Pharmaceutical Potential of Moringa oleifera: A Review of Bioactive Constituents, Therapeutic Mechanisms, Formulation Prospects, and Clinical Relevance

Kulwinder Singh[1]

Lamrin School of pharmaceutical sciences, Lamrin Tech Skills University, Punjab, India

ABSTRACT

Phytomedicine development relies upon utilizing medicinal plants as a reservoir of potential medicines, but strong interdisciplinary connections of phytochemistry to mechanism and formulation, with safety and clinical evidence, are necessary to transition from plant to medicine. Moringa oleifera is an excellent example as its leaves, seeds, flowers, pods, bark, and roots contain numerous bioactive compounds. The constituents of different Moringa oleifera parts have been studied for their antioxidant, anti-inflammatory, antimicrobial, antidiabetic, anticancer, and wound-healing activities. The mechanisms of action are theorized to involve regulation of redox signaling and Nrf2/HO-1 signaling, NF-kappaB and inflammation, AMPK and glucose transport, mitochondrial apoptosis and proliferation. Due to the nature of the extraction methods, crude extracts differ and many constituents of Moringa oleifera also suffer from stability, solubility, permeability, and bioavailability. Due to the stability, solubility, permeability, and bioavailability issues of extracts, different materials that can increase formulation strategy are being explored and are mainly still in the preclinical phase. Research to date is encouraging, particularly the human intervention studies in metabolic and nutritional deficiency settings, but the studies are heterogeneous and generally small. The key gaps are the generation of equivalence of different extracts along with the establishment of marker compounds and clinical pharmacokinetics. The safety of concentrated extracts also requires pharmacokinetic assessment and toxicological evaluation along with the potential for latter interactions. In summary, while there is potential for medicinal use of Moringa oleifera, the clinical potential will reside in the alignment of research efforts in formulation, safety, and clinical pharmacology.

Keywords: Moringa oleifera; Bioactive compounds; Phytopharmaceuticals; Therapeutic mechanisms; Drug delivery; Clinical evidence

AIM AND REVIEW OBJECTIVES

Aim. The objective of this review is to evaluate the pharmaceutical potential of Moringa oleifera considering the major bioactive compounds, mechanism of action, therapeutic activities, opportunities for formulation, safety, and available human data, as well as to identify the barriers to the standardization of pharmaceutical transformation. The aim is to compare the distribution of constituents, mechanisms of action and the level of evidence; to assess biopharmaceutical and formulation issues; to assess clinical effectiveness and safety; and to identify pharmacokinetic, toxicological, standardization, regulatory, and research challenges.

1. Introduction

Plant-based compounds continue to be important building blocks of drug candidates. However, a plant is considered to have a strong basis for pharmaceutical use only when its identity, composition, exposure, mechanism of action, and safety are all readily reproducible. Moringa oleifera, consumed as food and with diverse traditional uses, is grown in the tropics and subtropics. Leaves are the most researched. The other parts, including the seeds, flowers, pods, bark, and roots provide constituents with considerably different chemical profiles. Some recently published reviews show the plant has a great range of phytochemicals,

though there is also an emphasis that the constituents detected and quantified depend on the type of processing and the analytical method used (Camilleri & Blundell, 2024; Gharsallah et al., 2023; Su et al., 2023; Panova et al., 2025; Arshad et al., 2025).

There is interest in pharmaceutical applications from preclinical evidence for redox, inflammatory, metabolic, antimicrobial, anti-neoplastic and vascular effects, protection of organ function, and control of cytostasis and apoptosis in cancer models, as well as from evidence of organ protective effects. Redox effects are biologically plausible since flavonol glycosides, phenolic acids, isothiocyanates, thiocarbamates, sterols, lipids, proteins, and peptides can interact with different molecular targets. However, traditional use and antioxidant assay results cannot substitute for clinical efficacy. Even positive results at biological or cellular levels may have used concentrations of extracts, solvent systems, or exposure conditions that cannot be compared with what would occur after oral administration.

What is of interest is whether the defined constituents or standardized extracts can be converted into stable, bioavailable, and reproducible dosage forms with clinically relevant effects. Recent analytics, formulations, and human studies enable this assessment and have revealed the shortcomings of pharmacokinetics, dose standardization, interactions, and multicenter validation (Fitri et al., 2025; Meireles et al., 2020; Jikah & Edo, 2023; Amin et al., 2024).

1.1 **Literature search strategy**

This narrative review is based on literature databases like PubMed, Scopus, Web of Science covering search term such as Moringa, phytochemistry, bioactive compound, Flavonoids, pharmacological activities, Mechanism, Clinical trial, standardization from time period of 2020 to 2025. Original research articles, systematic and narrative review, and randomized or controlled human studies are considered for the review article.

2. Phytochemical and bioactive constituent profile

2.1 FLAVONOIDS

The phytochemical composition of Moringa is diverse and is dependent on the plant part. Leaves contain abundant flavonoids, which include quercetin and kaempferol derivatives, as well as chlorogenic, caffeic, ferulic and gallic acids. A process targeted by LC-MS and molecular networking appears to expand the flavonoid region, through the glycosylation and acylation of flavonoids (Gao et al., 2025; Hassan et al., 2021; Ndou et al., 2023).

2.2 Phenolic Acids

Rutin and myricetin occur in smaller amounts in the leaves but are reported. Like other phenolics, they exhibit radical scavenging and metal chelating capacities and interact with enzymes and signaling proteins. However, the measured amounts of these phenolics vary with the cultivar, maturity, temperature of

drying, polarity of solvent, solid-to-liquid ratio, and the type of extraction technique (Bennour et al., 2021; Chatzimitakos et al., 2024; Peng et al., 2025).

2.3 Glucosinolates and Isothiocyanates

Glucosinolates and the isothiocyanates derived from their myrosinase action are unique to some extent. The rhamnosylated benzyl glucosinolate in Moringa can be transformed to moringin, a relatively stable isothiocyanate that has been reported to possess the inflammatory, sensory-channel, and antiproliferative activities (Wang et al., 2025; Srivastava et al., 2024). The seeds contain the thiocarbamate glycosides such as niazimicin along with a rich source of oil containing a high level of oleic acid and proteins of economic importance, as well as sterols, and peptides and lectins (Abdelsayed et al., 2021; Chandrashekar et al., 2020; Nubi et al., 2021). The hydrolysis of proteins can yield peptides that have an alpha glucosidase inhibitory activity and antioxidant capacity, among others (Wang et al., 2022; Bassogog et al., 2024).

2.4 Other Bioactive Constituents

The other constituents include several carotenoids, vitamins, and other molecules with a varied structure, such as tannins, alkaloid-like components, phytosterols, and saponins. However, their pharmaceutical relevance is dependent on their identification and exposure and not on their sheer presence. Extraction techniques, including the use of pressurized liquids, microwaves and natural deep eutectic solvents, can improve the extraction yield and possibly change the pattern of constituents. Therefore, Moringa is best represented as an authenticated plant material with controlled processing, and a chromatographic fingerprint rather than a “leaf extract” or “seed extract” (Souza et al., 2024; Kheyar et al., 2025; Chatzimitakos et al., 2024).

Table 1. Major bioactive constituents of Moringa oleifera and their pharmaceutical relevance.

Bioactive class	Representative compound(s)	Plant part used for extract	Reported pharmacological relevance	Mechanistic target/pathway	Representative reference(s)
Flavonoids	Quercetin and kaempferol glycosides; rutin; myricetin where detected	Leaves; flowers; pods	Antioxidant, anti-inflammatory, metabolic modulation	Nrf2/HO-1; COX-2; inflammatory signaling	Gao et al., 2025; Hassan et al., 2021; Ndou et al., 2023; Chen et al., 2021
Phenolic acids	Chlorogenic, caffeic, ferulic, gallic acids	Predominantly leaves; variable across tissues	Redox modulation; enzyme and metabolic effects	Radical scavenging; AMPK-related effects for selected phenolics	Bao et al., 2020; Kheyar et al., 2025; Peng et al., 2025

Bioactive class	Representative compound(s)	Plant part used for extract	Reported pharmacological relevance	Mechanistic target/pathway	Representative reference(s)
Glucosinolates / isothiocyanates	Rhamnosylated benzyl glucosinolate; moringin	Seeds and other tissues	Anti-inflammatory and antiproliferative potential	NF-kappaB-linked signaling; multiple cancer pathways; TRP-channel pharmacology	Wang et al., 2025; Srivastava et al., 2024
Thiocarbamates / alkaloid-rich fractions	Niazimicin; alkaloid-enriched fractions	Seeds; leaves depending on fraction	Neuroprotective and antiproliferative activity	Caspase/iNOS-related mechanisms; JAK2/STAT3 in experimental cancer models	Abdelsayed et al., 2021; Xie et al., 2021
Proteins, peptides and lectins	Bioactive seed peptides; hypoglycemic peptides; lectins	Seeds; leaves	Antimicrobial, metabolic and antioxidant functions	Alpha-glucosidase inhibition; PI3K/AMPK; membrane interactions	Chandrashekar et al., 2020; Wang et al., 2022; Nubi et al., 2021; Bassogog et al., 2024
Lipids and phytosterols	Oleic-acid-rich seed oil; sterols	Seeds	Topical repair, barrier and anti-inflammatory potential	Local inflammatory modulation; wound microenvironment	Cretella et al., 2020; Ventura et al., 2021; Souza et al., 2024
Carotenoids, vitamins, terpenoids, saponins, tannins	Multiple micronutrients and secondary metabolites	Leaves and other plant parts	Contribute to nutritional and multicomponent bioactivity	Context-dependent; often indirect or incompletely resolved	Camilleri & Blundell, 2024; Divya et al., 2024; Panova et al., 2025

3. Therapeutic activities and pharmacological mechanisms

3.1 Antioxidant Activity

Extracts and compounds of Moringa have been assessed in chemical, cellular and animal models, showing promising antioxidant and anti-inflammatory activities. Extract of Moringa leaf increased the levels of Nuclear factor erythroid 2-related factor 2 (Nrf2) in skeletal muscle cells and increased the levels of glutathione, catalase and Superoxide dismutase (SOD) level, and decreased the levels of lipid peroxidation in other models (Duranti et al., 2021; Ndlovu et al., 2023; Saaha et al., 2025). These results create an evidence base for redox-responsive pharmacology. However, 2,2-diphenyl-1-picyl hydrazyl (DPPH), 2,2'-

azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) or ferric reducing antioxidant power assays, or any antioxidant activity assay in isolation, are not able to infer the efficacy of antioxidant therapy in humans, because the processes of absorption, metabolism, exposure to the tissue and redox homeostasis are not tested.

3.2 Anti-Inflammatory Activity

The most significant results in the literature are the inhibition of the transcription of inflammatory genes, cyclooxygenase-2 (COX-2), and Inducible nitric oxide synthase (iNOS) , and the decrease in the production of inflammatory mediators: TNF-α, IL-1 β and IL-6. Using Affinity ultrafiltration before LC-MS, quercetin and kaempferol were documented to have affinity to COX-2. Seed oil also exhibited anti-inflammatory and anti-proliferative properties in topical models (Chen et al., 2021; Cretella et al., 2020). The reviews have additionally documented the clinical importance of mitogen-activated protein kinase (MAPK) inflammasome activation, and unbalanced evidence and model dependency have limited research in this area (Chis et al., 2024; Parente et al., 2025). Thus, it can be stated that the pre-clinical results support anti-inflammatory activity, but the clinically relevant dose and the degree of efficacy compared to known anti-inflammatory drugs remain unknown.

3.3 Antidiabetic and Metabolic Effects

Extracts and isolated compounds have been reported to inhibit α-amylase or α-glucosidase and enhance insulin sensitivity and insulin mediated glucose uptake and have the potential to modulate lipid metabolism. One phenolic glycoside promoted AMP-activated protein kinase (AMPK), and thereby improved carbohydrate and lipid metabolism, in db/db mice model. Aqueous leaf extract promoted Glucose transporter type 4 (GLUT4) signaling in diabetic rat models. Hypoglycemic seed peptides have been shown to engage the Phosphoinositide 3-kinases (PI3K) and AMPK pathways in various experimental models and hypoglycemic peptides in some studies (Bao et al., 2020; Adedapo et al., 2020; Wang et al., 2022). Systematic or scoping reviews indicate that the preclinical data substantiate the biological activity whereas the clinical data are still lagging (Watanabe et al., 2021; Owens et al., 2020; Nova et al., 2020). New clinical investigations have relevance, but analysis of leaf powder variability, dose, and co-administration of numerous drugs makes it difficult to develop a standardized pharmaceutical dose.

3.4 Anticancer Potential

Cell culture and animal models dominate most cancer studies (Barhoi et al., 2021). Mitofusion dysfunction; activation of caspases; shifts in the balance of Bax/Bcl-2; cell-cycle arrest; and inhibition of proliferation pathways have been reported. Extracts with alkaloids have been reported to modulate JAK2/STAT3 in non-small cell lung cancer models; methanolic leaf extract has been shown to down-regulate the Hedgehog signaling pathway in prostate cancer models; moringin has been shown to regulate multiple signaling pathways in breast cancer models; and in other models, leaf extracts or their peptides have induced apoptosis or growth arrest (Xie et al., 2021; Khan et al., 2020; Srivastava et al., 2024; Do et al., 2021; Aviles-Gaxiola et al., 2024; Kumar et al., 2023). In the case of oral and breast cancers, most cancer studies are still pre-clinical (Rajkumar et al. 2024; Moremane et al., 2023). Computational studies

focusing on HIF-1 α/VEGF/GLUT1 and the use of Moringa-based metallic nanoparticles have been used to generate hypotheses rather than prove therapeutic value (Masarkar et al., 2025; Qian et al., 2025). Until evidence of human clinical efficacy is published, Moringa should not be considered a cancer treatment.

3.5 Antimicrobial Activity

Extracts from leaves and seeds exhibit antimicrobial activity against selected bacteria and fungi in vitro. The different mechanisms of action have been attributed to membrane disruption, phenolics, proteins and interference with biofilm formation. The activities and studies carried against Pseudomonas aeruginosa and Staphylococcus aureus, including biofilm endpoints and studies against resistant clinical isolates, indicate the possible local or adjunctive uses of the extracts (Zubair, 2020; Royani et al., 2023; Anzano et al., 2022; Apenteng-Takyiako et al., 2025). However, the composition of the extracts differs, as do the minimum inhibitory concentrations. The concentrations of extracts active against microorganisms in vitro may not be attainable in vivo.

3.6 Cardiovascular and Hepatoprotective Effects

Vascular studies show that extract of Moringa leaf enhances endothelial nitric-oxide-dependent relaxation and provides a mechanism of action for blood pressure lowering, although clinical syntheses consider the evidence for the anti-hypertensive effect of Moringa to be limited (Menichetti et al., 2025; Qadi et al., 2025; David et al., 2025). Many studies show a dose-dependent reduction in lipid levels and hepatic protection, mainly due to the reduction in oxidative stress and inflammatory injury and not due to a particular mechanism. HepG2 studies and systematic histopathological syntheses support the hypothesis of cytoprotection, but do not support the treatment of human liver disease (Ndlovu et al., 2023; Sowunmi & Gonzo, 2023; Nurhayati et al., 2024).

3.7 Neuroprotective and Other Pharmacological Activities

Neuroprotection is attributable to Nrf2/HO-1 activation, NF-κB inhibition, reduction of oxidative stress, preservation of the mitochondrial pool, and cholinesterase-linked activities. Among these, research studies have identified niazimicine and seed/leaf extracts as major preclinical candidates (Mundkar et al., 2022; Abdelsayed et al., 2021; Arozal et al., 2024; Azlan et al., 2023; Worku & Tolossa, 2024). Reno protective, gastroprotective, and wound healing activities and immunomodulatory activities have been reported and explained mechanistically. However, they are still in the experimental/research stage (Sharma et al., 2025; Alissa et al., 2025; Shafie et al., 2022; Ventura et al., 2021). The broad scope of bioactivities that have been documented is indeed interesting. However, this also highlights the need to avoid making unverified therapeutic claims for complex extracts, considering their broad range of activities.

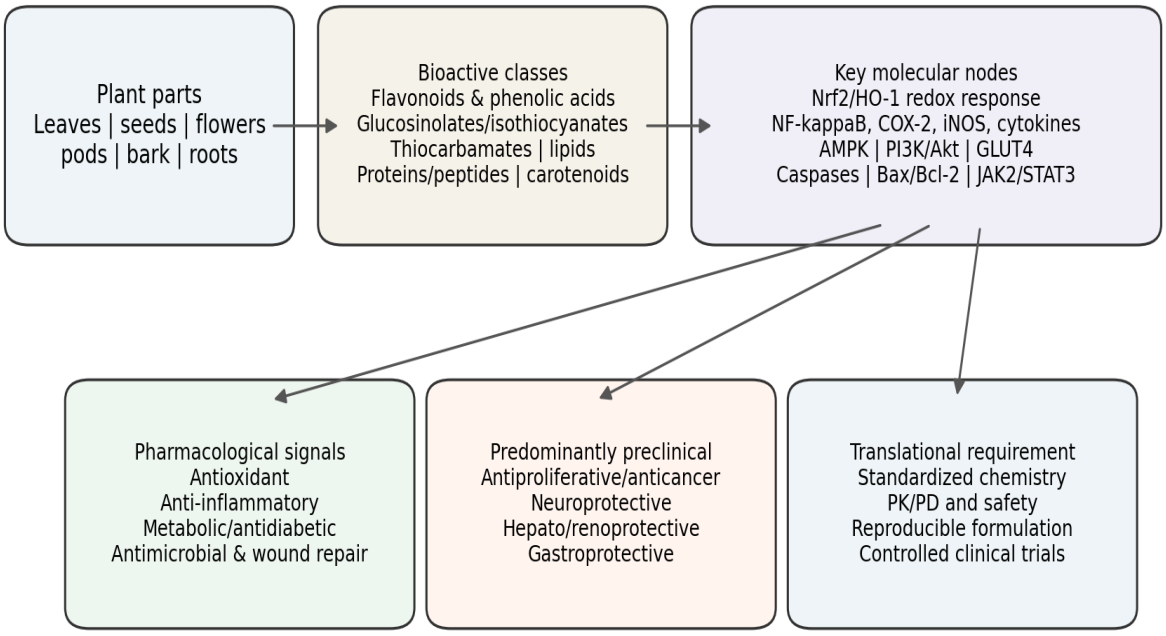
Table 2. Major therapeutic activities, proposed mechanisms and evidence level.

Therapeutic activity	Bioactive constituent/extract	Experimental model	Major mechanism	Key outcome	Evidence level	Reference(s)
Antioxidant	Leaf polyphenols; proteins/peptides	Chemical assays; cells; animal models	Direct radical scavenging plus endogenous antioxidant-response signaling	Improved redox indices in preclinical models	In vitro / preclinical	Duranti et al., 2021; Saaha et al., 2025; Ndlovu et al., 2023
Anti-inflammatory	Leaf flavonoids; isothiocyanates; seed oil	RAW264.7 and topical/in vivo models	NF-κB, COX-2, iNOS, cytokines; MAPK-related pathways	Reduced inflammatory mediators in experimental systems	Preclinical; clinical evidence limited	Chen et al., 2021; Cretella et al., 2020; Chis et al., 2024; Parente et al., 2025
Antidiabetic / metabolic	Leaf extracts; phenolic glycosides; seed peptides	db/db mice; STZ rats; cells; human studies	AMPK, PI3K/Akt, GLUT4; digestive-enzyme inhibition	Improved glucose-related outcomes across models	Strong preclinical; limited human	Bao et al., 2020; Adedapo et al., 2020; Watanabe et al., 2021; Nova et al., 2020; Owens et al., 2020
Anticancer	Leaf phenolics; alkaloid fraction; moringin; peptides	Cancer cell lines and animal models	Mitochondrial apoptosis, caspases, cell-cycle arrest, JAK2/STAT3, Hedgehog	Antiproliferative effects under experimental conditions	Predominantly in vitro / in vivo preclinical	Barhoi et al., 2021; Do et al., 2021; Xie et al., 2021; Khan et al., 2020; Kumar et al., 2023; Moremane et al., 2023;

Therapeutic activity	Bioactive constituent/extract	Experimental model	Major mechanism	Key outcome	Evidence level	Reference(s)
						Rajkumar et al., 2024
Antimicrobial / antibiofilm	Leaf and seed extracts; proteins	Planktonic and biofilm assays; resistant isolates	Membrane effects, phenolics, proteins; biofilm interference	Inhibition of selected pathogens	In vitro; translational uncertainty	Zubair, 2020; Royani et al., 2023; Anzano et al., 2022; Shafiq et al., 2024; Apenteng-Takyiako et al., 2025
Cardiovascular	Leaf preparations	Vascular experiments; human studies/reviews	Endothelial nitric oxide and metabolic/redox effects	Vasorelaxant and blood-pressure signal	Preclinical plus limited clinical	Menichetti et al., 2025; Qadi et al., 2025; David et al., 2025
Hepato / renal protection	Leaf extracts	HepG2; animal models; systematic syntheses	Redox and inflammatory modulation	Reduced injury markers/histological damage in models	Mostly preclinical	Nurhayati et al., 2024; Sowunmi & Gonzo, 2023; Sharma et al., 2025
Neuroprotection	Niazimicin; seed/leaf preparations	Neuronal, dementia and dietary animal models	Nrf2/HO-1; NF-κB; cholinesterase and mitochondrial mechanisms	Improved experimental neurotoxicity/cognition endpoints	Preclinical	Mundkar et al., 2022; Worku & Tolossa, 2024; Arozal et al., 2024; Azlan et al., 2023;

Therapeutic activity	Bioactive constituent/extract	Experimental model	Major mechanism	Key outcome	Evidence level	Reference(s)
						Sakr et al., 2021
Wound / gastroprotection	Seed oil; leaf/seed extracts	Wound models; gastroprotective models	Local inflammation, antimicrobial activity, tissue repair; acid/H. pylori related effects	Accelerated repair or protection in experimental models	Preclinical	Ventura et al., 2021; Shafie et al., 2022; Al-Ghanayem et al., 2022; Alissa et al., 2025

Bioactive constituents and mechanistic pharmacology of Moringa oleifera



Evidence strength is indication-specific: mechanistic plausibility and preclinical efficacy do not by themselves establish clinical effectiveness.

Figure 1. Original schematic linking Moringa oleifera plant parts and bioactive classes with molecular pathways, pharmacological signals and the clinical-translation requirement.

4. Molecular basis of pharmacological action

Different pathways are impacted by moringa constituents resulting in a complex form of pharmacology. For instance, isothiocyanates, redox-active polyphenols, and flavonoids influence Keap1-Nrf2 and antioxidant response; additionally, metabolic constituents and peptides impact AMPK, PI3K/Akt/GLUT4, and other glucose regulation pathways. There are numerous impacts on the NF-kappaB, MAPK, COX-2, iNOS, cytokines, and other inflammatory pathways in the context of anti-inflammatory studies. In cancer studies, impacts on mitochondrial apoptosis; the Bax/Bcl-2; JAK2/STAT3, Hedgehog; and other pathways associated with hypoxia have been reported (Chis et al., 2024, Bao et al., 2020, Xie et al., 2021, Srivastava et al., 2024).

Pleiotropy of moringa compounds poses a significant challenge but also offers a unique opportunity. Complex nature of interactions poses challenges on targets to be prioritized; however, if multiple effects of moringa are studied at different exposure concentrations, the targeted effects may be identified. To advance the field, innovative research incorporating multiple approaches including quantitative phytochemistry, bioassay-guided fractionation, and mechanistic perturbations and profiling of drug metabolites in the context of PK/PD may be undertaken. This should allow a consistent drug effect to be achieved with a consistent chemical (Camilleri & Blundell, 2024, Chen et al., 2021, Wang et al., 2025).

5. Pharmaceutical formulation and drug delivery prospects

5.1 Conventional Dosage Forms

The use of Moringa extract in pharmaceutical formulations is restricted due to the prevalence of the inhomogeneous form of the active pharmaceutical ingredient. Polyphenols may be extensively metabolized or poorly permeable, and lipophilic compounds may be poorly water-soluble. Isothiocyanates may undergo chemical reactions. Proteins and peptides may be degraded in the gastrointestinal tract, and crude extracts may be of varying sizes, may absorb water, may be contaminated with microorganisms, and may contain variable concentrations of marker compounds. While convenient powder, capsule, tablet, suspension, and liquid extract forms of the material may be considered, they will have to be formulated after specifying the plant part, extraction ratio, solvent, assay marker, dissolution or disintegration time, contaminants, and stability (Meireles et al., 2020; Gharsallah et al., 2023).

5.2 Nano and Advanced Drug Delivery Systems

The most advanced formulation of 'Moringa extract' has been designed for local delivery. Extracts of Moringa seeds have been incorporated into hydrogel and Moringa/chitosan-coated silk sutures for wound healing, while a microemulsion hydrogel has been formulated for the treatment of atopic dermatitis (Ali et al., 2022; Butt et al., 2024; Garg et al., 2025). The swelling potential of Moringa gum/poly (vinyl alcohol) matrices has been studied, and the local antimicrobial activity and delivery of repair-oriented constituents has been studied for healing of infected wounds (Ahmad et al., 2020; Al-Ghanayem et al., 2022). These

systems may provide a controlled local release of drug and act as a barrier and protect the active components. Standardization of the batch and the release kinetics of the system need to be studied further.

Separating nanotechnology may be necessary. The so-called 'Moringa nanoparticles' mostly use an extract as a green reducing or capping agent for metal nanoparticles, such as gold, copper, or zinc oxide, and are not nanocarriers for a standardized Moringa drug (Perumalsamy, et. al. 2024; Alsamhary. 2023; Sarwar et al., 2025; Qian et al., 2025). Polymeric or lipid nanoparticles, liposomes, phytosomes, and Nano emulsions are potential rational solutions to address stability and solubility issues of active components. However, the real improvement of clinical bioavailability would require more thorough pharmacokinetic studies. The Quality by Design approach should define the loading, size, release, stability, scaling, positive-minded toxicity assessment, and the impact of scale up.

To make the status of each approach explicit, the formulations in Table 3 are grouped as follows. Experimentally evaluated formulations (the chitosan-coated suture, seed-extract hydrogel, microemulsion hydrogel, and infected-wound preparation) have been tested only in preclinical models. Platform or material studies (Moringa gum/poly (vinyl alcohol) hydrogels and metal nanoparticles synthesized using Moringa extract) describe material properties or nanomaterial activity and do not demonstrate delivery of a standardized Moringa drug. Prospective strategies (liposomes, phytosomes, SLN/NLC, and polymeric nanoparticles of defined actives) are presented as opportunities and have not been validated for Moringa actives. For all of these, stability, bioavailability, safety, and therapeutic efficacy still require validation, and none of the formulations in Table 3 have human pharmacokinetic or efficacy data in the cited studies.

Table 3. Reported and prospective formulation strategies involving Moringa oleifera or its constituents.

Active material	Formulation type	Carrier/excipient	Purpose	Key formulation outcome	Major limitation	Reference
Moringa/chitosan coating	Coated silk suture (experimentally evacuated; preclinical)	Chitosan + silk suture	Local wound-supporting biomaterial	Improved wound-healing formulation investigated	Preclinical; standardization and translational validation required	Butt et al., 2024
Seed hydroalcoholic extract	Hydrogel (experimentally evacuated; preclinical)	Hydrogel matrix	Wound repair	Improved local handling and sustained contact	Preclinical; batch and stability data needed	Ali et al., 2022
Seed extract	Microemulsion hydrogel (experimentally	Microemulsion plus gel network	Atopic dermatitis/local delivery	Enhanced topical delivery concept	Disease model only; no clinical	Garg et al., 2025

Active material	Formulation type	Carrier/excipient	Purpose	Key formulation outcome	Major limitation	Reference
	evacuated; preclinical)			evaluated in vivo	pharmacokinetics	
Moringa gum	Superabsorbent hydrogel (platform study)	Poly(vinyl alcohol)	Polymeric platform / controlled local delivery potential	High swelling and matrix functionality	Platform study rather than validated Moringa drug product	Ahmad et al., 2020
Leaf extract	Local infected-wound preparation (experimentally evacuated; preclinical)	Extract-based topical exposure	Antimicrobial plus wound repair	Promoted healing in diabetic-rat infected wounds	Animal evidence; standardized human product absent	Al-Ghanayem et al., 2022
Plant extract as synthesis agent	Metal nanoparticles (platform study)	Gold / copper / zinc oxide systems	Green nanomaterial synthesis; antimicrobial or anticancer testing	Bioactivity demonstrated for selected nanoparticles	Moringa often acts as reducing/capping agent, not payload	Qian et al., 2025; Alsamhary, 2023; Sarwar et al., 2025; Perumalsamy et al., 2024
Defined Moringa actives	**Prospective** liposomes, phytosomes, SLN/NLC, polymeric nanoparticles	Lipid or polymer carriers	Improve solubility, protection, exposure and release	Rational pharmaceutical opportunity	Must not be described as clinically established without direct studies	Perumalsamy et al., 2024

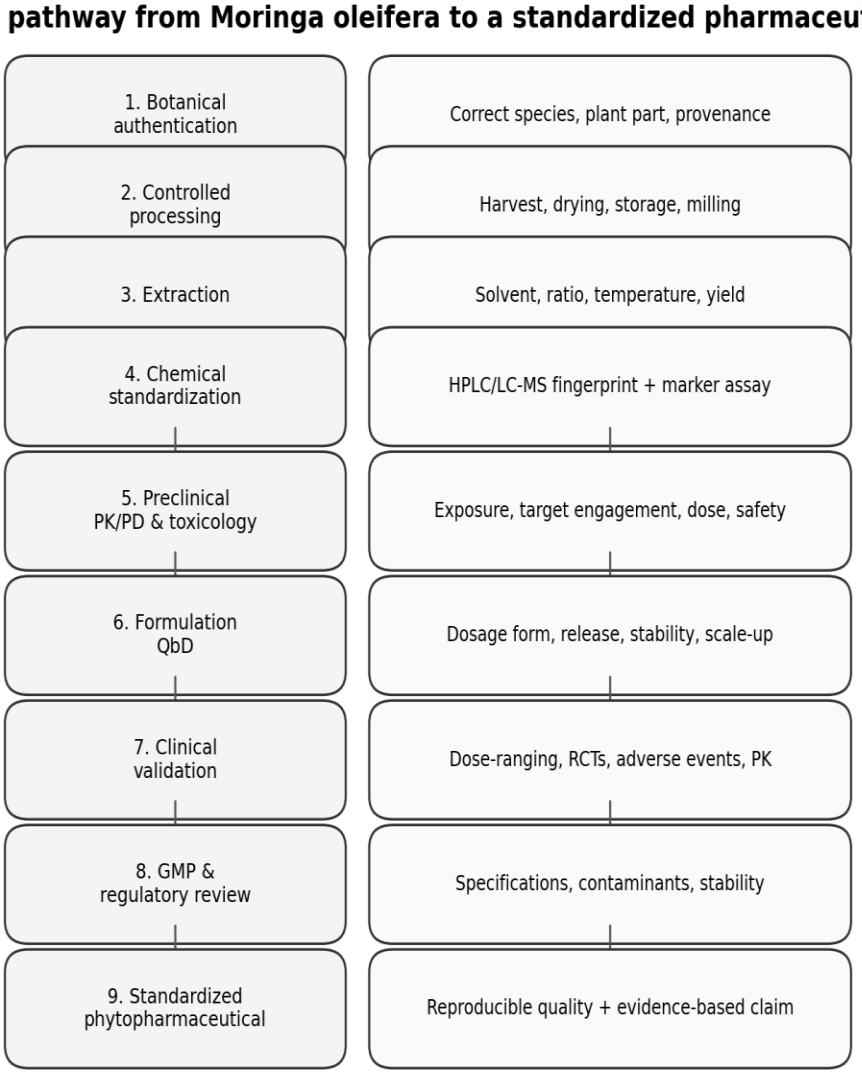


Figure 2. Original translational pathway from botanical authentication and controlled extraction to standardized formulation, clinical validation and regulatory-quality pharmaceutical products.

6. Clinical evidence and translational relevance

There is not much published evidence surrounding the use of natural products, as most of the available literature is pre-clinical. Prediabetes studies examine the role of leaf supplementation on markers of glucose metabolism, chronic inflammation, and cardiovascular health. Afiaenyi and colleagues reported on the results of a parallel-group randomized trial on the effects of the leaf on markers of glucose, blood pressure, and lipid metabolism in patients with type 2 diabetes. A 2025 unblinded randomized trial in 45 Sahrawi women taking glucose-lowering drugs reported using 10 g of leaf powder daily for 3 months of the study and reported better hemoglobin A1c levels than the control group, while a different randomized

control trial used Moringa as a supplement to metformin. A double-blind randomized trial also examined the effect of leaf powder supplementation in adult patients taking antiretroviral therapy.

These studies represent some of the first efforts to explore a potential role for Moringa leaves in the clinic. However, the studies have not provided enough evidence to support a universally accepted phytopharmaceutical indication. Most of these efforts have faced challenges including lack of large sample sizes, short study duration, varying background therapies and significant heterogeneity in the intervention (i.e. leaf powder vs. extract), etc. The resulting evidence primarily supports the need for additional controlled studies, rather than a replacement of established therapies, as polyphenol exposure in the blood is rarely correlated to pharmacokinetic results. Future studies need to consider the use of chemical standardization for the active ingredients (if available), and, if possible, may look to compensate for the challenges encountered by the original studies in this area and include longer blinded placebo-controlled studies with adequate processes for drug withdrawals and adverse effect reporting.

Table 4. Human clinical evidence for Moringa oleifera interventions relevant to pharmaceutical translation.

Clinical condition	Study design	Population	Intervention and dose	Duration	Main outcome	Safety findings	Limitations	Reference
Prediabetes	Double-blind, randomized, placebo-controlled, parallel-group trial	Adults with prediabetes (n=31 moringa and n=34 placebo)	Moringa leaf supplementation(2400mg/day); study-specific regimen	12 weeks	Glycemic-control biomarkers evaluated	No major safety signal highlighted in report	Limited duration; preparation-specific; PK not linked	Gomez-Martinez et al., 2022
Prediabetes	Ancillary analysis of the randomized,Double-blind, placebo-controlled	Subjects with prediabetes (n=31 moringa and n=34 placebo)	Leaf supplementation (2400mg/day)	12 weeks	Inflammatory and cardiometabolic markers evaluated	Monitoring reported	Small/heterogeneous evidence base	Diaz-Prieto et al., 2022
Type 2 diabetes	Parallel-group randomiz	Adults with type 2	Moringa leaf intervention	Study-specific	Blood glucose, blood pressure and lipid	Trial-level safety	Single-study context; standardization limits	Afiaenyi et al., 2025

Clinical condition	Study design	Population	Intervention and dose	Duration	Main outcome	Safety findings	Limitations	Reference
	ed clinical trial	diabetes			outcomes assessed	assessment	generalizability	
Type 2 diabetes	3-month unblinded randomized controlled trial	45 Sahrawi women on oral glucose-lowering drugs	10 g leaf powder daily plus usual therapy vs control	3 months	HbA1c improved in intervention group; fasting and anthropometric outcomes measured	No serious product-specific safety signal emphasized	Unblinded, small sample, 2:1 group sizes; single population	Leone et al., 2025
Type 2 diabetes	Randomized controlled adjunct study	Adults with type 2 diabetes	Moringa with metformin vs comparator regimen	Study-specific	Glycemic control assessed	Safety evaluated within trial	Need replication and chemical standardization	Irfan et al., 2025
Adults on antiretroviral therapy	Double-blind randomized controlled trial	Adults receiving ART	Moringa leaf powder supplementation	Study-specific	Immune/anthropometric outcomes examined	Trial monitoring	Population and nutritional context limit extrapolation to pharmaceutical indications	Gambo et al., 2021

7. Safety, toxicology and herb-drug interactions

We cannot rely on how safe something is to eat when considering safety for pharmaceuticals because food extraction will not produce pharmaceutical-strength concentrations. Human safety data are limited to the short term supplementation trails given in Table 4 .Safety for some cell-based and acute toxicity studies of leaf preparations has been assessed in these situations. However, some studies using animals have found the opposite and showed that high or repeated dosing resulted in changes to the liver or kidneys. This showcases the importance of the solvent system, the fraction studied, and the dose. (Saleem et al., 2020; Alves et al., 2024; Aliyu et al., 2021; Kambuno et al., 2024). Some studies have also shown that the leaves can cause skin toxicity (Sagrera et al., 2021) and, therefore, must be studied in detail. Roots and bark should be studied the most, as their chemistry is the furthest from the leaves that are consumed.

Though clinically validated herb-drug interaction studies are scarce, we should consider that Moringa bioactive compounds have the potential for decreasing blood glucose and blood pressure. Due to the lack of available data, we must consider that interactions may occur. Until data is studied at the product level, this interaction must be monitored. We cannot draw conclusions on CYP450 or anticoagulant interactions. The developmental phase of the drug should include essential studies such as genotoxicity, repeat dose toxicology, reproduction and reproductive toxicity, CYP and transporter studies, and interaction focused clinical pharmacology studies.

8. Standardization, quality control and regulatory considerations

Standardization starts with botanical authentication and the control of genotype, geography, harvest stage, drying, storage, and plant part. The extraction of phenolic and isothiocyanate compounds can be significantly impacted by the extraction solvent, temperature, time, and solid-to-liquid ratio. For this reason, HPLC or LC-MS fingerprints should be conducted alongside quantitative marker assays. Depending on the final product, useful markers could include quercetin or kaempferol derivatives, chlorogenic acid, the glucosinolate/isothiocyanate system, or selected seed constituents, but the marker should correlate with the biological activity of the product.

Specifications may include identity, assay, moisture, microbial limits, heavy metals, pesticides, residual solvents, stability, and batch-to-batch reproducibility. Regulatory classification might differ for foods, supplements, traditional medicines, and phytopharmaceuticals. Claims of higher therapeutic value will likely require more evidence of quality, safety, dose, and efficacy. Analytical standardization is vital to connect the known variables of farming and extraction to the unknowns of clinical efficacy and pharmacokinetics.

9. Research gaps and future directions

The main gap in research is translational integration. Future studies should include authenticated plant material, chemical profiles, a dose-response relationship, an absorption/distribution/metabolism/excretion profile, target engagement, and a clinical endpoint. It is important to study each of leaves, seeds, and purified constituents separately, as different preparations cannot be assumed to be equivalent. Long-term safety and reproductive safety, as well as herb-drug interactions should be evaluated for each individual product.

Experimentally proven exposure problems need to take precedence over the use of nanotechnology for novelty in formulation research. Quality by Design and Design of Experiments may be used to optimize process steps, excipient selection, and the identification of critical quality attributes and their relationship to scale-up. Green extraction technologies, metabolomics, pharma metabolomics, proteomics, and validated biomarkers, may be used to identify active chemical signatures. AI and/or ML may be useful in cases of multivariate extraction or optimization of the formulation, while network pharmacology and molecular modeling may be useful for prioritizing mechanisms; however, both require prospective

experimental validation. The next most important step is standardized multicenter randomized clinical trials involving pharmacokinetic studies and clinical endpoints (Peng et al., 2025; Perumalsamy et al., 2024; Fitri et al., 2025)

Table 5. Research gaps and recommended future strategies.

Current limitation	Scientific consequence	Required research	Potential pharmaceutical impact
Undefined or variable extract composition	Poor cross-study comparability and uncertain dose equivalence	Authenticated material, marker assay and LC-MS/HPLC fingerprint	Reproducible active ingredients and clinical dosing
Sparse human pharmacokinetics	Unknown systemic exposure and active metabolites	ADME, metabolomics and PK/PD studies for standardized preparations	Exposure-based dose selection
Predominantly preclinical efficacy evidence	High risk of overtranslation from cells/animals	Multicentre randomized controlled trials with clinically meaningful endpoints	Defensible therapeutic claims
Limited long-term and interaction data	Uncertain chronic safety with medicines	Repeated-dose toxicology, CYP/transporter screening and interaction trials	Safer integration with standard care
Formulation chosen without demonstrated biopharmaceutical problem	Technological complexity without clinical gain	QbD/DoE linked to solubility, stability, permeability or local-retention targets	Efficient, scalable dosage-form development
Underused systems-level analytics	Incomplete linkage between chemistry and mechanism	Metabolomics, pharmacometabolomics, network pharmacology and validated biomarkers	Mechanistically anchored standardization
Scale-up and regulatory ambiguity	Variable quality and market claims	GMP specifications, stability, contaminant control and jurisdiction-specific regulatory strategy	Transition from supplement-like products to evidence-based phytopharmaceuticals

Evidence mapping note: Camilleri & Blundell, 2024; Gao et al., 2025; Leone et al., 2025; Afiaenyi et al., 2025; Gharsallah et al., 2023; Divya et al., 2024; Mahaveerchand & Abdul Salam, 2024; Parente et al., 2025; Su et al., 2023; Fitri et al., 2025; Taher et al., 2025; Irfan et al., 2025; Rajkumar et al., 2024; Barhoi et al., 2021; Singh et al., 2023; Cretella et al., 2020; Chis et al., 2024; Bao et al., 2020; Duranti et al., 2021; Mundkar et al., 2022; Saaha et al., 2025; Yousefi Rad et al., 2025; Chen et al., 2021; Ndlovu et al., 2023; Watanabe et al., 2021; Gul et al., 2025; Nova et al., 2020; Amina et al., 2024; Owens et al., 2020; Gomez-Martinez et al., 2022; Diaz-Prieto et al., 2022; Bassogog et al., 2024; Adedapo et al., 2020; Srivastava et

al., 2024; Do et al., 2021; Xie et al., 2021; Moremane et al., 2023; Masarkar et al., 2025; Qian et al., 2025; Khan et al., 2020; Aviles-Gaxiola et al., 2024; Kumar et al., 2023; Zubair, 2020; Ventura et al., 2021; Shafie et al., 2022; Royani et al., 2023; Anzano et al., 2022; Al-Ghanayem et al., 2022; Shafiq et al., 2024; Apenteng-Takyiako et al., 2025; Menichetti et al., 2025; Worku & Tolossa, 2024; Qadi et al., 2025; Nurhayati et al., 2024; Arozal et al., 2024; David et al., 2025; Sowunmi & Gonzo, 2023; Azlan et al., 2023; Butt et al., 2024; Garg et al., 2025; Ali et al., 2022; Ahmad et al., 2020; Perumalsamy et al., 2024; Alsamhary, 2023; Sarwar et al., 2025; Hassan et al., 2021; Peng et al., 2025; Souza et al., 2024; Chatzimitakos et al., 2024; Ndou et al., 2023; Bennour et al., 2021; Wang et al., 2025; Abdelsayed et al., 2021; Chandrashekar et al., 2020; Wang et al., 2022; Nubi et al., 2021; Bezerra et al., 2023; Jikah & Edo, 2023; Panova et al., 2025; Arshad et al., 2025; Amin et al., 2024; Alves et al., 2024; Saleem et al., 2020; Aliyu et al., 2021; Kambuno et al., 2024; Sagrera et al., 2021; Gambo et al., 2021; Sakr et al., 2021; Meireles et al., 2020; Jiang et al., 2020; Sharma et al., 2025; Alissa et al., 2025; Lin et al., 2021; Kheyar et al., 2025; Wu et al., 2024; Kumar et al., 2022; Liu et al., 2023; de Barros et al., 2022; Borgonovo et al., 2020; Wolff et al., 2020

10. Conclusion

Moringa oleifera is a medicinal-food plant rich in different compounds and possesses promising pharmaceutical potential. These compounds include flavonoids, phenolic acids, thiocarbamates, carotenoids, peptides, and lipids. These compounds help provide the potential for use in multiple clinical areas such as regenerative medicine, antimicrobial, wound-healing, anti-inflammatory, and antioxidant domains. Even with these areas covered by existing findings, there is unevenness in the coverage of diseases and pathological conditions. Many of the potential uses are still in the preclinical stage while human studies are few and are often heterogeneous, and where they exist, many are lacking in systemic exposure.

The best and most likely translational pathway isn't the marketing of unprocessed Moringa. Rather, the transformation of known plant materials into standardized, bioavailable, and stable preparations is the likely and most effective pathway. Possible formulations based on existing microemulsion technology and hydrogels are possible. If stability and solubility of the formulation are problems, new delivery technologies and systems should be employed and supported by pharmacokinetics. Until validated chemical markers and quality controls are employed, coupled with pharmacokinetics, toxicology, dose-ranging studies, determination of clinical trial interactions, and properly designed, controlled clinical trials, the potential of Moringa to move from being ethnobotanically and clinically unsupported to supported practice remains potential.

ABBREVIATIONS

ADME - Absorption, distribution, metabolism and excretion

AMPK - Adenosine monophosphate-activated protein kinase

COX-2 - Cyclooxygenase-2

CYP - Cytochrome P450

GMP - Good Manufacturing Practice

GSH - Glutathione

HPLC - High-performance liquid chromatography

HO-1 - Heme oxygenase-1

IL - Interleukin

iNOS - Inducible nitric oxide synthase

LC-MS - Liquid chromatography-mass spectrometry

MAPK - Mitogen-activated protein kinase

NF-kappaB - Nuclear factor kappa B

Nrf2 - Nuclear factor erythroid 2-related factor 2

PK/PD - Pharmacokinetics/pharmacodynamics

QbD - Quality by Design

RCT - Randomized controlled trial

ROS - Reactive oxygen species

SLN/NLC - Solid lipid nanoparticles/nanostructured lipid carriers

TNF-alpha - Tumor necrosis factor alpha

REFERENCES

Abdelsayed, E. M., Medhat, D., Mandour, Y. M., Hanafi, R. S., & Abdel Motaal, A. (2021). Niazimicin: A thiocarbamate glycoside from *Moringa oleifera* Lam. seeds with a novel neuroprotective activity. *Journal of Food Biochemistry, 45*(12), e13992. https://doi.org/10.1111/jfbc.13992

Adedapo, A. A., Ogunmiluyi, I. O., Falayi, O. O., et al. (2020). The lyophilized aqueous leaf extract of *Moringa oleifera* blunts streptozocin-induced diabetes in rats through upregulation of GLUT4 signaling pathway and anti-oxidant effect. *Scientific African, 10*, e00619. https://doi.org/10.1016/j.sciaf.2020.e00619

Afiaenyi, I. C., Ngwu, E. K., Okafor, A. M., & Ayogu, R. N. (2025). 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. *Nutrition and Health, 31*(1), 281–291. https://doi.org/10.1177/02601060231176873

Ahmad, S., et al. (2020). Morphological and swelling potential evaluation of *Moringa oleifera* gum/poly(vinyl alcohol) hydrogels as a superabsorbent. *ACS Omega, 5*(29), 17955–17961. https://doi.org/10.1021/acsomega.0c01023

Al-Ghanayem, A. A., Alhussaini, M. S., Asad, M., & Joseph, B. (2022). *Moringa oleifera* leaf extract promotes healing of infected wounds in diabetic rats: Evidence of antimicrobial, antioxidant and proliferative properties. *Pharmaceuticals, 15*(5), 528. https://doi.org/10.3390/ph15050528

Ali, A., et al. (2022). An efficient wound healing hydrogel based on a hydroalcoholic extract of *Moringa oleifera* seeds. *South African Journal of Botany, 145*, 192–198. https://doi.org/10.1016/j.sajb.2021.05.003

Aliyu, A., et al. (2021). *Moringa oleifera* hydroethanolic leaf extract induced acute and sub-acute hepato-nephrotoxicity in female ICR-mice. *Science Progress, 104*. https://doi.org/10.1177/00368504211004272

Alissa, M., et al. (2025). Fraction K3 from *Moringa oleifera* exhibits gastroprotective effects through inhibitory activity against *Helicobacter pylori* and gastric acid secretion. *Chemistry & Biodiversity, 22*(10), e00580. https://doi.org/10.1002/cbdv.202500580

Alsamhary, K. E. (2023). *Moringa oleifera* seed-based green synthesis of copper nanoparticles: Characterization, environmental remediation and antimicrobial activity. *Saudi Journal of Biological Sciences, 30*(11), 103820. https://doi.org/10.1016/j.sjbs.2023.103820

Alves, R. R. V., et al. (2024). Evaluation of cytotoxicity and acute oral toxicity of saline extract and protein-rich fraction from *Moringa oleifera* Lam. leaves. *Pharmaceuticals, 17*(8), 1045. https://doi.org/10.3390/ph17081045

Amin, M. F., et al. (2024). *Moringa oleifera*: A review of the pharmacology, chemical constituents, and application for dental health. *Pharmaceuticals, 17*(1), 142. https://doi.org/10.3390/ph17010142

Amina, E., Ejike, E., Adisa, J. O., Gamde, S. M., Omoruyi, E. B., Kwaambwa, H. M., & Mwapagha, L. M. (2024). Hypoglycemic assessment of aqueous leaf extract of *Moringa oleifera* on diabetic Wistar rats. *Biochemistry Research International, 2024*, 9779021. https://doi.org/10.1155/2024/9779021

Anzano, A., et al. (2022). Chemical analysis and antimicrobial activity of *Moringa oleifera* Lam. leaves and seeds. *Molecules, 27*(24), 8920. https://doi.org/10.3390/molecules27248920

Apenteng-Takyiako, S., et al. (2025). In vitro antibacterial activity of *Moringa oleifera* leaf and seed extracts against antibiotic-resistant bacteria and clinical isolates. *BMC Complementary Medicine and Therapies, 25*, 257. https://doi.org/10.1186/s12906-025-05006-6

Arshad, M. T., Maqsood, S., Ikram, A., & Gnedeka, K. T. (2025). Recent perspectives on the pharmacological, nutraceutical, functional, and therapeutic properties of *Moringa oleifera* plant. *Food Science & Nutrition, 13*(4), e70134. https://doi.org/10.1002/fsn3.70134

Arozal, W., et al. (2024). Comparative neuroprotective effects of *Moringa oleifera* seed oil and aqueous extract on cognitive functions on a high-fat, high-fructose diet mice: Focus on senescence markers. *BioMed Research International, 2024*, 8034401. https://doi.org/10.1155/2024/8034401

Aviles-Gaxiola, S., et al. (2024). *Moringa oleifera* Lam. leaf peptides: Antioxidant and antiproliferative activity in human colon cancer Caco-2 cell line. *Antioxidants, 13*(11), 1367. https://doi.org/10.3390/antiox13111367

Azlan, U. K., et al. (2023). An insight into the neuroprotective and anti-neuroinflammatory effects and mechanisms of *Moringa oleifera*. *Frontiers in Pharmacology, 13*, 1035220. https://doi.org/10.3389/fphar.2022.1035220

Bao, Y., Xiao, J., Weng, Z., Lu, X., Shen, X., & Wang, F. (2020). A phenolic glycoside from *Moringa oleifera* Lam. improves the carbohydrate and lipid metabolisms through AMPK in db/db mice. *Food Chemistry, 311*, 125948. https://doi.org/10.1016/j.foodchem.2019.125948

Barhoi, D., Upadhaya, P., Barbhuiya, S. N., Giri, A., & Giri, S. (2021). Aqueous extract of *Moringa oleifera* exhibits potential anticancer activity and can be used as a possible cancer therapeutic agent: A study involving in vitro and in vivo approach. *Journal of the American College of Nutrition, 40*(1), 70–85. https://doi.org/10.1080/07315724.2020.1735572

Bassogog, C. B. B., et al. (2024). Protein hydrolysates of *Moringa oleifera* seed: Antioxidant and antihyperglycaemic potential as ingredient for the management of type-2 diabetes. *Heliyon, 10*(7), e28368. https://doi.org/10.1016/j.heliyon.2024.e28368

Bennour, N., et al. (2021). *Moringa oleifera* leaves: Could solvent and extraction method affect phenolic composition and bioactivities? *Preparative Biochemistry & Biotechnology, 51*(10), 1018–1025. https://doi.org/10.1080/10826068.2021.1891550

Bezerra, J. J. L., et al. (2023). Antimalarial potential of *Moringa oleifera* Lam.: Review of ethnomedicinal, pharmacological, toxicological and phytochemical evidence. *Journal of Venomous Animals and Toxins Including Tropical Diseases, 29*, e20220079. https://doi.org/10.1590/1678-9199-JVATITD-2022-0079

Borgonovo, G., et al. (2020). Moringin, a stable isothiocyanate from *Moringa oleifera*, activates the somatosensory and pain receptor TRPA1 channel in vitro. *Molecules, 25*(4), 976. https://doi.org/10.3390/molecules25040976

Butt, M. S., Malik, Z., Ghaffar, R., Baluch, A. H., Saleem, M., & Ghaffar, A. (2024). *Moringa oleifera*/chitosan-coated silk sutures for improved wound healing. *Materials Chemistry and Physics, 313*, 128737. https://doi.org/10.1016/j.matchemphys.2023.128737

Camilleri, E., & Blundell, R. (2024). A comprehensive review of the phytochemicals, health benefits, pharmacological safety and medicinal prospects of *Moringa oleifera*. *Heliyon, 10*(6), e27807. https://doi.org/10.1016/j.heliyon.2024.e27807

Chandrashekar, S., Vijayakumar, R., Chelliah, R., & Oh, D.-H. (2020). Identification and purification of potential bioactive peptide of *Moringa oleifera* seed extracts. *Plants, 9*(11), 1445. https://doi.org/10.3390/plants9111445

Chatzimitakos, T., et al. (2024). Optimization of pressurized liquid extraction parameters for extraction of bioactive compounds from *Moringa oleifera* leaves and bioactivity assessment. *International Journal of Molecular Sciences, 25*(9), 4628. https://doi.org/10.3390/ijms25094628

Chen, G., Xu, Y., et al. (2021). Anti-inflammatory properties and potential bioactive components from *Moringa oleifera* leaves revealed by affinity ultrafiltration LC-MS and molecular docking. *ACS Food Science & Technology, 1*(10), 1953–1962. https://doi.org/10.1021/acsfoodscitech.1c00275

Chis, A., Noubissi, P. A., Pop, O.-L., et al. (2024). Bioactive compounds in *Moringa oleifera*: Mechanisms of action, focus on their anti-inflammatory properties. *Plants, 13*(1), 20. https://doi.org/10.3390/plants13010020

Cretella, A. B. M., et al. (2020). Expanding the anti-inflammatory potential of *Moringa oleifera*: Topical effect of seed oil on skin inflammation and hyperproliferation. *Journal of Ethnopharmacology, 254*, 112708. https://doi.org/10.1016/j.jep.2020.112708

David, S., Dapar, M. P., & Jimam, N. S. (2025). Clinical antihypertensive efficacy and safety of *Moringa oleifera* Lam. (Moringaceae) leaf: A systematic review. *Journal of Pharmacy & Bioresources, 22*(1), 1–12. https://doi.org/10.4314/jpb.v22i1.1

de Barros, M. C., Silva, A. G. B., Souza, T. G. D. S., et al. (2022). Evaluation of acute toxicity, 28-day repeated dose toxicity, and genotoxicity of *Moringa oleifera* leaves infusion and powder. *Journal of Ethnopharmacology, 296*, 115504. https://doi.org/10.1016/j.jep.2022.115504

Diaz-Prieto, L. E., et al. (2022). Effects of *Moringa oleifera* Lam. supplementation on inflammatory and cardiometabolic markers in subjects with prediabetes. *Nutrients, 14*(9), 1937. https://doi.org/10.3390/nu14091937

Divya, S., Pandey, V. K., Dixit, R., et al. (2024). Exploring the phytochemical, pharmacological and nutritional properties of *Moringa oleifera*: A comprehensive review. *Nutrients, 16*(19), 3423. https://doi.org/10.3390/nu16193423

Do, B. H., Hoang, N. S., Nguyen, T. P. T., et al. (2021). Phenolic extraction of *Moringa oleifera* leaves induces caspase-dependent and caspase-independent apoptosis through the generation of reactive oxygen species and the activation of intrinsic mitochondrial pathway in human melanoma cells. *Nutrition and Cancer, 73*(5), 869–888. https://doi.org/10.1080/01635581.2020.1776885

Duranti, G., Maldini, M., Crognale, D., Horner, K., Dimauro, I., Sabatini, S., & Ceci, R. (2021). *Moringa oleifera* leaf extract upregulates Nrf2/HO-1 expression and ameliorates redox status in C2C12 skeletal muscle cells. *Molecules, 26*(16), 5041. https://doi.org/10.3390/molecules26165041

Fitri, Z. A., et al. (2025). A systematic review of extraction methods, phytochemicals, and food applications of *Moringa oleifera* leaves using PRISMA methodology. *Food Science & Nutrition, 13*, e70138. https://doi.org/10.1002/fsn3.70138

Gambo, A., Moodley, I., Babashani, M., Babalola, T. K., & Gqaleni, N. (2021). A double-blind, randomized controlled trial to examine the effect of *Moringa oleifera* leaf powder supplementation on the immune status and anthropometric parameters of adult HIV patients on antiretroviral therapy in a resource-limited setting. *PLOS ONE, 16*(12), e0261935. https://doi.org/10.1371/journal.pone.0261935

Gao, Q., et al. (2025). Polyphenols in different parts of *Moringa oleifera* Lam.: Composition, antioxidant and neuroprotective potential. *Food Chemistry, 475*, 143207. https://doi.org/10.1016/j.foodchem.2025.143207

Garg, P., et al. (2025). Exploring the potential of *Moringa oleifera* seed extract-loaded microemulsion hydrogel in the DNCB-induced atopic dermatitis model. *Inflammopharmacology, 33*(8), 4841–4858. https://doi.org/10.1007/s10787-025-01740-y

Gharsallah, K., et al. (2023). *Moringa oleifera*: Processing, phytochemical composition, and industrial applications. *South African Journal of Botany, 160*, 180–193. https://doi.org/10.1016/j.sajb.2023.07.008

Gomez-Martinez, S., et al. (2022). *Moringa oleifera* leaf supplementation as a glycemic control strategy in subjects with prediabetes. *Nutrients, 14*(1), 57. https://doi.org/10.3390/nu14010057

Gul, P., Khan, J., Li, Q., & Liu, K. (2025). *Moringa oleifera* in a modern time: A comprehensive review of its nutritional and bioactive composition as a natural solution for managing diabetes mellitus by reducing oxidative stress and inflammation. *Food Research International, 201*, 115671. https://doi.org/10.1016/j.foodres.2025.115671

Hassan, M. A., et al. (2021). Health benefits and phenolic compounds of *Moringa oleifera* leaves: A comprehensive review. *Phytomedicine, 93*, 153771. https://doi.org/10.1016/j.phymed.2021.153771

Irfan, A., et al. (2025). Synergistic effects of *Moringa oleifera* with metformin in improving glycemic control in type 2 diabetics through a randomised controlled trial. *Journal of Herbal Medicine, 52*, 101029. https://doi.org/10.1016/j.hermed.2025.101029

Jiang, M.-Y., Lu, H., Pu, X.-Y., & Huang, X.-Z. (2020). Laxative metabolites from the leaves of *Moringa oleifera*. *Journal of Agricultural and Food Chemistry, 68*(30), 7850–7860. https://doi.org/10.1021/acs.jafc.0c01564

Jikah, A. N., & Edo, G. I. (2023). *Moringa oleifera*: A valuable insight into recent advances in medicinal uses and pharmacological activities. *Journal of the Science of Food and Agriculture, 104*. https://doi.org/10.1002/jsfa.12892

Kambuno, N. T., et al. (2024). In vivo toxicity study in Sprague-Dawley rats receiving different doses of *Moringa oleifera* extract. *Open Veterinary Journal, 14*(9), 2294–2309. https://doi.org/10.5455/OVJ.2024.v14.i9.18

Khan, F., et al. (2020). *Moringa oleifera* methanolic leaves extract induces apoptosis and G0/G1 cell cycle arrest via downregulation of Hedgehog signaling pathway in human prostate PC-3 cancer cells. *Journal of Food Biochemistry, 44*, e13338. https://doi.org/10.1111/jfbc.13338

Kheyar, F., Kheyar, N., Amiali, M., Boulekbache-Makhlouf, L., Kadi, A., Benchabane, A., & Bitam, A. (2025). Impacts of microwave-assisted extraction parameters on total phenolic compounds yield from Algerian *Moringa oleifera* leaves, using response surface methodology. *Natural Product Research, 39*(14), 4126–4134. https://doi.org/10.1080/14786419.2024.2333044

Kumar, M., Selvasekaran, P., Kapoor, S., Barbhai, M., et al. (2022). *Moringa oleifera* Lam. seed proteins: Extraction, preparation of protein hydrolysates, bioactivities, functional food properties, and industrial application. *Food Hydrocolloids, 131*, 107791. https://doi.org/10.1016/j.foodhyd.2022.107791

Kumar, S., et al. (2023). *Moringa oleifera* L. leaf extract induces cell cycle arrest and mitochondrial apoptosis in Dalton's lymphoma. *Journal of Ethnopharmacology, 302*, 115849. https://doi.org/10.1016/j.jep.2022.115849

Leone, A., Di Lello, S., Bertoli, S., et al. (2025). *Moringa oleifera* leaf powder enhances glycemic control in Sahrawi women with type 2 diabetes: Findings from a 3-month unblinded randomized controlled trial. *PharmaNutrition, 31*, 100434. https://doi.org/10.1016/j.phanu.2025.100434

Lin, X., Wu, L., Wang, X., Yao, L., et al. (2021). Ultrasonic-assisted extraction for flavonoid compounds content and antioxidant activities of India *Moringa oleifera* L. leaves: Simultaneous optimization, HPLC characterization and comparison with other methods. *Journal of Applied Research on Medicinal and Aromatic Plants, 20*, 100284. https://doi.org/10.1016/j.jarmap.2020.100284

Liu, W., Wei, G., He, R., et al. (2023). Health-promoting activities of *Moringa oleifera* Lam. seeds protein hydrolysates and its ultra-filtered peptide fractions. *Food Chemistry Advances, 2*, 100324. https://doi.org/10.1016/j.focha.2023.100324

Mahaveerchand, H., & Abdul Salam, A. A. (2024). Environmental, industrial, and health benefits of *Moringa oleifera*. *Phytochemistry Reviews, 23*, 1497–1556. https://doi.org/10.1007/s11101-024-09927-x

Masarkar, N., et al. (2025). In-silico screening of bioactive compounds of *Moringa oleifera* as potential inhibitors targeting HIF-1alpha/VEGF/GLUT-1 pathway against breast cancer. *Journal of Complementary and Integrative Medicine, 22*(1), 149–164. https://doi.org/10.1515/jcim-2024-0176

Meireles, D., Gomes, J., Lopes, L., Hinzmann, M., & Machado, J. (2020). A review of properties, nutritional and pharmaceutical applications of *Moringa oleifera*: Integrative approach on conventional and traditional Asian medicine. *Advances in Traditional Medicine, 20*(4), 495–515. https://doi.org/10.1007/s13596-020-00468-0

Menichetti, F., et al. (2025). *Moringa oleifera* and blood pressure: Evidence and potential mechanisms. *Nutrients, 17*(7), 1258. https://doi.org/10.3390/nu17071258

Moremane, M. M., et al. (2023). *Moringa oleifera*: A review on the antiproliferative potential in breast cancer cells. *Current Issues in Molecular Biology, 45*(8), 6880–6902. https://doi.org/10.3390/cimb45080434

Mundkar, M., Bijalwan, A., Soni, D., & Kumar, P. (2022). Neuroprotective potential of *Moringa oleifera* mediated by NF-kB/Nrf2/HO-1 signaling pathway: A review. *Journal of Food Biochemistry, 46*(12), e14451. https://doi.org/10.1111/jfbc.14451

Ndou, D. L., et al. (2023). A relook into the flavonoid chemical space of *Moringa oleifera* Lam. leaves through a combination of LC-MS and molecular networking. *Journal of Analytical Methods in Chemistry, 2023*, 1327886. https://doi.org/10.1155/2023/1327886

Ndlovu, S. S., et al. (2023). *Moringa oleifera* Lam. leaf extract stimulates NRF2 and attenuates ARV-induced toxicity in human liver cells (HepG2). *Plants, 12*(7), 1541. https://doi.org/10.3390/plants12071541

Nova, E., et al. (2020). Potential of *Moringa oleifera* to improve glucose control for the prevention of diabetes and related metabolic alterations. *Nutrients, 12*(7), 2050. https://doi.org/10.3390/nu12072050

Nubi, T., et al. (2021). Purification and erythrocyte-membrane perturbing activity of a ketose-specific lectin from *Moringa oleifera* seeds. *Biotechnology Reports, 31*, e00650. https://doi.org/10.1016/j.btre.2021.e00650

Nurhayati, T., et al. (2024). Effects of *Moringa oleifera* leaf extract on liver histopathology: A systematic review. *Journal of Nutrition and Metabolism, 2024*, 6815993. https://doi.org/10.1155/2024/6815993

Owens, F. S., III, Dada, O., Cyrus, J. W., Adedoyin, O. O., & Adunlin, G. (2020). The effects of *Moringa oleifera* on blood glucose levels: A scoping review of the literature. *Complementary Therapies in Medicine, 50*, 102362. https://doi.org/10.1016/j.ctim.2020.102362

Panova, N., Gerasimova, A., Gentscheva, G., et al. (2025). *Moringa oleifera* Lam.: A nutritional powerhouse with multifaceted pharmacological and functional applications. *Life, 15*(6), 881. https://doi.org/10.3390/life15060881

Parente, T. S. J. D. S., et al. (2025). Effect of *Moringa oleifera* on inflammatory diseases: An umbrella review of 26 systematic reviews. *Frontiers in Pharmacology, 16*, 1572337. https://doi.org/10.3389/fphar.2025.1572337

Peng, W., et al. (2025). Efficient polyphenol extraction from *Moringa oleifera* Lam. leaves using natural deep eutectic solvents: COSMO-RS screening, ANN-GA optimization and antioxidant activity evaluation. *LWT, 223*, 117687. https://doi.org/10.1016/j.lwt.2025.117687

Perumalsamy, H., et al. (2024). A comprehensive review on *Moringa oleifera* nanoparticles: Importance of polyphenols in nanoparticle synthesis, nanoparticle efficacy and their applications. *Journal of Nanobiotechnology, 22*, 71. https://doi.org/10.1186/s12951-024-02332-8

Qadi, W. S. M., et al. (2025). An insight review on the potential anti-hypertensive effects of *Moringa oleifera*. *Biomedicine & Pharmacotherapy, 191*, 118500. https://doi.org/10.1016/j.biopha.2025.118500

Qian, D., et al. (2025). *Moringa oleifera*-mediated green synthesis of gold nanoparticles and their anti-cancer activity against A549 cells. *Frontiers in Chemistry, 13*, 1521089. https://doi.org/10.3389/fchem.2025.1521089

Rajkumar, C., et al. (2024). Anticancer effect of *Moringa oleifera* in oral squamous cell carcinoma: A systematic review. *Discover Oncology, 15*, 688. https://doi.org/10.1007/s12672-024-01557-1

Royani, A., et al. (2023). Analysis of the antibacterial activity and the total phenolic and flavonoid contents of the *Moringa oleifera* leaf extract as an antimicrobial agent against *Pseudomonas aeruginosa*. *Scientifica, 2023*, 5782063. https://doi.org/10.1155/2023/5782063

Saaha, S., Sawatdichaikul, O., & Pantoa, T. (2025). Antioxidant, anti-inflammatory and cytoprotective potential of enzymatic protein hydrolysate from *Moringa oleifera* Lam. leaves in lipopolysaccharide-stimulated RAW 264.7 macrophages. *Cogent Food & Agriculture, 11*(1), 2591288. https://doi.org/10.1080/23311932.2025.2591288

Sagrera, A., et al. (2021). Cutaneous toxicity due to *Moringa oleifera*. *Actas Dermo-Sifiliograficas (English Edition), 112*(10), 953–954. https://doi.org/10.1016/j.adengl.2021.09.008

Sakr, S., et al. (2021). The ameliorative effect of *Moringa oleifera* oil on tributyltin-induced brain toxicity in albino rats. *Environmental Toxicology, 36*(10), 2025–2039. https://doi.org/10.1002/tox.23320

Saleem, A., et al. (2020). HPLC analysis, cytotoxicity, and safety study of *Moringa oleifera* Lam. (wild type) leaf extract. *Journal of Food Biochemistry, 44*(10), e13400. https://doi.org/10.1111/jfbc.13400

Sarwar, K., et al. (2025). Biosynthesis of zinc oxide nanoparticles using *Moringa oleifera* leaf extract, probing antibacterial and antioxidant activities. *Scientific Reports, 15*, 20413. https://doi.org/10.1038/s41598-025-08839-w

Shafiq, N. E., Mahdee, A. F., & Mohammed Hasan, Z. Y. (2024). Leaf extracts of *Moringa oleifera* cultivated in Baghdad: Characterization and antimicrobial potential against endodontic pathogens. *The Scientific World Journal, 2024*, 6658164. https://doi.org/10.1155/2024/6658164

Shafie, N. M., et al. (2022). Scoping review: Evaluation of *Moringa oleifera* (Lam.) for potential wound healing in in vivo studies. *Molecules, 27*(17), 5541. https://doi.org/10.3390/molecules27175541

Sharma, V., Mahajan, G., & Gupta, R. (2025). Nutritional content and renoprotective potential of miracle tree (*Moringa oleifera*). *BioTechnologia, 106*(2), 223–239. https://doi.org/10.5114/bta/204529

Singh, S., Dubey, S., & Rana, N. (2023). Phytochemistry and pharmacological profile of drumstick tree *Moringa oleifera* Lam.: An overview. *Current Nutrition & Food Science, 19*(5), 529–548. https://doi.org/10.2174/1573401319666221226144613

Sowunmi, B. O., & Gonzo, M. (2023). The effect of *Moringa oleifera* crude extract on liver cell line, HepG2. *BMC Complementary Medicine and Therapies, 23*, 380. https://doi.org/10.1186/s12906-023-04181-8

Souza, D. E. S., et al. (2024). Microwave-assisted vs. conventional extraction of *Moringa oleifera* seed oil: Process optimization and efficiency comparison. *Foods, 13*(19), 3141. https://doi.org/10.3390/foods13193141

Srivastava, A., et al. (2024). Moringin, an isothiocyanate modulates multiple cellular signalling molecules in breast cancer cells. *Cellular Signalling, 119*, 111181. https://doi.org/10.1016/j.cellsig.2024.111181

Su, X., et al. (2023). *Moringa oleifera* Lam.: A comprehensive review on active components, health benefits and application. *RSC Advances, 13*, 24353–24384. https://doi.org/10.1039/D3RA03584K

Taher, M. A., Islam, M. A., Tasmi, S. F., et al. (2025). Phytochemical profiling and bioactivity validation of *Moringa oleifera* leaves: Antimicrobial, antidiarrheal, analgesic, and in silico insights. *PLOS ONE, 20*(9), e0332048. https://doi.org/10.1371/journal.pone.0332048

Ventura, A. C. S. S. B., de Paula, T., Gonçalves, J. P., et al. (2021). The oil from *Moringa oleifera* seeds accelerates chronic skin wound healing. *Phytomedicine Plus, 1*(3), 100099. https://doi.org/10.1016/j.phyplu.2021.100099

Wang, J., Yang, S., et al. (2025). Biological activities of glucosinolate and its enzymatic product in *Moringa oleifera* (Lam.). *International Journal of Molecular Sciences, 26*(15), 7323. https://doi.org/10.3390/ijms26157323

Wang, X., Fan, Y., Xu, F., Xie, J., Gao, X., Li, L., Tian, Y., & Sheng, J. (2022). Characterization of the structure, stability, and activity of hypoglycemic peptides from *Moringa oleifera* seed protein hydrolysates. *Food & Function, 13*(6), 3481–3494. https://doi.org/10.1039/D1FO03413H

Watanabe, S., Okoshi, H., Yamabe, S., & Shimada, M. (2021). *Moringa oleifera* Lam. in diabetes mellitus: A systematic review and meta-analysis. *Molecules, 26*(12), 3513. https://doi.org/10.3390/molecules26123513

Wolff, K., Jaja-Chimedza, A., Kim, Y., Waterman, C., Poulev, A., Raskin, I., & Ribnicky, D. (2020). Moringa isothiocyanate-1 is bioaccessible and bioavailable as a stable unmodified compound. *Phytochemistry Letters, 38*, 33–38. https://doi.org/10.1016/j.phytol.2020.

Worku, B., & Tolossa, N. (2024). A review on the neuroprotective effect of *Moringa oleifera*. *Oxidative Medicine and Cellular Longevity, 2024*, 7694516. https://doi.org/10.1155/2024/7694516

Wu, Q., Zhou, H.-J., Sheng, J., Su, L.-Y., & Tian, Y. (2024). Extraction, structural properties, and bioactivities of *Moringa* (*Moringa oleifera* Lam.) isothiocyanates: A review. *Food Bioscience, 57*, 103447. https://doi.org/10.1016/j.fbio.2023.103447

Xie, J., et al. (2021). Alkaloid extract of *Moringa oleifera* Lam. exerts antitumor activity in human non-small-cell lung cancer via modulation of JAK2/STAT3. *BioMed Research International, 2021*, 5591687. https://doi.org/10.1155/2021/5591687

Yousefi Rad, A., et al. (2025). *Moringa oleifera* and its biochemical compounds: Potential multi-targeted therapeutic agents against COVID-19 and associated cancer progression. *Biochemical Genetics, 63*(2), 936–959. https://doi.org/10.1007/s10528-024-10758-w

Zubair, M. (2020). Antimicrobial and anti-biofilm activities of *Citrus sinensis* and *Moringa oleifera* against *Pseudomonas aeruginosa* and *Staphylococcus aureus*. *Cureus, 12*(12), e12337. https://doi.org/10.7759/cureus.12337