



Moringa Tree, Gift of Nature: a Review on Nutritional and Industrial Potential

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Abstract

Purpose of Review Worldwide occurring *Moringa* plant is commonly famous as a fruit vegetable, known as *drumstick* or *shevga* all over India. The miraculous nutritional potential of the drumstick plant was already proved by worldwide research. But in the common population, it is unknown for the nutritional potential of its leaves. The majority of the population is known to only use it as a fruit vegetable. The *Moringa* leaves contain almost all essential nutrients, growth factors, vitamins, amino acids, proteins, minerals, and metals like potassium, iron, and zinc. Besides these, nowadays, plant leaves may be used to prepare various nutritional supplements and medicine.

Recent Findings Besides this, this review takes into account some joint efforts of NASI, Allahabad-funded project to use these *Moringa* leaves for different formulations and its popularization efforts for malnutrition eradication in tribal, i.e., development of recipes of *Moringa* leaves that will not only make easy preparations but also help to make habitual use of *Moringa* leaves today.

Summary This review describes the morphology, occurrence, and distribution of *Moringa* sp., chemical constitutions of *Moringa* leaves, its potential as anticancer, antidiabetes, and antimicrobial agent and as a nutritional supplement and the commercial future of various products.

Keywords Magic tree · Phytochemical · Therapeutic potential · Nutraceutical · Malnutrition

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Introduction

In our country, around 194 million people go hungry every day. The COVID situation created this scenario more tragic. Most of the population lack feasibility and affordability for sufficient and nutritious food to maintain their health, i.e., immunity. 50% of children and women from the tribal community are anemic. The COVID-mediated unemployment created a problem of food security among the poor; it will be fulfilled by some national programs but still, the nutrient insecurity problem remains as it is. During the COVID pandemic situation, the immunity booster remains a trending topic. Most of the promoted advertisements and posts of immunity boosting during pandemics nearly all have commercial interest. So there is an urgent need to provide people and make them aware of easily available natural green nutritious supplements available in their local area. This review will take account of commonly available nutritional supplements from the “*Moringa*” plant along with its pharmacological components; its potential as antioxidants, antimicrobial,

and anticancer agents; its mode of action; and its important commercial importance.

The food factors promoting human beings' health are related to their nutritional values. The term nutraceutical has been very familiar among the scientific community and public for a brief period after its coining by Stephen DeFelice in 1989 [1] for food with nutritional and pharmaceutical values. A nutraceutical is a substance that can be considered a food or part that, in addition to average dietary value, provides health benefits, including promoting health and preventing diseases like heart disease, cancer, hypertension, and diabetes [2].

Nutrients are the important metabolites for the growth and development of human beings obtained from food sources. Whatever food we are consuming in our routine, daily diet does not necessarily contain only the nutrients but may also contain antinutrients and toxicants. So based on these factors, we can easily categorize plants' food sources as edible or nonedible plants. The edible plant contains more nutrients and fewer toxicants or anti-nutrients, and the nonedible plant contains more toxicants and significantly fewer nutrients. Nutrients can be classified into macronutrients and micronutrients. Macronutrients are required in very high amounts for growth and development, including proteins, carbohydrates, and fats. Micronutrients are needed in less quantity, which contain vitamins and minerals.

In the nutraceutical approach, secondary plant metabolites play an important role in imparting medicinal value. Fruit, leaf, seed, etc. possess many pigments like chlorophyll, anthocyanins, and carotenoids, which are the derivatives of fats and flavonoids, whereas lycopene is derived from lycopene polyphenols. These pigments have antioxidant properties which reduce the risk of chronic diseases

like cancer. Along with this, alkaloids, flavonoids, flavanols, phenols, polyphenols, carotenoids, anthocyanins, contents of fruits, flowers, and other plant materials also provide very high health benefits. So many botanists, pharmacists, and food industrialists have taken an interest in their role in promoting human health.

The food rich in nutrient content, as well as secondary metabolites, comes in the category of nutraceuticals. Such foods provide nutrients for the average growth and development and provide high health benefits and prevent humans from chronic diseases. Recently, Meireles et al. [3] reported that *Moringa oleifera* improves the mental, emotional, energetic, and spiritual levels, which altogether have a strong effect on personality development. Similarly, *Moringa oleifera* had antidepressive and anxiolytic effects; hence, this tree is considered an adaptogenic and antistress herb [4, 5].

***Moringa oleifera* Lam**

Moringa oleifera is the magic tree found indigenous to northern parts of India but also located in other tropical and subtropical places. Traditional medicine found the use of *Moringa* leaves, flowers, seeds, and roots for centuries.

It is native to the sub-Himalayan region in the north of India, Pakistan, Africa, Asia Minor, and Arabia and has been introduced in other parts of the world. *Moringa* is the only genus present in the monotypic family Moringaceae, which includes 13 species (Table 1) distributed throughout the world [6]. It is found native to the range from Angola to Namibia and Egypt to Kenya, Madagascar, the Indian subcontinent, and Arabian Peninsula. In the Indian subcontinent, it is found in the range of NE Pakistan to NW India.

Table 1 Diversity of *Moringa* Species with habit and habitat

Species	Habit	Habitat	Native
1. <i>Moringa arborea</i> Verdc	Tree	Wild	N. Kenya
2. <i>Moringa borziana</i> Mattei	Shrub	Wild	Somalia to E. Kenya
3. <i>Moringa concanensis</i> Nimmo ex Dalzell and A. Gibson	Small tree	Wild	Pakistan to NW. India
4. <i>Moringa drouhardii</i> Jum	Tree	Wild	Madagascar
5. <i>Moringa hildebrandtii</i> Engl	Tree	Wild	Madagascar
6. <i>Moringa longituba</i> Engl	Shrub	Wild	E. and S. Ethiopia to N. Kenya
7. <i>Moringa oleifera</i> Lam	Small tree	Cultivated	NE Pakistan to NW India
8. <i>Moringa ovalifolia</i> Dinter and A. Berger	Tree	Wild	SW Angola to NW and W Central Namibia
9. <i>Moringa peregrina</i> (Forssk.) Fiori	Shrub	Cultivated	Egypt to NE. Tropical Africa, Jordan to Arabian Peninsula
10. <i>Moringa pygmaea</i> Verdc	Small shrub	Wild	NE. Somalia
11. <i>Moringa rivae</i> Chiov	Small tree	Wild	E. and SE. Ethiopia to S. Somalia and N. Kenya
12. <i>Moringa ruspoliana</i> Engl	Shrub	Wild	E. and S. Ethiopia to Somalia
13. <i>Moringa stenopetala</i> (Baker f.) Cufod	Small tree	Cultivated	SW and S. Ethiopia to Kenya

Due to its economic and medicinal properties now, it has been introduced to most parts of the world for cultivation purposes. Most of the species of *Moringa* are restricted in distribution and with very little information. They are represented by herbaceous plants to the huge tree as a life form. Only three species that are widely cultivated are *Moringa oleifera* (Fig. 1), *M. stenopetala*, and *M. peregrina*.

Macro Morphology

A medium-sized tree with spreading profuse branches. Stem covered with thick, corky whitish brown bark, which is fissured vertically. Leaves are tripinnately compound, 30–50 cm long. Rachis thickened and articulated at base; leaflets small, opposite, elliptic to obovate with entire margin, 1–2 cm long, mucronate or obtuse apex, glabrous on both surfaces, petiole sheathing at base. Flowers in large terminal or axillary panicles. Calyx 5, gamosepalous, cup-shaped, unequal 5-lobed segments, petaloid, linear-lanceolate 10.12 mm long, reflexed. Petals 5, spatulate, unequal, 10–15 mm long, creamy white. Stamens 5 alternating with 5–7 staminodes. Gynoecium tricarpeal, syncarpous, ovary oblong, style cylindrical. Pods pendulous, cylindrical to triquetrous, linear, straight, 9-ribbed, up to 50 cm long. Seeds 3 angled with wing [7, 8].

Flowers and Fruiting: Throughout the year, mostly from January to June.

Distribution: Very common and naturalized around the villages and cultivated.

Vernacular Names:

Marathi: Shevga or Mungana.

Gujarati: Midhosaragavo, Saragavo.

Hindi: Munga, Shajna.

Kannada: Nugge.

Konkani: Maissang.

Malayalam: Murinna, Sigru.

Oriya: Sajina.

Punjabi: Sainjna, Soanjna.

Sanskrit: Shobhanjana, Sigru.

Tamil: Murungai.

Telegu: Mulaga, Munaga.

Classification (APG-IV, 2016):

Eudicots.

Core eudicots.

Pentapetalae.

Superrosides.

Rosides.

Malvids.

Brassicales.

Moringaceae.

Presently the taste of *Moringa oleifera* leaves taste is not extensively studied, but it might be due to the uses and action of metabolites it has. It is present in a sweet and bitter taste. The sweet taste drugs can refill, reunite, encourage smelting, nurture, tonify, and mitigate pain. The bitter taste drugs can free, dry, clear the heat and eliminate the fire, persuade venting, reverse energy (qi), and move stool as per the traditional Chinese medicine (TCM) theory [3].

International *Moringa* Ingredient Market: Current and Future

The outstanding nutritional characteristics of the *Moringa* tree with its diverse parts such as seeds, leaves, bark, pods, flowers, and others are responsible for its expansion in the worldwide market. The bioactive components and

Fig. 1 *Moringa oleifera* Lam with flowers and pods



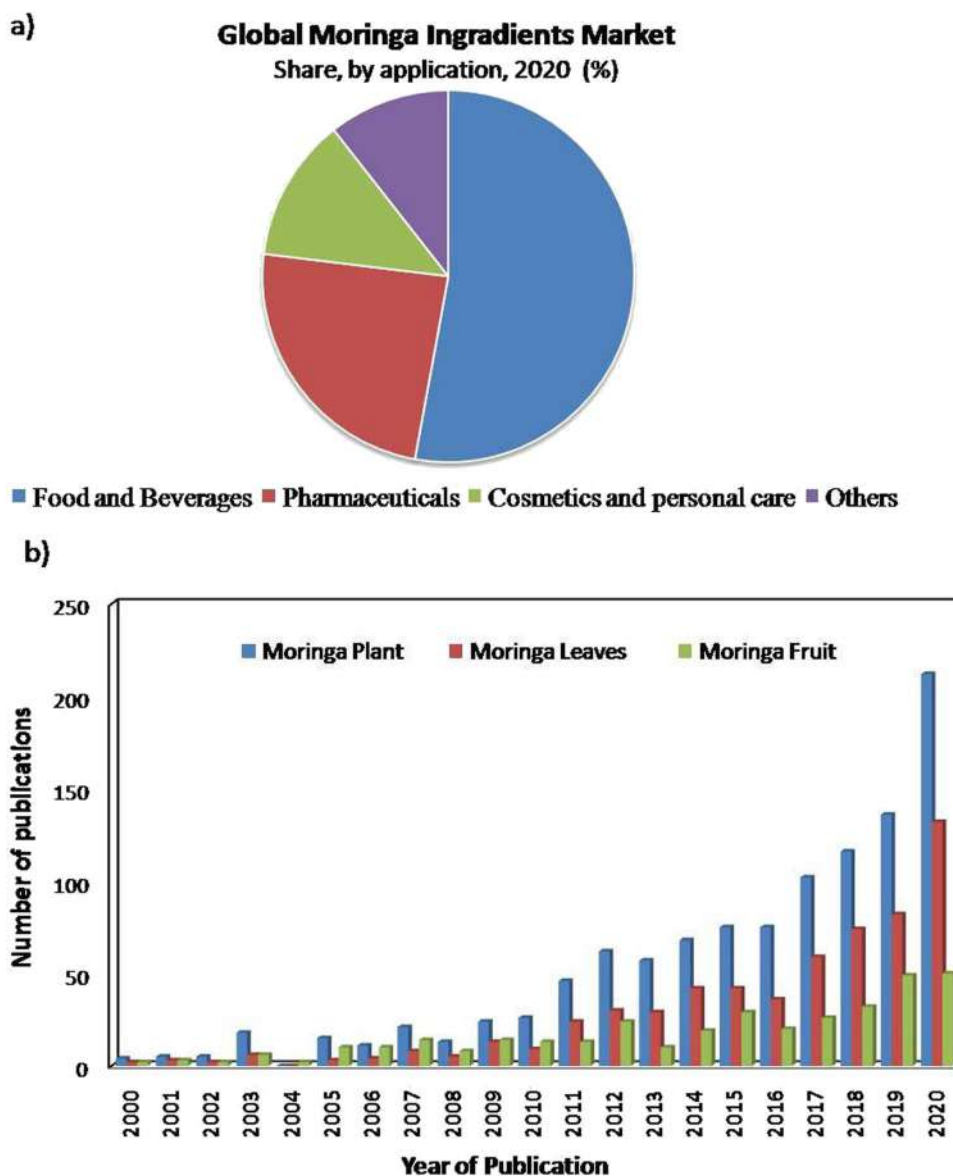
nutritional elements like carbohydrate, protein, calcium, vitamins, phosphorus, potassium, iron, beta-carotene make it more famous for a wide range of health concern regulars. *Moringa* components are also applicable in pharmaceutical fields due to their anticancer, antioxidant, antimicrobial, antiulcer, and properties.

The worldwide *Moringa* constituent marketplace was approximate 6.9 billion USD for 2020. The universal *Moringa* element market is likely to grow by 9.5% from 2021 to 2028 to reach USD 14,270.6 million at a compound annual growth rate by 2028 because of the growing demand for nutritional complements food along with pharmaceutical and cosmetics [9, 10] (Fig. 2a). The publications related to the use of *Moringa* and its parts have been increasing immensely in the last few years (Fig. 2b).

The Asia Pacific appeared as a major province with 45.8% in the year 2020 due to the increasing demand for dietary food constituents across the quickly budding economies of the area, extremely counting India. The key marketplace performer in the worldwide *Moringa* components market includes HNCO Organics Private Limited, Organic India Pvt Ltd., Earth Expo Company, KuliKuli, Inc., Botanica Natural Products, Grenera Nutrients Pvt Ltd, Aayuritz Phytonutrients Pvt Ltd., Moringa Initiative Ltd., Green Virgin Products LLC, Ancient Greenfields Pvt Ltd, and Dominate Industries.

The leaves are very much nutritious and are available in powdered form across the global market. The growing demand for dried *Moringa* leaves powder across the globe is primarily driving the market growth. As per the trend, the leaves of *Moringa* are reported for the maximum revenue share in the global market in 2020. Its leaves contain iron,

Fig. 2 a) Global *Moringa* ingredient market (source: [9]). b) Year wise publications on *Moringa* plant parts. Increase in the number of publications in last 20 years for *Moringa* and its plant parts indicating more emphasis on use of leaves



calcium, and potassium along with vitamin A, C, and E. Vitamin A assists in keeping healthy immunity, vision, and fetal growth.

The traditionally originated *Moringa* constituent counted for 53.5% of revenue share in 2020. Agriculture has tremendous use of synthetic fertilizers and pesticides while dealing with the altering ecological situation that can influence the output of the farmlands. Furthermore, the use of conservative seeds also takes the indemnity of quantitative manufacture of *Moringa* elements to farmers that sustain the high accessibility of traditional origin *Moringa* in the worldwide marketplace. The cosmetics and personal care sector deserve to witness a CAGR of 10.0% throughout the estimated period from 2020 to 2028. The growing demand for organic and non-synthetic contents in high-end cosmetics and individual goods is further boosting the growth over the period. The healthy and ecological profit of using natural and organic ingredients in cosmetics lessens the long-lasting counter effects on the skin from using artificial cosmetics. In addition, the utilization of organically originated *Moringa* elements is high in the cosmetics and personal care sector due to their sustainability and fewer chemical usages.

The growing *Moringa* market determined by France, the UK, Germany, and Italy may go beyond 2 billion USD up to 2025. The growing requirement for food complements to avoid illness may maintain local industry expansion. The rising insistence for *Moringa* tea in the area encourages weight loss, offers nutrition, assists in food absorption, and advances skin health which may promote commercial demand. Natural cosmetics are in high need in the USA and Canada, facilitating growth in the region.

The market is expected to practice the fastest CAGR of 10.1% in the Asia Pacific through the estimated timeframe from 2020 to 2028 [11]. The rising production and utilization of dietary and healthy grains regionally involve the regional market value. India, Japan, and China are estimated to lead this market size in the Asia Pacific at around 8% throughout the forecast period. The growing demand for nutritional supplements may accelerate the growth of this region. Market growth could be supported by the increasing number of major manufacturers using electronic media for product promotion.

Nutritional Composition of *Moringa* Leaves

Every part of *Moringa oleifera* is a depot of significant nutritious and nonnutritive components. *Moringa oleifera* Lam is a very important plant known to man for its vast diversified uses, so it is known by its popular name as the miracle tree. This is as well popularly known as drumstick, horseradish, or miracle tree. *Moringa* is an incredibly significant source of food, fiber, medicine, and other products. Although the

whole plant of *Moringa* is termed as a miraculous tree, it indicates that all part of *Moringa* has a beneficial effect on living organisms (Fig. 3). As the use of *Moringa* beans/pods is popular all over the world for vegetable purposes, its leaf application or nutritional potential is comparatively unnoticed.

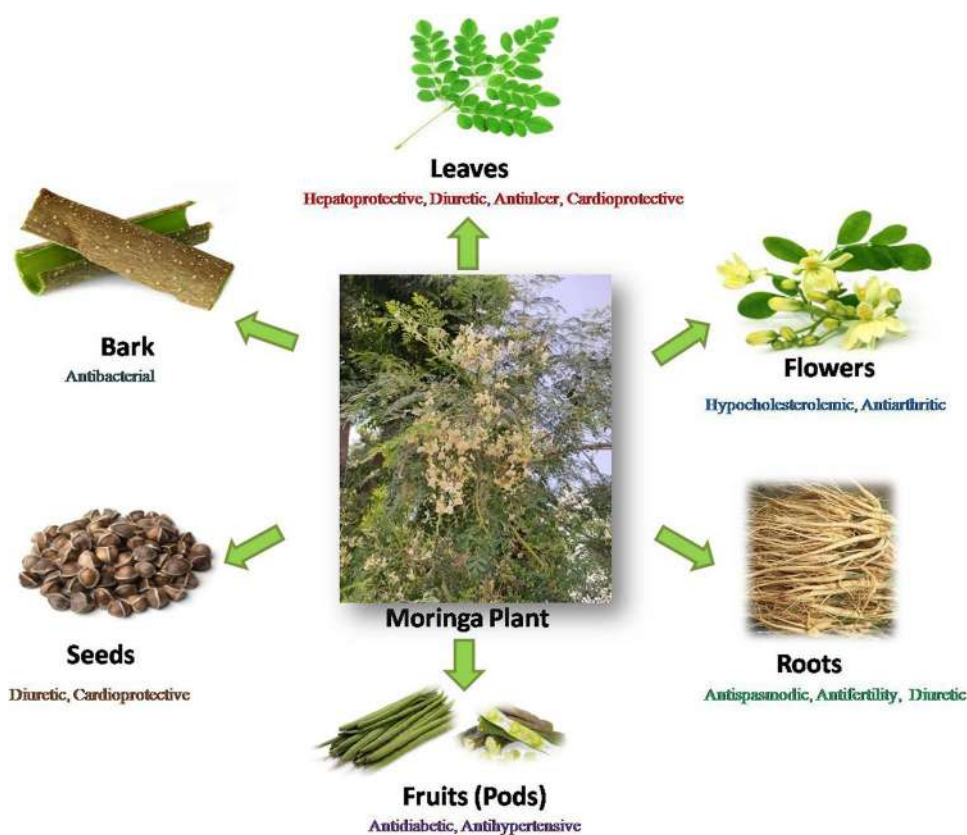
The published data on the nutrient content of this interesting plant is quite variable, both in terms of quantity of information and differences between published sources. Much of the variability is likely due to differences in soil, climate, plant age, and processing techniques such as drying emphasis on vitamin content. The substantial variation in the nutritional composition may be due to factors such as growth environment, stage of harvest, soil type, and method of processing.

Moringa oleifera leaf, despite low carbohydrate and fat, is an excellent source of protein and essential amino acids [12] and is viewed as a total dietary supplement. Moreover, *Moringa oleifera* contains a significant nutritional composition that is high in protein (19–29%) and dietary fiber (19–37%), with about 205–350 cal per gram [13, 14]. The leaves and seeds contain appreciable amounts of essential minerals, vitamins, amino acids, and fatty acids [14]. Apart from the micronutrients, like iron, magnesium, and folate, it also has B complex vitamins, such as B6, and vitamins A, C, and E [13]. Leaf, pod, and seed extracts contain a variety of phytochemicals that provide multifaceted nutrition, including vitamins A, B, C, D, and E, folic acid, pyridoxine, and nicotinic acid, which act as natural antioxidants [13, 15]. The leaves of *Moringa oleifera* contain a variety of minerals as well, such as potassium, zinc, magnesium, iron, sodium, calcium, and copper [16]. Proteins, vitamins A, D, C, E, folic acid, pyridoxine, and nicotinic acid as well as nutrients such as essential amino acids, antioxidants, flavonoids, and isothiocyanates are abundant in *Moringa oleifera*. [17, 18].

The minerals requisite for development and growth are present in *Moringa*, like calcium. *Moringa* leaves powder is a wealthy resource of calcium than milk. It also has iron which could be an alternative source in the treatment of anemia due to iron deficiency compared with beet and spinach [19]. Likewise, it contains vitamin C, vitamin A, protein, and potassium in comparison with oranges, carrots, yogurt, and bananas, respectively [10]. Zinc is essential for the good growth of sperm cells and as well as required for DNA and RNA synthesis. *Moringa oleifera* leaves fulfil the daily intake need of zinc from the diet (25.5–31.03 mg/kg) [20].

PUFAs are linoleic and linolenic acids; these PUFAs have the ability to control cholesterol. Research shows that *Moringa* seed oil contains around 76% PUFA, making it ideal for use as a substitute for olive oil [21]. The noteworthy point is that nutrient components change as per the location. Season also influences nutrient content [19]. It was shown that vitamin A

Fig. 3 *Moringa oleifera* plant parts and uses



was found abundantly in the hot-wet season, while vitamin C and iron were more in the cool-dry season [22] (Table 2).

Phytochemical Analysis

Moringa has several phytochemicals like tannins, alkaloids, sterols, anthraquinones, terpenoids, flavonoids, saponins, and reducing sugar [23••]. The useful properties of *Moringa oleifera* are mainly related to its bioactive phytochemicals like flavonoids or isothiocyanates. *Moringa oleifera* is rich in simple sugar rhamnoses novel cluster compounds like glucosinolates and isothiocyanates [27]. *Moringa*'s various phytochemicals include glucosinolate, phenolic acid, terpene, niiazirin, niiazinin, gossypetin, quercetin sitosterol, ascorbic acid [27], and so on (Fig. 4). The variation is observed as per the plant part and extraction process (Table 3).

Pharmacological Components of *Moringa* Leaves

Besides various nutritional components, *Moringa oleifera* Lam leaves contain abundant pharmacological and medically important chemicals belonging to phenol and flavane, glucosinolates, isothiocyanates, and alkaloids, i.e., catechins,

chlorogenic acid kaempferol, quercetin, apigenin, gallic acid, ferulic acids, niiazicin, niiazirin, rosmarinic acid, murimocides, and cyclophosphamides (Fig. 4), having antidiabetic, antioxidant, antitumor, and antimicrobial activity (Fig. 5).

Various pharmacological functions of *Moringa oleifera* extract have been reported, such as anti-inflammatory, neuroprotective, anticancer, hepatoprotective, antioxidant, and blood lipid-lowering effects [28]. Additionally, studies have been conducted for its medicinal value in treating diabetes, rheumatoid arthritis, atherosclerosis, infertility, pain relief, depression, and diuretic and thyroid disorders [17, 33].

Moringa Leaf Potential Performance in Clinical Trials

In clinical trials, 90% of respondents experienced no side effects when *Moringa oleifera* has given along with HIV drugs [34]. In a pilot clinical study, *Moringa oleifera* leaf powder reduced post-prandial glycemia in diabetic patients [35]. Phenolics and other antioxidant substances in the blood reduce Blood glucose levels. Several studies showed that *Moringa* leaves could cure both types of diabetes. The inhibition of pro-inflammatory mediators and increased antioxidant level confirmed *Moringa* leaves are a potent antidiabetic agent [36]. *Moringa oleifera* leaf

Table 2 Nutritional composition of *Moringa oleifera* leaves (changes as per geographical locations, climate and environmental factors)

Nutritional component	Concentration range	Reference
(g/100 g)		
Carbohydrates	13.41–63.11	[23•]
Protein	10.74–30.29	[23•]
Crude fiber	7.09–35.00	[23•]
Fat	6.50–20.00	[23•]
Ash	7.64–10.71	[23•]
Vitamins (mg/100 g)		
Vitamin C	15.2	[24]
Vitamin A	6.80	[25••]
Vitamin B1	0.326	[24]
Vitamin B2	20.5	[25••]
Vitamin B3	8.2	[25••]
Vitamin E	113	[25••]
Minerals (mg/100 g)		
Calcium	2003	[25••]
Potassium	1317–2025	[26]
Phosphorous	204	[26]
Magnesium	368	[25••]
Copper	0.07	[25••]
Iron	0.85	[25••]
Zinc	1.00–3.10	[23•]
Manganese	8.68	[23•]
Sulphur	870	[25••]
Total amino acid	76.40	[23•]
(g/100 g)		
Total saturated fatty acid (%)	58.00	[23•]
Total carotenoids (β -carotene)	1.108 \pm 0.12	[24]
(mg/100 g)		

extract suspension at 50 mg/5 ml exhibit a significant decrease in serum glutamate oxaloacetate transaminase and glutamate pyruvate transaminase confirming hepatoprotective activity in oral drug formulation [37].

The phytochemicals glucosinolate glucomoringin and isothiocyanates moringin from *Moringa* leaves after myrosinase enzyme hydrolysis exhibited effective antioxidant and anti-inflammatory activity in clinical trials [38]. *Moringa oleifera* leaf extract-loaded alginate-pectin (SA-PC)-based film dressing for wound healing application containing vicenin-2, chlorogenic acid, gallic acid, quercetin, kaempferol, rosmarinic acid, and rutin showed the highest human dermal fibroblast and human keratinocytes cell proliferation and migration properties [37]. Moreover, further clinical trials on the medicinal properties of *Moringa* leaves are required to measure their safety for human utilization [39].

Health Benefits of *Moringa*

Moringa oleifera Lam (syn. *M. pterygosperma*) generally reputed as “the miracle tree,” “horseradish tree,” or “Ben oil tree” is the most familiar and widely dispersed species of the Moringaceae family and has a remarkable array of medicinal uses with high nutritional value throughout the world.

Each part of this plant has been consumed for a long time by human beings and applied for diverse domestic intentions like domestic water treatment, alley cropping, biogas, animal fodder, fertilizer, spraying nutrients for plants, green manure, gum (from tree trunks), juice-clarifier for sugar cane and honey, tannin for tanning hides ornamental use, biopesticide, pulp, oil for machine lubrication, rope, and perfume making, and hair care stuff [40].

Moringa has many important vitamins and minerals. It also contains various minerals, iron, protein, and fiber that retains body healing and muscle building. It has antioxidant compounds which protect the cells from damage and enhance the immune power. Antioxidants work to lower blood pressure and fat reduction.

Anciently *Moringa* leaves and natural products are utilized in periodic diet to maintain the mental health and smoothening of skin [41]. Every part of *Moringa* has importance as medicine, nutraceutical, water treatment, and oil preparation [32].

The *Moringa* flowers, unripened fruits, and leaves are utilized worldwide for cooking [42]. Majorly these are utilized for human beings and animal purposes for getting nutrition and disease treatment [18]. Although it is extensively utilized for consumption and the medical point of view (Table 4), very few clinical trials were run to prove the efficiency for malnutrition cure and therapeutic action of *Moringa* leaf and other products in human beings [24].

Medicinal Properties of *Moringa* Leaves

Besides various nutraceutical potential of the leaves having high medicinal properties, the recent reports revealed the therapeutic potential of *Moringa* leaves (Fig. 3a and b, and Tables 3 and 4). The important applications of leaves are categorized in the major fields as below:

1. Antimicrobial potential
2. Anticancer potential
3. Antidiabetic potential and Antioxidant potential

Anticancer Potential of *Moringa*

Besides the antimicrobial effect of *Moringa* leaves, seeds, and roots, *Moringa* is also reported for its antiproliferative activity. Different extracts of *Moringa* induced the reactive

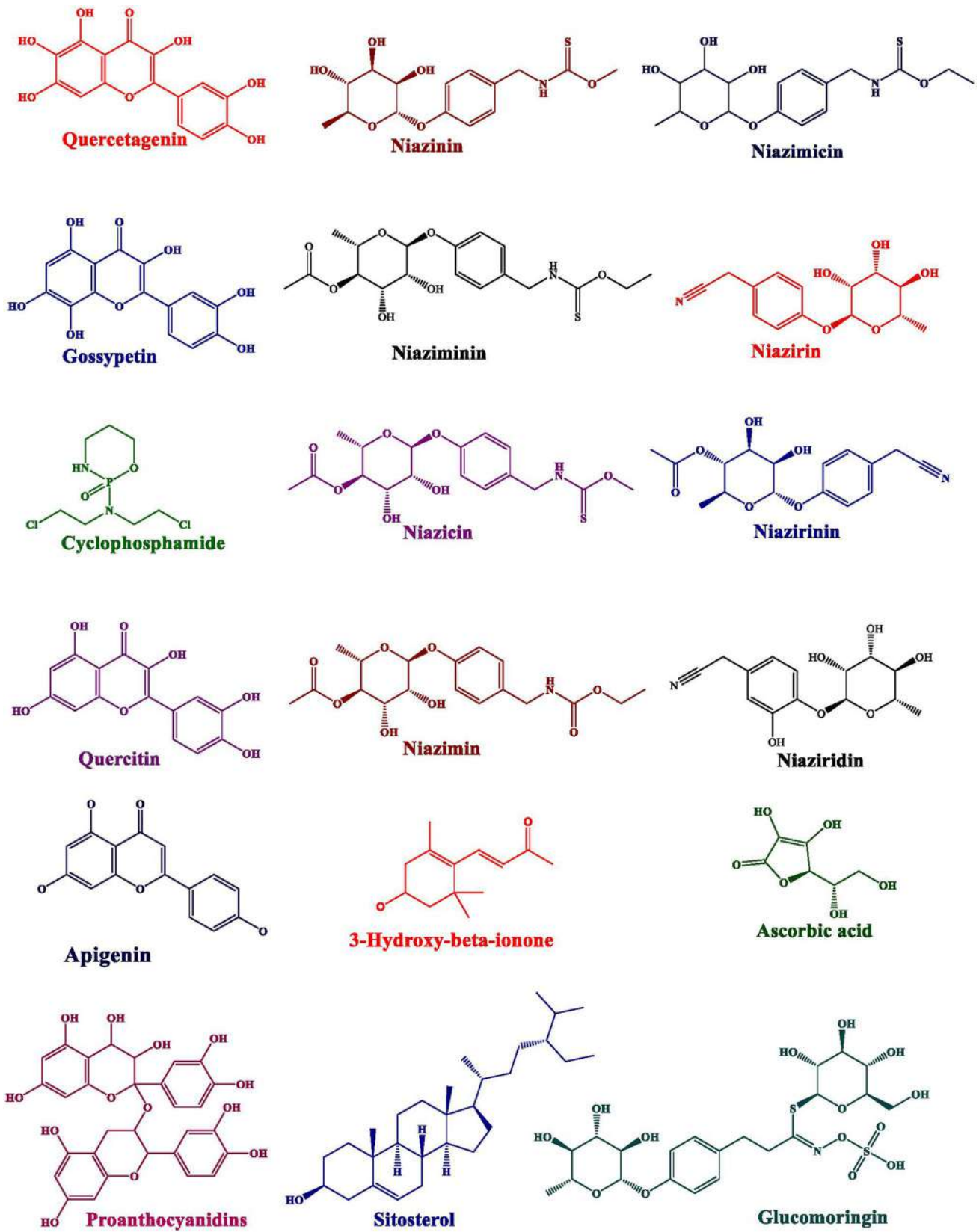


Fig. 4 Molecular structure of diverse phytochemical of *Moringa* plant

Table 3 Phytochemical analysis of *Moringa oleifera* plant parts (changes as per geographical locations, climate and environmental factors)

Plant part	Phytochemical	References
Stem bark	Alkaloids: moringine, moringinine, vanillin, β sitosterol, 4-hydroxymellin, octacosanoic acid	[28]
Flower	Amino acids, sucrose, D-glucose, alkaloids, wax, quercetin, kaempferol, alkaloids, rhamnetin, iso-quercitrin, kaempferitin	[28]
Leaves	Isothiocyanates, total polyphenols, flavonoid, omega-3 and 6-PUFA, E-lutein	[29, 30]
Fruits	Cytokinins, glucosinolates (glucomoringin), and isothiocyanates, E-lutein	[26, 28–31]
Seeds	O-ethyl-4-(α -L-rhamnosyloxy) benzyl carbamate, 4-(α -L-rhamnosyloxy) benzyl isothiocy-anate, niazimicin, 3-O-(6'-O-oleoyl- β -D-glucopyranosyl)- β -sitosterol, β -sitosterol-3-O- β -D-glucopyranoside, niazirin, β -sitosterol, glycerol-1(9-octadecanoate), glucosinolate, quercetin, isorhamnetin	[28, 32]
Roots	Benzyl glucosinolate (glucotropaeolin), quercetin, and isorhamnetin	[32]
Whole gum exudate	L- arabinose, galactose, glucuronic acid, L- rhamnose, mannose, xylose	[26, 28, 29]
Pod extract	Thiocarbamate, isothiocyanate glycosides, monounsaturated fatty acids	[28, 32]

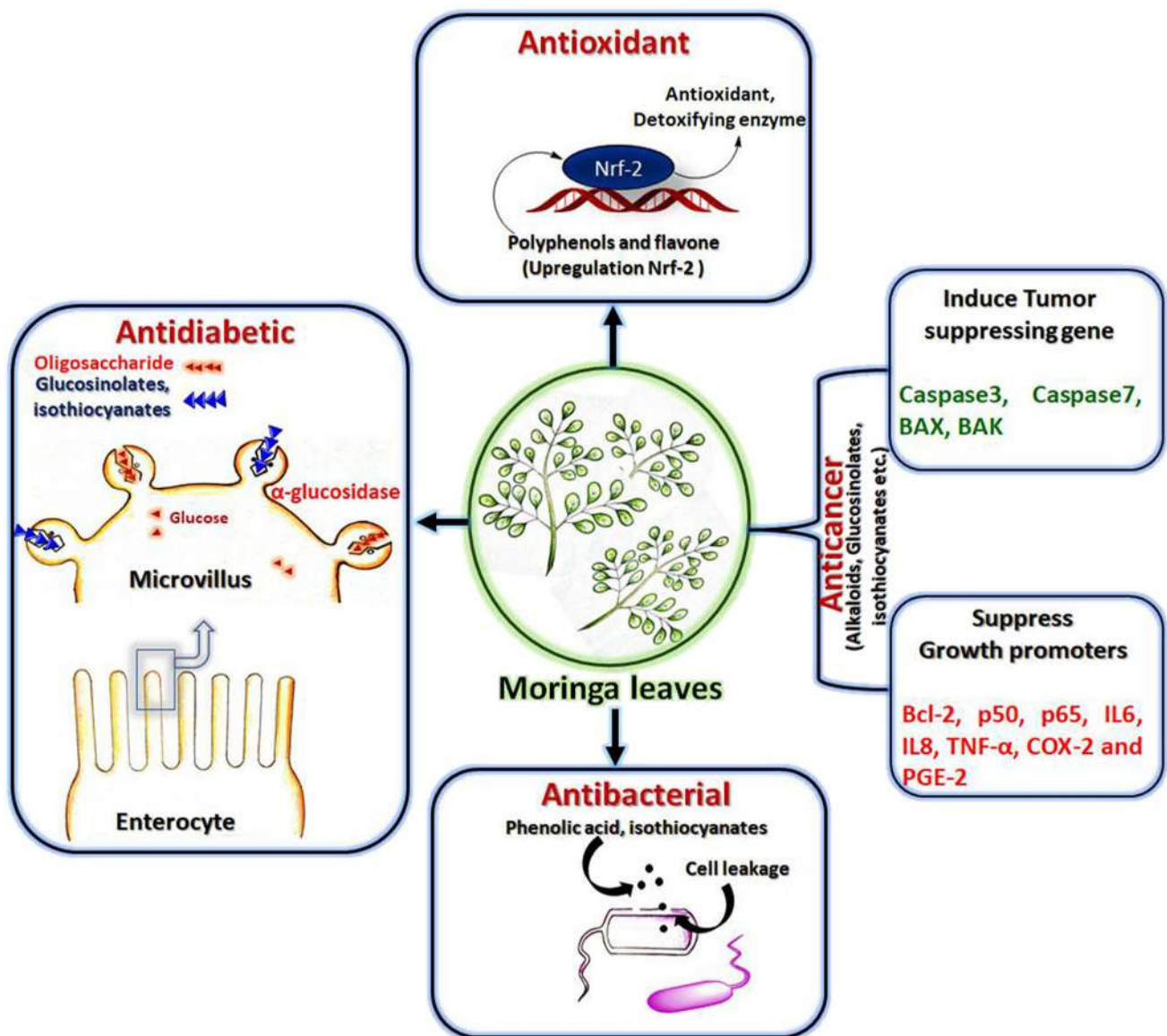
**Fig. 5** Pharmacological activities of *Moringa* with mechanism of action

Table 4 Summary of *Moringa* plant part metabolites for medicinal uses

Plant part	Identified metabolites	Medicinal use	Reference
Leaves	-	Neuroprotective effect by promoting neuronal survival and outgrowth	[31]
	Flavonoids	Useful in Alzheimer's disease	[31]
	Niaziridin	Leaf extract alters the brain monoamine levels and electrical activity	[31, 43]
	-	Hypocholesterolemic, antihyperglycemic, antihypertensive, and hepatoprotective activities	[44, 45]
	Gossypetin, quercetin, and proanthocyanidins, 4-(α -L-rhamnosyloxybenzyl)-O-methyl thiocarbamate	Anti-inflammatory agents	[45–47]
	Niazimin, niaziminin, niazimin, niazirin, niazicin, niazirin, niazirin 4-[(4'-O-acetyl- α -rhamnosyloxy)benzyl], isothiocyanate, glucomoringine, isothiocyanates, nitriles, and thiocarbamates	Cardioprotective drug; it actively alters the circulatory system/capillaries and reduce mortality and morbidity as a consequence of coronary heart diseases	[28, 48–50]
	Cyclophosphamide	Hypotensive and bradycardiac activities attributed to and useful in blood pressure problems	
	Ascorbic acid (vit. C), β -carotene, quercetin, kaempferol, phenolic acids	Immunomodulator and immune protective activity which is responsible for the immunosuppression as it mediates the cellular and humoral immunity	[51]
	Quercitin	Antioxidant	[52, 53, 54]
	Seeds	-	Hepatoprotective and antispasmodic, well-known flavonoid found in the roots
Vitamin A		Anti-tumor and anti-malignancy cytotoxicity behavioral activity could be observed in the extract derived from the stems and seeds	[28]
Root and leaves	-	Useful in vitamin A deficiency night blindness	[56, 57]
	Niaziminin	Antispasmodic activity	[58]
Sitosterol	-	Antitumor activity, cytotoxic effects on human multiple myeloma cell lines, inducing carcinogen hydrolyzing enzymes in the liver	[59–61]
	-	Cholesterol-reducing effect in mammals	[62]

“-” unidentified metabolite

oxygen species in cancerous cells, which resulted in apoptosis. It was also proved that *Moringa* extracts regulate the caspase3 and caspase 9 in the apoptotic pathway [63–65]. Tiloke et al. [66] reported the inducing effect of crude extract of *Moringa oleifera* on enzymes like glutathione S transferase, which inhibit the antioxidants system and make it an ideal anticancer agent. Besides this production of oxidative stress in a mouse model, the *Moringa* extract was reported to inhibit human hepatocellular carcinoma (HepG2) cells and A549 cells. The *Moringa* extract at 50 µg/ml of dose resulted in 70% reduction in HepG2 cells colonies. This was further revealed as a result of DNA damage [66]. HepG2 and A549 cells were decreased by 60% and 50% with *Moringa* leaf extract (maximum dose of 200 mg/kg). There was a significant inhibition compared with the standard anticancer agent, i.e., doxorubicin.

Nair and Varalakshmi [67] proved that hot water extract of *Moringa* leaves causes inhibition of cervical cancer cells (HeLa cell line) and reported IC_{50} 70 µg/ml, while other solvent extracts like methanol hexane have not shown any significant activity against the cancerous cell.

Various primary studies for a different solvent extract of *Moringa* leaf as an anticancer agent showed significant results. Paravathy and Ummaahshwari [59] reported different *Moringa* leaf extracts, i.e., methanol, ethanol, ethyl acetate, and chloroform, against the human B-lymphocyte plasmacytoma—U266B1 cell line. U266B1, the methanol extract, showed the highest cytotoxic and antiproliferative activity against the cancerous cell. They reported at a very small concentration, and ethanol shows inhibition cells, i.e., IC_{50} : 0.32 µg/ml.

Besides these, *Moringa* leaves ethanol and hot water extract reported in vitro anticancer activity against HepG2 cells and primary leukemia cells of the patient, i.e., acute lymphoblastic leukemia (ALL) and acute myeloid leukemia (AML) [68].

Krishnamurthy et al. [69] reported Dalton's lymphoma ascites (DLA) in a mouse model, showing ethyl acetate extract of *Moringa* leaves has an effective anticancer potential than the 5-fluorouracil treatment.

Moringa supplementation alone did not diminish tumor growth compared to chemotherapy solely and, in the blend, exacerbated tumor succession. *Moringa* supplementation solely decreased angiogenesis; however, this outcome was abrogated combined with chemotherapy [70].

The distribution of apigenin in the *Moringa* plant is wide, as it has been found in many parts, especially in leaves. Apigenin is one of the important major flavonoids which are extensively studied for their biological actions on different aspects like health [47•] and is a chemotherapeutic agent for cancer [71]. Apigenin is well studied for its biological potential, which includes antioxidant, antimutagenic, anticarcinogenic, anti-inflammatory, antiproliferative, and

antiproliferative [72]. It acts as a moderate antioxidative agent due to its specific structure like the presence of the double bond at 2 and 3 carbons, absence of hydroxyl groups at 3, and the presence of catechol structure in ring B. It was also found to arrest transcriptional activation of inducible COX-2 (cyclooxygenase) and production of nitric oxide synthase in macrophage cell lines like, i.e., RAW 264.7, induced by lipopolysaccharides (LPS). Apigenin was also reported to inhibit nitric oxide induction by the gamma interferon stimulations [73, 74].

Similarly, apigenin reported neutralizing virulence factors such as alpha hemolysin activity produced by *S. aureus* and offers protection to human alveolar basal epithelial cells (A549 cells) [75].

The *Moringa* leaf extract was found to induce apoptosis and interfere in the G2/m phase of the cycle of the SSC15 cell line, also found to inhibit colony formation. The tested extract induced apoptosis by inducing upregulations of cleaved caspase-3, Bax cell migration, and downregulation of antiapoptotic B cell lymphoma 2 (Bcl-2). The fractionated leaf extract containing 3-hydroxy-ionone showed an inhibitory effect on the tested SCC15 cell line by the same mechanism.

Moringa leaf extract provides anti-inflammatory potential by reducing the production of pro-inflammatory mediators such as interleukin-6 and tumor necrosis factor- α [76, 77]. The compound like 3-hydroxy- β -ionone (3-HBI) found in the leaves has been reported for its potential as an anti-inflammatory and also found to be responsible to enhance apoptosis and inhibition of hepatocellular carcinoma, i.e., Hep G2 and lung cancer cell A549 which inhibited tumor cell growth in human non-small cell lung cancer A549 [39,40].

In another study, it was also proved that the *Moringa* leaf extract contains mixtures of compounds such as allose, isothiocyanate, and other flavonoids, and their esters cause apoptosis of breast cancer and colorectal cancer cell lines [78]. Similarly, the *Moringa oleifera* leaf extract containing astragaloside and isoquercetin is responsible for the suppression of colon cancer, i.e., HCT116 colon cancer cell lines, by controlling regulations of ERK1/2 protein kinases that catalyze the phosphorylations of human ERK1/2 at Thr204 /187 which has a vital role in various process in cell migration and cell cycle progressions [79].

Similarly, glucomoringin of *Moringa oleifera*-induced leaves controls the oxidative stress and apoptosis in human astrocytoma grade IV CCF-STTG1 cells by activation inducing accumulations of p53 in the cytoplasm of the cell and further causes oligomerizations of Bcl-2 protein Bax and Bcl-2 inhibition in human astrocytoma cancer cell line IV (CCF-STTG1) [80]. The apoptosis of SH-SY5Y human neuroblastoma cells was observed by *Moringa oleifera* leaf extracts by modulating nuclear factor-kappa B (NF- κ B), a

transcriptional regulation factor responsible for the regulation of innate immunity [81].

Antidiabetic Activity and Antioxidant Activity

Diabetes is a chronic lifestyle disease in which the pancreas cannot produce enough insulin or formed insulin is not used by the body, which regulates the body's sugar. This uncontrolled raised sugar condition damages many vital body systems such as circulatory neuronal. As per WHO, the number is ever increasing as a function of time; e.g., in 2014, 8.5% of adults aged 18 or more had diabetes but in 2019, and 1.5 million of death took place by direct diabetes. The serious thing is that 48% of deaths occur before 70 years [82]. This report indicates the alarming situation of diabetes, and on this background, the importance of the *Moringa* plant increases because of the significant reports on its ant diabetes potential. Besides these, the major problem in diabetes is the degeneration of neurons due to damage by free radicals produced in diabetic conditions. The *Moringa* plant is extensively studied for its antidiabetes potential and has been shown to have the potential to cure both types I and II diabetes. The aqueous extract of *Moringa* leaves was reported for curing streptozotocin-induced type I and II diabetes in a rat model.

Streptozocin in *Moringa* resulted in ATP dephosphorylation and xanthine oxidase action, resulting in free radicals' development in beta cells leading to cell dysfunctioning. This leads to the entry of high glucose in mitochondria and further production of reactive oxygen species as beta cells are already damaged. They cannot neutralize the toxic stress of oxygen and cause apoptosis of beta cells [83]. The flavonoids and vitamins in *Moringa* leaves act as free radical scavengers and protect beta. The primary two metabolites, quercetin and kaempferol, in *Moringa* leaves recover the damaged beta cells and maintain their natural morphology and functions after water extracts treatment in the streptozocin-induced rat model [84]. Similar recovery *Moringa* extract treatment was reported by [85]. In streptozocin-induced rat models, Khan et al. [85] also supported that *Moringa* leaf treatment restores all vital metabolism, i.e., sugar level, hepatic enzymes, and lipid profiles, in streptozocin-induced rat models.

Yassa and Thoimi [86] found in artificial diabetes-induced model rat that the significant effect was an increase in serum glucose, potassium, sodium, creatinine uric acid, and albumin level, which further leads to diabetic nephropathy, i.e., disturbed glomerular infiltration and elevated blood pressure. *Moringa* leaf diet in the rat model significantly reported increased serum protein content and decreased extra urea and creatinine in the blood [87]. *Moringa* was

also proved as a neuroprotectant. In cerebral ischemia, the obstruction of blood flow to the central nervous system is occurred and leads to lipid peroxidation and free radicals formation; it was reported that the *Moringa* leaf extract reduces these effects by scavenging free radicals and protecting CNS [88]. Besides these, *Moringa* leaf extract treatment resulted in improving the cholinergic function.

A protein Mo-LPI isolated from *Moringa* leaves showed antihyperglycemic activities in alloxan-induced mice at a dose of 300 or 500 mg/kg administered intraperitoneally [89]. Azad et al. [90] found an ethanolic extract of *Moringa* leaves changed the hyperglycemic condition of diabetic rats after 30, 90, and 120 min at a 500 mg/kg dose compared with glibenclamide (0.5 mg/kg) as a reference drug or water (control), with a glucose solution (2.5 g/kg) in 12-h fasted diabetic rats. Similarly, ethanol and butanol extract of *Moringa* at 1000 and 500 mg/kg, respectively, most actively reduced the blood glucose level acutely in diabetic rats [91].

The flavonoids and phenolic acid extracts of *Moringa* leaves decreased intestinal absorption of glucose and advanced glycation by inhibiting the activity of pancreatic α -amylase and intestinal α -glucosidase [92, 93]. Thus, it reduces directly the risk of developing diabetes mellitus and maintains the glucose levels in prediabetic and diabetic patients.

Antimicrobial Potential of *Moringa* Leaves

Antibiotic resistance is the major problem of the current era. The majority of infectious agents becomes resistant to available antibiotics due to the indiscriminate use of antibiotics responsible for this forever resistance against the chemotherapeutic agents and antibiotics. There is a necessity to find new antimicrobial agents having multiple actions. *Moringa* leaves contain various bioactive compounds, and its multiple extracts were well documented for their various antibacterial, antifungal, antiviral, and antiparasitic potential. However, some reports advocate that the *Moringa* leaves containing chemical metabolites like

pterygospermin, moringine, and benzyl isothiocyanate were responsible for antimicrobial actions, significant reports are available on crude leaf extract (Table 5).

Apigenin is considered as a future green chemical to fight against the antibiotics resistance problem because the enhanced activity of some apigenin derivatives found to be most effective against both Gram-positive and Gram-negative bacteria such as *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa* [72].

It was also reported for its potential antiviral potential against the herpes simplex virus HSV-1 and HSV-2, hepatitis C virus, influenza virus; hand, foot, and mouth disease virus; and African swine fever virus (ASFV) [72].

Table 5 *Moringa* plant parts for antimicrobial potential

Plant part extract	Antimicrobial activity against pathogen	Reference
Ethanol extracts of seeds and foliage	<i>Escherichia coli</i> , <i>Klebsiella pneumonia</i> , <i>Proteus mirabilis</i> , <i>Pseudomonas aeruginosa</i> , and <i>Staphylococcus aureus</i> <i>Candida albicans</i> , <i>Aspergillus fumigatus</i> , <i>Cryptococcus neoformans</i> , <i>Trichophyton rubrum</i> , <i>Trichophyton mentagrophytes</i> , <i>Epidermophyton floccosum</i> , and <i>Microsporum canis</i>	[94, 95]
Ethanol/water extracts of seeds and foliage	<i>E. coli</i> , <i>S. typhi</i> , <i>P. aeruginosa</i> , <i>E. cloacae</i> , <i>P. vulgaris</i> , <i>S. aureus</i> , <i>M. kristinae</i> , <i>E. aerogenes</i> , <i>Shigella</i> , <i>B. cereus</i> , <i>Streptococcus-B-haemolytica</i> , <i>B. subtilis</i> , <i>K. pneumonia</i> , <i>B. megaterium</i> , <i>S. lutea</i> , <i>B. sterothermophilus</i> , <i>S. pyogenes</i> , <i>V. cholera</i> , <i>S. entridi</i>	[96, 97, 98, 94, 99, 100, 101, 102]
Seed extract	HSV-1	[103, 15]
Leaves	Epstein-Barr virus (EBV), HIV, and HSV-1	[104–107]
Seed flour extract	<i>Bacillus cereus</i> , <i>Staphylococcus aureus</i> , <i>Escherichia coli</i> and <i>Yersinia enterocolitica</i> , <i>Candida albicans</i>	[108], [95]
Ethanol extracts of seeds and foliage	Anti-dermatophytes: <i>Trichophyton rubrum</i> , <i>Trichophyton mentagrophytes</i> , <i>Epidermophyton floccosum</i> , and <i>Microsporum canis</i>	[109, 110]

The catechin, epicatechin, and Vallin-like phenols and vicinin-like anthocyanates, and glucosinolate are abundantly reported in *Moringa* leaves. These all compounds are lipophilic in nature which may be responsible for antimicrobial activity reported for leaf extract in different reports. The lipophilic character of phenolic compounds enhances their antimicrobial activity by favoring their interaction with the cell membrane and other lipophilic cell components [111]. The interaction causes permanent changes in the cytoplasmic membrane and aggregations of cell contents which results in the dysfunction of channels and enzymes. It was reported that tanning and phenylpropanoid condensed cell content lead to disruption of channels, membrane parts, and vital enzymes of metabolism [112–114]. Borges et al. [2013] reported phenolic acids to cause disruption of cytoplasm membrane integrity and causes the breakdown of osmotic balance and cell integrity by leaking essential intracellular constituents.

Bouarab-Chibane et al. [115] previously reported the antibacterial potential of plant polyphenols against various food pathogen, *L. monocytogenes* ATCC19115, *B. subtilis* ATCC6633, and *S. aureus* CNRZ3, and three Gram-negative ones, *P. aeruginosa* ATCC2785, *S. enteritidis* E0220, and *E. coli* ATCC25922. This inhibitory action may be due to the potential of polyphenol to alter the outer membrane [116].

Rahaman et al. [97] reported various solvent extracts of *Moringa oleifera* that showed growth arrest of Gram negative pathogenic bacteria such as *S. dysenteriae*, *E. coli*, *Klebsiella pneumoniae*, *Enterobacter* sp., and *Salmonella* sp. and antistaphylococcal potential as similar to tetracycline. The ethanolic extract reported against the *Vibrio parahaemolyticus*, *Aeromonas caviae*, and *Enterococcus faecalis*.

Besides, these isothiocyanates were reported from *Moringa* leaves [74], and these compounds are well documented for their biological activities such as antimicrobial

and antioxidant. Glucomoringin and various metabolites from *Moringa oleifera* are documented for its anti-inflammatory, antioxidant, antibacterial, antifungal, and antiviral potential [64, 80, 117].

Various isothiocyanates showed high antimicrobial potential by different mechanisms such as membrane integrity, inhibiting bacterial quorum sensing, etc. [118, 119]. The Iberian from *Moringa oleifera* was also reported for inhibiting *E. coli*, *P. aeruginosa*, and *S. aureus* [97].

Still, there is a need to find the antimicrobial potential of specific pure compounds isolated from *Moringa* leaves. There are controversial reports, i.e., Buker et al. [109] reported the antimicrobial activity of *Moringa* leaf extract in ethanol, water, and chloroform against the *Staphylococcus aureus* and six Gram-negative bacteria (*Escherichia coli*, *Salmonella typhi*, *Enterobacter aerogenes*, *Salmonella typhimurium*, *Shigella* spp.) while there is no inhibition was observed at any tested concentration. But the *Moringa* leaf extract showed significant antifungal potential against *Mucor* spp. and *Rhizopus* spp. Similarly, Pinal et al. showed aqueous and ethanol *Moringa* leaf extract to have a high potential to inhibit *Candida tropicalis* and *Saccharomyces cerevisiae*. Still, *Candida albicans* showed resistance to these extracts. Similar results were observed of *Moringa* leaf extract against *Aspergillus flavus*, *Aspergillus fumigates*, *Aspergillus niger*, *Cryptococcus neoformans*, and *Candida albicans* [120, 121].

Moringa Against Coronavirus Infections

Surprisingly, in light of the novel universal and striking circumstances surrounding the coronavirus, scientists advised using a high dosage of bitter and cold herbs to clear heat and detoxify the infectivity in its early beginning, as well

as to cool blood and eradicate blood stasis quickly in the middle and late stages. [122]. *Moringa oleifera* leaf has a sweet and bitter taste, as well as a cool, venting, and dehumidifying inductor with successor impact. Due to this, it is an ideal choice for treating the disease's deep general immunological abnormalities. When integrated with conventional medicine, it is feasible to hypothesize a sufficient and supportive therapy for coronavirus infection [3]. Kaempferol, pterygospermin, morphine, quercetin, and apigenin are some of the *Moringa* components that play a role. Apigenin has the highest anti-SARS activity against MPro-Cov-2 [123]. In a molecular docking simulation investigation, three flavonoids, isorhamnetin, kaempferol, and apigenin, demonstrated excellent binding empathy stable protein–ligand complexes with high binding energy and alike binding poses in contrast to recognized SARS-CoV-2 Mpro inhibitor baicalein [124]. *Moringa* flavonoids, rutin, and isorhamnetin-3-O-rutinoside are potent to hinder the SARS-CoV-2 selected target main protease (Mpro), as reported in a dynamic simulation study, authenticated by in vivo and in vitro studies [125].

Industrial Applications

Moringa leaves, seeds, and flowers show insecticidal, larvicidal, and ovicidal activity against the *Anopheles stephensi* and *Aedes aegypti* vector species [126, 127]. Besides, the water extract of *Moringa oleifera* seeds has antilarvicidal potential against *A. aegypti*. The methanol root extract effectively controls the mosquitoes *Culex quinquefasciatus* and *Aedes albopictus*, vectors of nematodes and viruses of public health importance, respectively [40].

Moringa oleifera seeds also have natural coagulation potential for the water effluent treatment in common water supply for clarification, lessening the microbial load, and managing helminths like *Schistosoma mansoni* [128]. The coagulant activity of *Moringa oleifera* seeds is due to the water-soluble lectin having the flocculation and sedimentation potential. *Moringa oleifera* seeds show a 90% decrease in turbidity and color of polluted water and a 90–99% decline in the bacterial load [129]. *Moringa oleifera* crude, ethanol, and aqueous extracts are used for water treatment and reduction of microbial load in fish, prawn, and shrimp farming [98]. The antibacterial and antifungal activity of *Moringa oleifera* against opportunistic zoonotic pathogens is significant due to heavy economic losses in aquaculture along with community health concerns. The *Moringa oleifera* leaf and seed crude extract inhibit protease action of that microorganism which is responsible for muscular damage of fish and shrimp through storage [40].

The *Moringa* seed yields up to 39% oil for various cosmetics products such as skin moisturizer, softening cream, conditioner, sunscreen soaps, salves ointment, and creams

[130]. The *Moringa* flowers have caseinolytic properties owing to aspartic acid, serine, cysteine, and protease-based calcium ions. Subsequently, it has application in the dairy industry [131].

Moringa stems and leaves have fodder prospect by giving it to ruminants, as a component of food enhancing weight and milk production [132]. It improves growth, food absorption, enteric fitness, skin color, and egg laying [133]. *Moringa oleifera* affects development, egg laying, egg grade, and health level in broilers and laying hens. Supplementation of *Moringa oleifera* may play a role in poultry's immunity, sound health, and production efficiency [134].

Moringa seed oil has application as a practical resource of biodiesel due to its significant characteristics as low temperature, lubricity, and high viscosity index, all of which no need to change, hence producing clean emissions following the ASTM D6751 and EN 14,214 standards [135]. *Moringa oleifera* extracts have effective application in the production of zeatin for plant growth, enhancing crop yields [136]. Apart from it, *Moringa oleifera* has application in food, e.g., partly substituted fishmeal in tilapia feed in Mexico owing to its rich carbohydrate and content [137].

Moringa oleifera is employed absolutely in bread, biscuits, brownies, cookies, and meat stuff, with dietetic, industrial, and preservation purposes [138]. *Moringa oleifera* use in bakery products will create novel products with modified dietary and functional value [139]. According to Ogunsina et al. [140], incorporating *Moringa oleifera* seed flour influences the organoleptic characteristics of diverse bread and biscuits. Currently, *Moringa oleifera* intends to advance the dietary function of fortified goods. *Moringa* claims to be an outstanding complement to treat a variety of diseases with nutritious and nutraceutical foods [141].

Our Efforts to Promote *Moringa* for Malnutrition Eradication

Malnutrition in tribes is one of the major problems, to overcome the nutritional importance of *Moringa* leaves, we validated from nutritional analysis to toxicity testing. The nutritious and safe *Moringa* products based on common people's lifestyle were made and popularized in the North Maharashtra area in Jalgaon, India.

Moringa leaf powder was optimized for the following value-added material as a nutritional supplement. As per the survey study and discussion, it was noted that 85–90% of rural populations use the bread of Jowar, Bajra, Maize, and Chilli Chutneys as an everyday meal. On this basis, 1.5 gm of *Moringa oleifera* leaf powder per 30 gm flour was optimized for Jowar, Bajra, and Maize flour fortification. The physical parameters like rollability, viscosity, and taste were maintained. Besides that, we also kept the aesthetic

Fig. 6 *Moringa oleifera* leaves powder fortified food products. **a** *Moringa* jam, **b** *Moringa* energy drink, **c** *Moringa* tea, **d** *Moringa* roti prepared at the Dr. Satish V Patil's Laboratory, KBC North Maharashtra University India



parameter as per consumer psychology. We took a workshop with the student to know how this fortification is essential to fight malnutrition in daily diet products. We prepared some attractive products like various chutneys of Sesam, Groundnuts, and Karal (tribal oilseed) in combination with *Moringa* leaves powder, *Moringa* jams, *Moringa* tea, amaranth grain starch (Rajgira grain powder) bread with *Moringa* powder, *Moringa* leaf tablet (500 mg), and *Moringa* energy drink (Fig. 6). We also tried to promote the educated youth for future entrepreneurship of *Moringa* farming, opportunities for green business like *Moringa* leaf powder, dried leaves, and tablets.

Conclusion

Presently, extensive research is going on to identify and characterize the *Moringa oleifera* proteins and their functions. *Moringa oleifera* is a plant whose properties are still being explored. Therefore, *Moringa oleifera* deserves extensive investigation to elucidate the action mechanisms better. The improved knowledge of *Moringa oleifera* will make efficient use of *Moringa* in various fortified nutraceutical as well as health booster products. The application of *Moringa*, as a natural constituent for drug supplementation, may promote novel drug development. The drawbacks of synthetic drugs application could be minimized by combination with *Moringa*. But the comprehensive risk assessment studies need to carry out to assure the safety of the *Moringa* fortified products and formulated drugs. The dietary intake of *Moringa oleifera* products could be devised based on the insightful analysis and legal safety regulations.

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Declarations

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest The authors declared that there is no conflict of interest.

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