REVIEW ARTICLE Asian Journal of Dairy and Food Research, Volume 44 Issue 5: 721-730 (October 2025)

Moringa oleifera: Nutritional Supplementation, Phyto-Pharmaceutical Frontiers and Navigating Musculoskeletal Health: A Review

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10.18805/ajdfr.DR-2329

ABSTRACT

Moringa oleifera (MOL), a significant arboreal species, has long held a revered position in traditional ethno medicine due to its distinguished medicinal properties. This plant has been extensively studied for its therapeutic benefits, demonstrating effectiveness in pain relief, inflammation, fever management, cancer prevention, antioxidant activity, cognitive support, liver and stomach protection, obesity, asthma, diabetes and prevention of urinary stone formation. This comprehensive review, amalgamating scientific inquiry and meticulous documentation, constitutes an exhaustive compendium of MOL's phytochemical composition, pharmacological activities and its traditional and modern therapeutic applications. Extracts from Moringa leaves show promise in muscle recovery and exhibit antioxidant, anticancer, anti-inflammatory and neuroprotective properties, primarily owing to their high flavonoid and isoquercetin content, suggesting potential in addressing musculoskeletal disorders. Recognized for managing various disorders, including musculoskeletal issues, MOL's neurotropic and neuroprotective effects support neuronal growth and survival. By elucidating its phytochemical constituents, mechanisms of action, historical and contemporary utilization, this review aims to provide a comprehensive understanding of MOL's potential across health and medicine. It serves as a definitive resource for scholars, researchers and medical practitioners, offering insights into the plant's bioactive compounds and their therapeutic implications, fostering a nuanced approach to leveraging MOL's therapeutic potential in modern healthcare.

Key words: Diabetes, Evaluation, *Moringa oleifera*, Pharmacological, Phytochemical.

Moringa oleifera, a member of the Moringaceae family, is recognized for its nutritional benefits in addressing malnutrition. Its leaves, pods and seeds are rich in essential phytochemicals, contributing to its high nutrient density (Ravani *et al.,* 2017). Its exceptional nutrient profile underscores its potential as a sustainable dietary intervention for improving nutritional status and health. Moringa contains significantly higher levels of key nutrients compared to common dietary sources, including vitamin C (7 times higher than oranges), vitamin A (10 times higher than carrots), calcium (17 times higher than milk), protein (9 times higher than yogurt), potassium (15 times higher than bananas) and iron (25 times higher than spinach) (Gopalakrishnan *et al.*, 2016). A significant proportion of the population in numerous emerging nations depends on conventional healers and their knowledge of medicinal flora to address their healthcare needs. While contemporary pharmaceuticals may coexist with these traditional practices, herbal remedies persist in their popularity due to historical and cultural factors. These products have gained increased commercial availability, particularly in developed nations (Al-Asmari *et al*., 2015). Within the extensive spectrum of Moringa cultivars, which includes the following species are: *M. arborea, M. rivae, M. longituba, M. stenopetala, M. concanensis, M. pygmaea, M. borziana, M. ruspoliana, M. drouhardii, M. hildebrandtii, M. ovalifolia* and *M. peregrine* plant's historical significance remains noteworthy, MOL stands out as a noteworthy subject of investigation. The demand for food supplements is on a

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How to cite this article: Manoharan, K., Gopakumar, G., Shriraam, V., Joseph, A. and Sameer, M. (2025). *Moringa oleifera*: Nutritional Supplementation, Phyto-Pharmaceutical Frontiers and Navigating Musculoskeletal Health: A Review. *Asian Journal of Dairy and Food Research*. **44(5):** 721-730. doi: 10.18805/ajdfr.DR-2329.

Submitted: 10-03-2025 **Accepted:** 24-07-2025 **Online:** 14-08-2025

continual upward trajectory, particularly in the realm of immunity-boosting products, an area in which moringa finds its niche. Among the European nations, those in Western Europe, such as Germany, the UK, France, the Netherlands, Italy and Spain, stand out as the most promising prospects for moringa. These countries boast sizable food supplement markets and possess relatively high levels of awareness regarding moringa. Furthermore, it has been intentionally cultivated and has become acclimated to various regions globally, including Afghanistan, Nepal, Bangladesh, Sri Lanka, in addition to regions spanning South and Central America, the West Indies, the Philippines and Cambodia (Singh, 2017; Paliwal *et al.,* 2011). Traditional cuisine from various regions incorporates these tender young plants, fully grown leaflets and flowers in the preparation of soups and sauces. In the historical context, the Ancient Egyptians held MOL oil in high esteem, particularly for its cosmetic applications attributes and skin-related preparations (Anwar and Rashid, 2007). Although not widely adopted by the Greeks and Romans, historical records indicate their recognition for its medicinal properties (Ferreira *et al.,* 2008).

Furthermore, it has proven instrumental in cultivating strategies for environmentally conscious agricultural frameworks, thereby constituting a linchpin in the nexus of research and innovation (Kidmose *et al.,* 2006). The extensive research and the endeavor to commercialize the drumstick tree and its associated products have underscored the pressing need for its preservation. This imperative arises from various standpoints, encompassing dietary, pharmacological, ethnobotanical and biotechnological considerations (Ahmed *et al.,* 2019). Numerous exhaustive pharmacological inquiries have incontrovertibly substantiated its extraordinary prowess in manifesting diverse therapeutic characteristics, encompassing, though not confining itself solely to, analgesic, anti-inflammatory, antipyretic, anti-cancer, antioxidative, nootropic, hepatoprotective, gastroprotective, anti-ulcerogenic, cardiovascular, anti-obesity, antiepileptic, antiasthmatic, antidiabetic, anti-urolithiatic, diuretic, local anesthetic, anti-allergic, anthelmintic, wound-healing, antimicrobial, immunomodulatory and antidiarrheal attributes (Hamza and Azmach, 2017). Moringa seeds have garnered recognition for their commendable therapeutic efficacy in the amelioration of a spectrum of medical conditions, encompassing hyperthyroidism, Crohn's disease, herpes simplex virus infection, arthritis, rheumatism, gout, muscular cramps, epilepsy and maladies of a sexually transmitted nature (Bhattacharya *et al.,* 2018).

MOL is traditionally recognized for its potential in addressing various disorders, to its neurotropic and neuroprotective effects, which promote the growth and survival of neurons. Additionally, recent studies have emphasized its significant role in alleviating musculoskeletal discomfort by reducing inflammation, improving joint flexibility and promoting bone regeneration (Esakkimuthu *et al.,* 2021). These effects are primarily attributed to bioactive compounds such as quercetin, isothiocyanates and calcium, which collectively modulate inflammatory pathways and enhance skeletal strength. This review attempts to thoroughly examine MOL's phytochemical profile, pharmacological actions and traditional uses in order to provide a stronger scientific foundation for its role in promoting musculoskeletal health.

The primary data sources for this review were from published literature that was gathered over a four-month period from a variety of databases, including PubMed, Web of Science, Scopus, Google Scholar and botanical references from various nations. A total of 209 studies were acquired through various search engines and subsequently, 52 articles meeting specific criteria were chosen for inclusion in this review. This review exclusively encompasses articles published in English-language journals that provide a substantial amount of ethnomedicinal information. During the screening phase, articles characterized by indistinct or equivocal information, as well as publications originating from diverse geographical regions in local vernaculars, were intentionally omitted, as delineated (Fig 1). During the course of data retrieval, an array of semantically pertinent terminological elements, including, but not limited to, "ethnomedicinal connotations", "ancestral medicinal attributes", "nutritional adjuncts", "nutritional entities", "phytochemical constitution" and "pharmacodynamical manifestations", were judiciously enlisted. In circumstances where exigencies arose concerning the attainment of an all-encompassing corpus of research data, concerted efforts were made to establish electronic correspondence with the principal authors and co-authors of said scholarly works, primarily utilizing electronic mail as well as the Research Gate platform as vehicles for communication. The collected data was categorized into various subsections (Phytoconstituents/ Phytochemistry, Taxonomy, Traditional Use, Nutritional Benefits, MOL as Nutritional Supplements, MOL as Nutritional Supplements marketed products, Pharmacological activity, Phyto pharmaceutical formulations, Moreinga in musculo skeletal disorders.

Taxonomy

MOL is classified within the following divisions

Within the taxonomy of the plant kingdom, the classification hierarchy includes the following levels: The taxonomic classification of the organism is as follows: Kingdom Plantae, Division Magnoliophyta, Class Magnoliopsida, Order Brassicales and Family Moringaceae. The plant MOL is recognized by various names across the globe. In Latin, it is known as MOL, while in Sanskrit, it goes by the name Subhanjana. In Hindi, it is referred to as Saguna and Sainjna and in Gujarati, it is called Suragavo. The Tamil language designates it as Mulaga or Murungai and in Malayalam, it is known as Murinna or Sigru. Similarly, in Punjabi, it assumes the names Sainjna and Soanjna and

in Unani, it is recognized as Sahajan. This array of names reflects the diverse linguistic and cultural backgrounds that have embraced and named this remarkable plant (Mallenakuppe *et al.,* 2015; Ganga *et al.,* 2019).

Traditional use

MOL finds applications in both human and animal nutrition, as well as within the realm of traditional medicine. Its leaves have substantial quantities of protein, essential minerals, beta-carotene and potent antioxidant compoun. In the context of traditional medicine, these leaves have been employed to address a spectrum of health issues, encompassing conditions such as swelling, parasitic diseases, typhoid fever, cuts, arthritis, malaria, skin ailments, genitourinary disorders, hypertension and diabetes (Popoola and Obembe, 2013). Leaves represent a valuable source of Protein, minerals, beta-carotene and a variety of antioxidant substances, Nutrients frequently found to be lacking in the populace of less developed or developing nations. MOL leaves possess incorporated into culinary preparations to supplement dietary requirements. In the realm of traditional medicine, these leaves find application in the treatment of various conditions, this range of applications encompasses the management of diverse conditions such as malaria, typhoid fever, parasitic infections, arthritis, edemas, dermatological disorders, genitourinary complications, hypertension and diabetes. Furthermore, these substances are harnessed to induce lactation and bolster the immune system particularly in addressing symptoms associated with HIV/AIDS (Judith *et al.,* 2019). The utilization of Moringa seeds holds significance in both human nutrition and traditional medicinal practices. The bark is subjected to boiling and alcohol soaking to create beverages and infusions used for alleviating stomach discomfort, ulcers, aiding digestion, enhancing visual health, mitigating joint pain and addressing conditions like diabetes, anemia and hypertension (Oyeleye *et al.,* 2023). Roots are similarly processed through soaking and boiling, often in combination with other herbal components, to produce infusions and drinks. These are utilized as remedies for toothaches, anthelmintics and antiparalytics. The decoction finds application as a gargling agent in the management of Symptoms characterized by Hoarseness and inflammation of the throat. The root and fruit have antiparalytic effects. The juice extracted from the leaves is employed to alleviate hiccough with emetic effects observed at Symptoms characterized by hoarseness and a sore throat administered in cases of Influenza and catarrhal illnesses. The root bark functions as an agent possessing antiviral and anti-inflammatory properties and analgesic properties. The hypoglycemic properties of the stem-bark and flowers are well-documented and acknowledged. An infusion of the seeds displays anti-inflammatory, antispas modic

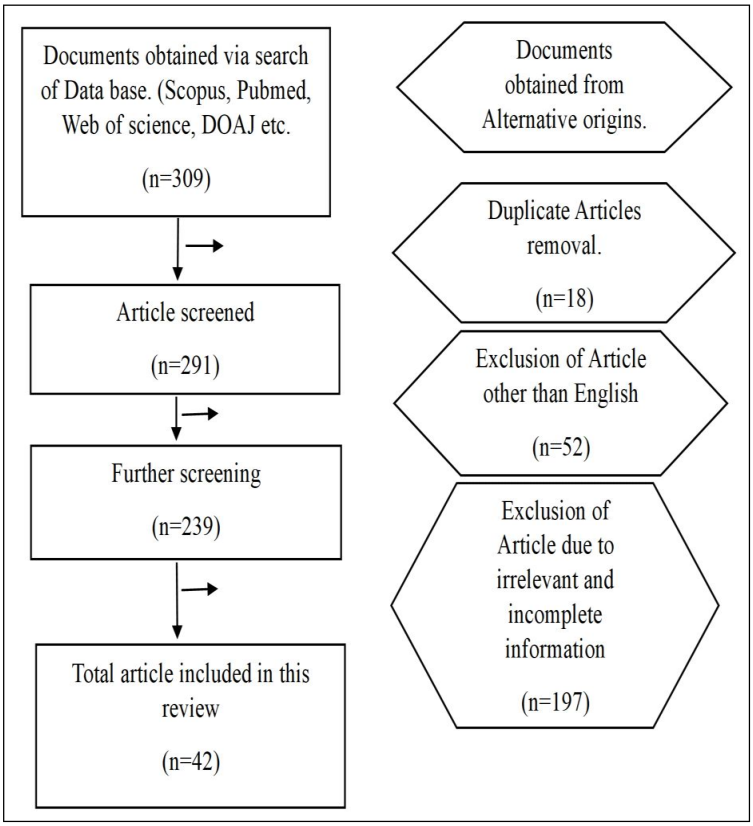


Fig 1: Flow diagram a schematic illustration delineating the principal stages within the comprehensive review procedure.

and diuretic attributes and is also administered in the context of venereal diseases. These therapeutic applications, in conjunction with others, underscore the diverse uses of this plant (Mishra *et al.,* 2011).

Moringa oleifera as nutritional supplements

Moringa and spirulina are known for their exceptional nutritional density, derived from rich natural biological resources and offer substantial health benefits. Early studies have shown that their nutritional profiles complement each other. When combined in specific proportions to form complex tablets, they provide a more comprehensive and well-balanced range of nutrients. The formulation of these nutritional tablets, integrating *Moringa oleifera* and spirulina, is not only cost-effective but also highly suitable for widespread adoption. These two valuable biological resources contribute significantly to human well-being (Ashoush and Mahdy, 2019).

A recommended daily dosage of 6-8 grams of these nutritional supplements in tablet form, containing a blend of moringa and spirulina, offers superior benefits compared to individual spirulina tablets or *Moringa oleifera* leaf sheets. This combination enhances overall nutrient intake and promotes better well-being with a more balanced nutritional profile (Zheng *et al.,* 2017).

Fortifying nutritional supplement with MOL leaves enhances its value, as these leaves are packed with essential nutrients, including vitamins B and C, alpha-tocopherol, essential amino acids and key minerals like iron, calcium, phosphorus and copper. They also contain beneficial nitrates and sulfur compounds. Incorporating MOL leaves into the diet offers a natural and effective approach to supporting maternal nutrition. The development of a MOL based bio-fortified food supplement represents a commendable approach to addressing malnutrition in both pregnant women and children, particularly in developing nations (Salem *et al.,* 2013). Furthermore, it is imperative to note that leaves are harnessed in the culinary domain for salad confection in conjunction with leguminous seeds and are also incorporated into the formulation of herbal infusions, porridge preparations and as components of complementary nourishment for infants, while additionally serving as a culinary condiment and garnish. These leafy greens can be enjoyed raw, offering a nutritious and satisfying snack. Their fresh, natural state enhances both flavour and nutritional benefits, making them a great addition to a healthy diet. Tender and mature pods yield seeds that are commonly utilized in pickling, as highlighted. The seeds of green pods are traditionally ingested in a parboiled state, whereas those of mature pods undergo a process of roasting or frying prior to their consumption, bestowing upon them a gustatory profile redolent of the leguminous character akin to that of peanuts (Zungu *et al.,* 2020; *Coello et al.,* 2022). Dried formulations in the form of soup powders are esteemed for their capacity to mitigate enzymatic and oxidative degradation, concurrently upholding the organoleptic integrity of the comestible over protracted periods when stored at ambient conditions (Ansari *et al.,* 2020). In light of these substantial nutritional benefits offered by MOL, its seeds, leaves and bark have found utility in the formulation of a diverse range of consumables, including salads, juices, soups and medicinal products (Mbusa, 2023). The soy-mushroom-moringa soup powder stands out as the preferred option among locally available soup powders due to its remarkably low moisture content, granting it an extended shelf life. From a microbiological perspective, this soup powder remains safe for consumption for a duration of up to six months. The soup in question exhibits a distinctive profile marked by its elevated concentration of protein, ash, fiber, as well as a complement of indispensable vitamins and minerals, encompassing vitamin D, vitamin C, sodium, potassium, manganese, zinc and iron. Additionally, it maintains a low fat and energy profile. The amalgamation of these salient characteristics collectively substantiates the contemporaneously formulated powdered amalgamation of soy, mushroom and moringa for the fulfilment of the nutritional requisites inherent to the nation, rendering it an exemplary choice (Farzana *et al.,* 2017; Mohajan *et al.,* 2018). The inclusion of extracts from moringa leaves and soybeans is anticipated to augment the nutritional content of biscuits. The Moringa Protein Concentrate (MPC) derived from moringa leaves exhibits superior nutritional quality in comparison to milk protein, demonstrating both quantitative and qualitative advantages. The quality attributes of MPC biscuits are as follows: the concentrate contains a protein content of 60.48%, while the biscuits themselves possess a protein content of 7.11%. Furthermore, the protein digestibility stands at an impressive 80.45% and the Protein Efficiency Ratio (PER) is elevated to 2,291. Moringa leaf protein concentrate emerges as a compelling option for substituting milk components in biscuits designed for young children suffering from Protein Energy Malnutrition (PEM) (Lestari *et al.,* 2024; Aderinola *et al.,* 2020). Fig 2 shows the various food product incorporate with moringa (Milla *et al.*, 2021).

Phyto-pharmaceutical formulations

A micro-dispersion containing moringa oil was developed using a vortexing technique with Span 80 and Tween 80 and was assessed for its anti-inflammatory effects. The results indicated that the micro-dispersion facilitated better permeation than pure oil, with Tween 80 playing a key role in improving absorption. Separately, polyherbal formulations derived from leaves were investigated for their anti-ulcer potential. Using ethyl acetate in a carboxymethyl cellulose-based suspension resulted in highly effective anti-ulcer activity (Devaraj and Krishna, 2013).

Lozenges containing ethanolic extracts of moringa leaves were produced *via* the wet granulation method, incorporating polyvinyl-pyrrolidone, magnesium stearate, menthol and vanillin. These lozenges were evaluated for antimicrobial efficacy and consumer acceptance, with findings suggesting that flavoring agents significantly

enhanced palatability. Additionally, due to the low solubility of quercetin in aqueous mediums, only 40-50% of it was released in the lozenges (Panya *et al.,* 2016).

Nano-micelles formulated from moringa seed oil through a microemulsion method using Tween 80 and ethanol exhibited potential in inducing apoptosis in mitochondrial cancer cells. This structured nano-micelle formulation was more effective in reducing colon cancerous Caco-2 cells by 50%, whereas the seed oil alone resulted in a 40% reduction (Elsayed *et al.,* 2016).

A thermo-reversible *in-situ* nasal gel was developed using extracts from moringa leaves and fruits, incorporating PEG400, Pluronic F127, xanthan gum, carbopol 934 and hydroxypropyl methylcellulose (HPMC K4M). This gel was evaluated for its effectiveness in managing allergic rhinitis. It was observed that increasing the concentration of PF127 led to higher viscosity, though it exhibited lower mucoadhesive properties compared to a combination of HPMC, carbopol and xanthan gum. The formulation aimed to improve bioavailability and reduce first-pass metabolism (Srivastava *et al.,* 2017).

Wound-healing applications were explored through aqueous and ethanolic film dressings prepared using the solvent casting method, with alginate and pectin as the primary components. The aqueous extracts demonstrated enhanced cell proliferation and migration capabilities while maintaining favorable physicochemical properties. Additionally, a moringa seed oil-based anti-inflammatory cream was formulated through a triturating process. The optimized cream inhibited protein denaturation by 60%, closely matching the 65% inhibition observed in the standard formulation. The cream also reduced paw edema by 70%, surpassing the 64% reduction achieved by pure oil (Suryadevara *et al.,* 2018).

Silver nanoparticles (AgNPs) derived from moringa leaves were synthesized using a shaking method, leading to enhanced antifungal activity against Candida albicans. As AgNP concentrations increased, the zone of inhibition expanded, demonstrating their effectiveness in controlling fungal growth (Roa Cordero *et al.,* 2023).

Antioxidant properties were assessed in composites incorporating moringa leaf extracts, silver nanoparticles and other substances such as sodium hypophosphite, silver nitrate, citric acid, kaolin, chitosan and sodium carbonate. Ethanolic extracts exhibited superior characteristics and antimicrobial activity compared to aqueous extracts. Fabrics infused with AgNPs composites also demonstrated enhanced UV protection compared to clay composites. Additionally, moringa seed oil was incorporated into suppositories formulated using macrogol, dika fat, liquid paraffin and polyethylene glycol. These suppositories effectively treated hemorrhoids, though they lowered the melting point (Zulkarnain *et al.,* 2024).

An ethanolic moringa leaf extract was used to develop an oral suspension containing sodium carboxymethyl cellulose, propylene glycol, benzoate and sorbitol. Increased suspending agent concentration led to higher viscosity. Granules developed through wet granulation for anti-inflammatory and anti-arthritic effects showed improved solubility and dissolution rates, reducing paw thickness. Variations in body weight were also noted, with initial weight loss followed by an increase due to the presence of gum (Arabic Alsammarraie *et al.,* 2021).

Chewable gummy tablets (CGTs) incorporating moringa leaf powder were developed using heating and congealing methods, employing excipients such as gelatin, pectin, mannitol, sugar, citric acid, maize oil and sodium benzoate. The selection of a suitable gelling agent

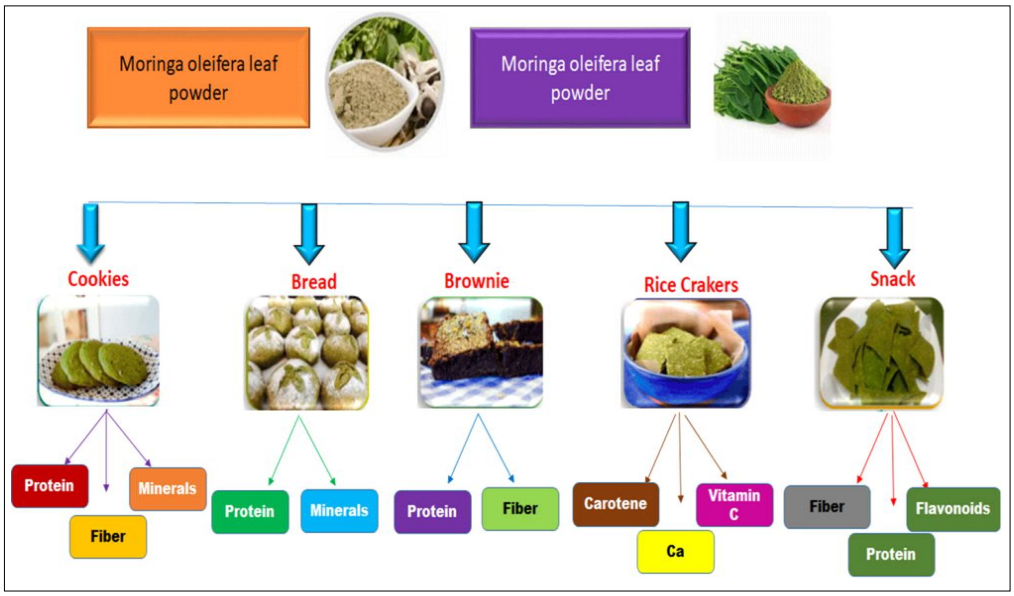


Fig 2: Various foods combined with moringa and their nutritional content.

influenced the physicochemical properties of the final formulation, where pectin-based CGTs exhibited greater swelling capacity compared to gelatin-based ones, thereby affecting dissolution rates. Furthermore, pectin-based formulations demonstrated resistance to syneresis, whereas increasing gelatin concentrations resulted in greater tablet hardness. The integration of moringa into CGTs aligns with phyto-pharmaceutical formulations, as it facilitates the delivery of plant-derived bioactives in a stable, bioavailable and patient-compliant dosage form. By incorporating medicinal phytochemicals into structured matrices, CGTs enhance the controlled release and absorption of bioactive compounds, positioning them as a promising strategy for the development of plant-based therapeutic formulations (Rani *et al.,* 2021; Rani *et al.,* 2022).

A hydrogel was formulated using moringa seeds and n-hexane, incorporating carbopol, propylparaben, methylparaben, propylene glycol and triethanolamine. This hydrogel demonstrated significant wound-healing properties, promoting cell proliferation and epithelialization. Furthermore, phytosomes derived from moringa were developed using a thin-layer hydration method with soy phosphatidy lcholine and TrizolTM. These phytosomes exhibited anti-cancer potential against breast cancer cells, with doses below 2000 mg/kg showing optimal *in vivo* results (Ali *et al.,* 2020; Wanjiru *et al.,* 2022).

An ethanolic extract-based emulgel containing moringa leaf extract was developed using carbopol 940, triethanolamine and Tween 80, focusing on antioxidant properties. A notable reduction in pH was observed after eight weeks of storage, attributed to fatty acid degradation in the moringa leaves, which could impact the stability of such formulations (Iskandar *et al.,* 2022).

These findings collectively highlight the diverse pharmaceutical applications of moringa-based formulations and underscore their potential in medicine and health care.

Moringa oliefera **in Musculo-skeletal disorders**

The use of plant-based supplements has gained increasing recognition among athletes competing at various levels. Intense and prolonged training often leads to oxidative stress and muscle fatigue, which can negatively impact performance and recovery. To address these challenges, MOL leaf extracts have been studied for their potential role in muscle repair and endurance enhancement. Alongside well-known adaptogens like green tea and ginseng, MOL has been suggested as an anti-fatigue agent due to its rich phenolic content, which may help in improving muscle protein functionality (Mardiana *et al.,* 2023). Additionally, a combination of MOL leaves and honey has been observed to enhance physical performance, with statistically significant improvements recorded in athletic endurance (Hasan *et al.,* 2016).

Beyond its impact on muscle function, Moringa oleifera plays a crucial role in bone health, particularly in conditions like osteoporosis, a major global health concern (Brown *et al.,* 2016). Osteoporosis leads to fragile bones and an increased risk of fractures, especially in aging populations. Research has indicated that both MOL fruit and flower extracts contribute positively to bone metabolism (Patel *et al.,* 2015). The fruit extract has been linked to increased alkaline phosphatase (ALP) activity, a key enzyme in bone formation, promoting osteogenesis. Meanwhile, the flower extract stimulates osteoblast proliferation, facilitating collagen synthesis and ultimately enhancing bone mineral density (BMD) (Patel *et al.,* 2013; Hairi and Sadikan, 2024).

In animal studies, MOL extracts have demonstrated remarkable bone-regenerative properties. Experiments on adult Wistar rats revealed that bioactive compounds in MOL leaf extracts supported hematological recovery and bone marrow regeneration (Owolabi *et al.,* 2012). Moreover, when MOL ethanolic extract was administered at 600 mg/kg, it significantly reduced calcium loss through urine while increasing calcium retention in bones, a protective effect comparable to estradiol, a standard treatment for osteoporosis (Sharma *et al.,* 2023).

Further investigations on MOL leaf, flower and fruit extracts using osteoblastic SaOS-2 cells have provided additional insights. The fruit extract enhanced ALP activity, collagen production and bone mineral deposition, while the flower extract notably increased osteoblast cell numbers, reinforcing its role in bone health management. These findings highlight the anti-osteoporotic potential of Moringa and suggest its application in bone-strengthening interventions (Khan *et al.,* 2022).

Moringa oleifera contains bioactive compounds that contribute to musculoskeletal health through multiple mechanisms. These include the inhibition of nuclear factor kappa-light chain enhancer of activated B cells (NF-KB) pathway by isothiocyanates, which reduces pro-inflammatory cytokines such as TNF-α and IL-6. Quercetin contributes to analgesic and antioxidant effects by scavenging reactive oxygen species (ROS), thereby supporting muscle recovery. Additionally, Moringa's high calcium and phosphorus content promotes bone mineralisation by stimulating osteoblast activity and enhancing alkaline phosphatase (ALP) levels, which are vital for bone formation (Triwardhani *et al.,* 2023), A. Isothiocyanates present in moringa exhibit potent anti-inflammatory properties, which help in alleviating musculoskeletal discomfort. Additionally, quercetin, a flavonoid found in moringa, is known for its analgesic effects, aiding in pain relief and further reducing discomfort. Moreover, moringa serves as a rich source of bioavailable calcium, playing a crucial role in maintaining bone health and preventing musculoskeletal issues (Lucarini *et al.,* 2022); Ferraz *et al.,* 2021; Soliman *et al.,* 2021). *Moringa oleifera* is well-known for its ability to regenerate bone by altering particular pathways that are involved in bone remodelling. Its sterols and flavonoids increase the expression of bone morphogenetic proteins (BMPs) and runt-related transcription factor 2 (RUNX2), two essential regulators of osteoblast maturation. Additionally, moringa inhibits the receptor activator of

Table 1: Major phytoconstituents of *Moringa oleifera* and their pharmacological roles in musculoskeletal health.

Phytochemical	Pharmacological role	Mechanism of action	Musculoskeletal effect
Quercetin	Antioxidant, Analgesic	Scavenges ROS, downregulates inflammatory mediators	Reduces muscle inflammation and oxidative stress.
Isothiocyanates	Anti-inflammatory (*via* NF-κB inhibition)	Inhibits NF-κB pathway, reduces cytokines TNF-α, IL-6	Decreases joint inflammation, protects cartilage.
Calcium	Bone mineralization cofactor	Promotes osteoblast proliferation and ALP activity	Enhances osteoblast activity, increases BMD.
Chlorogenic acid	Antioxidant, Immunomodulator	Modulates oxidative stress pathways	Mitigates oxidative stress in muscles and bones.

nuclear factor kappa-B ligand (RANKL), which is in charge of bone resorption and osteoclast differentiation (Hairi *et al.,* 2025). Osteoporosis and age-related bone loss benefit greatly from this, which encourages a healthy balance between bone creation and breakdown. Through its effects on the Akt/mTOR pathway, which controls the synthesis and repair of muscle proteins, moringa also aids in the recuperation from physical harm and exhaustion (Chen *et al.,* 2024) *Moringa*'s quercetin and chlorogenic acid inhibit catabolic enzymes such as atrogin-1 and MuRF1, which prevents muscle atrophy and promotes muscle growth. The antioxidant nature of moringa helps protect muscular tissues from lipid peroxidation and maintain mitochondrial activity. In diseases like rheumatoid arthritis, it also promotes immunological balance by changing the cytokine response from an inflammatory profile dominated by Th1/Th17 to a more controlled Th2/Treg profile. These processes demonstrate how *Moringa* may be able to address several facets of musculoskeletal dysfunction, such as muscle rehabilitation, arthritis alleviation and bone healing (Kim *et al.,* 2024); Vargas-Robles *et al.,* 2019). Table 1 highlights major phytoconstituents of MOL and their pharmacological roles in musculoskeletal health.

Future perspectives on the impact of *Moringa oleifera*

MOL is a nutrient-dense plant with significant potential in musculoskeletal health. Its leaves, pods and seeds contain essential vitamins (A, C, E), minerals (calcium, potassium) and proteins, contributing to dietary enrichment. Bioactive compounds such as quercetin and chlorogenic acid exhibit strong antioxidant and anti-inflammatory properties, mitigating oxidative stress and inflammation-key factors in musculoskeletal disorders. Moringa's integration into various dietary forms, including powders, teas and capsules, enhances accessibility. Research supports its role in alleviating arthritis and muscle pain while promoting skeletal integrity. Its incorporation into therapeutic strategies presents a sustainable approach to addressing micronutrient deficiencies and musculoskeletal health concerns.

CONCLUSION

The thorough analysis of "*Moringa oleifera*: Nutritional Supplementation, Phyto-Pharmaceutical Frontiers and Navigating Musculoskeletal Health" concludes by highlighting the plant's diverse possibilities for enhancing general health. The plant is a good dietary supplement for treating nutritional deficiencies and promoting overall health due to its rich nutritional composition, which includes vitamins, minerals and antioxidants. The plant's bioactive substances, including flavonoids and polyphenols, have anti-oxidative, anti-microbial and anti-inflammatory qualities, indicating that they may be used as a natural treatment for a variety of illnesses.

The utilization of biotechnological tools is poised to address the existing limitations in the commercialization of M. oleifera, promising to elevate its overall economic value. The traditional recognition of MOL leaf for its efficacy in managing a wide range of musculoskeletal disorders stems from its inherent neurotropic and neuroprotective effects. These effects play an active role in supporting the growth and survival of neurons, underlining its potential therapeutic value in addressing musculoskeletal ailments. It is undeniable that future research endeavors in this realm hold the potential to position MOL as a pivotal solution to contemporary health and environmental challenges. It is imperative to conduct a comprehensive examination of the preservation of nutrients and bioactive components within bakery products. While numerous investigations have explored the functional attributes of bioactive compounds, there remains a notable scarcity of research on the assimilation and accessibility of these bioactive compounds, both in *in vivo* and *in vitro* models. Consequently, it is essential to embark on further clinical trials aimed at elucidating the functional attributes of the bioactive compounds found in *Moringa oleifera.*

ACKNOWLEDGEMENT

Not applicable.

Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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