Moringa oleifera Lam.: A Miracle Tree and its Phytochemistry, Nutritional Value, and Therapeutic Potential

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***Abstract*—Moringa oleifera is often referred to as the "Miracle Tree" or the "Tree of Life"; it is much more than just a resilient, drought-tolerant plant native to the Himalayan hills. For over 4,000 years, it has been in staple use in Ayurveda and Siddha medicine, used to treat hundreds of different ailments, and this review dives deep into the modern science that explains why it works. The plant is packed with over 90 bioactive compounds, including powerful antioxidants like quercetin and kaempferol that help protect the body. Nutritionally, a powerhouse that rivals superfoods like "spirulina", offering a rare complete plant protein containing all nine essential amino acids, along with high concentrations of vitamins like vitamin A, C, and E. This review also highlights how moringa acts as a natural defence system for the body. It fights inflammation and oxidative stress by blocking specific inflammatory pathways (such as NFκB and COX-2). The review also details its potential to help manage diabetes by improving how cells absorb sugar and its potential ability to selectively target cancer cells, particularly in breast cancer models. Toxicology studies confirm it has a high safety margin with no adverse effects even at high doses, making it suitable for wide-ranging uses like supporting maternal health to purifying water using seeds extracts and are suitable for human consumption. Ultimately, this review presents Moringa oleifera as an important link between ancient wisdom and modern innovation, offering a sustainable solution for the future of nutrition and medicine.**

***Index Terms*—Moringa oleifera, Miracle tree, Moringaceae family, quercetin, kaempferol, glucomoringin, niazimicin, β-sitosterol, moringin, niazirin.**

I. INTRODUCTION

Fig.no. 1.1 Illustration of Moringa oleifera.

Moringa oleifera Lam., commonly known as the drumstick tree, horseradish tree, or even the Miracle tree, is a fast-growing and drought-resistant species from the Moringaceae family. Native to the southern foothills of the Himalayas, it has been cultivated across tropical and subtropical regions due to its exceptional adaptability to marginal soils and arid climates [1,2,15]. Historically, M. oleifera has been used in Ayurvedic and Siddha medicine for over 4,000 years to treat more than 300 diseases, including inflammation, infections, digestive disorders, and metabolic dysfunctions [25]. It is widely used in African, Southeast Asian, and Latin American cultures, and has earned its names such as "never-die tree" and "tree of life" due to its resilience and therapeutic versatility [15,42]. Its phytochemical constituents include over 90 bioactive compounds

such as quercetin, kaempferol, glucomoringin, niazimicin, β-sitosterol, and moringin [2,3,6,8]. These compounds contribute to its therapeutic versatility and support its use in nutraceuticals, functional foods, and integrative medicine [24,33]. M. oleifera is increasingly recognised and known for its role in combating malnutrition due to its high nutrient density [7,9,10], supporting food security through its resistance to drought and poor soils [21,36], and Environmental remediation, including water purification and soil stabilisation [27,44]. It has a low cultivation cost, rapid growth, and minimal input requirements, making it ideal for agroecological interventions and public health nutrition programs [22,31].

II. TAXONOMY AND MORPHOLOGY

Taxonomic Classification of Moringa oleifera Moringa oleifera Lam. belongs to the family Moringaceae, which comprises 13 species in total, with M. oleifera being the most widely cultivated and studied. Its taxonomic hierarchy is as follows:

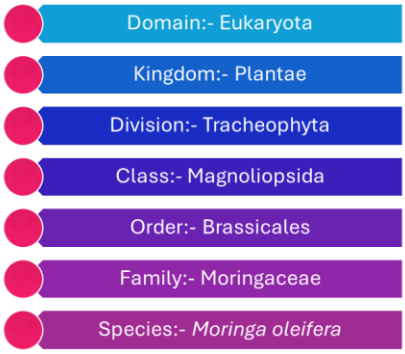


Fig.no. 2.1 Taxonomic Classification of Moringa oleifera.

2.1 Morphological Features

- Leaves: These are either bipinnate or tripinnate, packed with small oval-shaped leaflets. They are rich in chlorophyll and lots of bioactive compounds such as flavonoids and phenolics [2,6].
- Flowers: Zygomorphic flowers are observed, white or cream-colored, with a distinguishable fragrance. They occur in clusters along the stem and contain sterols and glycosides with antimicrobial properties [3,8].
- Pods: Long, slender, and pendulous or hanging pods, containing round seeds packed with a high oil content rich in oleic acid.
- Roots and Bark: They contain alkaloids like moringin and niazirin, leading to their anti-inflammatory and analgesic effects [4,18].

Recent studies have revealed that M. oleifera had a surge of plastid-to-nucleus gene duplications, in return enhancing its adaptability to environmental stress. It is closely related to the Brassicaceae family (Broccoli and mustard), explains the presence of glucosinolates like glucomoringin, which are structurally similar to those in broccoli and mustard but exhibit unique bioactivation profiles or behave differently in the body.

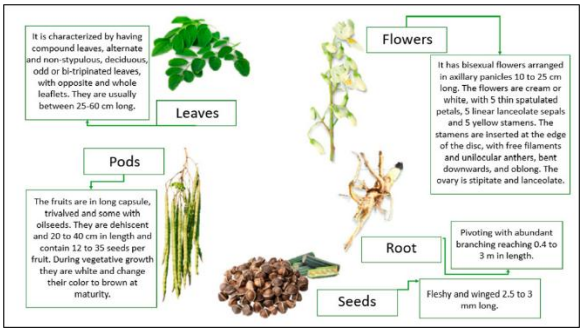


Fig.no. 2.2 Morphology of Moringa oleifera.

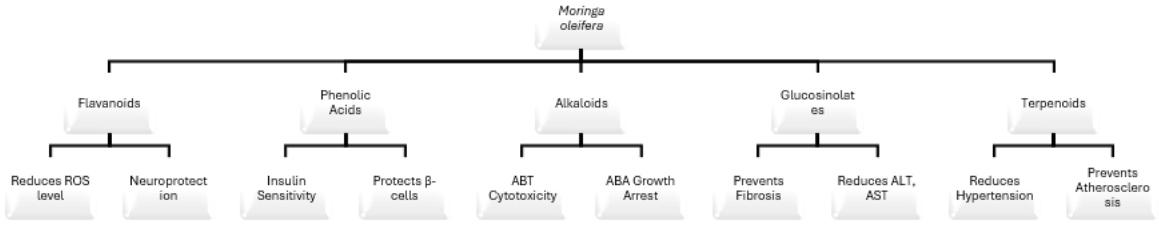
III. PHYTOCHEMICAL COMPOSITION

Moringa oleifera contains over 90 distinct bioactive compounds distributed across its leaves, seeds, bark, roots, and flowers [2,3,4]. These compounds belong to several major phytochemical classes:

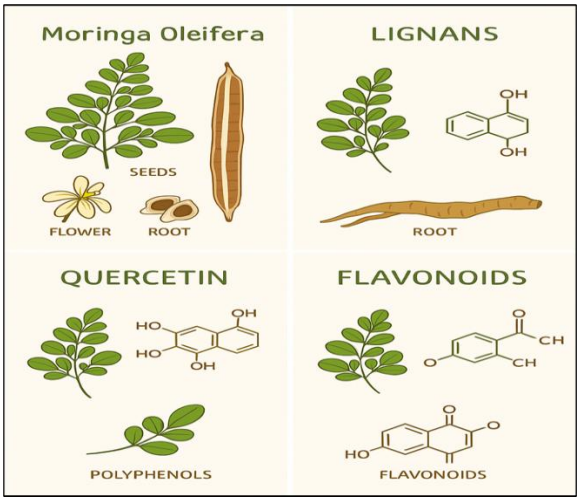
- Flavonoids: Quercetin and kaempferol are potent antioxidants and anti-inflammatory agents present in Moringa oleifera [2,6,8].
- Phenolic acids: Gallic acid, ferulic acid, and cinnamic acid contribute to help fight free radical scavenging [8,11].
- Alkaloids: Moringine and niazirin are involved in analgesic and anti-inflammatory effects [4,18].
- Glucosinolates: Glucomoringin is structurally similar to those found in Brassica vegetables, with its own unique bioactivation profiles [19,37].
- Glycosides: Niazimicin, a type of glycoside, exhibits anticancer and antimicrobial properties [1,28].

- Sterols: β-sitosterol supports lipid regulation and anti-inflammatory activity.
- Terpenoids: β-carotene, a terpenoid, contributes to its antioxidant and boosts vitamin A activity.

Recent metabolomic profiling via LC-MS and NMR techniques has revealed synergistic interactions among flavonoids, alkaloids, and sterols, contributing to multi-targeted bioactivity [20,39]. Comparative studies show upregulation of antioxidant and detoxification genes in M. oleifera leaves, showing just how active these compounds are.



(a)



(b)

Fig.no. 3.1(a & b) Phytochemical Composition of Moringa oleifera,

IV. NUTRITIONAL PROFILE

Moringa oleifera is widely recognised as a true nutritional powerhouse. Particularly, its leaves and pods contain a dense matrix of essential nutrients. Its nutrient profile surpasses many conventional vegetables and rivals leading nutraceuticals like spirulina and turmeric [7,9,10,22,38].

- Vitamins: It contains high amounts or levels of vitamin A (β-carotene), vitamin C, and vitamin E, which contribute to antioxidant activity and immune support [7,11,38].
- Minerals: Rich in calcium, iron, magnesium, potassium, and zinc, essential for bone health, haemoglobin synthesis, and enzymatic functions running smoothly [9,10,36].
- Proteins and Amino Acids: Contains all nine essential amino acids, making it a complete plant-based protein source [7,38].
- Fatty Acids: Seed oil is rich in oleic acid, comparable to olive oil, and beneficial for cardiovascular health.
- Fibre: High dietary fibre content supports and keeps digestive health in check and glycemic control [8,11].

Research studies show that the bioavailability of iron and calcium from M. oleifera leaf powder is better than that of spinach and most of the other leafy greens due to the presence of chelating agents like flavonoids and vitamin C. Its amino acids support muscle repair, immune function, and metabolic regulation. Due to its nutrient density, M. oleifera leaf powder is used in:

Prevention of malnutrition programs in Africa and South Asia.
It gives maternal and child health supplement action.
Functional food formulations or boosting foods such as biscuits, soups, and beverages.

V. PHARMACOLOGICAL ACTIVITIES

Moringa oleifera exhibits a wide range of pharmacological effects due to its diverse mix of secondary metabolites. These effects have been validated through in vitro, in vivo, and emerging clinical studies or early clinical trials.

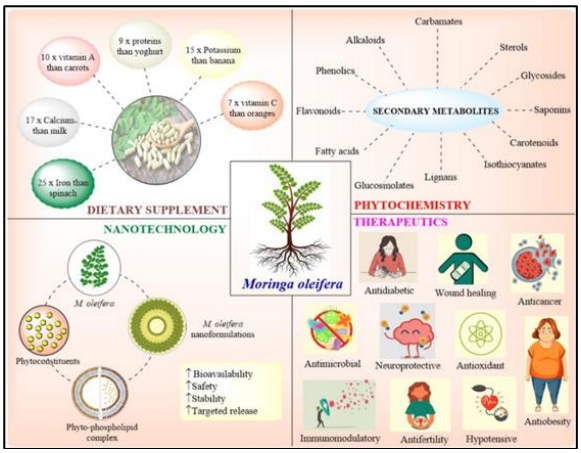
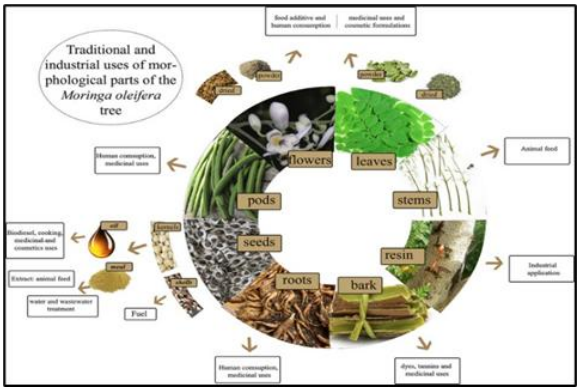


Fig.no. 5.1(a) Pharmacological activity of M. oleifera



(b) Application of different parts of the plant M. oleifera

5.1 Antioxidant Activity

Extracts from leaves and roots (aqueous, methanolic, ethanolic) demonstrate potent antioxidant activity by neutralising reactive oxygen species (ROS), reducing lipid peroxidation, and enhancing the body's own antioxidant enzymes such as superoxide dismutase (SOD), catalase, and glutathione peroxidase produced by the body [2,6,8,12]. Phenolic acids (gallic, ferulic) and flavonoids (quercetin, kaempferol) are key contributors [8,11]. Leaf extract mitigates or protects against oxidative damage induced by high-fat diets and drug toxicity [12,29].

5.2 Anti-inflammatory Effects

Moringa oleifera fights inflammation in a few ways, like it blocks NFκB and COX-2, which are big players in the body's inflammatory response. It also dials down pro-inflammatory cytokines like IL-6 and TNF-α. In animal studies, it actually reduces swelling and helps with bronchospasm. Interestingly, extracts from the root and seeds work about as well as phenylbutazone in easing inflammation. [5,13].

5.3 Anticancer Potential

Some compounds in Moringa-niazimicin, benzyl isothiocyanates, and rhamnosyloxy carbamates trigger cancer cells to self-destruct. They do this by activating caspase-8 and p53, boosting or enhancing Bax, and releasing cytochrome c. These compounds are especially tough on MCF7 breast cancer cells, showing a selectivity index greater than 9.5. Researchers have confirmed these effects using various tests like MTS assays, Annexin V-FITC staining, and Western blots. [14,28]

These effects are validated using MTS assays, Annexin V-FITC staining, and Western blotting.

5.4 Anti-diabetic Activity

Moringa oleifera helps the body manage blood sugar in a few ways. It encourages GLUT4 to move to the cell surface, which makes it easier for cells to take up glucose. It also shields pancreatic β-cells from oxidative damage and tweaks the AMPK and PI3K/Akt pathways. Clinical trials back this up: people with type 2 diabetes who took Moringa leaf powder observed better control of their blood sugar. [30,32].

5.5 Clinical trials show improved glycemic control in type 2 diabetic patients supplemented with leaf powder [28,30].

Hepatoprotective and Cardioprotective Effects

Moringa oleifera steps up for your liver and heart. It lowers serum ALT, AST, and creatinine, keeping those markers in check. At the same time, it boosts antioxidant enzyme activity and blocks lipid peroxidation and fibrosis [29,30]. It mitigates damage from drugs like acetaminophen, rifampicin, and isoniazid [12,29].

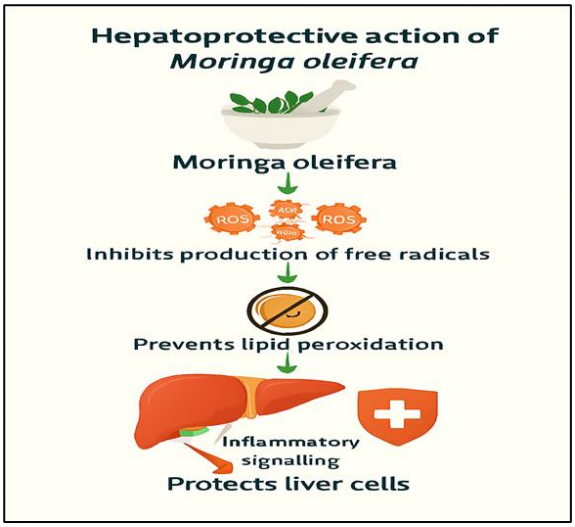


Fig.no. 5.2 Hepatoprotective action of M. oleifera

5.6 Neuroprotective Effects

M. oleifera improves and sharpens cognitive function and protects neurons by preventing, reducing neuroinflammation and enhancing cholinergic transmission.

VI. SAFETY AND TOXICOLOGY

When it comes to safety, Moringa oleifera is really the one that delivers. It has been extensively evaluated for safety across preclinical and clinical studies, demonstrating a high margin of safety and excellent tolerability.

6.1 Acute and Chronic Toxicity

- Acute toxicity studies in rodents show LD_{50} values >2000 mg/kg for leaf and seed extracts, indicating low toxicity [12,14,43].
- Chronic administration of leaf powder over 90 days did not result in hepatic, renal, or haematological abnormalities [12,39].
- No genotoxic or teratogenic effects were observed in reproductive toxicity studies, supporting its use in maternal nutrition [14,43].

6.2 Clinical Safety and Tolerability

Human trials report excellent tolerability of M. oleifera leaf powder and seed oil at dietary doses [28,36]. HIV-positive patients, for example, had no side effects and even saw improved antioxidant status after its use. No significant interactions were observed with common medications, although caution is advised with anticoagulants due to potential vitamin K interference [12,39].

6.3 Water Purification and Antimicrobial Safety

Seed extracts used for water purification are safe for human consumption and effectively reduce microbial load without introducing toxicity [27,40]. Antimicrobial peptides and isothiocyanates from seeds exhibit selective activity against pathogens without harming or acting on beneficial gut flora [18,40].

VII. DISCUSSION AND CONCLUSION

Moringa oleifera's therapeutic versatility comes from its rich phytochemical diversity and synergistic bioactivity. Comparative analysis reveals that its total phenolic and flavonoid content is equal to or greater than that of other leading nutraceuticals available in the market, such as Camellia sinensis (green tea) and Curcuma longa (turmeric) [8,22,37].

7.1 Comparative Phytochemical Potency

- Glucosinolates in M. oleifera (e.g., glucomoringin) resemble those in Brassica vegetables but exhibit unique enzymatic activation pathways, leading to enhanced anticancer and antimicrobial effects [19,37].
- Flavonoid synergy: Quercetin and kaempferol interact with alkaloids and sterols to produce multi-targeted effects, including NFκB inhibition, COX-2 downregulation, and enhanced insulin signalling [2,4,30].
- Phenolic richness: Its phenolic content exceeds that of spinach and matches antioxidant-rich herbs like rosemary and oregano [8,11].

7.2 Omics-Based Insights

- Metabolomics: LC-MS and NMR profiling reveal over 90 metabolites, including rare isothiocyanates and glycosides with potent bioactivity [20,32].
- Transcriptomics: Comparative gene expression studies show upregulation of antioxidant, detoxification, and anti-inflammatory genes in M. oleifera leaves [37,39].
- Proteomics: Protein-level studies confirm activation of caspase pathways, insulin receptors, and hepatic detox enzymes [1,14,30].
- M. oleifera offers a unique combination of Low cultivation cost and high biomass yield [21,23],

Adaptability to drought-prone and marginal soils, making it ideal for climate-resilient agriculture [15,16]. Dual nutritional and pharmacological utility, unlike single-function plants such as spirulina (nutritional) or turmeric (pharmacological) [22,24].

It is increasingly integrated into the following:

- Public health nutrition programs for maternal and child health
- Functional food industries for fortified products
- Phytopharmaceutical development for multi-targeted therapies [24,31,33].

7.3 Conclusion

Moringa oleifera Lam. stands out as a multifunctional botanical resource with well-observed neutraceutical, pharmacological, and ecological significance. Its rich phytochemical composition, including flavonoids, alkaloids, glucosinolates, sterols, and glycosides, translates into multi-targeted therapeutic effects such as antioxidant, anti-inflammatory, antidiabetic, anticancer, hepatoprotective, and cardioprotective actions.

The plant's nutritional density, including essential amino acids, vitamins, and minerals, supports its use in combating malnutrition and enhancing public health, particularly in areas that are limited in resources. Its safety profile, confirmed through acute, chronic, and clinical studies, reinforces its suitability for long-term dietary and therapeutic use.

Comparative analyses with other nutraceuticals that are available in the market, like spirulina, turmeric, and green tea, show that M. oleifera offers a broader spectrum of benefits, combining both nutritional and pharmacological advantages. Emerging omics-based research further supports its multi-pathway bioactivity and gives avenues for targeted drug development, functional food innovation, and integrative medicine [20,32,39].

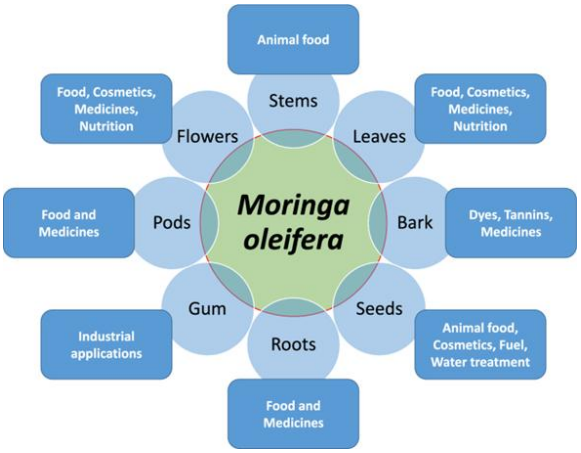


Fig.no. 7.1 Applications of M.oleifera.

Because it's cheap to grow, survives tough conditions, and serves multiple purposes, Moringa is set to play a big role in sustainable farming, global nutrition, and the future of plant-based medicine. Continued interdisciplinary research integrating agronomy, pharmacology, metabolomics, and clinical science will be essential to further harness its potential.

VIII. FUTURE APPLICATIONS

While Moringa oleifera has been extensively studied, several promising avenues remain for future exploration:

8.1 Molecular Mechanisms and Target Validation

Systems biology approaches such as transcriptomics, proteomics, and metabolomics are beginning to unravel the complex interactions between M. oleifera phytochemicals and cellular pathways [19,20,32,37].

Further target-based studies are needed to validate the modulation of key signalling cascades like NFκB, PI3K/Akt, MAPK, and AMPK in human models [30,33].

Structure-activity relationship (SAR) studies on isothiocyanates and glycosides (e.g., niazimicin, glucomoringin) could lead to the development of novel semi-synthetic derivatives with enhanced bioavailability and potency [1,4,28].

8.2 Clinical Trials and Translational Research

Although preclinical data are robust, large-scale, randomised controlled trials (RCTs) are essential to confirm efficacy in humans for conditions such as type

2 diabetes, hyperlipidemia, and inflammatory disorders [28,30,34].

Standardisation of extracts and dosage forms is critical for reproducibility and regulatory approval. Current variability in phytochemical content due to geography, cultivation, and processing methods must be addressed [23,31].

Moringa oleifera is more than a traditional remedy; it is a scientifically validated, globally adaptable, and economically viable plant with the potential to make a huge impact on health, nutrition, and sustainability. Its integration into modern pharmacology, food systems, and environmental solutions represents a way to bridge ancient knowledge with modern science.

Standardisation of extracts and dosage forms is critical for reproducibility and regulatory approval. Current variability in phytochemical content due to geography, cultivation, and processing methods must be addressed [23,31].

M. oleifera's incredible ability to thrive in arid, nutrient-poor soils makes it a candidate for climate-resilient agriculture and agroforestry systems [21,23].

Its use in phytoremediation and wastewater treatment through seed-based flocculants offers eco-friendly solutions for water purification [27,40].

Genetic improvement programs focusing on yield optimisation, phytochemical enhancement, and pest resistance are under development and need further enhancements [23,32].

8.3 Functional Foods and Nutraceutical Innovation

M. oleifera is increasingly incorporated into fortified foods, herbal teas, nutraceutical capsules, and cosmeceuticals [24,25,33].

Its synergistic potential with other botanicals (e.g., turmeric, ginger, green tea) is being explored for combination therapies and functional formulations [22,34].

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