research should prioritize standardized preparations and clinically relevant biomarkers.

23. Future Perspectives

Future research should focus on establishing standardized *M. oleifera* preparations with clearly defined phytochemical profiles. Quantification of marker compounds such as quercetin derivatives, kaempferol derivatives, glucosinolates and isothiocyanates could improve reproducibility.

Well-designed randomized controlled trials should evaluate clinically meaningful endpoints including glycated hemoglobin, fasting glucose, insulin sensitivity, lipid profile, inflammatory biomarkers and oxidative stress markers.

Pharmacokinetic studies are also needed to determine which compounds or metabolites reach systemic circulation after oral administration.

The interaction between *M. oleifera* phytochemicals and the gut microbiome represents another promising area. In addition, research should investigate whether combinations of flavonoids, phenolic compounds and isothiocyanates produce additive or synergistic biological effects.

Importantly, future investigations should distinguish between dietary consumption of *M. oleifera* and pharmacological doses of concentrated extracts.

24. Conclusion

Moringa oleifera is a nutritionally valuable plant with a diverse phytochemical profile and considerable potential as a nutraceutical. Experimental evidence supports antioxidant and anti-inflammatory activities associated with flavonoids, phenolic compounds, glucosinolates and isothiocyanates. Proposed mechanisms include direct radical scavenging, enhancement of endogenous antioxidant defenses, activation of Nrf2-associated cytoprotective pathways and suppression of NF- κ B-mediated inflammatory signaling.

The plant also shows promising metabolic effects, particularly in experimental models of hyperglycemia, oxidative stress and metabolic dysfunction. Preliminary human studies suggest possible benefits for glycemic regulation and insulin secretion, although results are inconsistent and the number of well-controlled clinical studies remains limited.

Therefore, *M. oleifera* should be considered a promising functional food and nutraceutical candidate rather than a replacement for established pharmacological treatment. Standardization of plant material, chemical

characterization, appropriate dose selection, safety assessment and rigorous randomized controlled trials are essential before definitive therapeutic claims can be made.

Overall, the interconnected antioxidant, anti-inflammatory and metabolic actions of *M. oleifera* provide a scientifically plausible basis for further development of standardized nutraceutical preparations. Future research integrating phytochemistry, molecular pharmacology, pharmacokinetics, microbiome science and clinical investigation may help clarify its role in the prevention and management of chronic metabolic disorders.

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References

1. Wang R, Xie M, Koo I, et al. *Moringa oleifera*: a systematic review of its botany, traditional uses, phytochemistry, pharmacology and toxicity. *J Pharm Pharmacol*. 2022;74(3):296-316.
2. Leone A, Spada A, Battezzati A, et al. Cultivation, genetic, ethnopharmacology, phytochemistry and pharmacology of *Moringa oleifera* leaves: an overview. *Int J Mol Sci*. 2015;16(6):12791-12835.
3. Vergara-Jimenez M, Almatrafi MM, Fernandez ML. Bioactive components in *Moringa oleifera* leaves protect against chronic disease. *Antioxidants*. 2017;6(4):91.
4. Saini RK, Sivanesan I, Keum YS. Phytochemicals of *Moringa oleifera*: a review of their nutritional, therapeutic and industrial significance. *3 Biotech*. 2016;6(2):203.
5. Mehwish HM, Rajoka MSR, Fang H, et al. *Moringa oleifera* phytochemicals and their therapeutic potential. *Nutrients*. 2021;13.
6. Lawrence T. The nuclear factor NF-kappa B pathway in inflammation. *Cold Spring Harb Perspect Biol*. 2009;1(6):a001651.
7. Taniguchi K, Karin M. NF-kappa B, inflammation, immunity and cancer: coming of age. *Nat Rev Immunol*. 2018;18(5):309-324.
8. Ma Q. Role of Nrf2 in oxidative stress and toxicity. *Annu Rev Pharmacol Toxicol*. 2013;53:401-426.
9. Sies H, Berndt C, Jones DP. Oxidative stress. *Annu Rev Biochem*. 2017;86:715-748.

10. He F, Ru X, Wen T. NRF2, a transcription factor for stress response and beyond. *Int J Mol Sci.* 2020;21(13):4777.
11. Abdull Razis AF, Ibrahim MD, Kntayya SB. Health benefits of *Moringa oleifera*. *Asian Pac J Cancer Prev.* 2014;15(20):8571-8576.
12. da Silva Parente L, Sarandy MM, de Araújo MM, et al. Effect of *Moringa oleifera* on inflammatory diseases: an umbrella review of 26 systematic reviews. *Phytother Res.* 2025.
13. Sreelatha S, Padma PR. Antioxidant activity and total phenolic content of *Moringa oleifera* leaves in two stages of maturity. *Plant Foods Hum Nutr.* 2009;64(4):303-311.
14. Sreelatha S, Padma PR. Antioxidant activity and total phenolic content of *Moringa oleifera* leaves. *Food Chem Toxicol.* 2009;47(7):1585-1589.
15. López-Rodríguez G, et al. Glucosinolates and isothiocyanates from *Moringa oleifera*: chemical and biological approaches. *Plants.* 2020;9(9):1181.
16. Waterman C, Cheng DM, Rojas-Silva P, et al. Stable, water-extractable isothiocyanates from *Moringa oleifera* leaves attenuate inflammation in vitro. *Phytochemistry.* 2014;103:114-122.
17. Siddhuraju P, Becker K. Antioxidant properties of various solvent extracts of total phenolic constituents from three different agroclimatic origins of drumstick tree (*Moringa oleifera* Lam.) leaves. *J Agric Food Chem.* 2003;51(8):2144-2155.
18. Vongsak B, Sithisarn P, Mangmool S, et al. Maximizing total phenolics, total flavonoids contents and antioxidant activity of *Moringa oleifera* leaf extract by the appropriate extraction method. *Ind Crops Prod.* 2013;44:566-571.
19. Chiş A, Noubissi PA, Pop OL, et al. Bioactive compounds in *Moringa oleifera*: mechanisms of action, focus on their anti-inflammatory properties. *Plants.* 2024;13(1):20.
20. Jaja-Chimedza A, Graf BL, Hills T, et al. Bioactive properties of *Moringa oleifera* isothiocyanates and their potential role in inflammation. *Nutrients.* 2018.
21. Arulselvan P, Tan WS, Gothai S, et al. The potential role of antioxidants in modulating oxidative stress in inflammatory diseases. *Front Pharmacol.* 2016;7:56.
22. Mthiyane F, Dlodla PV, Ziqubu K, et al. A review on the antidiabetic properties of *Moringa oleifera* extracts: focusing on oxidative stress and inflammation as main therapeutic targets. *Front Pharmacol.* 2022;13:957066.
23. Girija A, et al. *Moringa oleifera* leaf supplementation as a glycemic control strategy in subjects with prediabetes. *Nutrients.* 2022;14(1):57.
24. Leone A, et al. Effect of *Moringa oleifera* leaf powder on postprandial blood glucose response: in vivo study on Saharawi people living in refugee camps. *Phytomedicine.* 2018.
25. Taweerutchana R, Lumlerdkij N, Vannasaeng S, et al. Effect of *Moringa oleifera* leaf capsules on glycemic control in therapy-naïve type 2 diabetes patients: a randomized placebo controlled study. *Evid Based Complement Alternat Med.* 2017;2017:6586279.
26. Anthanont P, Lumlerdkij N, Akarasereenont P, et al. *Moringa oleifera* leaf increases insulin secretion after single dose administration: a preliminary study in healthy subjects. *Evid Based Complement Alternat Med.* 2016;2016:8506219.
27. Afiaenyi IC, Ngwu EK, Okafor AM, Ayogu RN. Effects of *Moringa oleifera* leaves on the blood glucose, blood pressure, and lipid profile of type 2 diabetic subjects: a parallel group randomized clinical trial of efficacy. *Nutr Health.* 2025;31(1):281-291.

28. Adarthaiya S, Sehgal A. *Moringa oleifera* Lam. as a potential plant for alleviation of the metabolic syndrome—a narrative review based on in vivo and clinical studies. *Phytother Res.* 2024;38(3):1200-1218.