PHARMACY-PHARMACOGNOSY AND PHYTOCHEMISTRY

Pharmacological Activities of Moringa oleifera Lam.: A Review of Antioxidant, Anti-Inflammatory, Anticancer and Antimicrobial Activities

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Abstract

Moringa oleifera Lam., a member of the Moringaceae family, is a nutritious and therapeutic plant that grows widely throughout tropical and subtropical areas. It has a long history of traditional use and is popularly referred to as the drumstick tree or miracle tree. Numerous physiologically active components can be found in various plant sections, especially the leaves, seeds, flowers, pods, bark, and roots. These comprise secondary metabolites such as flavonoids, phenolic acids, carotenoids, glucosinolates, isothiocyanates, alkaloids, tannins, and saponins. Four significant pharmacological effects of M. oleifera —antioxidant, anti-inflammatory, anticancer, and antibacterial activities—are the subject of this review. Phenolic chemicals, flavonoids, carotenoids, and other components that can scavenge reactive oxygen species and promote cellular processes are primarily linked to antioxidant action. Modulation of inflammatory mediators and signaling pathways, such as NF-κB and MAPK, has been used to study anti-inflammatory activity.

Several M. oleifera extracts and components have been shown in anticancer investigations to exhibit antiproliferative, cytotoxic, and apoptosis-related actions against a variety of cancer cell lines. Antimicrobial research has demonstrated antibacterial and antifungal properties against a variety of microbes, with a focus on isothiocyanates and seed proteins derived from Moringa. Despite the encouraging experimental results, there are significant discrepancies between research because of differences in plant parts, geographic origin, concentration, formulation, extraction solvent, and experimental model. Additionally, a large portion of the research supporting antibacterial and anticancer uses is still preclinical or in vitro. Standardized extracts, the identification of active ingredients, pharmacokinetic investigations, toxicity assessment, and carefully planned clinical trials are thus necessary. Although M. oleifera is a promising source of bioactive chemicals, more investigation is required before these activities may be converted into proven medicinal uses.

Keywords: Moringa oleifera; Moringaceae; antioxidant; anti-inflammatory; anticancer; antimicrobial; phytochemicals; medicinal plant

1 Introduction

Medicinal plants continue to support pharmaceutical research and are a significant source of bioactive chemicals. *Moringa oleifera* Lam. has garnered significant scientific interest among medicinal plants due to its varied pharmacological qualities, traditional uses, and nutritional makeup. M. oleifera is indigenous to the Indian subcontinent and a member of the Moringaceae family. Nowadays, it is commonly grown in tropical and subtropical areas. The plant is distinguished by its quick development and capacity to endure in environments that are rather dry.

Traditionally, practically every part of the plant has been utilized. However, due to their high quantities of polyphenols, flavonoids, carotenoids, vitamins, and other bioactive substances, the leaves have been the subject of especially thorough scientific research. Because they contain cationic proteins, isothiocyanates, and glucosinolates, seeds are also significant.

The antibacterial, anti-inflammatory, anticancer, and antioxidant qualities of M. oleifera have been documented in numerous reviews. In experimental cancer models, recent systematic evidence has also shown antibacterial and antioxidant activity in addition to cytotoxic and antiproliferative effects.

This review's objective is to present a concentrated analysis of these four main pharmacological actions.

2 Botanical description and taxonomy

Moringa oleifera Lam. is a medicinal and nutritional plant belonging to the family Moringaceae. It is native to the Indian subcontinent and is now cultivated extensively across tropical and subtropical regions. Its rapid growth and ability to tolerate relatively dry environmental conditions contribute to its widespread cultivation. The plant is commonly known as the drumstick tree or miracle tree because of its nutritional value and traditional medicinal applications (Anwar et al., 2007; Leone et al., 2015).

2.1 Botanical description

Different parts of M. oleifera, including the leaves, seeds, flowers, pods, bark, and roots, have been used traditionally and investigated for their potential biological activities. These plant parts differ in their phytochemical composition, which may influence their nutritional properties and pharmacological effects. The leaves are among the most extensively studied parts of the plant because they contain various bioactive constituents, particularly polyphenols, flavonoids, carotenoids, vitamins, and other phytochemicals. These compounds have been associated with the antioxidant potential of M. oleifera and have also been investigated for their possible contributions to other pharmacological activities. The seeds represent another important plant component. They contain glucosinolates, isothiocyanates, and cationic proteins, which have attracted scientific interest because of their potential biological and antimicrobial properties. Flowers and pods have also been investigated for their chemical constituents and biological effects. Research indicates that differences in the composition of individual plant parts can contribute to variations in their observed pharmacological activities. The botanical characteristics are summarised in Table 1.

Table 1. Botanical description of Moringa oleifera Lam.

Characteristic	Description
Scientific name	Moringa oleifera Lam.
Family	Moringaceae
Common name	Drumstick tree, Miracle tree
Origin	Indian subcontinent
Growth regions	Tropical and subtropical regions
Plant parts used	Leaves, seeds, flowers, pods, bark and roots
Growth characteristics	Fast-growing and relatively drought-tolerant

2.2 Distribution and adaptability

Moringa oleifera is widely cultivated in tropical and subtropical areas. Its ability to grow rapidly and withstand relatively dry conditions makes it suitable for cultivation in environments where water availability may be limited. Its widespread distribution has also contributed to its use as a nutritional resource and a subject of medicinal plant research. However, the geographical origin and environmental conditions of the plant may influence its phytochemical composition. Differences in plant material, maturity, and extraction procedures have been associated with variations in the biological activities reported in experimental studies. Consequently, the geographical source and characteristics of the plant material should be considered when evaluating research findings involving *M. oleifera*.

2.3 Pharmacognostic significance

From a pharmacognostic perspective, M. oleifera is important because several of its plant parts contain potentially valuable bioactive constituents. Its leaves are particularly relevant to investigations of antioxidant and anti-inflammatory properties, whereas its seeds have received attention for their isothiocyanates and antimicrobial proteins. Other plant parts have also been examined for their phytochemical composition and potential biological effects. The variation in chemical composition among different plant parts highlights the importance of selecting appropriate plant material for pharmacological investigations. Consistent identification, careful preparation, and standardized extraction procedures are necessary to improve the comparability and reproducibility of research findings.

Overall, the botanical characteristics, geographical distribution, adaptability, and diverse phytochemical composition of *Moringa oleifera* make it a significant subject of pharmacognostic and pharmacological research. Its potential medicinal applications require further investigation through standardized experimental approaches and appropriate safety assessments.

3 Phytochemical constituents

The pharmacological potential of Moringa oleifera Lam. is closely associated with its diverse phytochemical composition. Different parts of the plant contain several classes of biologically active compounds that have been investigated for their antioxidant, anti-inflammatory, anticancer, and antimicrobial properties. The major constituents reported include flavonoids, phenolic acids, carotenoids, glucosinolates, isothiocyanates, alkaloids, tannins, and saponins. The distribution and concentration of these compounds may vary according to the plant part, geographical origin, maturity, and extraction method (Saini et al., 2016; Abd Rani et al., 2018). The structures of two of the main flavonoids, quercetin and kaempferol, are shown in Figure 1.

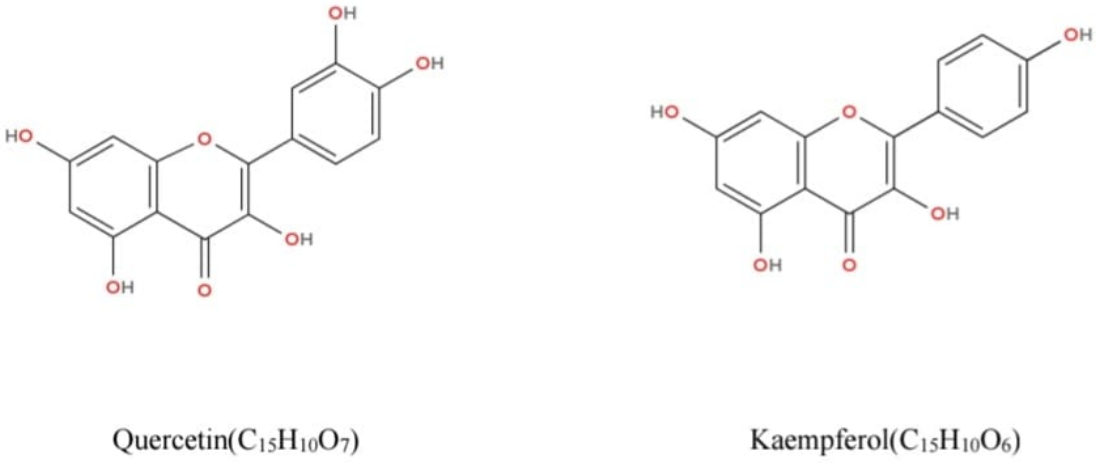


Figure 1. Chemical structures of quercetin and kaempferol.

3.1 Flavonoids

Flavonoids are important plant-derived compounds associated with the biological activities of *M. oleifera*. Quercetin, kaempferol, and rutin are among the flavonoids identified in the plant. These compounds have attracted considerable attention because of their potential contribution to antioxidant activity and their possible involvement in the regulation of inflammatory processes. The chemical structures of flavonoids enable them to donate hydrogen atoms or electrons to reactive molecules, thereby contributing to free-radical scavenging. Their potential biological effects have also been investigated in relation to inflammatory signaling and the growth of cancer cells in experimental models. However, the magnitude of these effects depends on the compound, its concentration, and the experimental conditions.

3.2 Phenolic acids and polyphenols

Phenolic acids and other polyphenolic compounds represent important components of *M. oleifera*, particularly its leaves. These substances have been associated with antioxidant activity because of their ability to interact with reactive species and potentially reduce oxidative damage. Phenolic compounds may contribute to the neutralization of free radicals and the inhibition of lipid peroxidation, which can otherwise damage cellular membranes. Their potential influence on oxidative stress is also relevant to research examining inflammatory responses and cellular protection.

Studies using chromatographic analytical techniques have identified numerous phenolic compounds in different parts of *M. oleifera*. Gao et al. (2025) identified 105 phenolic compounds and reported antioxidant activity across different plant parts. These findings emphasize the chemical diversity of the plant and the importance of investigating its individual constituents.

3.3 Carotenoids and vitamins

Carotenoids and vitamins are additional constituents reported in *M. oleifera*, particularly in its leaves. They contribute to the plant's nutritional value and have been investigated for their potential role in protecting cells against oxidative damage.

The presence of these compounds, together with flavonoids and phenolic acids, may contribute to the overall antioxidant potential of the plant. Nevertheless, the biological activity of a plant extract cannot necessarily be attributed to a single constituent because several compounds may contribute simultaneously to the observed effects.

3.4 Glucosinolates and isothiocyanates

Glucosinolates and their derivatives, isothiocyanates, are important sulfur-containing compounds associated with the pharmacological research on *M. oleifera*. These constituents have received attention because of their potential antimicrobial, anti-inflammatory, and anticancer activities. Isothiocyanates derived from *M. oleifera* have been investigated for their effects on inflammatory signaling and their ability to inhibit the growth of selected microorganisms. Their possible involvement in cellular signaling has also attracted interest in experimental cancer research.

Water-extractable isothiocyanates from *M. oleifera* leaves have been studied for their ability to reduce inflammatory responses in vitro (Waterman et al., 2014). In addition, isothiocyanates isolated from the seeds have demonstrated antibacterial and antifungal activity against selected microorganisms in experimental investigations (Padla et al., 2012). These findings support further examination of this group of compounds, although laboratory results alone do not establish therapeutic effectiveness in humans.

3.5 Alkaloids, tannins and saponins

Alkaloids, tannins, and saponins are other classes of secondary metabolites reported in *M. oleifera*. Along with phenolic compounds and flavonoids, these constituents contribute to the plant's overall phytochemical diversity.

Different plant extracts have shown variations in their phytochemical profiles, including the presence of alkaloids, tannins, and other secondary metabolites. Such differences may influence the biological properties observed during experimental investigations. However, the contribution of each individual compound to the pharmacological activity of *M. oleifera* requires further investigation.

3.6 Bioactive proteins in the seeds

The seeds of *M. oleifera* contain cationic proteins that have been investigated for their potential antimicrobial properties and applications in water purification. These proteins may interact with microbial surfaces and cellular structures, providing a possible explanation for some of the biological effects observed in experimental studies.

The coexistence of protein-based constituents and smaller phytochemical molecules makes the seeds an important subject for pharmacological investigation. Further research is needed to clarify the individual contributions of these constituents, their mechanisms of action, and their suitability for potential pharmaceutical applications.

3.7 Factors influencing phytochemical composition

The phytochemical profile of *M. oleifera* is not uniform across all preparations. The plant part selected, geographical origin, maturity stage, environmental conditions, extraction solvent, and processing method can influence the compounds recovered and their relative concentrations. Research comparing extracts prepared using different solvents has reported variations in phenolic composition, antioxidant potential, antimicrobial activity, and cytotoxic effects. Consequently, the term *M. oleifera*

extract does not necessarily represent a chemically consistent preparation. Standardized extraction procedures and reliable analytical techniques are therefore important for identifying active constituents and improving the reproducibility of experimental findings. Establishing the chemical composition of extracts will also help researchers investigate relationships between specific phytochemicals and their observed pharmacological effects.

In summary, *Moringa oleifera* Lam. contains a broad range of phytochemicals, including flavonoids, phenolic acids, carotenoids, glucosinolates, isothiocyanates, alkaloids, tannins, saponins, and bioactive seed proteins. These constituents provide a basis for investigating the plant's reported pharmacological properties. However, further characterization, standardization, and evaluation of individual compounds are necessary to establish their precise biological roles and potential therapeutic applications.

4 Antioxidant activity

Oxidative stress develops when the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) exceeds the capacity of the body's endogenous antioxidant defense systems. An imbalance of this kind can damage important cellular components, including lipids, proteins, carbohydrates, and nucleic acids. Persistent oxidative stress has been associated with cellular ageing and several chronic diseases. Consequently, the identification of natural substances capable of reducing oxidative damage has become an important area of pharmacological research. *Moringa oleifera* Lam. has attracted scientific interest as a potential source of natural antioxidants because of its diverse phytochemical composition. Its leaves, in particular, contain phenolic acids, flavonoids, carotenoids, vitamins, and other biologically active compounds. Polyphenols and flavonoids are considered important contributors to the antioxidant properties reported for this plant (Sreelatha and Padma, 2009; Vergara-Jimenez et al., 2017).

4.1 Phytochemicals associated with antioxidant activity

The antioxidant potential of *M. oleifera* is closely related to its phenolic and flavonoid content. Quercetin, kaempferol, rutin, and various phenolic acids are among the compounds identified in the plant. Their chemical structures enable them to donate hydrogen atoms or electrons to reactive molecules, thereby helping to neutralize free radicals. Carotenoids and antioxidant vitamins present in the leaves may also contribute to cellular protection. The overall antioxidant effect of a plant extract may reflect the combined contribution of several constituents rather than the activity of a single compound. Accordingly, the chemical composition of the extract must be considered when interpreting experimental findings.

4.2 Mechanisms of antioxidant action

The antioxidant activity of M. oleifera has been investigated through several possible mechanisms (Figure 2):

- **Free-radical scavenging:** Phenolic compounds can donate hydrogen atoms or electrons to reactive species, helping to neutralize them and reduce their potential to damage cellular structures.
- **Inhibition of lipid peroxidation:** Lipid peroxidation can compromise the integrity of cellular membranes. Experimental findings indicate that certain M. oleifera extracts may inhibit this

process and thereby contribute to the protection of membrane components against oxidative damage.

- **Support of endogenous antioxidant defenses:** The phytochemicals present in M. oleifera may help maintain antioxidant defense systems involving glutathione-related enzymes, catalase, and superoxide dismutase. These systems participate in controlling reactive species within cells.
- **Reduction of oxidative stress:** Through these potential mechanisms, constituents of M. oleifera may help limit the accumulation of ROS and reduce oxidative injury to cellular components.

These mechanisms provide a basis for understanding the antioxidant potential of the plant, although their relative contributions may differ among extracts and experimental models.

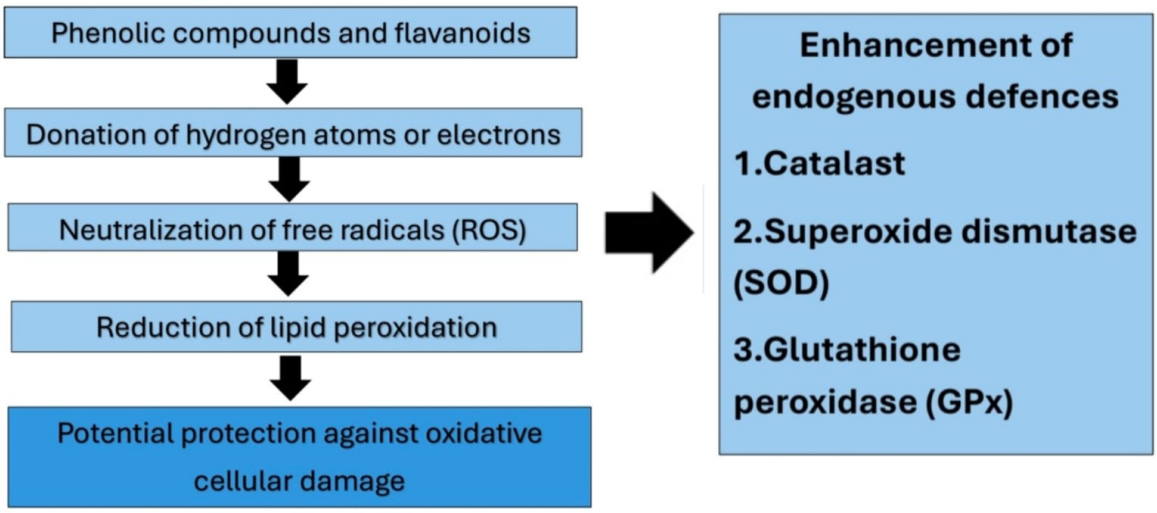


Figure 2. Proposed antioxidant mechanism of M. oleifera.

4.3 Experimental evaluation of antioxidant activity

Several in vitro methods have been used to evaluate the antioxidant properties of M. oleifera. These include the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical-scavenging assay, the 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical-scavenging assay, ferric-reducing antioxidant power (FRAP), nitric oxide-scavenging assays, and lipid-peroxidation assays.

The DPPH method is used to assess the capacity of an extract to donate a hydrogen atom or electron to DPPH radicals. In a typical procedure, 2.5 mL of DPPH solution at a concentration of 0.5 mM was mixed with 0.5 mL of *M. oleifera* extract. The mixture was vortexed and incubated for 30 minutes at room temperature in the dark.

The percentage of DPPH radical-scavenging activity was calculated using the following equation:

$$\text{DPPH scavenging activity}\left(\%\right) = \frac{A_c - A_s}{A_c} \times 100 \quad (1)$$

where A_c is the absorbance of the control and A_s is the absorbance of the sample.

A higher percentage indicates greater DPPH radical-scavenging activity under the specified experimental conditions. The result should be interpreted in relation to the concentration of the extract and the assay conditions.

4.4 Experimental findings

Several studies provide evidence of antioxidant activity in different *M. oleifera* preparations. Sreelatha and Padma (2009) reported DPPH, superoxide, and nitric oxide radical-scavenging activities, together with inhibition of lipid peroxidation, in research on *M. oleifera* leaves at different stages of maturity. Other studies have shown that phenolic components of leaf extracts demonstrated scavenging activity against hydroxyl and nitric oxide radicals and inhibited lipid peroxidation. These observations support the potential contribution of phenolic compounds to the antioxidant effects of the plant.

Research comparing different plant parts has further indicated that antioxidant activity is not necessarily uniform across leaves, seeds, flowers, and stems. Variations in phenolic composition and the selection of extraction solvents may influence the activity observed in experimental assays. Gao et al. (2025) identified 105 phenolic compounds across different parts of *M. oleifera* and reported antioxidant activity. This finding highlights the chemical diversity of the plant and the importance of investigating individual plant parts when evaluating its antioxidant properties.

4.5 Factors affecting antioxidant activity

The antioxidant activity of *M. oleifera* extracts may vary considerably according to several factors:

- **Plant part:** Leaves, seeds, flowers, and stems may differ in their phenolic content and antioxidant potential.
- **Geographical origin:** Differences in the origin of plant material may influence its chemical composition.
- **Maturity stage:** The developmental stage of the plant material may affect the concentration of bioactive compounds.
- **Environmental conditions:** Growing conditions may contribute to variations in phytochemical composition.
- **Extraction method and solvent:** Different extraction procedures may recover different quantities and types of antioxidant constituents.

These factors make direct comparisons between studies challenging. Therefore, consistent extraction procedures, chemical characterization, and clearly defined assay conditions are important for obtaining reproducible results.

4.6 Relationship between antioxidant and anti-inflammatory activities

Oxidative stress and inflammation are closely interconnected biological processes. Excessive ROS production may activate inflammatory signaling pathways and contribute to the release of inflammatory mediators. Conversely, inflammatory processes can increase oxidative stress and further damage cellular structures. The antioxidant properties of *M. oleifera* may therefore contribute indirectly to its reported anti-inflammatory and cytoprotective effects. Its flavonoids, phenolic acids, carotenoids, and other bioactive constituents are relevant to investigations of these overlapping mechanisms. However, antioxidant activity demonstrated in laboratory assays does not by itself establish that an extract can prevent or treat oxidative stress-related diseases in humans. Further studies are required

to determine how these experimental findings translate into biological effects under clinical conditions.

In summary, *Moringa oleifera* Lam. exhibits promising antioxidant potential associated with its diverse phytochemical composition. Experimental investigations have reported free-radical scavenging and inhibition of lipid peroxidation, particularly in studies involving leaf extracts. Nevertheless, differences in plant material, extraction procedures, and assay conditions influence the results. Standardized preparations and further investigations are necessary to establish the reproducibility and potential therapeutic relevance of these findings.

5 Anticancer activity

Cancer comprises a group of complex diseases characterized by uncontrolled cell proliferation, impaired regulation of programmed cell death, alterations in cell-cycle progression, and, in many cases, the ability of abnormal cells to invade surrounding tissues and spread to distant sites. The identification of naturally occurring compounds with potential anticancer properties is an important area of pharmacognosy and drug discovery. In this context, *Moringa oleifera* Lam. has attracted scientific interest because of the diverse phytochemicals present in its leaves, seeds, and other plant parts. The potential anticancer activity of *M. oleifera* has been associated with several classes of compounds, including flavonoids, phenolic compounds, glucosinolates, and isothiocyanates. Experimental investigations have reported cytotoxic and antiproliferative effects of certain extracts and constituents against cancer cells. However, these observations represent preliminary evidence and require further investigation to determine their relevance to cancer treatment in humans.

5.1 Phytochemicals associated with anticancer activity

The anticancer potential of *M. oleifera* appears to involve multiple phytochemical groups rather than a single constituent. Quercetin and kaempferol are among the flavonoids investigated for their biological effects, while glucosinolate-derived isothiocyanates have received attention because of their potential to influence cellular signaling pathways. Phenolic compounds and other secondary metabolites may also contribute to the biological effects observed in studies of *M. oleifera* extracts. Reviews of its phytochemistry and pharmacology have identified cytotoxic, antiproliferative, and chemopreventive properties as important areas of ongoing research.

The activity of an extract may depend on the types and concentrations of compounds it contains. Consequently, the anticancer effects reported for one preparation cannot automatically be attributed to all *M. oleifera* extracts.

5.2 Inhibition of cancer cell proliferation

One proposed mechanism underlying the anticancer potential of *M. oleifera* is the inhibition of cancer cell proliferation. Cancer cells may exhibit abnormal cell-cycle regulation, allowing them to multiply uncontrollably. Experimental studies have therefore examined whether *M. oleifera* extracts can reduce cancer cell growth or alter cell-cycle progression. Depending on the composition of the extract and the cancer model used, changes in cell-cycle regulatory proteins and associated signaling pathways may contribute to the inhibition of cellular proliferation. These findings suggest that certain constituents of the plant warrant further investigation as potential sources of compounds that influence cancer cell growth.

5.3 Induction of apoptosis

Apoptosis is a regulated process of programmed cell death that helps eliminate damaged or abnormal cells. Its regulation is important in cancer research because cancer cells may develop mechanisms that allow them to avoid normal cell-death processes. Several experimental investigations have reported apoptosis-related effects following exposure to *M. oleifera* extracts or isolated compounds. Potential mechanisms include alterations in mitochondrial function, changes in the balance of pro-apoptotic and anti-apoptotic proteins, and activation of caspase-related pathways.

These findings provide possible explanations for the cytotoxic effects observed in certain cancer cell models. Nevertheless, further studies are necessary to establish which compounds are responsible for these effects and whether they can selectively affect cancer cells without causing unacceptable damage to normal cells.

5.4 Role of oxidative stress

Oxidative stress may influence the relationship between *M. oleifera* phytochemicals and cancer cells. Although antioxidant compounds may help protect healthy cells from oxidative damage, excessive reactive oxygen species (ROS) can also damage cancer cells under certain conditions. Some constituents of *M. oleifera* may therefore influence the balance of oxidation and antioxidant defense differently in normal and cancerous cells. Understanding these differences is important when investigating the potential development of anticancer compounds, particularly those intended to act selectively against malignant cells.

However, the effects of individual compounds on cellular redox balance may vary with their concentration, chemical characteristics, and the experimental model. Further investigation is needed to clarify these relationships.

5.5 Relationship between inflammation and anticancer activity

Chronic inflammation may contribute to tumour development and progression through changes in oxidative stress, cellular proliferation, and the production of inflammatory mediators. Since *M. oleifera* contains compounds that have been investigated for anti-inflammatory activity, modulation of inflammatory pathways has been proposed as another possible contributor to its anticancer potential. The suppression of certain inflammatory signaling processes could potentially influence biological conditions associated with tumour growth. Nevertheless, this proposed relationship does not establish that *M. oleifera* can prevent or treat cancer in humans. The specific contributions of its anti-inflammatory constituents to anticancer effects require further experimental and clinical evaluation.

5.6 Experimental evidence across cancer models

Preparations of *M. oleifera* have been examined in experimental models involving breast, colon, liver, cervical, prostate, pancreatic, and oral cancer cell lines. Research has described cytotoxic, apoptosis-related, and antiproliferative effects across several of these models. A systematic review of studies on oral squamous cell carcinoma (Rajkumar et al., 2024) included 11 investigations involving in vitro, molecular, and animal studies. Such research contributes to the understanding of possible biological mechanisms and identifies areas for further investigation.

Although the reported findings are encouraging, the experimental response may vary according to the cancer type, plant preparation, dose, and study design. Results obtained using isolated cells or animal models cannot independently establish clinical effectiveness in humans.

5.7 Influence of extraction methods

The method used to prepare *M. oleifera* extracts can substantially influence their chemical composition and biological activity. Research has found differences in phenolic composition, antioxidant potential, antibacterial activity, and cytotoxic effects among leaf extracts prepared using different solvents and extraction techniques. One preparation containing compounds such as rutin, quercetin, and syringic acid demonstrated comparatively strong antioxidant, antibacterial, and cytotoxic properties. These observations highlight the importance of chemical characterization when evaluating the pharmacological potential of plant extracts.

Standardized extraction procedures and reliable analytical methods are therefore necessary to improve consistency between studies and identify the constituents most closely associated with the observed anticancer effects.

5.8 Limitations and future research requirements

Despite the encouraging experimental findings, the available evidence has important limitations. Most investigations of the anticancer properties of *M. oleifera* have involved cancer cell lines or animal models. Such studies can help identify potentially active compounds and investigate biological mechanisms, but they do not demonstrate that the plant is an effective cancer treatment in humans.

Further research should focus on identifying and characterizing active molecules, determining their pharmacokinetic properties, establishing effective concentrations, and evaluating their toxicity. Potential interactions between *M. oleifera* preparations and conventional anticancer medicines also require careful investigation. Well-designed clinical trials using standardized preparations are necessary to determine whether the effects observed in preclinical studies can be translated into safe and effective therapeutic applications.

In conclusion, *Moringa oleifera* Lam. represents a potential source of phytochemicals with anticancer properties. Its reported effects on cell proliferation, apoptosis, oxidative stress, and inflammatory signaling provide several directions for further research. However, it should not be regarded as an established anticancer medicine on the basis of the currently described experimental evidence. Further chemical, pharmacological, toxicological, and clinical investigations are required before its potential therapeutic role can be determined.

6 Anti-inflammatory activity

Inflammation is a complex physiological response involving immune cells, inflammatory mediators, signaling molecules and vascular changes. The host must mount an acute inflammatory response to combat infection and tissue damage, but prolonged or excessive inflammation has been linked to chronic diseases. Because inflammation, oxidative stress, and cellular signaling are related, medicinal plants that contain flavonoids, phenolic compounds, and isothiocyanates have been extensively studied for their anti-inflammatory activity. One such plant is Moringa oleifera, which has demonstrated anti-inflammatory effects in a variety of experimental models.

Several classes of phytochemicals have been linked to M. oleifera's anti-inflammatory activity. Particular attention has been given to flavonoids such as quercetin and kaempferol, phenolic compounds, carotenoids and sulphur-containing compounds such as isothiocyanates. A recent review on the mechanisms of Moringa bioactive compounds indicated that flavonoids may influence inflammatory enzymes and isothiocyanates may modulate inflammatory signaling pathways and cytokine production.

The NF-κB signaling pathway is one significant mechanism. Numerous genes involved in inflammation, such as those linked to cytokines and inflammatory enzymes, have their expression regulated by NF-κB. Tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), interleukin-6 (IL-6), inducible nitric oxide synthase (iNOS), and cyclooxygenase-2 (COX-2) are among the inflammatory mediators that can be produced when this pathway is overactivated. According to experimental data, some Moringa extracts and components may lessen the activation of inflammatory signaling pathways, which in turn may lessen the production of inflammatory mediators.

An 80% hydroethanolic extract of M. oleifera flowers was tested in lipopolysaccharide-stimulated RAW 264.7 macrophages in a particularly pertinent experimental study. Numerous inflammatory mediators, such as nitric oxide, prostaglandin E2, IL-6, IL-1β, TNF-α, NF-κB, iNOS, and COX-2, were markedly reduced in production or expression by the extract. This study offers mechanistic proof that components of moringa flowers can affect several inflammatory pathways at once.

Isothiocyanates derived from moringa have also garnered a lot of interest. The plant's glucosinolates may give rise to these sulfur-containing substances. Their potential to affect cytokine production and inflammatory signaling has been studied experimentally. These discoveries are especially significant because they offer a potential molecular explanation for some of the traditional anti-inflammatory applications of moringa.

M. oleifera's anti-inflammatory and antioxidant properties are intimately related. Inflammatory processes can raise ROS production, and oxidative stress can activate inflammatory pathways. Thus, inhibiting inflammatory signaling may prevent additional oxidative damage, and reducing oxidative stress may indirectly reduce inflammation. The simultaneous anti-inflammatory and antioxidant properties of Moringa extracts may be partially explained by this interaction.

The proposed anti-inflammatory mechanism is illustrated in Figure 3.

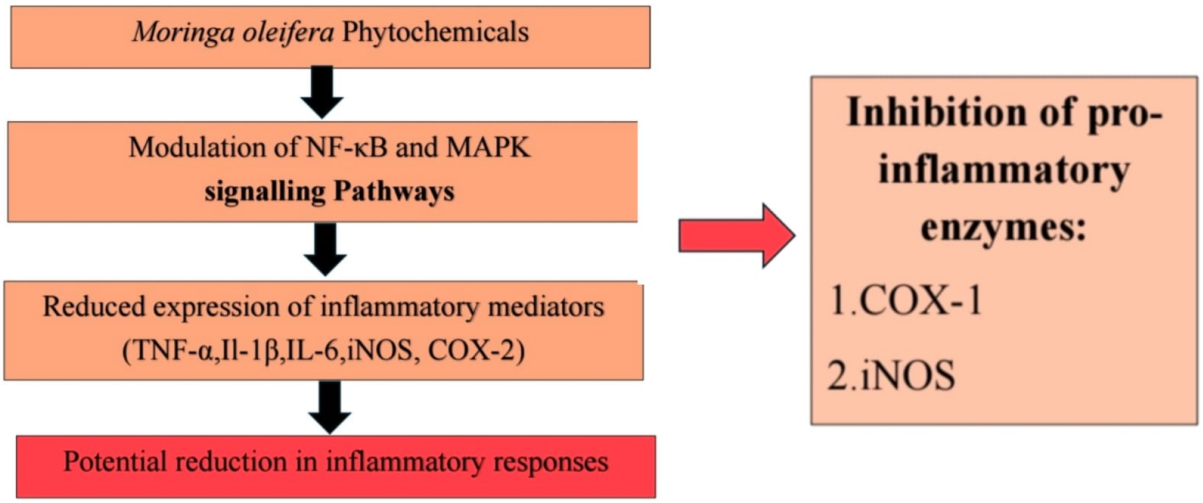


Figure 3. Proposed anti-inflammatory mechanism of M. oleifera.

It is crucial to distinguish between laboratory results and clinical efficacy, even in the face of encouraging experimental evidence. Animal models or isolated cells have been used to gather a large portion of the mechanistic evidence. Direct comparison is also challenging due to variations in extract composition, dosage, and experimental setup. Therefore, before Moringa can be regarded as a proven treatment for particular inflammatory diseases, controlled human clinical studies are necessary.

In a clinical study in volunteer smokers, lozenges containing M. oleifera, alone or combined with Cyanthillium cinereum (CC), reduced oral inflammation and the gingival index after four weeks (Figure 4) (Luetragoon et al., 2021).

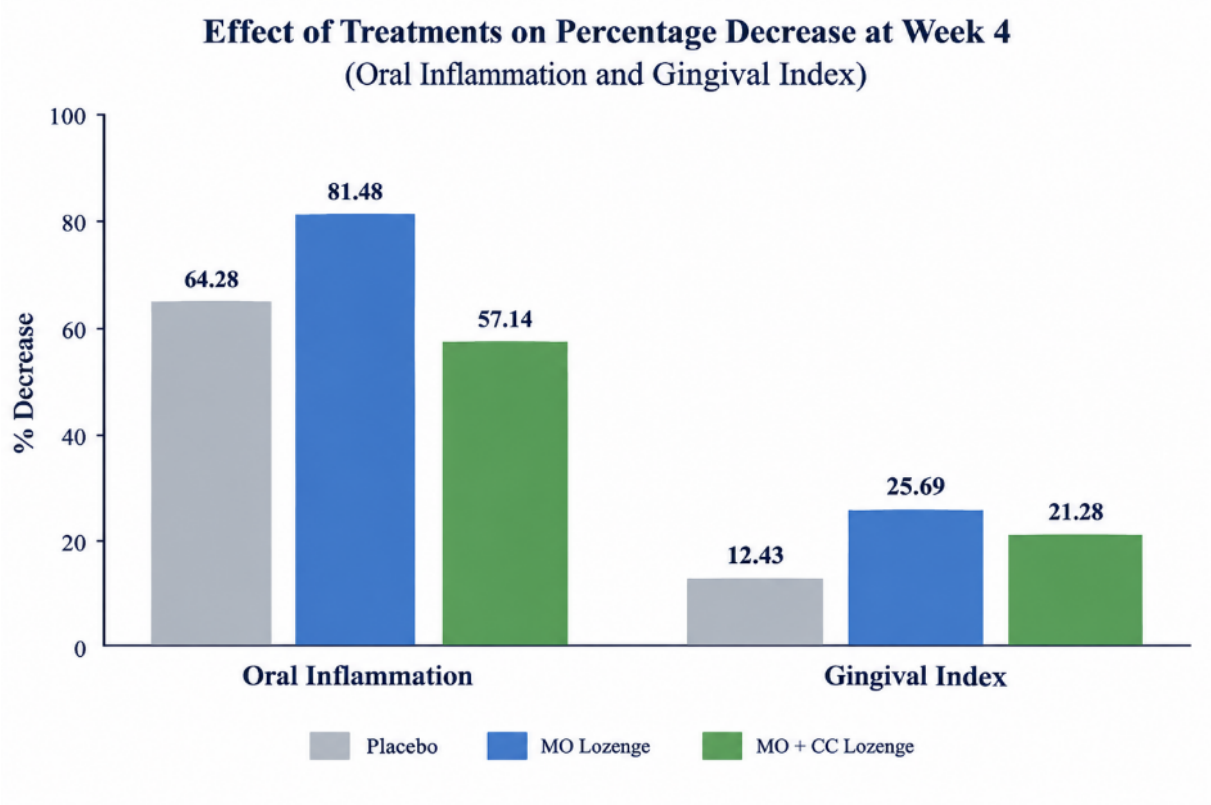


Figure 4. Percentage decrease in oral inflammation and gingival index at week 4 in the placebo, M. oleifera (MO) lozenge and combined MO + CC lozenge groups (data from Luetragoon et al., 2021).

7 Antimicrobial activity

There is an ongoing need for new antimicrobial compounds and alternative sources of antimicrobial agents because antimicrobial resistance has grown to be a significant global health concern. Chemically varied secondary metabolites found in medicinal plants have the potential to combat microorganisms in a variety of ways. The antibacterial, antifungal, and, in certain cases, antiviral properties of Moringa oleifera have been thoroughly studied.

7.1 Phytochemicals responsible for antimicrobial activity

Leaves, seeds, roots, and bark are just a few of the plant parts from which M. oleifera's antimicrobial qualities have been documented. A variety of phytochemicals, such as phenolic compounds, flavonoids, tannins, alkaloids, isothiocyanates, and specific seed proteins, are linked to the activity. According to reviews, one of the plant's key pharmacological characteristics is its antimicrobial activity.

7.2 Antibacterial activity

The antibacterial activity of Moringa has been investigated against both Gram-positive and Gram-negative organisms. Experimental studies have included organisms such as Staphylococcus aureus and Escherichia coli, among others. The antibacterial response can vary considerably according to the bacterial strain, plant part, extraction solvent and concentration.

7.3 Experimental studies on antimicrobial activity

An early experimental investigation examined Moringa leaves, roots, bark and seeds against several microorganisms. Fresh leaf juice and aqueous seed extracts demonstrated inhibitory effects against Pseudomonas aeruginosa and Staphylococcus aureus, although activity was not observed against all organisms tested. Interestingly, the study also reported that heating above 56 °C reduced the activity of the aqueous preparations. This finding demonstrates that preparation and processing conditions can influence antimicrobial activity.

Additionally, various organic and aqueous solvents have been used to assess moringa leaf extracts. Alkaloids, carbohydrates, tannins, phenolic compounds, terpenoids, and other phytochemicals were found in various leaf extracts. Different extracts had different antibacterial and antifungal properties, indicating that the choice of solvent can affect the recovery of antimicrobial components.

The inhibition zones reported for two isolated compounds against selected microorganisms are compared in Figure 5.

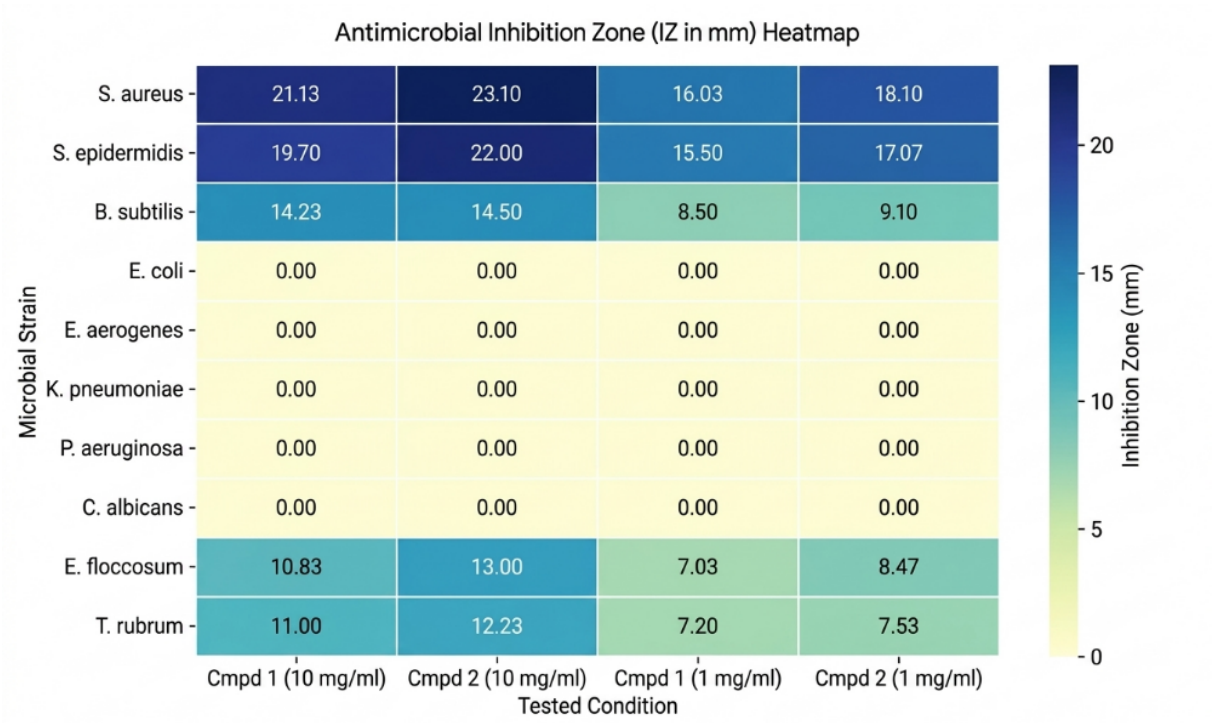


Figure 5. Comparison of inhibition-zone diameters (mm) for selected microbial strains exposed to two test compounds at different concentrations.

7.4 Antimicrobial activity of isothiocyanates

The isothiocyanate-related chemistry of M. oleifera is one of its most intriguing antimicrobial features. Moringa's glucosinolates can be hydrolyzed by enzymes to create isothiocyanates. The antimicrobial, anti-inflammatory, and anticancer properties of these compounds have been studied. They could be candidates for additional antimicrobial research due to their capacity to interact with microbial cellular components and disrupt crucial biochemical processes.

7.5 Antimicrobial activity of seed proteins

Another noteworthy feature of moringa seeds is the presence of cationic proteins, which have been investigated for their potential to interact with microbes and for use in water purification. These

proteins may interact with cellular structures and microbial surfaces to produce antimicrobial effects. From a pharmacognostic standpoint, the seeds are especially intriguing because they contain both protein-based and small-molecule antimicrobial constituents.

7.6 Summary of antimicrobial evidence

The antimicrobial evidence is summarised in Table 2.

Table 2. Summary of antimicrobial evidence.

Plant material or constituent	Reported observation
Fresh leaf juice	Inhibitory effects against selected microorganisms in an earlier study
Aqueous seed extract	Activity reported against selected bacteria
Leaf extracts prepared using different solvents	Variable antibacterial and antifungal effects
Seed-derived isothiocyanates	Antimicrobial activity reported against selected organisms
Certain extracts and isolated compounds	No inhibition observed in a separate investigation

7.7 Mechanism of antimicrobial action

Disruption of microbial cell membranes, modification of membrane permeability, inhibition of microbial enzymes, interaction with cellular proteins, and interference with vital metabolic processes are among the potential mechanisms of antimicrobial action. Instead of working against a single microbial target, phenolic compounds and flavonoids may also contribute through a variety of mechanisms.

7.8 Activity against antimicrobial-resistant organisms

Antimicrobial potential, including activity against some multidrug-resistant strains, was reported in a recent systematic review of M. oleifera's biological characteristics. However, the review also highlighted the evidence's predominantly experimental nature. This is especially pertinent given the rise in antimicrobial resistance.

7.9 Limitations of antimicrobial activity

Antimicrobial activity found in lab tests, however, should not be taken as evidence of clinical efficacy. It's possible that human tissues cannot safely reach the minimum inhibitory concentrations seen in vitro. Prior to therapeutic application, factors like absorption, metabolism, toxicity, formulation, and tissue penetration must be taken into account.

7.10 Future perspectives

Future studies should concentrate on identifying the molecular targets of particular antimicrobial compounds, analyzing their activity against resistant organisms, assessing their synergistic effects with traditional antibiotics, and carrying out suitable safety and clinical investigations.

8 Mechanisms of pharmacological action

The pharmacological activities of Moringa oleifera Lam. are associated with its diverse phytochemical constituents. Experimental studies suggest that these compounds may influence oxidative stress, inflammatory signaling, cancer cell growth, and microbial cellular processes. The proposed mechanisms are summarized in Table 3 and Figure 6.

8.1 Summary of proposed mechanisms

Table 3. Summary of the proposed mechanisms.

Pharmacological activity	Major constituents or pathways	Proposed action
Antioxidant	Flavonoids, phenolic acids, carotenoids	Free-radical scavenging and reduction of lipid peroxidation
Anti-inflammatory	Quercetin, kaempferol, isothiocyanates; NF-κB and MAPK pathways	Modulation of inflammatory signaling and mediator production
Anticancer	Flavonoids, phenolic compounds, isothiocyanates	Inhibition of cell proliferation and promotion of apoptosis-related processes
Antimicrobial	Isothiocyanates, phenolic compounds, flavonoids, seed proteins	Possible disruption of microbial membranes and interference with cellular functions

8.2 Antioxidant mechanism

Phenolic compounds and flavonoids may neutralize reactive species by donating hydrogen atoms or electrons. Other proposed effects include reducing lipid peroxidation and supporting endogenous antioxidant defenses involving glutathione-related enzymes, catalase, and superoxide dismutase. These actions may help protect cellular components from oxidative damage.

8.3 Anti-inflammatory mechanism

Certain *M. oleifera* constituents may influence inflammatory pathways, particularly NF-κB and MAPK. Experimental findings also suggest possible reductions in inflammatory mediators, including TNF-α, IL-1β, IL-6, iNOS, and COX-2. Isothiocyanates may contribute by affecting inflammatory signaling and cytokine production.

8.4 Anticancer mechanism

The proposed anticancer effects include inhibition of cancer cell proliferation, changes in cell-cycle regulation, and activation of apoptosis-related pathways. Reported mechanisms include alterations in mitochondrial function, changes in pro-apoptotic and anti-apoptotic proteins, and caspase-related activity. These findings remain primarily experimental and do not establish clinical effectiveness.

8.5 Antimicrobial mechanism

Potential antimicrobial actions include disruption of microbial cell membranes, changes in membrane permeability, inhibition of microbial enzymes, and interference with essential metabolic processes. Isothiocyanates and cationic seed proteins have received particular attention in experimental investigations. Overall, the different pharmacological activities of *M. oleifera* may involve multiple compounds and overlapping biological pathways. However, the precise mechanisms, active concentrations, and contributions of individual constituents require further investigation. Most

importantly, the proposed mechanisms should be interpreted in the context of the experimental evidence rather than as established therapeutic effects in humans.

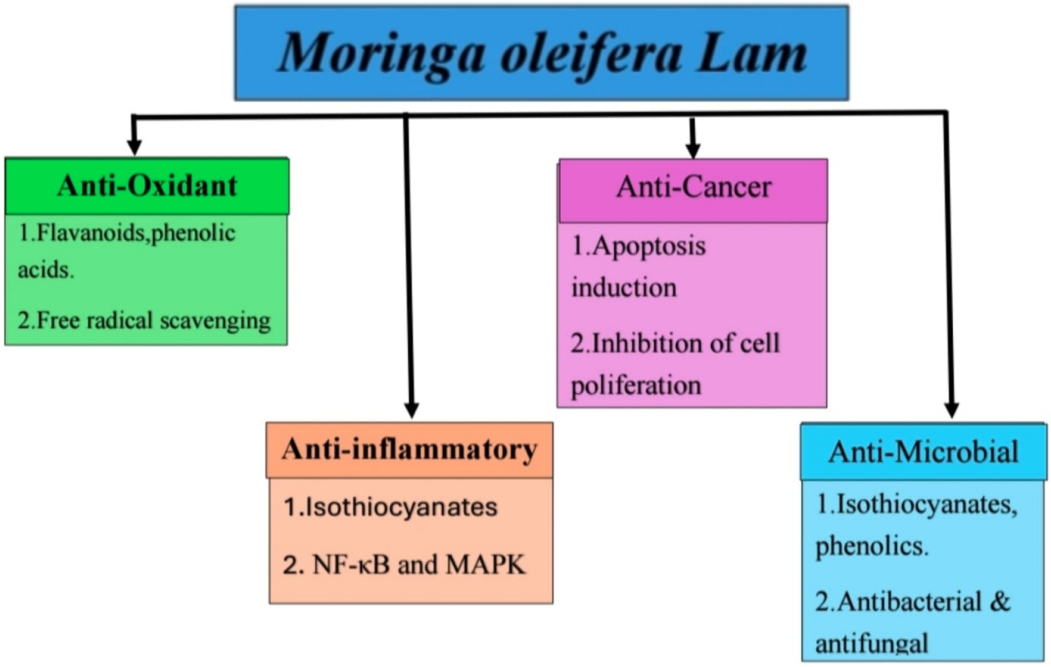


Figure 6. Overview of the four major pharmacological activities of M. oleifera.

9 Safety and toxicity

The safety assessment of *Moringa oleifera* Lam. is essential for determining whether its reported pharmacological properties can be translated into safe medicinal applications. Although the plant contains several potentially beneficial bioactive compounds, its biological activity alone does not establish the safety of every extract or preparation.

9.1 Importance of toxicity assessment

The safety of *M. oleifera* preparations may depend on several factors:

- **Plant part:** Different parts of the plant have different phytochemical compositions.
- **Concentration and dosage:** The amount of extract used may influence its biological effects.
- **Extraction method:** Different solvents and processing techniques can produce preparations with varying chemical profiles.
- **Formulation:** Differences in preparation may affect the characteristics of the final product.
- **Experimental model:** Findings from laboratory and animal studies may not directly predict safety in humans.

9.2 Current evidence and limitations

Toxicity assessment is an important requirement for the further development of M. oleifera as a medicinal resource; the safety and efficacy of the plant have been reviewed by Stohs and Hartman (2015). However, comprehensive toxicity thresholds, safe dosage ranges and long-term safety have not been established for all preparations, and specific safety claims therefore cannot yet be made.

9.3 Requirements for future safety evaluation

Further research should prioritize:

1. Systematic toxicity assessment of standardized extracts.
2. Identification and characterization of the active constituents.
3. Investigation of pharmacokinetic properties.
4. Evaluation of potential interactions with conventional medicines.
5. Carefully designed clinical studies to assess safety and tolerability in humans.

In conclusion, safety and toxicity evaluation is necessary before *M. oleifera* preparations can be recommended for specific therapeutic purposes. Standardized formulations and adequate preclinical and clinical investigations are required to establish their safety profile and support evidence-based medicinal applications.

10 Research gaps and future perspectives

Although *Moringa oleifera* Lam. has demonstrated promising antioxidant, anti-inflammatory, anticancer, and antimicrobial properties in experimental studies, further research is necessary to confirm its therapeutic value and safety.

10.1 Research gaps

The major limitations in the current research are:

- **Variation in extracts:** Differences in plant parts, extraction methods, and solvents may influence the chemical composition and biological activity of the extracts.
- **Identification of active compounds:** Further investigations are needed to determine which phytochemicals are mainly responsible for the reported pharmacological effects.
- **Limited clinical evidence:** Many findings are based on laboratory experiments and animal studies. Their effectiveness in humans remains insufficiently established.
- **Safety evaluation:** More studies are required to assess toxicity, possible adverse effects, appropriate dosage, and interactions with other medicines.
- **Unclear mechanisms:** The biological pathways responsible for some of the reported effects require further investigation.

10.2 Future perspectives

Future research should focus on the following areas:

1. Developing standardized extraction and testing methods to improve the consistency of research findings.
2. Identifying and characterizing the phytochemicals responsible for specific pharmacological activities.
3. Investigating the mechanisms underlying antioxidant, anti-inflammatory, anticancer, and antimicrobial effects.
4. Evaluating the safety, toxicity, pharmacokinetics, and possible drug interactions of Moringa extracts.

5. Conducting well-designed clinical trials to determine whether experimental findings can be translated into meaningful health benefits.

6. Exploring the antimicrobial potential of Moringa-derived compounds against different microorganisms, including resistant strains.

11 Conclusion

Moringa oleifera Lam. is a medicinal plant that contains several biologically active compounds, including flavonoids, phenolic compounds, and isothiocyanates. These constituents may contribute to its antioxidant, anti-inflammatory, anticancer, and antimicrobial activities. The studies discussed in this review indicate that Moringa extracts have the potential to reduce oxidative damage, influence inflammatory responses, affect the growth of certain cancer cells, and inhibit some microorganisms under experimental conditions. However, the effects may vary depending on the plant part used, the extraction method, and the chemical composition of the extract. Despite these promising findings, much of the available evidence comes from laboratory experiments and animal studies. Therefore, the reported activities should not be considered proof that Moringa can prevent or cure diseases in humans. More research is needed to understand its mechanisms of action, evaluate its safety, determine suitable dosages, and identify possible interactions with medicines. Well-designed clinical trials are also necessary to establish its effectiveness in humans. In conclusion, *Moringa oleifera* is a promising source of natural bioactive compounds with several potential pharmacological applications. Further scientific investigation may help clarify its benefits and limitations and determine whether these compounds can be developed into safe and effective healthcare products.

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