Plant Science Review

PLANT SCIENCE REVIEW

Review Article

Journal homepage: https://psr.crcjournals.org/

ISSN No: 3041-7279

Moringa oleifera: A Multifunctional and Multipurpose Tropical Tree Treasure for Sustainable Environmental Food Security in the Functional Agroecosystem

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16 April 2025: Received | 07 May 2025: Revised | 10 June 2025: Accepted | 12 July 2025: Available Online

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Citation: Siddhuraju Perumal and Sasipriya Gopalakrishnan (2025). *Moringa oleifera*: A Multifunctional and Multipurpose Tropical Tree Treasure for Sustainable Environmental Food Security in the Functional Agroecosystem. ***Plant Science Review***. **DOI: https://doi.org/10.51470/PSR.2025.06.02.06**

Abstract

The pretty Indian tree Moringa oleifera is a main example of a multifunctional tree that yields highly nutritious food products and thrives swiftly in arid environments. M. oleifera leaves are used as animal feed in the tropics and as a nutrient - and micronutrient-rich powder in several nations to help pregnant mothers and children who are lacking in certain nutrients. It is a significant food product that has received a lot of attention as the "Natural Nutrition of the Tropics" and has a lot of potential as a means of addressing some of the most urgent issues facing the developing world, such as poverty, deforestation, starvation, and contaminated water. The numerous economic uses of this tree, together with its easy propagation, have raised growing international interest in it. It originated in India and is found in most tropical countries (Africa, Asia, and the Americas). Apart from its various uses, M. oleifera has an impressive range of medicinal value. Therefore, the current review summarizes the nutritional, nutraceutical, pharmacological and phytochemical components of this miracle tree, M. oleifera, as well as its properties for water purification attributes, crop growth performance, and other ecosystem functions.

Keywords: *Moringa oleifera, Nutritive potential, Medicinal uses, Phytochemicals, Animal forage, Drought tolerant, Biofuel, Water purification*

Introduction

The single-genus family of Magnoliopsida known as Moringaceae contains 13 species, of which *Moringa oleifera* (syn. *Moringa pterygosperma* Gaertn.) is the most well-known and commonly cultivated. It is known that there are several species of Moringa, such as *Moringa arborea*, *Moringa borziana*, *Moringa concanensis*, *Moringa drouhardii*, *Moringa hildebrandtii*, *Moringa longituba*, *Moringa ovalifolia*, *Moringa peregrina*, *Moringa pygmaea, Moringa rivae* and *Moringa ruspoliana*, globally distributed [1]. The Moringa tree (*Moringa oleifera*), which is easy to reproduce and propagate, can thrive in any kind of soil, from acidic to alkaline, and can also withstand a six-month dry season. The common global names for the Moringa plant are the West Indian ben tree, horseradish tree, radish tree, never-die tree and drumstick. Further, the same tree species is known by many names in different parts of India, and it is called 'Saragvo' in Gujarati, 'Soanjna' in Hindi, 'Sajna' in Bengali, 'Nugge' in Kannada, 'Sigru' in Malayalam, 'Shevga' in Marathi, 'Shobhanjana' in Sanskrit, 'Munaga' in Telugu and 'Murungai' in Tamil [2]. *Moringa* is one of the most promising species, according to an assessment of more than 120 species of native Asian vegetables for nutrient levels, antioxidant activity, and local knowledge of their medicinal benefits [3]. Although Moringa is grown in 82 countries under 210 distinct names, "the miracle tree" is the only term that accurately describes all of its qualities. Protein, carotene, calcium, iron, and vitamins A, B, and C are among the macro-and micronutrients found in very high concentrations in these fresh leaves. Moringa pods and powdered dry leaves are utilised as dietary supplements [4].

These leaves are found to be one of the best tropical vegetables in terms of nutritional value. Many countries, especially those in India, Pakistan, the Philippines, Latin America, Hawaii, and many parts of Africa, use this tree's leaves, fruit, blossoms, and immature pods as a highly nutritious vegetable [5]. According to reports, the plant contains a number of bioactive molecules, such as vitamins, minerals, fatty acids, and amino acids [6]. The indigenous medical system, especially in South Asia, uses the leaves, roots, seeds, bark, fruit, flowers, and immature pods to treat different types of illnesses. They have antitumor, antipyretic, antiepileptic, anti-inflammatory, antiulcer, antispasmodic, diuretic, antihypertensive, cholesterol-lowering,

antioxidant, antidiabetic, hepatoprotective, antibacterial, and antifungal properties [9]. On the other hand, non-governmental organizations (NGOs) and community-based organizations have extensively and vigorously promoted Moringa to help individuals who are impacted by HIV/AIDS meet their nutritional needs [10].

Moreover, *M. oleifera* is a low-cost substitute plant for underprivileged individuals experiencing malnourishment and poverty [11]. Parts of Moringa are used in a number of different commercial formulations for a range of ailments, including Livospin (Herbals APS Pvt Ltd, Patna, India), Kupid Ford (Pharma Products Pvt Ltd, Thayavur, India), Orthoherb (Walter Bushnell Ltd, Mumbai, India), and Rumalaya and Septilin (The Himalaya Drug Company, Bangalore, India) [12]. It is grown for its culinary and cosmetic oil (seeds), medicinal properties (whole plant parts), and as a vegetable (leaves, green pods, blooms, and roasted seeds) [13]. The only factor which influences the *M. oleifera* cultivation and the significance of plant secondary metabolites for therapeutic potential and nutritional values is found to be cultivar variations [14].

Phytochemical constituents

The numerous phytochemical components of the different parts of the Moringa plant are listed in Table 1, along with their biological activity. Phytochemical screening of the leaf extract revealed the presence of alkaloids, glycosides, phenols, saponins, tannins, volatile oils, and hydrolysable tannins [46]. The extracted oil from the seeds of the Indian cultivar Periyakulam 1 (PKM 1) was found to contain notable amounts of β-sitosterol, stigmasterol, campesterol, and α-γ-δ-tocopherols [47]. Due to glycosylation, it was shown that *M. oleifera* has more flavonoids than *M. ovalifolia* [23]. Gamma radiation was found to have an impact on the levels of hydroxycinnamoyl derivatives and flavonoid chemicals in *M. oleifera* leaves [48].

Nutritional potential of *M. oleifera*

Moringa leaves are rich in vital, disease-preventing nutraceuticals, according to nutritional studies. Both people and animals use the leaves and pods as dietary supplements [49]. When compared to the World Health Organisation (WHO) recommended pattern, the protein composition of Moringa leaves showed that they contain more than 100% of the suggested pattern in all essential and important amino acids except lysine, which received a score of 98% [50]. In contrast to the absence of trypsin inhibitors and lectins, Moringa leaves have a very little amount of tannins and saponins (5.0% as diosgenin equivalent) [51]. Iron (up to 582 mg/kg DM), β-carotene (up to 400 mg/kg DM), and vitamin C (up to 9.2 g/kg DM) are all abundant in the leaves, and eating them helps mothers who gave birth to premature babies produce more breast milk [52]. The cabinet tray method (cross-flow drying) can be suggested as an alternative to lyophilisation for the preservation of phytoconstituents and antioxidant potential in dried *M. oleifera* leaves.

To maintain nutritional and antioxidant activity, oven drying is advised as the optimal leaf dehydration technique for domestic usage rather than open sun light drying. Cabinet tray-dried *M. oleifera* leaves were used to create a ready-to-use chutney powder (additive) that is well-liked and has an overall good quality score. This powder can preserve the most nutrients [53]. When maize and Moringa ground leaves were combined, the iron level of Nigerian infants aged 6 to 12 months rose [54]. Moringa seed extract had a remarkably high amount of methionine and cysteine (43.6 g kg^{-1} protein), which was comparable to that of cow's milk, chicken eggs, and human milk. Compared to other conventional legumes and cereals, the seed protein concentration (332.5 g kg^{-1} dry matter) is found to be higher [55]. When compared to vegetables like taro, pumpkin, amaranth, mushrooms, and cassava leaves, the leaves are incredibly nutrient-dense [56]. and can be used as a supplement to help patients who use prescription and over-the-counter medications regain nutrients they have lost [57]. Histidine and arginine, which are particularly crucial for new-borns, are found in the leaves. The vitamin A in carrots is four times (6780 mcg), the vitamin C in oranges is seven times (220 mg), the calcium in cow's milk is four times (440 mg), the potassium in bananas is three times (259 mg), and the protein in milk is twice (6.7 g) [58]. When Moringa oil was properly blended with sunflower and soybean oil, the amount of linoleic acid in the substrate oils decreased, the amount of oleic acid increased, and the oxidative stability was enhanced. These findings demonstrated that properly mixing Moringa oil with different oils will satisfy dietary requirements while enhancing stability for deep-frying and home cookery [59]. Moringa leaves were the highest concentration of β-carotene (19210 µg/100 g fresh weight) among the sixteen green leafy vegetables [60]., and they also had a high lutein content (24.8 mg/100 g edible fresh leaves) [61]. Vitamin A insufficiency was successfully overcome by β-carotene from Moringa leaves [62]. The potential use of Moringa leaves as a plant meal to improve vitamin A nutrition and possibly delay the onset of some degenerative disorders like cataracts is supported by the comparatively high bioaccessibility of β-carotene and lutein from Moringa leaves consumed with oil [63]. More micronutrients were found to be preserved by freezing, steaming, and sterilising, and the majority of processing techniques increased the amounts of bioavailable β-carotene, lutein, and α-tocopherol. Only heating was found to be an effective cooking technique for enhancing the release of bioactive chemicals from Moringa leaves [64]. [65]. The oral and sub-acute toxicity of the leaf aqueous extract were assessed, and the findings indicated that this plant is reasonably safe for use in medicine and nutrition [66]. Table 2 displays the nutritional makeup of Moringa green pods, fresh leaves, and powdered dried leaves.

Health-related attributes of *Moringa oleifera*

Antioxidant activity

Because of Moringa leaves contain different types of antioxidant biomolecules, including ascorbic acid, flavonoids, phenolics, and carotenoids, they can serve as a good source of natural antioxidants and extend the shelf life of foods that contain fat and fatty acids [67]. To increase shelf life of buffalo and cow ghees (butter oil), the tribal and indigenous people of India use these fresh leaves as a natural antioxidant. Following the preparation and production of liquid ghee, the boiled rice mixture, remaining salt residues, and fried Moringa leaves are together served to the local school children as a nutritionally complete meal. The optimal solvents for extracting antioxidant biochemicals from Moringa leaves were determined to be methanol (80%) and ethanol (70%) [13]. Other research has also reported the biological property of high antioxidant activity [47]. [68]. The polyphenolic fraction of the leaves has a high phenolic content and strong antioxidant activties that protect against carbon tetrachloride-induced toxicity in both *in vitro* and *in vivo*. Moreover, the HPLC analysis revealed the presence of flavonoids (kaempferol, quercetin and rutin) and phenolic acids (gallic, chlorogenic, ellagic and ferulic acid) [13]. [17]. When added to biscuits, the leaf extract had a high antioxidant activity and was more impact in preventing lipid oxidation during storage than butylated hydroxyl anisole (BHA), a synthetic antioxidant [69]. In addition to inhibiting lipid peroxidation and bacterial anti-quorum sensing activity, aqueous extracts Moringa leaf, fruit, and seed can prevent organisms and cells from oxidative DNA damage linked to ageing, cancer and degenerative disorders [70]. The mature and tender leaves both protect cellular macromolecules from oxidative damage and exhibit strong antioxidant activity against free radicals [71].

Antihypertensive and antispasmolytic activity

Repeated oral administration of Moringa leaf aqueous extract reduced systolic blood pressure in rats with spontaneous hypertension [72]. Compounds like methyl p-hydroxybenzoate, β-sitosterol and p-hydroxybenzaldehyde from ethanolic and aqueous extracts of moringa pods; 4-[(4'-o-acetyl-α-L-rhamnosyloxy)benzyl].isothiocyanate; niaziminin A and B; o-methyl-4- [2',3',4'-tri-o-acetyl-α-L-rhamnosyloxy)-benzyl]. thiocarbamate; o-methyl-4-[(2',3',4'-tri-o-acetyl-α-L-rhamnosyloxy)-benzyl]. thiocarbamate; o-ethyl-4- [(2',3',4'-tri-o-acetyl-α-L-rhamnosyloxy)-benzyl]. nitrile thiocarbamate; and o-ethyl-4- [α-L-rhamnosyloxy) benzyl]. thiocarbamate from ethanolic extract of moringa leaves showed promising hypotensive activity [27]. [28]. The ethanolic extract of the moringa leaves contained substances such as niazinin A, niazinin B, niazimicin, and niaziminin A + B, which had bradycardic, spasmolytic, and hypotensive actions [18].

Anti-inflammatory and antiarthritic activity

The ethanolic extract of Moringa seeds demonstrated protection against airway inflammation and bronchoconstriction brought on by acetylcholine [73]. The methanol extract of root barks possesses local anaesthetic properties and decreased the analgesic writhing episodes caused by acetic acid and the anti-inflammatory paw oedema caused by carrageenin [74]. The leaves' aqueous extract has antinociceptive and anti-inflammatory properties that are both centrally opioid-mediated and peripherally non-opioid-mediated [75]. In rats with arthritis, the ethanolic extract of seeds reversed negative physiological changes such as paw oedema volume, arthritic index, and weight loss. It also reduced the serum levels of rheumatoid factor and specific cytokines (TNF-α, IL-1, and IL-6) [76]. The interleukin-2 and tumour necrosis factor-α were two inflammatory cytokines that were suppressed by the aurantiamide acetate derived from moringa roots [12]. Nonetheless, a hydroalcoholic extract of the flower prevented leukocyte infiltration into the possible target regions for rheumatoid arthritis and hindered the production and release of important proinflammatory cytokines [77].

Antimicrobial activity

It was reported that the Moringa seeds (sub-fractions seed ethyl acetic fraction and seed butanol fraction) and the essential oil (crude and sub-fraction of oxygenated fraction) had antifungal properties against *Trichophyton rubrum*, *Trichophyton mentagrophytes*, *Epidermophyton floccosum*, and *Microsporum canis* [24]. [78]. While the crude extract by itself shown strong activity against *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *Aspergillus niger*, the crude seed extract and dialysed samples of Moringa demonstrated very strong activity against *Fusarium solani* and *Metarhizium anisoplae* [79]. The aglycon of Deoxy-Niazimicine (N-benzyl, S-ethyl thioformate) that was separated from the root bark chloroform extract exhibited antifungal activity against *Aspergillus flavus* and *Candida albicans*, as well as antibacterial activity against *Salmonella typhi*, *Shigella dysenteriae, Shigella boydii*, and *S. aureus* [30]. Numerous harmful bacterial strains, including isolates of *Staphylococcus*, *Streptococcus*, and *Legionella* species that are resistant to antibiotics, were found to be susceptible to the antibacterial effects of the polypeptide "Flo" derived from the seed extract [41]. Antiviral activity against equine herpes virus-1 was found in alcoholic preparations of leaf and stem bark [80]. Significant growth inhibition of *Candida albicans* from urine and vaginal swabs, *Geotrichium candidum* from stool specimens (18.75%), and *Cryptococcus neoformans* (5%) from sputum specimens isolated from HIV-seropositive patients were demonstrated by methanolic seed extract, suggesting that natural products can be used to control yeast infections common in HIV/AIDS patients [81]. On the other hand, an aqueous extract of Moringa leaves proved more effective in controlling the pathogen *Colletotrichum destructivum* on cowpea (*Vigna unguiculata*) seeds [82].

Hepatoprotective activity

In order to prevent and control nutrient-borne diseases, especially liver diseases, which are brought on by dietary changes, rapid urbanisation, air and water pollution, and excessive consumption of animal meat and products under such climate change resilience, it is necessary to increase the consumption and use of green vegetables with enriched dietary bioactive molecules on a global scale. In this context, Moringa leaves are found to be one of the most readily and cheaply available, promising and affordable green vegetables throughout the tropical regions. The ethanol-induced lipid peroxidation in the liver was considerably decreased by 53% and 50% after pre-treatment with the hydroalcoholic extract of Moringa leaves [83]. It was also discovered that pretreatment with aqueous leaf extract protected the liver from acute alcohol-induced damage, and post treatment with the extract had a therapeutic effect and stopped the release of hepatocyte enzymes into the bloodstream when rats were given high doses of ethanol [84]. Moringa fruit [85]. and seed extracts [86]. have demonstrated strong hepatoprotective effects against hepatotoxicity caused by carbon tetrachloride. Iron deficiency-induced hyperlipidaemia and hepatocyte ultra-structural alterations can be avoided with the help of Moringa leaf aqueous extract [87]. Erythrocytes were shielded against oxidative stress caused by hydrogen peroxide and tert-butyl hydroperoxide by an alcoholic and aqueous extract of leaves and pods [88].

Immunoenhancing property

By releasing nitric oxide on the mouse monocyte cell line, an immunoenhancing polysaccharide (α-(1→4) linked Glucan) from the aqueous extract of mature Moringa pods demonstrated significant macrophage activity. It also improved the ratio of albumin/globulin, phagocyte cells, and respiratory burst cells in the fish system [89]. By lowering the levels of uric acid, triglycerides, and albumin/globulin ratio in the broiler's serum, as well as raising the sheep red blood cell antibody titer, y-globulin content, basophils ratio, and IgA concentration, dietary supplementation with Moringa leaf powder was found to improve the immune capacity of broilers [90].

Antidiabetic activity

Use of ethanolic pretreatment significant hypoglycemic action was demonstrated by Moringa leaf extract against diabetic albino rats produced by alloxan. [91]. From the methanolic fruit extract, N-benzyl thiocarbamates, N-benzyl carbamates, benzyl nitriles, and a benzyl ester were separated. These compounds had cycloxygenase enzyme and lipid peroxidation inhibitory properties and markedly increased insulin release from the mouse pancreatic beta cells [43]. In rats with sub-, mild-, and severe diabetes, the leaves' aqueous extract brought their elevated blood glucose levels back to normal [92]. People in Senegal commonly mentioned Moringa (65.90%) as a medicinal plant used to cure diabetes in a poll that included 41 different plants [93]. Rats with glucose intolerance responded favourably to the leaf aqueous extract [87].

Antitumor activity

The root of Moringa had benzyl glucosinolate, whereas the seed, root, leaf, and bark contained glucosesinolates such as 4-(α-L-rhamnopyranosyloxy)-benzylglucosinolate. [38]. Mammalian phase II detoxification enzymes, including glutathione S-transferase, quinone reductase, and glucoronosyl transferase, have been shown to be activated by glucosesinolates [94]. The differentiation activity of moringa leaf aqueous extract against human promyelocytic leukaemia cells (HL-60) suggested that it has a cancer-preventive impact [13]. The thiocarbamate niaziminin and the 4- [(4'-O-acetyl-α-L-rhamnosyloxy) benzyl]. isothiocyano group from moringa leaves shown significant inhibition against the activation of the Epstein-Barr virus (EBV) caused by tumour promoter teleocidin B-4 [19]. The ethanolic extract of moringa seeds yielded the chemical niazimicin, which was demonstrated in a mouse research to be a strong inhibitor of the phorbol ester (12-o-tetradecanoyl-phorbol-13-acetate)–Epstein-Barr virus early antigen activation in lymphoblastoid cells. [36]. In addition to improving antioxidant system enzymes, which provide protection against cellular damage and prevent cancer growth, the administration of a hydroalcoholic extract of moringa drumsticks was a viable chemopreventive strategy since it was a bifunctional inducer [95].

Antiulcer activity

The gastric mucosa was reported to be protected from the indomethacin action by the aqueous extract of Moringa leaves [46]. In experimental rats, dried leaves shown a remarkable capacity to repair ulcers in gastrointestinal lesions caused by acetylsalicylic acid, serotonin, and indomethacin [45]. It was demonstrated that pretreatment with the aqueous leaf extract raised the amount of serotonin (5 5-hydroxytryptamine; 5-HT) and enterochromaffin cells in ulcerated stomach tissue while decreasing the mean ulcer index [96].

Cholesterol-lowering effects

When a high-fat meal was combined with the administration of Moringa leaf aqueous extract, the increases in serum, liver, and kidney cholesterol levels caused by the high-fat diet were reduced by 14.4, 6.4, and 11.1%, respectively [97]. The methanol-extracted residues and leaf meal methanol extract decreased the Nile tilapia's muscle and plasma cholesterol levels [98]. It was shown that Moringa fruit powder had a hypolipidemic effect, which caused hypercholesterolemic rabbits to excrete more faecal cholesterol [99]. The aqueous extract of leaves dramatically decreased the cholesterol levels and atherosclerotic plaque formation in rabbits fed a high-cholesterol diet to roughly 50 and 86 percent, respectively [63].

Antipyretic, wound healing and analgesic activity

Significant antipyretic efficacy was demonstrated by the ethanolic and ethyl acetate seed extracts. By raising the rats' tensile strength, treatment with aqueous leaf extract [101]. and ethyl acetate seed extract [100]. enhanced the wound healing activity. Moringa root extract in methanol has the capacity to suppress the central nervous system and shown notable protection against convulsions caused by strychnine and leptazol [102]. Significant analgesic activity is exhibited by the alcoholic seed extract [103]., the methanolic root extract of Moringa [102]., and 1, 3-dibenzyl urea from the chloroform fraction of the alcoholic root extract [12].

Other effects

Moringa seed aqueous extract may help reduce fluoride toxicity in rabbits [104]. The brain's coordinated and integrated function was enhanced by the ethanolic leaf extract, which also restored the monoamine levels in the brain's colchicine infusion [105]. Because of its antioxidant, antiperoxidative, and myocardial preservation qualities, the hydroalcoholic leaf extract has a strong cardioprotective effect [106]. [107]. In addition to chelating arsenic from the cell, a combination treatment using Moringa seed powder and monoisoamyl DMSA (MiADMSA) improved antioxidant levels [108]. Urinary stones in rats with ethylene glycol-induced lithiasis were prevented and their growth was inhibited by an alcoholic and aqueous extract of Moringa root wood [109]. The mice's bone marrow chromosomes were significantly protected against radiation by pretreatment with methanolic leaf extract, which may have contributed to their increased 30-day survival following deadly whole body irradiation [110]. The seed kernels enhanced respiratory function and lessened the intensity of asthma symptoms [111]. Human platelet aggregation caused by agonists such adenosine diphosphate, collagen, and adrenaline was inhibited and protected by the leaf aqueous extract [112]. Table 3 lists some plant parts and how they are used to treat illnesses.

Plant growth enhancer

When young plants like peanuts, soy beans, black beans, maize, onions, sorghum, tomatoes, coffee, and sugarcane are sprayed with the ethanolic extract made from Moringa leaves, they become firmer and more resilient to pests and diseases. This is because the extract contains growth-enhancing principles, such as hormones of the cytokinine type. Higher yields are the result of the plants producing more and larger fruit [20]. It has been demonstrated that applying an ethanol extract (80%) of these leaves increases black-gram (*Vigna mungo* L.) nodulation [116].

Animal forage and feed

While it had no effect on milk composition, adding Moringa forage (leaves with soft twigs) as a protein supplement to low-quality diets enhanced dry matter intake, improved the diet's digestibility, and increased dairy cows' milk production [117]. When incubated with pure carbohydrates, the aqueous Moringa seed extract decreased the microbial degradation of the leaf protein, Ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco), which was nearly completely protected during the 12-hour fermentation period. Additionally, the degradation of soy proteins was postponed for at least 4–6 hours. It has a beneficial effect on protein metabolism, which may be helpful under strict supervision, according to these *in vitro* characteristics in ruminants [40]. The entirely extracted Moringa leaf diet resulted in a 17% reduction in daily methane emissions when compared to diets that contained rape seed or soybean meal. The feeding value of unextracted, ethanol-and acetone-extracted Moringa leaves is comparable to that of the popular soy bean and rapeseed meals, and they have a great potential as protein supplements for ruminants [118]. Since the ethanol-extracted Moringa leaves have low amounts of saponins and phytates and are free of tannins, lectins, trypsin inhibitors, and flatus factors, they would make a better feed (protein supplement) [51]. Mice were used to test the safe feeding levels of untreated Moringa seed cake (12.5, 25, and 50%). Changes such as weight loss, increased organ congestion and haemorrhage (heart, liver, gall bladder, and lung), hepatocyte degradation, interstitial pneumonia, and interstitial nephritis foci were noted in mice who were given 25% and 50%. Therefore, when utilised as a protein supplement for monogastric animals, the amount of seed cake added should not be greater than 12.5% of the daily total intake. [119]. Sugar cane (*Saccharum officinarum*), Elephant grass (*Pennisetum purpureum* cv Taiwan), or Moringa (*Moringa oleifera*) combinations were used to make fourteen distinct silages. Lactic acid concentration increased and silage spoiling time decreased with Moringa-containing treatments. Consequently, high-quality silages that also have significant levels of crude protein can be made with Moringa leaves [120]. In order to increase the development rate of lambs fed hay-soybean meal diets, defatted Moringa seed meal (DMM), at a low level of 4% in the diet, is advised as a supplement. DMM has the ability to improve rumen fermentation [121]. Moringa seeds contain a crude, pure protein that possesses potent anti-methanogenic properties. It has the ability to boost cattle productivity while simultaneously reducing ruminant methane emissions [42]. Fifty grams of *Moringa olifera* leaves powder (MOLP) supplementation to the diets of milking buffaloes improved milk yield, milk composition, nutrient digestibility, nutritive value and total antioxidant capacity. Blood serum total protein, albumin and globulin contents were significantly ($P < 0.05$) higher with feeding MOLP-supplemented diets than with the control, While there were significant ($P < 0.05$) decreases in urea, glucose and cholesterol, creatinine, AST and ALT were gradually increased with increasing MOLP level. Feed rations supplemented with MOLP were associated with an apparent increase ($P < 0.05$) of antioxidant enzymes (GR, GPx, Cat and SOD) and a decrease in free radicals, and the effect was more pronounced with increasing the

supplementation level [140]. Up to 33% of tilapia diets might contain the methanol-extracted Moringa leaf meal, which reduced antinutrients and enhanced the partial fermentation of dietary fibre, which increases fish nutrient availability [98]. The *M. oleifera* leaf extract and *Lactobacillus acidophilus,* individually or combined, fed to whiteleg shrimp (*Penaeus vannamei*) improved the growth performance, hepatopancreatic histology, enzyme activity, intestinal and intestinal microbiota, immune response and resistance against *Vibrio alginolyticus* and *Vibrio parahaemolyticus*. Particularly, whiteleg shrimps fed with a diet containing *M. oleifera* leaf extract at 2.5 g/kg of diet and *L. acidophilus* at 1 × 107 CFU/g of diet (ME2.5+P) significantly increased final weight, weight gain, specific growth rate, villi height, wall thickness, and abundance of hepatopancreatic R cells. Moreover, the immunological parameters such as total haemocyte count, phenoloxidase activity, phagocytic rate, superoxide anion production, and immune-related gene expression (including those of prophenoloxidase II, alpha-2 macroglobulin, penaeidin2, antilipopolysaccharide factor, crustin, lysozyme, glutathione peroxidase, and superoxide dismutase) were also reported to be higher in the experimental groups than in the control group [137]. The recent *in vivo* experiments revealed that *M. oleifera* leaf meal supplementation in early weaned Landlly piglets significantly improved growth performance with the treatment group achieving a 9.24% higher final body weight and a 17.73% greater body weight gain compared to the control group offered the control diet. Further it was also observed that it reduced the lipid peroxidation and oxidative stress significantly, and behavioural studies showed a notable decrease in stress-related activities, including belly nosing [138]. In another study, it is revealed that the *Moringa oleifera* aqueous leaf extract (MOALE) group (90 ml Moringa extract/L drinking water) followed by ascorbic acid (15 mg/L drinking water) supplemented and offered to broiler chickens improved the growth performance and feed conversion efficiency (FCR) without affecting the metabolism of nutrients. However, the MOALE-supplemented group, followed by the ascorbic acid group (6.28%), showed a better FCR (10.71%) in comparison with the control. Except for creatinine levels, most of the haematobiochemical profiles were unaffected by the treatment, and in addition to that, the antioxidant activity was also improved in the treatment group. Nonetheless, the immunity status of broiler chickens against NDV was also improved in both treatment groups and maximum benefit/profit were achieved in the MOALE group, followed by ascorbic acid-supplemented broiler chickens [139].

Water purification properties

The efficiency of powdered Moringa seeds as coagulants for water treatment has been demonstrated to be on par with that of alum, a common chemical coagulant [122]. Basic polypeptides with molecular weights ranging from 6000 to 16,000 daltons make up the cationic polyelectrolyte found in Moringa seed kernels. These peptides draw in primarily negatively charged particles (such clay, silk, bacteria, and other harmful particles in water) and are high in glutamic acid, methionine, and arginine. Moringa is a polyelectrolyte that uses inter-particle bridging and adsorption to eliminate hardness from water. Through interactions between amino acids and cadmium, shelled seed powder extracted cadmium from an aqueous solution. This discovery creates new opportunities for the safe, low-cost, and ecologically friendly removal of harmful/heavy metals from water bodies using shelled seeds [123]. Moringa bark seems to be a potential biosorbent material for the removal of heavy metal ions from wastewater effluents because of its quick kinetics, low cost, and strong absorption capacity [124]. The seeds were used to remove colours such as azoic (Palatine Fast Black WAN), indigoid (Indigo Carmine), and anthraquinonic (Alizarin Violet 3R) [125]. Activated carbon was made from Moringa wood, which has significant promise for cleaning industrial effluents that contain metals [126]. Silver in aqueous solutions and cadmium in alcoholic matrices were preconcentrated using Moringa seeds as a biosorbent material [127]. Moringa biomass has the potential to be utilised inexpensively and effectively to clean wastewater in the dairy industry [128]. According to reports, the economical coagulant made from *M. olifera* seed cake wastes has outstanding turbidity and bacterial reduction capabilities and is effective in removing heavy metals like Fe, Cu, Cd, and Pb from rivers and wastewater up to a range of 82.17 to 98 percent [129]. Similar to this, it was discovered that the cationic antibacterial proteins from Moringa seeds functioned as a natural coagulant to remove *Escherichia coli*, polystyrene particles, and turbidity from drinking water and wastewater through attractive electrostatic interactions. This could also be a more cost-effective, natural alternative to synthetic chemicals for water purification in developing regions [130].

Biodiesel and lubricant properties

Moringa oil is one of 75 indigenous (Indian) plant-derived non-traditional oils that have significant potential for producing biodiesel, according to a recent survey [131]. At the ideal production conditions under the following chemical mixtures, such as 1.0 weight percent catalyst, 30 weight percent methanol, 60°C reaction temperature, 400 rpm agitation rate, and 60 minutes reaction time, the conversion efficiency of Moringa fatty acids to methyl esters was discovered to be 82% [132]. The oil can be used as a multi-grade lubricant because its viscosity index is significantly higher than that of the other vegetable oils under study. The oil's high concentration of monounsaturated fatty acids contributes to its exceptional thermal and oxidative durability. It has a fair chance of being used as a base oil for lubricants and as a suitable substitute for expensive petroleum base oils and food oils [7]. [133].

Larvicidal and other properties

The Moringa seed's water-soluble lectin encouraged Aedes aegypti larval development delay and mortality [134]. These leaves' ethanolic extract exhibited strong anthelmintic properties [135]. Because of its low rate of vapour transmission and adequate tensile strength, the gum exudate from the Moringa stem has great promise for usage in the production of polymeric films as a medication delivery system and as a water-impervious coating agent in tablets [136].

Conclusion

Because of its many applications and potential as a sustainable crop that may improve human and animal nutrition, provide income, and act as a green energy source, Moringa has become known as a superfood. Each component of this tree has advantageous qualities that can help humanity satisfy its nutritional demands. Higher levels of calcium, iron, and protein found in Moringa leaves make them a rich source of dietary nutrients that can greatly meet human nutritional needs and are essential in the fight against malnutrition in developing nations' children, pregnant women, and the elderly. Furthermore, this tree has several medical use, and its seeds have the ability to filter and purify water. Different portions of this plant contain antioxidant, antihypertensive, analgesic, anti-inflammatory, antispasmodic, antibacterial, hepatoprotective, antidiabetic, anticancer, antiulcer, cholesterol-lowering, and other properties. Nonetheless, Moringa's ability to strengthen immunity is among its most significant advantages. Iron and vitamin A, which are abundant in Moringa, improve immune system performance. Additionally, its high antioxidant concentration strengthens and protects the immune system against illnesses. In order to strengthen their immunity against infection, most Indians eat *Moringa* leaf soup during COVID-19. It has been discovered that fresh Moringa leaves are a great natural source for efficient vitamin bioconversion and bioavailability in animal production. To ascertain the ideal dosage, course of treatment, and the function of each key component in charge of these actions, comprehensive clinical and experimental research is needed. To clarify the mode of action of the bioactive substances present, more research is also required. Therefore, promoting this plant's many applications should be given top priority in order to reap the rewards of this "miracle" tree. Additionally, agronomic research, breeding, and selection should be done to increase this tree's production and produce more valuable goods. The Moringa plants can be further widely exploited and utilised as a viable bioresource for sustainable development, a permanent circular green economy, and zero waste generation in agroecosystems under climate change resilience after carrying out thorough and pertinent laboratory studies and field trials. Further, there is a comprehensive and rigorous study on the wider collection, conservation, cultivation and assessment of germplasms at the local, regional, national and worldwide levels, especially the endangered and threatened native sweet varieties of *M. oleifera,* which are urgently needed.

Acknowledgement

PS and GSP are much thankful to Bharathiar University, Coimbatore, TN, India, for providing necessary laboratory facilities, and the authors are grateful to the Alexander von Humboldt (AvH) Foundation, Bonn, Germany, for awarding and approving an equipment grant and a long-term collaborative research project (Letter No. 3.4INI/1051260).

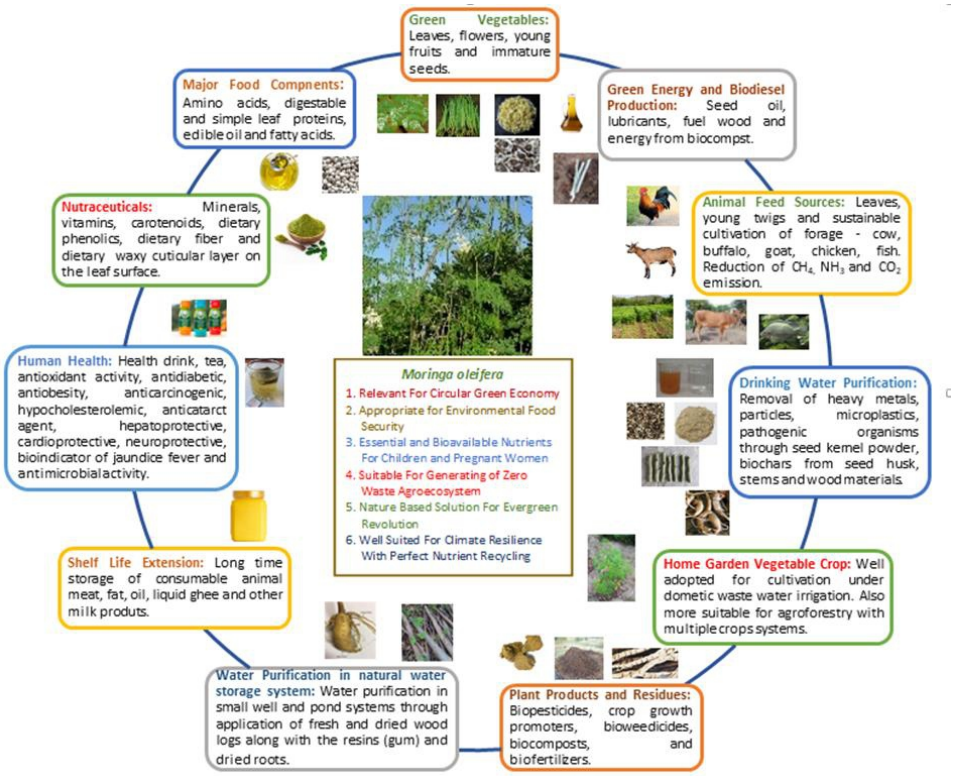

Figure 1. Multi-functional attributes of Moringa oleifera in the integrated and sustainable Agroecosystem.

Table 1. Phytochemical constituents of different parts of Moringa oleifera

Active principles isolated / reported from plant parts	Reported activity	References
Leaves Quercetin, isoquercetin and β-carotene	Antioxidant	[15]. [16].
Phenolic acids (gallic, chlorogenic, ellagic and ferulic acid) and flavonoids (kaempferol, quercetin and rutin)	Hepatoprotective	[17].
Niazinin A, niazinin B, niazimicin and niaziminin A + B	Hypotensive and bradycardiac, spasmolytic effects	[18].
	Anti-tumor	[19].
Niaziminin,4- [(4'-O-acetyl-α-L-rhamnosyloxy) benzyl].	Vitamin A precursor	[20].
β-carotene	A vitamin and an antioxidant	[20].
Vitamin- C	Antioxidant	[13].
Quercetin and kaempferol	Anticancer	[21]. [22].
Isothiocynates, 7-octenoic acid, oleamide, and 1-phenyl-2-pentanol		
Vicenin	Possess medicinal value	[23].
Leaf oil Pentacosane (17.41%), hexacosane (11.20%), (E)-phytol (7.66%) and 1- [2, 3, 6- trimethylphenyl]. - 2-butanone (3.44%).		
Monoterpenoid compounds like α-phellandrene and p-cymene	-	[24].
Leaves and pods	-	[25].
Carbamate, thiocarbamate and isothiocyanate glycosides		
Methyl p-hydroxybenzoate, β-sitosterol and p-hydroxybenzaldehyde	Hypotensive	[26].
	Hypotensive	[27].
Root Aurantiamide acetate and 1,3-diphenylurea	Inhibit tumor necrosis factors- α and Interleukin- 2	[12].
1,3-diphenylurea	Analgesic activity	[12].
Stem Vanillin, β-sitosterol, β-sitostenone, 4-hydroxymellin, octacosanoic acid	-	[28].
Stem bark Caffeic and fumaric acid	Hepatoprotective	[29].
Root bark	Antimicrobial	[30].
Aglycon of deoxy-niazimicine (N-benzyl, S-ethyl thioformate)		
Anthonine	Toxic to cholera bacterium	[31].
Seed	Relaxes bronchioles	
Alkaloid, Moringine	Antioxidant	[32].
		[33].
Flavonoids, Tocopherols, vitamin C, quercetin, kaempferol, myricetin and carotenoids	Antibiotic	[34].
4- [*α*-L-rhamnosyloxy]. benzyl isothiocyanate	Antimicrobial	[35].

4-(α-L-rhamnosyloxy)phenylacetonitrile, β-carotene, β-sterols, and lecithin *O*-ethyl-4-(α-L-rhamnosyloxy) benzylcarbamate i.e niazimicin, niazirin, β-sitosterol, glycerol-1-1-(9-octadecanoate), 3-*O*-(6'-*O*-oleoyl-β-D-glucopyranosyl)- β-sitosterol, and β-sitosterol-3-O-β- D-glucopyranoside	Anti-tumor promoting activity	[36].
4-(α-L-rhamnopyranosyloxy) benzyl glucosinolate (3%); 4-(4'-O-acetyl-α- L-rhamnopyranosyloxy) benzyl isothiocyanate; 4-(α- L-rhamnopyranosyloxy) benzyl isothiocyanate (10%), niazimicin and pterygospermin	Anticancer, hypotensive, antioxidant, antibacterial and insecticidal	[37]. [38].
Cationic protein		[39]. [40].
Flo polypeptide	Increase rumen by-pass protein	[41].
Proteins	Antimicrobial Decrease methane production from ruminants	[42].
Fruit N-Benzyl thiocarbamates, N-benzyl carbamates, benzyl nitriles and a benzyl ester	Anti-diabetic	
Niazicin A (=methyl *N*-{4- [(4'-*O*-acetyl-*α*-L- rhamnopyranosyl) benzyl].} thiocarbamate; 1-*O*-phenyl-*α*-L-rhamnopyranoside, 4- [(*β*-D-glucopyranosyl)-(1 → 3)- (*α*-L-rhamnopyranosyl)]. phenylacetonitrile, methyl *N*-{4- [(*α*-L-rhamnopyranosyl) benzyl].} carbamate, methyl *N*-{4- [(4'-*O*-acetyl-*α*-L-rhamnopyranosyl) benzyl].} carbamate.	Anti-diabetic	[43]. [43].
4- [(2'-*O*-acetyl-α-L-rhamnosyloxy) benzyl].isothiocyanate, 4- [(3'-*O*-acetyl-α-L-rhamnosyloxy)benzyl].isothiocyanate		
Flower Flavonoids: quercetin, kaempferol, rhamnetin, isoquercitrin and kaempferitrin	Anti-inflammatory Stimulant, aphrodisiac, diuretic and cholagogue in humans	[44]. [45].

Table 2. Nutritional composition of Moringa green pods, fresh leaves and dried leaf powder per 100 g of edible portion [31].

Component	Pods	Leaves	Leaf powder
Moisture (%)	86.9	75.0	7.5
Calories	26	92	205
Protein (g)	2.5	6.7	27.1
Fat (g)	0.1	1.7	2.3
Carbohydrate(g)	3.7	13.4	38.2
Fiber (g)	4.8	0.9	19.2
Minerals (g)	2.0	2.3	-
Calcium (mg)	30	440	2,003
Copper (mg)	3.1	1.1	0.57
Potassium (mg)	259	259	1,324
Iron (mg)	5.3	7	28.2
Magnesium (mg)	24	24	368
Phosphorus (mg)	110	70	204
Sulfur (mg)	137	137	870
Selenium (mg)	-	-	0.09
Zinc (mg)	-	-	3.29
Oxalic acid (mg)	10	101	1,600
Vitamin A (mg)	0.11	6.8	18.9
Vitamin B (mg)	423	423	-
Vitamin B_1 (mg)	0.05	0.21	2.64
Vitamin B2 (mg)	0.07	0.05	20.5
Vitamin B3 (mg)	0.2	0.8	8.2
Vitamin C	120	220	17.3
Vitamin E (mg)	-	-	113
Amino acids			
Arginine (mg)	90	402	1,325
Histidine (mg)	27.5	141	613
Isoleucine (mg)	110	422	825
Leucine (mg)	163	623	1,950
Lysine (mg)	37.5	288	1,325
Methionine (mg)	35	134	350
Phenylalanine (mg)	108	429	1,388
Threonine (mg)	98	328	1,188
Tryptophan (mg)	20	127	425
Valine (mg)	135	476	1,063

Table 3. Moringa plant parts and their uses in the treatment of diseases [113]. [114]. [115].

Plant parts	Treatment
Leaf juice	Blood pressure, anxiety, antidiabetic, diuretic, conjunctivitis, skin antiseptic
Leaf	Diarrhoea, dysentery, colitis, glandular swelling, expel intestinal worms, fever, bronchitis, eye and ear infections, scurvy, catarrh, anthelmintic, purgative, sores, skin infections, increase woman's milk production, anaemia, anticancer, restores *bifidobacteria* and *lactobacilli* in inflammation associated with obesity in mice.
Leaf and young buds	
Flower	Headache
Flower juice	Diuretic, anthelminitic, inflammation, muscle diseases, tumor, enlarged spleen, abortifacient, tonic
Flower infusion	Sore throat and catarrh
Flower decoction	Eye wash, cold symptoms
Pods	Hysteria
Roots	Anthelminitic, liver and spleen affection, articular pains
Root juice	Carminative, laxative, intermittent fevers, cold, abortifacient, diuretic, cardiac and circulatory tonic, epilepsy, nervous debility, hysteria, rheumatism, articular pains, lower back or kidney pain, purgative, inflammation, swelling of tissues in the foot, sores, ulcers, scurvy, chewed and applied to snakebite will keep the poison from spreading
Fresh root, bark and leaf juice	Rubefacient, counterirritant or vesicant, hiccoughs, asthma, gout, lumbago, rheumatism, enlarged spleen or liver, internal and deep-seated inflammations, calculous affection, liniment on rheumatism, earache, toothache
Root and stem Bark	Inserted into nostrils to arouse a patient from coma or stupor
Root bark	Scurvy, appetizers, digestives, aphrodisiacs, anthelmintic, delirious patients, rubefacient, vesicant, abortifacient and cold
Stem bark	Boils, sore and skin infections, epilepsy, hysteria, intestinal spasms, calculous affections, enlarged spleen, rheumatism, scorpion bites, sprains, tumor, ulcer, tuberculous glands of the neck, earaches, pain killer in toothache
Gum	Eye diseases
Seeds	Headache, earache, intestinal complaints, dental caries, diuretic, fevers, dysentery, asthma, astringent, rubefacient, abortifacient, syphilis, rheumatism, applied on the soles of the feet to treat typhoid

Seed kernel Seed oil	Fevers, abdominal tumors, seed paste applied externally against warts, modulate gut microbiome (*Verrucomicrobia*, *Proteobacteria, Firmicutes, Bacteroidetes, Actinobacteria*) in obese mice. Pain, inflammation of arthritis, back pain Skin diseases, externally applied to relieve pain and swelling in case of gout or rheumatism, hysteria, scurvy, prostrate and bladder troubles, tonic, purgative

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