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Phytochemical and Nutritional Insights into *Moringa oleifera* Leaves: Composition

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Abstract

Known for its remarkable nutritional makeup, *Moringa oleifera* has attracted a lot of interest lately due to its use in the nutritional and nutraceutical fields. This tree's leaves have comparatively low concentrations of anti-nutritional substances but are excellent sources of a variety of beneficial substances, such as phytochemicals, carotenoids, and glucosinolates. The functional characteristics of these bioactive substances have been clarified by an increasing amount of *in vitro* and *in vivo* research, which has shown several different pharmacological actions, such as anti-inflammatory, anti-diabetic, antibacterial, and anticancer properties. The high concentration and cooperative action of phytochemical substances found in the leaf are primarily responsible for these medicinal advantages. Because of their strong health-promoting qualities and resistance to a range of pathophysiological disorders and environmental stresses, *Moringa* leaves are also being investigated more and more as a value-added component in the creation of functional meals. The bio accessibility and bioavailability of these chemicals after consumption are still poorly understood, despite a great deal of phytochemical profiling and characterisation. Current research on the nutritional and phytochemical makeup of *Moringa* leaves, their possible health advantages, and their developing uses in food systems is summarised in this study. *Moringa* leaves have great potential as a functional food ingredient and medicinal agent because of their potent protective ability against environmental pollutants and chronic illnesses. However, further multidisciplinary research is necessary to clarify the pharmacokinetics, therapeutic effectiveness, and translational use of chemicals produced from *Moringa* in pharmaceutical and nutraceutical formulations to fully realise their potential.

Major Findings: *Moringa oleifera* leaves are rich in bioactive phytochemicals with anti-inflammatory, antidiabetic, antibacterial, and anticancer potential, supporting their use as functional food and nutraceutical ingredients. However, bioavailability, pharmacokinetics, and clinical efficacy require further investigation.

Keywords: Antioxidant Activity, Functional Foods, *Moringa oleifera*, Nutritional Composition, Phytochemicals

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1. Introduction

The discovery and use of therapeutic phytochemicals, which have enormous potential for the creation of new pharmacological drugs, are driving the ongoing expansion of the field of medical plant research. Numerous secondary metabolites generated from plants, including glucosinolates, alkaloids, flavonoids, tannins, carotenoids, phenolic acids, and flavonoids, have shown important biological actions that support human health and disease prevention. These phytochemicals, which are classified as secondary aromatic metabolites, are widely found in the kingdom of plants and are well known for their ability to protect against a number of degenerative and chronic illnesses[1]. Their effectiveness in lowering the occurrence and progression of illnesses, including cancer, heart problems, and neurological disorders, is well-supported by scientific research. Furthermore, their therapeutic modulation in the treatment and management of various conditions emphasises how vital they are to the development of evidence-based and integrative medicine[2].

The *Moringaceae* family includes the drumstick tree, *M. oleifera* Lam. and is widely dispersed throughout the Indian subcontinent, portions of Africa, and other tropical and semi-arid countries. Respected for its many uses in medicine and cooking, this hardy plant thrives in dry environments because of its remarkable resistance to drought and its capacity to tolerate root-level water-logging. *Moringa* may grow in a wide range of soil types, although it prefers sandy or well-drained loamy soils with a pH between 5 and 9.

Almost every component of the *Moringa* tree, including its bark, roots, seeds, leaves, and pods, is used for household, industrial, medicinal, and nutritional purposes. It is acknowledged as a priceless botanical resource[3]. Because of its high content of vital nutrients and bioactive chemicals, the leaves in particular may be eaten raw, in salads, roasted, or powdered, although the powder keeps its nutritional value for a long time. Because of their rich phytochemical makeup, including carotenoids, flavonoids, phenolic acids and glucosinolates, *Moringa* leaves are of great interest in the creation of functional foods and nutraceuticals in addition to their nutritional applications[4].

Moringa leaves include important phytoconstituents such as astragalin, iso-quercetin, and cryptochlorogenic acid, which are primarily linked to the plant's strong anti-inflammatory, antihypertensive, and antioxidant qualities. Numerous *in vitro* investigations concentrating on their bioactive makeup and antioxidant mechanisms have supported these medicinal potentials. The plant's exceptional antioxidant efficiency is primarily attributed to its high concentration of phenolic chemicals[5]. Because of these pharmacological characteristics, *Moringa* has been used to create a wide range of pharmaceutical formulations that are now marketed both domestically and internationally, highlighting the plant's importance in medicine worldwide.

Due to its remarkable nutritional, medicinal, and ecological value, *M. oleifera* is frequently referred to as the "Miracle Tree" or the "Tree of Life". The leaves of *Moringa* have traditionally been utilised in traditional Indian medicine to cure a variety of conditions, such as intestinal parasite infections and conjunctivitis. Additionally, eating fresh *Moringa* leaves has been used traditionally to treat anaemia and has been linked to improved lactation in expectant and nursing mothers. *Moringa* leaf juice is frequently eaten by diabetics to help control blood pressure and glycaemic levels[5].

It is crucial to remember that the stability and bio accessibility of essential nutrients and polyphenolic compounds might be impacted by the post-harvest processing and storage of *Moringa* leaves. This calls for the creation of sophisticated processing methods meant to maintain these phytoconstituents' functional integrity. The use of herbal medicine has increased dramatically worldwide in recent years, especially in underdeveloped nations where access to traditional medical treatment may be restricted[6]. *Moringa* is a culturally acceptable, affordable, and easily available treatment option in these situations.

Comprehensive information on the bioactive content, bio accessibility, and related health effects of *Moringa* leaves is still lacking in the literature, despite the plant's extensive traditional use and rising scientific interest[7]. By compiling recent studies on the nutritional profile, phytochemical components, and health-promoting qualities of *M. oleifera* leaves, this review aims to close this important information gap. The paper also seeks to facilitate the incorporation of *Moringa* into contemporary nutritional and therapeutic paradigms by promoting more research into the plant's

potential as a component in functional foods in a variety of dietary applications[8].

2. The Nutritional Makeup of the Leaves of *Moringa oleifera*

Because of its remarkable nutritional value and extensive usage as a dietary supplement, especially in the battle against childhood malnutrition, *M. oleifera* is sometimes referred to as the "miracle tree". The leaves' dry weight ranges from 10.74% to 30.29% for crude protein, 13.41% to 63.11% for carbs, 6.50% to 20% for lipids, 7.09% to 35% for crude fibre, and 7.64% to 10.71% for total minerals[9]. *Moringa* leaves stand out from other leafy greens that are frequently eaten for their high protein content, which contains all of the necessary amino acids. Moreover, the leaves are very high in provitamin A (β-carotene), which adds to their nutritional advantage. However, environmental factors and genetic variety among cultivars can affect the precise nutritional makeup of *M. oleifera*. For example, the nutritional profiles of leaves gathered from different parts of Thailand vary, with protein values ranging from 19% to 29% and fibre contents from 16% to 24%. *Moringa* leaf samples showed protein levels close to 28% to 30%. Surprisingly, 100 grams of fresh *Moringa* leaves can provide up to 17.5% of the daily amount of protein that is advised. The majority of the lipids in *Moringa* leaves are unsaturated fatty acids, with the most prevalent being the omega-3 fatty acid α-linolenic acid[10]. A wealth of polyunsaturated fatty acids, such as omega-3 and omega-6, which are essential for systemic vitality and cardiovascular health, further improves this fatty acid profile. On the other hand, the leaves have a significant monounsaturated fatty acid content and very little saturated fat, which adds to their overall health advantages. Notably, a new study has isolated a novel polysaccharide from *Moringa* leaves called MOP-2. This polymer was extracted using hot water procedures and processed using sophisticated chromatographic methods. This substance shows great promise as an immunomodulatory agent, indicating useful uses in the creation of functional foods and nutraceuticals. *M. oleifera's* remarkable nutritional and biochemical makeup confirms its significance as a vital botanical resource for tackling global health and nutritional issues[11]. Table 1 shows the nutritional benefits of *M. oleifera* leaves, both fresh and dried, as well as leaf powder.

With around 57% of the lipids in *M. oleifera* leaves being unsaturated fatty acids and 43% being saturated fatty acids, the leaves' lipid composition shows a good equilibrium. The main unsaturated component among them is α-linolenic acid, an essential omega-3 fatty acid. The leaves are also a great supply of amino acids, with 16–19 different kinds found in them, 10 of which are considered essential. These amino acids, which are essential for protein synthesis and human metabolic processes, include Histidine, phenylalanine, methionine, tryptophan, lysine, tyrosine, leucine, threonine, isoleucine, and valine[12].

Moringa leaves are a great dietary addition for people who are trying to control their weight because of their low calorie density. It is often known that the leaves are a rich source of the nutrients required for physiological growth and development. Notably, *M. oleifera* leaves are a good natural substitute for calcium and protein supplements since they have four times the amount of digestible protein and twice as much calcium as milk. Additionally, they are enhanced with important minerals including potassium, magnesium, zinc, iron, and copper, all of which support vital cellular functions and the preservation of general health[13].

At about 28 mg per 100 g, the iron level of *Moringa* leaf powder is especially remarkable. It much outweighs that of typical food sources like spinach and beef (2 mg). Therefore, in the treatment of anaemia, *Moringa* powder has shown promise as a natural alternative to traditional iron supplementation[14]. A variety of vital vitamins are also found in the leaves, including water-soluble B-complex vitamins like folic acid, pyridoxine (B6), nicotinic acid (niacin), and vitamin C, as well as fat-soluble vitamins A (as beta-carotene), D, and E. About 7564 IU of vitamin A and 145 µg of vitamin C, which correspond to 252% and 235% of the daily recommended intakes for these vitamins, respectively, are found in fresh *Moringa* leaves[15].

The effectiveness of *M. oleifera* in preventing malnutrition has been further supported by clinical findings. Compared to a control group, malnourished youngsters who took 10 grams of powdered dry *Moringa* leaf every day showed markedly better weight growth and quicker recovery over six months. *Moringa* leaves are rich in bioactive phytochemicals such as

Table 1. The nutritional benefits of *Moringa oleifera* leaves, both fresh and dried, as well as leaf powder

Nutrients	Fresh Leaves	Dried Leaves	Leaf Powder
Calories (cal)	92	329	205
Crude protein (g)	6.7	29.4	27.1
Fat (g)	1.7	5.2	2.3
Carbohydrate (g)	12.5	41.2	38.2
Fiber (g)	0.9	12.5	19.2
Calcium (mg)	440	2185	2003
Potassium (mg)	259	1236	1324
Iron (mg)	0.85	25.6	28.2
Magnesium (mg)	42	448	368
Phosphorus (mg)	70	252	204
Copper (mg)	0.07	0.49	0.57
Sulphur (mg)	–	–	870
Vitamin A (mg)	1.28	3.63	16.3
Vitamin B_1 (mg)	0.06	2.02	2.64
Vitamin B_2 (mg)	0.05	21.3	20.5
Vitamin B_3 (mg)	0.8	7.6	8.2
Vitamin C (mg)	220	15.8	17.3
Vitamin E (mg)	448	10.8	113
Chlorophyll (mg)	80	45	1268
Arginine (g/16 gN)	6%	1.78%	1.33%
Histidine (g/16 gN)	2.1%	0.716%	0.61%
Lysine (g/16 gN)	4.3%	1.637%	1.32%
Tryptophan (g/16 gN)	1.9%	0.486%	0.43%
Phenylalanine (g/16 gN)	6.4%	1.64%	1.39%
Methionine (g/16 gN)	2%	0.297%	0.35%
Threonine (g/16 gN)	4.9%	1.357%	1.19%
Leucine (g/16 gN)	9.3%	1.96%	1.95%
Isoleucine (g/16 gN)	6.3%	1.177%	0.83%
Valine (g/16 gN)	7.1%	1.413%	1.06%

All values are per 100 g of plant material[16,17].

phenolic acids, tannins, saponins, flavonoids, and alkaloids, in addition to their remarkable nutritional profile. The potential anticancer properties and wide-ranging therapeutic uses of these substances and their derivatives are becoming more widely acknowledged[16].

In fresh *M. oleifera,* there are several carotenoids in leaves with significant amounts of trans-lutein (~30%), trans-β-carotene (~18%), and trans-zeaxanthin (~6). These bioactive pigments' antioxidant qualities make them essential for preserving cellular and ocular health. Together with additionally, the leaves contain high concentrations of carotenoids, tocopherol (36.9 mg/100 g) and ascorbic acid (271 mg/100 g), both of which significantly enhance the plant's antioxidant capacity and immune-stimulating properties[17].

Tannins, oxalates, saponins, and phytates are examples of naturally occurring antinutritional agents that are present in minute amounts in *M. oleifera*, despite its remarkable nutrient profile. While excessive use of these substances may hinder the absorption and bioavailability of vital minerals, including calcium, magnesium, iron, and zinc, they are not intrinsically harmful. Phytate and saponin levels in *Moringa* seeds and leaves, however, are far lower than those usually

seen in legumes like soybeans. Because of their comparatively lower antinutrient content, *M. oleifera* leaves are safer to eat and more suited for everyday human consumption[18].

3. *Moringa oleifera* Leaf Bioactive Profile

Numerous secondary metabolites, including flavonoids, tannins, isothiocyanates, phenolic acids, and saponins, are naturally produced by plants. These compounds have strong physiological activity and are being used more and more in food and nutraceutical applications. Depending on their structural traits and biological objectives, these phytochemicals may either have a therapeutic effect or function as inactive ingredients. Primarily, their production is a defensive mechanism that plants have developed to counteract environmental stresses such as microbial invasion and ultraviolet (UV) exposure[19].

Particularly, *M. oleifera* is known to be a phytochemically rich plant, particularly in its leaves, which are rich in bioactive substances such as anthraquinones, flavonoids, catechol-type tannins, saponins, tannins, and different alkaloids (Figure 1). *Moringa* leaves provide a wide range of medicinal and health-promoting benefits due to the presence of these powerful and varied chemicals. Furthermore, *M. oleifera* leaves have shown effectiveness as a natural water purification agent, highlighting their multipurpose qualities beyond human nutrition and medicine and highlighting their importance for the environment and public health[20].

3.1 Phenolic Compounds

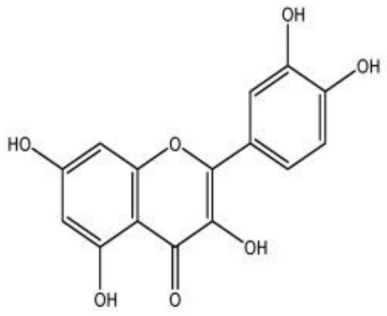
The two main structural forms of phenolic compounds, a kind of secondary metabolites that are present in plants, are derivatives of hydroxycinnamic acids (also known as free phenolics) and hydroxybenzoic acids (also known as bound phenolics)[21]. These substances, which are frequently found in plant tissues as esters or glycosidic conjugates, are distinguished by having an aromatic ring that is directly joined to one or more hydroxyl groups. These compounds' strong free radical scavenging capabilities are mostly because of the hydroxyl groups present[22].

The phenolic components found in *M. oleifera* have been well characterised, and both *in vitro* and *in vivo* tests have shown their biological effectiveness. Lignan glycosides, like epipinoresinol, medioresinol, isolariciresinol, and secoisolariciresinol, and a wide variety of 26 flavonoids, such as myricetin, apigenin, luteolin, kaempferol, and quercetin, are among the main phenolics present in the leaves. Eleven derivatives of phenolic acids, including isomers of coumaroylquinic, feruloylquinic, and caffeoylquinic acid, have also been found[23].

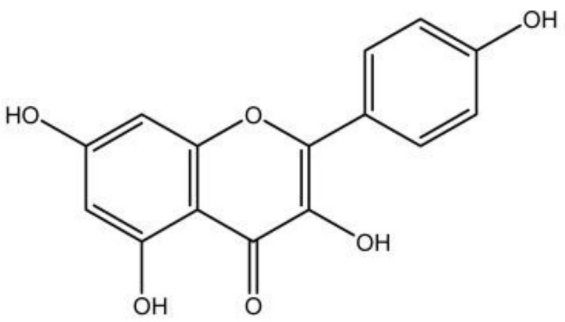
Total phenolic content in the methanolic extract of *M. oleifera* leaves ranges from 71.08 ± 12.05 to 76.63 ± 10.63 mg GAE/g, which is about 22% higher than that of young *M. peregrina* leaves. This indicates that *M. oleifera* is a superior source of phenolics. It is important to remember that a variety of factors, including agroclimatic conditions, developmental stage at harvest, and genetic heterogeneity, affect the phytochemical profile of *Moringa*. Furthermore, post-harvest variables like humidity and storage temperature have a big influence on these chemicals' stability and bioactivity[24].

Moringa leaf samples kept in aluminium foil pouches at two distinct temperature and humidity settings—25 ± 2 °C with 60 ± 5% relative humidity and 40 ± 2 °C with 75 ± 5% relative humidity—showed differing degrees of phytochemical degradation over six months in a controlled environment. A little decline in the amount of bioactive material (13–27%) and antioxidant potential (as determined by DPPH radical scavenging activity) of around 30% was noted at 60 ± 5% relative humidity and 25 ± 2 °C. On the other hand, samples kept at higher temperatures and humidity levels (40 ± 2 °C, 75 ± 5% RH) showed a 50% reduction in antioxidant capacity and a significant drop in phytochemical content (38–53%). These results emphasise how sensitive *Moringa*'s bioactive components are to environmental storage conditions and how crucial it is to use preservation techniques that are designed to preserve their functional efficiency[25,26].

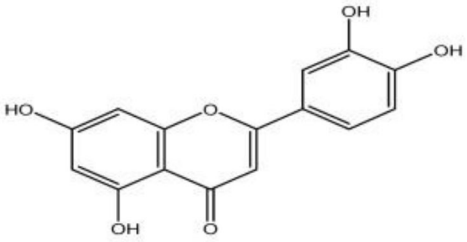
The main class of phenolic chemicals found in *M. oleifera* leaves are flavonoids, which greatly enhance the bioactive profile of these leaves. Among the several flavonoids found, the glycosidic forms of myricetin, kaempferol, apigenin, luteolin, and quercetin are noteworthy components. According to quantitative



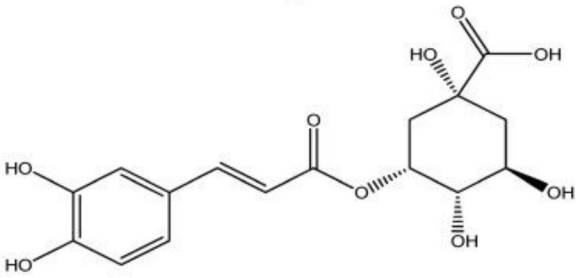
Quercetin



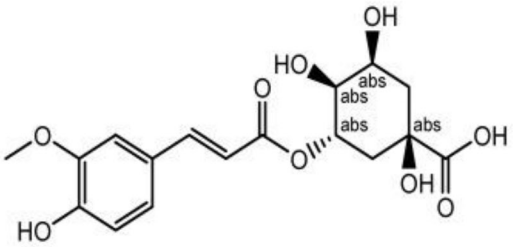
Kaempferol



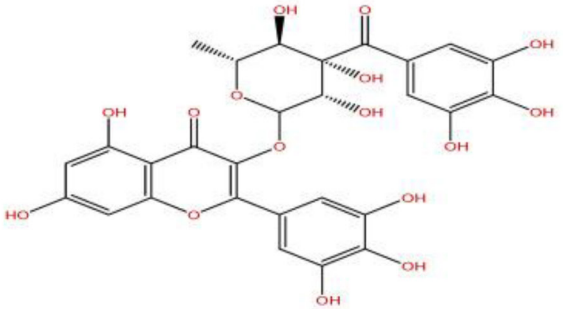
Luteolin



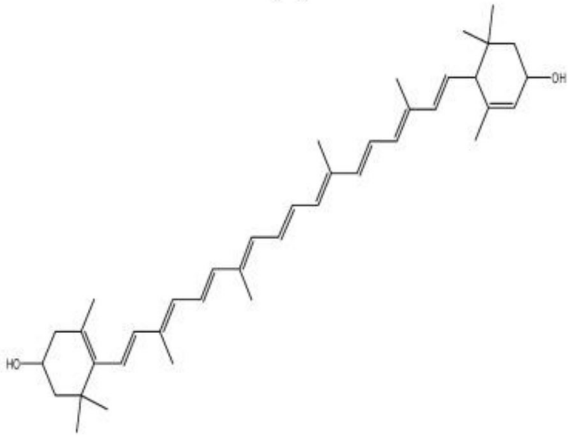
Neochlorogenic acid



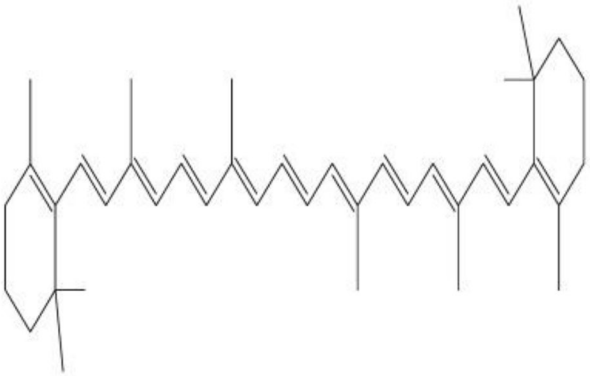
3-O-feruloylquinic acid



Myricetin



Lutein



B-carotene

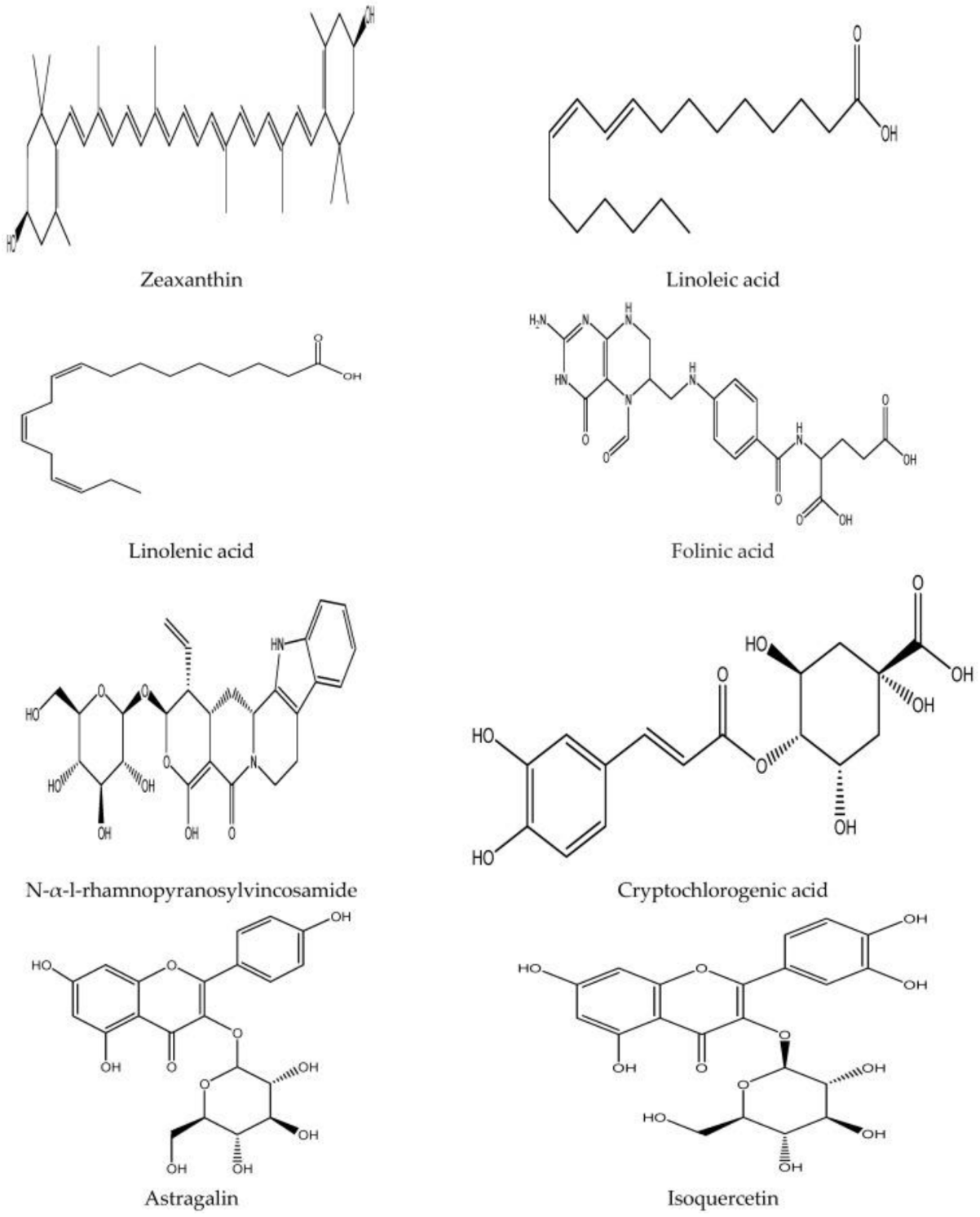


Figure 1. The molecular makeup of several bioactive substances found in *M. oleifera* leaves.

studies, quercetin is the most abundant flavonoid, making up around 43.75% of the total flavonoid content. The remaining flavonoids, such as kaempferol and others, each contribute about 18.75%.

Interestingly, the levels of kaempferol and quercetin in *M. oleifera* leaves are much greater than those in traditional green vegetables like spinach. Recorded values of 1362.6 mg/kg and 1933.7 mg/kg, respectively,

compared to spinach at 17.9 mg/kg and 215.3 mg/kg, respectively. The potential of *Moringa* as an excellent dietary source of flavonoid antioxidants is shown by these higher levels[27]. It has been demonstrated that environmental elements, including soil and climate, affect flavonoid synthesis, leading to regional variations in composition[28].

A thorough flavonoid profile of *Moringa* leaves from Namibia and South Africa using chromatography, using ultra-high performance liquid chromatography in conjunction with quadrupole time-of-flight mass spectrometry with electrospray ionisation (UHPLC-ESI-q-TOF-MS) revealed 17 different flavonoid derivatives. These comprised derivatives of apigenin (6%) and isorhamnetin (24%), as well as quercetin and kaempferol (35% each). Similarly, 12 different flavonoids were found in *Moringa* leaves from sub-Saharan Africa according to an HPLC-UV-MS study[29].

Moringa oleifera leaves are abundant in phenolic acids, which usually range from 77 to 187 µg per gram of dry matter, in addition to flavonoids. These comprise derivatives of hydroxybenzoic and hydroxycinnamic acids. Caffeoylquinic acid (about 45.45%) and coumaroylquinic acid isomers (36.37%) are major hydroxycinnamic acids[30]. There are also a lot of hydroxybenzoic acids, including P-hydroxybenzoic acid and gallic acid.

Moringa leaves were found to contain 63 phenolic acid components, mostly hydroxycinnamic acids, with Chlorogenic acid and gallic acid being the most common, according to a recent analytical study. Additionally, the phytochemical knowledge of *M. ovalifolia* has been expanded with the first report of the new detection of both cis- and trans-isomers of 3-acyl-, 4-acyl-, and 5-acyl-substituted caffeoylquinic, p-coumaroylquinic, and feruloylquinic acids[31].

3.2 Carotenoids

By dispersing surplus light energy and reducing photooxidative stress, carotenoids—lipophilic pigments naturally produced by photosynthetic organisms—play a vital role in protecting the photosynthetic apparatus. In addition to their physiological roles in plants, carotenoids are well known for their strong antioxidant qualities, which offer a host of health advantages such as preventing chronic diseases, reducing age-related degenerative processes, and protecting cells from oxidative damage[31]. Because of these qualities, they are commonly utilised as natural food colouring and added to dietary supplements.

Carotenoids are incredibly abundant in *M. oleifera* leaves, with total amounts varying among cultivars from 44.30 to 80.48 mg per 100 g fresh weight. Luteoxanthin, 13-Z-lutein, all-E-β-carotene, all-Z-β-carotene, all-E-lutein, all-E-zeaxanthin, and β-carotene are the main carotenoids found in these leaves[32]. Of them, luteoxanthin has the lowest purity (89%) in carotenoid-enriched extracts, while all-E-β-carotene shows the highest purity (94%).

According to research by Saini RK, Sivanesan I, Keum YS. fresh *M. oleifera* leaves had lutein and β-carotene concentrations of 418 mg/kg and 272 mg/kg dry weight. On the other hand, lutein and β-carotene levels in dried powdered leaves were 472 and 166 mg/kg, respectively, suggesting that processing techniques affect retention. Plant maturity, post-harvest treatment, and environmental factors all have a major impact on the amounts of these bioactive chemicals[31]. It is noteworthy that the carotenoid concentration peaks in the early stages of vegetative growth and decreases with plant maturity. Additionally, it has been demonstrated that carotenoid integrity is preserved by low-temperature storage (0°C), but these delicate molecules are significantly degraded by thermal processing, such as high-temperature cooking[33].

Carotenoids are gaining more scientific attention for their involvement in lowering the incidence of some cancers and other diseases linked to oxidative stress because of their strong antioxidant action.

3.3 Alkaloids, Glucosinolates and Iso-Thiocyanates[34]

Alkaloids are a well-known family of secondary metabolites formed from plants that are distinguished by the presence of basic nitrogen atoms and frequently show notable pharmacological activity. N,4'-hydroxyphenylethanamide-α-L-rhamnopyranoside, phenyl acetonitrile pyrrole marumine, α-L-rhamnopyranosyl vincosamide, and its corresponding glucopyranosyl derivative are important alkaloidal elements found in *M. oleifera* leaves. These substances are well known for their therapeutic potential in the treatment of several clinical disorders, as are their structural equivalents.

Moringa oleifera also includes glucosinolates, a type of beneficial secondary metabolite that is mostly found in the leaves and seeds, in addition to alkaloids. The main glucosinolate molecule found in this species is 4-O-(α-L-rhamnopyranosyloxy)-benzylglucosinolate, also known as glucomoringin. The natural plant enzyme myrosinase hydrolyses glucomoringin, causing it to biotransform into bioactive derivatives such as thiocarbamates, nitriles, and isothiocyanates. The strong hypotensive and antispasmodic actions of these degradation products highlight their importance in the creation of natural remedies.

3.4 Other Compounds

Folates, tannins, saponins, and fatty acids are just a few of the many bioactive components found in *M. oleifera* leaves, all of which greatly enhance their nutritional and medicinal value. Essential water-soluble B-group vitamins called folates are crucial for several metabolic processes, especially methylation and nucleotide synthesis[35]. 10-formylfolic acid, 5-methyl-5,6,7,8-tetrahydrofolic acid, 5,6,7,8-tetrahydrofolic acid, and 5-formyl-5,6,7,8-tetrahydrofolic acid are the main folate derivatives found in *M. oleifera*. Animal experiments in a rat model showed that folates produced from *Moringa* leaves had a higher absorption efficiency—up to 81.9%—than regular dietary folates, which have an average bioavailability of about 50%. *M. oleifera's* increased bioavailability makes it a desirable dietary folate source, especially for populations who are folate-deficient.

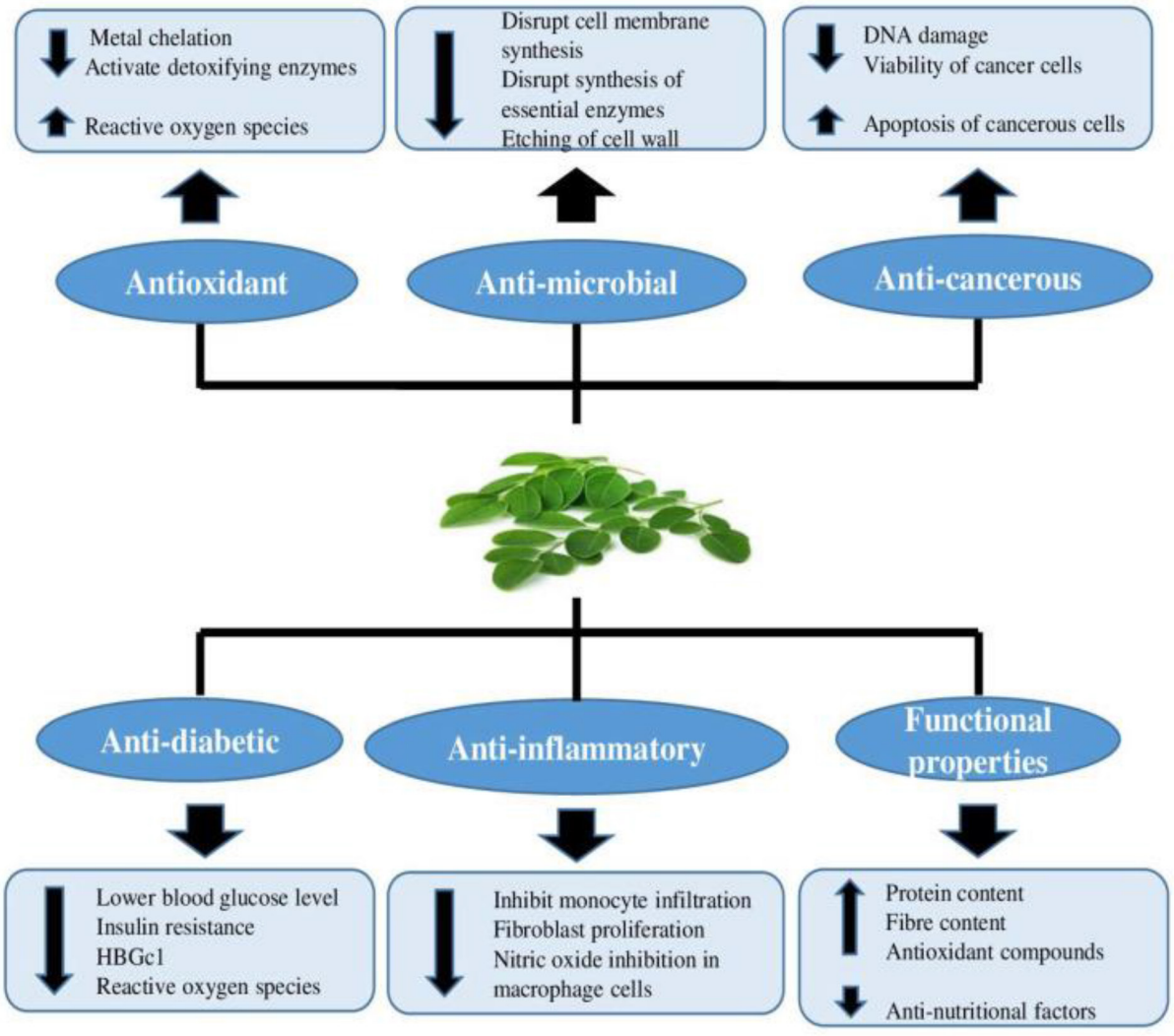


Figure 2. *Moringa oleifera* leaves' health advantages are based on their natural characteristics.

Additionally, the leaves of *M. oleifera* have a good lipid profile with a high percentage of polyunsaturated fatty acids (PUFAs), mainly linoleic acid (6–13%) and α-linolenic acid (49–59%). Palmitic acid is the most common saturated fatty acid, making up around 16–18% of all fatty acids. In contrast to the pods of the same plant, the leaf lipid profile is notably lower in monounsaturated fatty acids (MUFAs) and higher in polyunsaturated fatty acids (PUFAs)[36].

With quantities ranging from 13.2 to 20.6 g/kg on a dry weight basis, *Moringa* leaves are also rich in tannins, a type of water-soluble polyphenolic chemicals with potent protein-precipitating qualities. Furthermore, there are significant amounts of saponins—complex glycosides made of a triterpenoid or steroidal aglycone connected to sugar residues—found in freeze-dried leaf material, ranging from 64 to 81 g/kg. The many pharmacological properties of tannins and saponins, such as their immunomodulatory, hypocholesterolaemic, anti-inflammatory, and antioxidant properties, are well recognised[37].

4. Benefits of *M. oleifera* Leaves for Health[38]

Moringa leaves provide several health benefits, such as anti-inflammatory, anti-microbial, anti-cancerous, and antioxidant properties, as demonstrated in Figure 2.

4.1 Antioxidant Properties

When created in excess, reactive oxygen species (ROS) overwhelm the antioxidant defences of cells and cause oxidative damage to vital macromolecules such as proteins, carbohydrates, lipids, and nucleic acids. Numerous chronic disorders, such as hypertension, diabetes mellitus, and heart failure, have this oxidative stress as a pathological characteristic in their genesis and evolution[39]. Because of their improved biocompatibility, safety profile, and consumer preference, naturally produced antioxidants are frequently preferred over synthetic equivalents among prospective treatments. Strong antioxidants include quercetin, kaempferol, β-carotene, ascorbic acid, isothiocyanates, rutin, and a variety of polyphenolic components that are abundant in *M. oleifera* leaves.

Water, diethyl ether, chloroform, methanol, acetone, dichloromethane, and ethyl acetate are just a few of the solvent systems in which the antioxidant potential of *M. oleifera* leaf extracts has been confirmed. Interestingly, ethyl acetate extracts demonstrated strong superoxide radical (O_2^-) scavenging ability, reducing tissue damage and biomolecular damage brought on by free radicals. Phenolics are the main contributors to oxidative defence, as evidenced by the direct relationship that has been found between the extracts' antioxidant efficiency and total phenolic content. Because of this characteristic, *M. oleifera* is a good choice to be included in nutraceuticals and functional meals that are meant to improve oxidative stability[40].

Due to their rich polyphenolic composition, methanolic extracts of *M. oleifera* leaves showed significant antioxidant capacity in comparative tests, with an IC_{50} value of 49.86 μg/mL, which was lower than that of ascorbic acid (IC_{50} = 56.44 μg/mL). Additionally, *M. oleifera*'s antioxidant mechanism supports its cryoprotective role in plants and can be used as a natural lipid preservative. With up to 81% inhibition of DPPH radicals, herbal infusions like *Moringa* tea have shown significant free radical scavenging activity, outperforming vitamin C's 76.5% inhibition (0.1 mg/mL). This suggests that the tea may have a role in reducing chronic conditions linked to oxidative stress.

The protective effectiveness of *M. oleifera* is further supported by recent experimental data. While administration of 100 mg/kg body weight in rats exposed to aluminium phosphide (AlP) significantly reduced malondialdehyde (MDA) levels and restored antioxidant balance, suggesting its therapeutic promise as an adjunct treatment for AlP-induced cardiotoxicity, *Moringa* leaf extracts alleviated cadmium-induced stress in *Lepidium sativum*[40].

The use of hydroalcoholic extracts from *M. oleifera* leaves in the creation of topical treatments, particularly gels and nanoparticles. The formulations' suitability for cutaneous application was confirmed by an evaluation of their physicochemical stability, which included pH, viscosity, and particle size. All of these parameters fell within acceptable ranges. Seven bioactive components, mostly flavonoids and phenolic acids, were found in the formulations after phytochemical profiling. Additionally, the compositions' antioxidant capacity was noticeably high. Skin biophysical evaluations showed decreased trans epidermal water loss (TEWL)

and increased stratum corneum hydration, indicating great promise for formulations based on *M. oleifera* as innovative cutaneous medication delivery methods[41].

Moringa oleifera leaves were assessed as a nutritious alternative to alfalfa hay in goat feed to improve the quality of milk and serum in a different study. Three dietary regimens were used in the study: two experimental groups that received 25% inclusion of either *M. oleifera* or *M. peregrina* leaves, and a control group that was fed just alfalfa. Ten goats in each group had a two-week acclimation period before six weeks of data collection. The findings showed that, in comparison to the alfalfa-only group, goats given *Moringa* had higher levels of milk fat, nitrogen-free extracts, and overall phenolic content[33]. Furthermore, there was a significant improvement in the oxidative profile of milk and serum, as demonstrated by higher levels of vitamin C, catalase activity, and total antioxidant capacity, as well as lower levels of thiobarbituric acid reactive substances (TBARS), which suggests a protective antioxidative effect[39].

The *in vitro* antioxidant capacity of many *M. oleifera* leaf extracts at a range of doses (0.1563–5 mg/mL). Significant radical scavenging activity was shown by all studied extracts; the methanolic extract had the greatest DPPH activity at all doses. Furthermore, at 1 mg/mL, the methanolic extract demonstrated substantial reducing power (925.48 ± 0.45%) and outstanding hydrogen peroxide (H_2O_2) scavenging activity (70.56 ± 0.43%). The extract's higher total phenolic content (TPC) and total flavonoid content (TFC) were credited with this improved antioxidant efficacy[42].

The cardioprotective effects of *M. oleifera* methanolic leaf extract in a diabetic rat model generated by streptozotocin and exposed to oxidative stress. Over the course of 60 days, the animals were divided into six groups and given 300 mg/kg body weight of the extract orally: (1) normal control, (2) normal with *Moringa* treatment, (3) high-energy diet control, (4) diabetic control, (5) diabetic with *Moringa* treatment, and (6) diabetic with standard medications (atorvastatin and metformin). The study found that groups 3 and 4 had significantly lower levels of the antioxidant enzymes catalase (CAT), glutathione (GSH), glutathione peroxidase (GPx), and superoxide dismutase (SOD). In contrast, groups 2, 5, and 6 showed a notable recovery of these antioxidant enzymes. Hexadecenoic acid, phytol, DL-α-tocopherol, and other phytoconstituents are among the bioactive substances found in *Moringa* leaves that have been linked to the beneficial antioxidant action[43,44].

5. Bioaccessibility and Bioavailability[45]

The nutritive and bioactive makeup of food matrices and their by-products has been the subject of much research, but knowing these chemicals' bioaccessibility and bioavailability—rather than just counting their presence—is more important. The percentage of bioactive compounds, such as polyphenols, that are released from the food matrix and made accessible for absorption during gastrointestinal digestion is known as bioaccessibility. On the other hand, bioavailability refers to how well these broken-down substances are absorbed, enter the bloodstream, and undergo regular metabolic processes.

According to recent studies, the bio accessibility of *M. oleifera* leaves ranges from 6% to 210% for a variety of phenolic compounds (such as gallic acid, caffeic acid, morin, and kaempferol) and mono-/oligosaccharides (such as mannose and stachyose). While p-coumaric acid and quercetin showed increased release during the intestinal phase, some chemicals, such as gallic acid, chlorogenic acid, vanillin, and rutin, showed better bio accessibility during stomach digestion.

Furthermore, with the release of 49.6% of total phenolics and 58.4% of total flavonoids, the oral phase was especially successful, whereas stomach digestion made a smaller contribution. During intestinal digestion, phenolic acids predominated over flavonoids, most likely as a result of the enzymatic breakdown of flavonoid structures. The main phenolics found at different stages of digestion were quercetin-3-O-β-D-glucoside (intestinal phase), ferulic acid, 6,8-di-C-glucosylapigenin (oral phase), and catechin (gastric phase).

The majority of *M. oleifera*'s flavonoids, including apigenin, isorhamnetin, kaempferol, and quercetin, are mostly present in glycosylated forms. Unlike their glycosidic equivalents, which showed poor absorption, aglycone forms, such as quercetin, were absorbed in the stomach of Wistar rats. Similar to glycosidic isoflavones, isoflavone aglycones demonstrated fast gastric absorption with detectable metabolites in

plasma, confirming the stomach's restricted ability to absorb glycosylated substances. In both human and animal experiments, rutin, another glycosylated flavonoid, showed delayed absorption in comparison to quercetin.

On the other hand, natural folates, namely 5,6,7,8-tetrahydrofolic acid, 10-formylfolic acid, 5-methyl-5,6,7,8-tetrahydrofolic acid, and 5-formyl-5,6,7,8-tetrahydrofolic acid, are abundant in *M. oleifera* leaves. The bioavailability of these folates is higher than that of folates from other green vegetables. *Moringa*-derived folates outperformed synthetic folic acid supplementation in rat models, with a bioavailability of 81.9%. However, the high concentration of phytic acid, an anti-nutritional component that prevents mineral absorption, means that *M. oleifera's* iron bioavailability is still low. Because bioactive compounds vary in their chemical structure, solubility, and matrix interactions, digestion kinetics, enzymatic transformation, methylation, microbial fermentation, and intestinal absorption all play a significant role in the bio accessibility and bioavailability of polyphenols and micronutrients in *M. oleifera*. Therefore, in order to clarify the metabolic fate and absorption methods of phytochemicals produced from *Moringa*, thorough *in vitro* and *in vivo* assessments are required.

6. Utilising *Moringa* Leaves in Food Products for Dietary Use

The use of functional foods in daily nutrition has attracted a lot of interest due to the increase in the prevalence of chronic diseases worldwide. It is well known that certain meals, which are enhanced with health-promoting ingredients, can slow down or even stop the onset of many non-communicable illnesses. Because functional foods include bioactive substances that have therapeutic effects beyond basic nutrition, there is growing evidence that they can be incorporated into regular dietary habits. The breakdown of vital biological macromolecules like DNA, proteins, and lipids has been linked to oxidative stress, which is caused by an excessive buildup of free radicals. The pathogenesis of several chronic illnesses, such as cancer, diabetes, and cardiovascular ailments, is significantly influenced by this mechanism. Therefore, adding natural antioxidants to the diet is regarded as an essential tactic for preventing illness and preserving health. Because of its high nutritional density and quantity of powerful antioxidant components, *M. oleifera* has become a desirable functional food in this context (Figure 2).

Moringa oleifera leaves are a viable option for tackling the world's malnutrition problems because of their significant nutritional profile, which includes proteins, vitamins, minerals, and bioactive phytochemicals. Their antioxidative properties further support their use as components in functional foods and nutraceuticals. Recent developments have shown that *Moringa* leaves may be added to a variety of food items to improve their functional and nutritional aspects[46,47]. For example, found that adding 5% *Moringa* leaf powder to wheat flour bread resulted in notable increases in the bread's protein and crude fibre content, which increased by 54% and 56%, respectively. Similar fortification has been shown in other trials to result in a more modest improvement in protein (17%) and an even more notable increase in fibre (88%).

Additionally, the nutritional profiles of tortilla chips enhanced with 1%, 3%, and 5% *Moringa* leaf flour showed improvements, especially in terms of the protein and fat contents, the latter of which increased by 50%. Oleic and linoleic acids, which are both recognised for their cardioprotective qualities, were the main fatty acids found in the enriched chips. The addition of *Moringa* leaf powder also resulted in a considerable increase in antioxidant activity and total phenolic content (TPC)[48]. The usefulness of *Moringa* leaves in the creation of functional beverages was further illustrated by Fombang and Saa. The DPPH radical scavenging assay showed 81% inhibition under ideal extraction conditions (solid-to-liquid ratio of 1:20 mg/mL, temperature of 97 °C, and processing time of 35 minutes), indicating that their formulation of *Moringa*-based herbal tea produced high phenolic concentrations and demonstrated significant antioxidant efficacy.

The leaves of *M. oleifera* have also shown a great deal of promise in the fields of fermented food product improvement and microbial food preservation. The antifungal effectiveness of *M. oleifera* leaf and seed extracts against the pathogenic strains *Lasiodiplodia theobromae*, *Colletotrichum gloeosporioides*, and *Alternaria alternata* was incorporated into an edible coating that was applied to avocados. When compared

Table 2. Uses of *M. oleifera* leaves as a useful component in culinary goods

Food Stuff	Concentration of Leaves Used (%)	Functional Advantage	Related Bioactive Compounds	References
Snacks	1	High in mineral content and protein, with less fat	-	[39]
Vegetable soup powder	8.5	Longer shelf life Enhanced nutritional quality	Protein, fibre, vitamin D and C and minerals	[40]
Cattle feed	25	Higher milk yield, milk fat, lactose content	-	[41]
Yoghurt	0.5–2	Higher nutritional value	-	[42]
Bread	5	Better nutritional quality with less organoleptic change	Protein, fibre and minerals	[42]
Cookies	10–20	Higher protein content with acceptable sensory qualities	-	[43]
Yoghurt	0.5	Acceptable Sensory qualities	-	[44]
Sour cream	600, 800 and 1000 ppm	Higher protein, acidity and peroxide value Acceptable sensory quality during storage	-	[45]
Ready-to-eat snacks	20	Decrease in antinutritional factors	Phenolic compounds, saponins and phytic acid	[45]
Amala	2.5–10	Protein content increased by 48% at 10% leaf powder concentration; mineral content also increased, but addition above 2.5% adversely affected sensory attributes.	-	[47]
Cattle feed	10.85	Higher nutritional value, a higher concentration of total ruminal volatile acids, and greater relative expression of microbial genes.	-	[48]

to its methanolic cousin, the ethanolic extract of the leaves demonstrated greater antifungal efficacy. The fruits that were treated also showed decreased respiration rates and ethylene release, which is a sign of postponed ripening and longer shelf life. The high levels of phenolic chemicals in *M. oleifera* leaves are closely linked to these antifungal activities. The nutritional profile of the traditional beverage *Mahewu* was significantly improved when it was fortified with different quantities of *Moringa* leaf powder in the context of fermented food enhancement. At 2%, 4%, and 6% supplementation levels, respectively, mineral content—especially calcium and iron—showed notable increases, with calcium levels increasing by 106%, 214%, and 287% and iron levels increasing by 350%, 700%, and 900%. The 2% *Moringa*-enriched beverage showed the highest sensory acceptance among the evaluated formulations, indicating the best possible compromise between palatability and nutrients. Rich in proteins, vital minerals, and bioactive antioxidant components, including vitamins and polyphenols, *M. oleifera* leaves are said to offer a wide range of nutritional advantages, which highlights their appropriateness as a functional food ingredient. Their incorporation into different food systems supports a balanced and health-conscious diet by improving food preservation and nutritional content (Table 2).

7. Conclusions and Future Aspects

The leaves of *M. oleifera* are becoming more widely acknowledged as a powerful source of micronutrients and bioactive phytochemicals, which makes them an important ingredient in the creation of functional food items and nutraceuticals. Numerous phytoconstituents found in these leaves provide them with a wide range of medicinal benefits, including anti-inflammatory, anti-cancer, antibacterial, antidiabetic, and antioxidant qualities. Their potential to improve food items' nutritional profiles without sacrificing their sensory

appeal at levels as high as 10% has attracted a lot of interest in their integration into dietary formulations. Superior nutritional qualities, such as higher amounts of proteins, dietary fibres, vital micronutrients, and health-promoting antioxidant components, have been shown in foods enhanced with *M. oleifera* leaf powder. Crucially, it has been demonstrated that human ingestion is safe when done under strict control and within prescribed quantities. All of these qualities make *M. oleifera* leaves an excellent option for creating functional meals that are high in nutrients and have positive pharmacological effects. To fully realise their potential, however, more clinical research is necessary to confirm the safety and therapeutic effectiveness of *M. oleifera* leaves in human populations. Future studies should also clarify the bioavailability of polyphenols produced from *Moringa* and investigate the potential effects of complexation or interaction with other dietary ingredients on the bio accessibility and metabolic destiny of these compounds in the human gastrointestinal system.

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Author Contribution

All authors contributed to the study's conception and design. Mahavir Kumar Sharma reviewed the data and drafted the manuscript. All authors have read and agreed to the published version of the manuscript.