PLANT SCIENCE TODAY
Vol 12(2): 1-15
https://doi.org/10.14719/pst.5869

eISSN 2348-1900

REVIEW ARTICLE

A comprehensive review on multiple utilities of moringa: A divine tree

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Received: 16 October 2024; Accepted: 23 January 2025; Available online: Version 1.0: 17 May 2025; Version 2.0 : 27 May 2025

Cite this article: Shamini K, Saraladevi M, Anandhavalli M, Geetha LPR, Subramaniam L, Praveen G, Senjaeriputhur DS, Chakkarapani B, Kalipatty NG, Balaji K, Selvaraju K, Sudhagar R. A comprehensive review on multiple utilities of moringa: A divine tree. Plant Science Today. 2025; 12(2): 1-15. https://doi.org/10.14719/pst.5869

Abstract

Moringa is customarily cultivated in the Indian house backyards due to its richness in medicinal, nutritional, environmental and fodder value. The perennial trees, maintained with biannual pruning, are photo-insensitive and flower year-round regardless of light or temperature variations. From a human diet perspective, tender leaves are consumed as green leafy vegetables due to their high nutrient value and are also known to cure various human diseases. Pods are widely used in various culinary recipes. Environmentally, moringa can remove wastewater-based pollutants, making it ideal for areas lacking proper drainage systems by cleaning soil soaked in household wastewater. On small-scale farms, where livestock are raised based on the availability of crop residues or excess vegetation from non-arable lands or soils of poor fertility, moringa provides nutrient-rich foliage for animal feed. Incorporating moringa foliage and its byproduct into animal diet improves animal health and reduces the calving gap in dairy animals. Moringa also can impart plant resistance to various abiotic stresses and control plant diseases in an eco-friendly way. The antimicrobial (antifungal and antibacterial) properties of moringa are numerous and deserve noteworthy mention. This manuscript aims to provide comprehensive information on moringa utilities, promote further scientific research to explore its potential as a nutritionally rich food and feed, phytoremediation and pharmaceutical applications and provide sustainable environmental solutions to enhance agricultural productivity and combat malnutrition effectively.

Keywords: biofortification; feed; moringa; multiple utilities; phytoremidiation; sustainable agriculture

Introduction

Moringa is a food crop with multiple utilities (Fig. 1). Due to its excellent nutritional and pharmacological qualities, it is called the "Miracle Tree" (1). It is also known as the drumstick tree, horse radish tree, ben oil tree, mother's best friend and the tree of life (2). It is estimated that moringa leaf powder weighing approximately one tablespoon has a crude protein content ranging from 9.9% to 13.6%, making it a nutrient-rich plant that fights malnutrition in nursing women and infants, which affects 25% of children under the age of five. Its affordability makes it accessible to low-income populations.

Moringa has edible pods, seeds, roots and leaves. In human, supplementation of moringa leaf powder with cereal would ensure a balanced diet with ample nutrients, minerals and bioactive compounds (3). To enhance the nutritional status of children, a survey was carried out to find out their favourite snack foods, which included moringa leaf powder. The snacks with 1% moringa leaf extract showed higher concentrations of iron, potassium, manganese, phosphorus, magnesium, zinc and crude protein with lesser fat, preferred to children (4). Major sensory challenges in moringa products are bitterness, sour and herbal flavors. These can be nullified through the breeding or processing techniques. The protein content is maximum (28.65 mg/g) in moringa leaf flour and the fiber content is highest (32.45 mg/g) in moringa flowers (Table 1). Unlike other plant-based proteins, the amino acid profile of moringa defatted leaves is rich in sulfur-containing amino acids (cysteine and methionine), which could complement proteins currently utilized in the food industry (Table 2). The *in vitro* bioavailability of moringa protein concentrate and *Moringa oleifera* defatted leaves (MODL) were 99.8% and 64.7%, respectively. Moringa protein's functional characteristics (solubility and emulsifying stability) can be compared with widely used proteins like soybean. Their solubility makes them ideal for drink formulations and

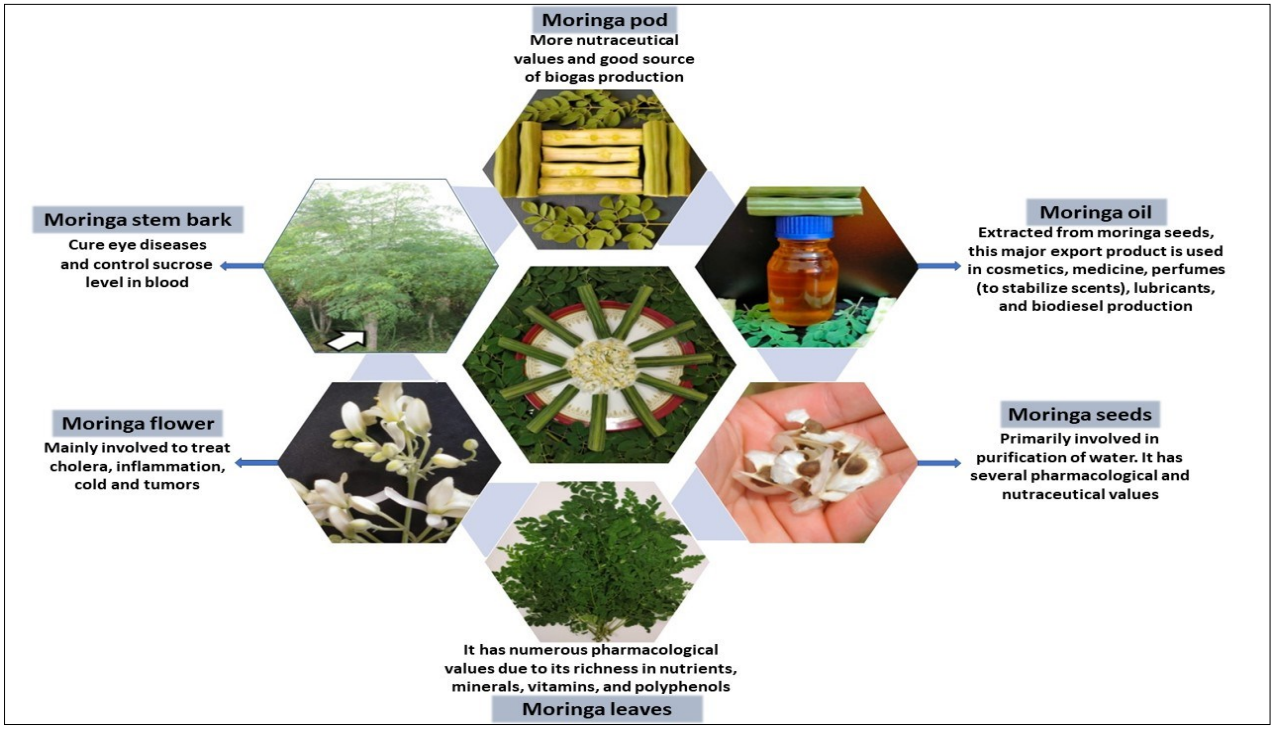

Fig. 1. Multiple utilities of moringa.

their emulsifying stability and foaming capacity make them appropriate for producing mayonnaise, salad dressings, ice creams, cakes and breads. The oil-holding capacity of moringa makes it the perfect plant-based meat analogue and is suitable to substitute meat products in fried and baked foods (8). Moringa leaf emulsions showed better physical stability than seed emulsions, making them better suited for emulsion-based beverages (9).

Moringa seed proteins exhibited better functional properties when digested sequentially with pepsin - trypsin, which increases their nutraceutical activities as antioxidants, anti - hypertensives and antidiabetics. Thus, the consumption of moringa is encouraged due to its richness in nutritional and pharmacological properties and because it is affordable to people with low incomes in developing countries. Hence, it may be referred to as famine food.

Bio-fortifying foods with moringa products could be an important strategy to eradicate malnutrition and undernutrition. For example, a greater variability for the folate content in the natural moringa leaves is reported. Each 100 g dry moringa leaf has a folate content ranging from 69.77 to 1107.80 µg. This natural folate does not have any side effects upon consumption. Worldwide, moringa-based biofortified products (raw powder, tea, tablets, gum powder and energy bars after value addition) are produced by many companies and are marketed for commercial usage (10).

Table 1. The nutrient content of moringa leaves, pods and flowers (%)

Nutrient	Moringa leaves	Moringa defatted leaf powder	Moringa leaf flour	Moringa pods	Flowers	References
Carbohydrates	28.4	34.0	44.36	4.3	36.04	
Proteins	23.6	24.1	28.65	3.32	18.92	
Ash	7.2	7.8	10.9	2.01	14.60	5, 6, 7
Fat	6.8	0.0	7.09	12.0	2.91	
Fibre	24.9	24.3	-	-	32.45	

Table 2. Protein and amino acid composition of moringa leaf, immature pods, flowers and defatted leaves (mg/g)

Amino acid	Leaves (mg/g)	Immature pods (mg/g)	Flowers (mg/g)	Defatted leaves (mg/g)	Protein concentrate (mg/g)	References
Aspartate	15.8	7.4	12.3	92.2	121.5	
Glutamate	17.1	14.6	17.0	71.3	108.2	
Serine	9.4	7.5	7.5	41.8	59.0	
Histidine	7.0	2.0	3.1	14.4	13.7	
Glycine	10.3	4.3	6.5	20.3	23.3	
Threonine	7.9	3.3	5.4	39.0	68.6	
Alanine	12.5	4.2	8.1	10.5	22.6	
Proline	12.4	4.0	6.6	20.0	27.9	
Tyrosine	4.8	0.4	0.4	24.2	39.4	
Arginine	12.2	8.1	20.1	143.3	94.2	5
Valine	11.3	4.3	6.4	42.8	53.1	
Methionine	1.4	0.9	1.0	15.4	14.4	
Isoleucine	8.9	3.1	5.2	28.8	36.1	
Leucine	17.5	5.6	8.7	56.6	58.9	
Phenylala nine	8.9	2.3	3.8	49.9	50.4	
Lysine	15.3	2.5	4.6	58.2	50.5	
Tryptophan	-	-	-	17.6	22.4	
Cysteine	-	-	-	56.0	81.2	

Moringa, rich in proteins, vitamins (A, B, C and E) and minerals (iron and calcium), is a perfect candidate for fortifying food products with essential amino acids, micronutrients and vitamins (Table 3, 4). Bio-fortifying bread, beverages, snacks, dairy and meat products with moringa leaf powder or extracts would increase the nutritional profile, thereby reducing malnutrition. In moringa, consumers preferred the sweet and floral flavours and the dislike traits are green, grass, herbal flavours, sour, bitter and presence of precipitate (20). However, the usage of moringa protein in the food industry requires potential evaluation for toxicity and allergy. Mo-CBP_3 is an antifungal protein in moringa, presenting >35% identity with allergens. Various research studies on toxicity confirm that moringa is safe for human consumption and a daily intake of up to 6 g/100 g of moringa leaves can supply a good quantity of proteins and essential nutrients. Thus, moringa can be practically utilized as an ingredient in the food industry to make different food products.

Bread fortified with moringa seed flour (1-5%) and dry leaf powder (1-15%) increased protein and fiber content (21). Protein digestibility corrected amino acid score (PDCAAS) showed a 32 - 60% increase in *M. oleifera* leaf protein (MOLP) and gluten-enriched bread. This is because the low lysine content in the wheat was complemented by the lysine in the moringa (22). Similarly, fortifying pasta with moringa leaf powder increased the mineral contents. Moringa leaf extracts can be used to fortify beverages and drink formulations. Smoothies fortified with moringa improves the minerals (calcium, potassium and vitamins).

Despite the efforts to fortify the food products with moringa, consumer acceptance is a major challenge. Including moringa powder or extracts negatively affects the sensory qualities of the food and, in turn, affects the consumer acceptance (4, 23). Adding moringa products imparts green colour and bitterness, which reduces consumer acceptance. These factors can be addressed either through genetic modification or fermentation. Adding moringa powder improved the nutritional content but affected the physical qualities of the bread, such as loaf volume, height and fluffiness. Adding moringa leaf powder to gluten-free biscuits increased the dietary fiber content up to 70g but affected the colour, spread ratio and hardness of the biscuits. The acceptability of the meat was reduced when increased concentrations of moringa extract were added to it. This calls for innovations in processing industries to mask the colour and off-flavours of moringa products to improve their utilization in biofortification (24). The global market for moringa products is projected to be 10 billion USD by 2025 and the CAGR (compound annual growth rate) is 8.9%. Growing awareness and using moringa products as dietary supplements expand the market potential in Canada, United States of America, United Kingdom, Germany, China, Australia and India. Several value - added products are sold in the market. Moringa leaf is marketed as raw powder, tea, tablets, gum powder and energy bars after value addition. Moringa oil and oil cake also earn a sizable foreign reserve. The United States, Western Europe and Japan are the largest markets for plant-based cosmetics and dietary supplements based on moringa. About 80% of the world's demand for moringa is met by supplies primarily from India. Moringa oil and moringa powder constitute the major moringa exports from India. At the global level, the market size for moringa

Table 3. Vitamin and mineral content of moringa

Nutrient	Dry leaves	Leaf powder	References
Vitamin B1 (mg)	2.02[a]	2.64[a]	11, 12
Vitamin B2 (ng)	21.3[a]	20.5[a]	
Vitamin B3 (mg)	7.6[a]	8.2[a]	
Vitamin C (mg)	15.8[a]	17.3[a]	
Vitamin E (mg)	10.8[a]	113[a]	
Calcium	1.48[b]	2.90[c]	
Magnesium	301.1[b]	0.64[c]	
Zinc	2.04[b]	27.50[c]	
Sodium	133.11[b]	0.04[c]	
Phosphorus	352.39[b]	0.26[c]	
Potassium	1.75[b]	1.44[c]	
Copper	0.45[b]	6.50[c]	
Iron	25.14[b]	1091.50[c]	
Manganese	7.21[b]	75.0[c]	

(Units: a: mg/100g dry weight; b: ng/100g dry weight; c: g/100g dry weight)

Table 4. Biochemical compounds in moringa

	Polyphenols		
	Range of the compounds	**Function**	**References**
Flavonoids	Major flavonoids of myricetin, quercetin and kaemferol content in dried leaves are 5.804 mg/g, 0.207 mg to 7.57 mg/g and 4.59 mg/g respectively. Moringa floweres are also contain the flavonoids of kaempferitrin, isoquercitrin, rhamnetin, kaempferol and quercetin.	Protective mechanism against bacterial, fungal, viral and degenerative diseases like cancers, cardiovascular issues and other ageing-associated diseases.	13-18
Phenolic acids	Leaves: gallic acid (1.034 mg/g), chlorogenic acid (0.018 to 0.489 mg/g), caffeic acid (up to 0.409 mg/g) and ellagic acid (upto 0.189 mg/g) and freeze-dried *o*-coumaric acid (6.457 mg/g). The ferulic acid ranged from 0.078 to 0.18 mg/g. It has traces of *p*-coumaric, synaptic, gentistic and synringic acids.	Phenolic acids are derived from hydroxybenzoic acid and hydroxycinnamic acid. It has several impacts on humans, such as antioxidant, anti -inflammatory, anti-mutagenic and anti-cancer properties.	15
Secondary metabolites	Dried leaves have 4-*O* -(α - L - rhamnopyranosyloxy) - benzyl glucosinolate (21.84 to 59.4 mg/g).	Major secondary metabolites: rhamnose, glucosinolates and Isothiocyanates. These compounds lower blood pressure and act as muscle relaxant.	14, 18, 19

products was 5.1 billion USD in 2023 and now in 2024, it is 5.5 billion USD, it may expect to grow more at the end of the financial year. In the future, it will reach 11.1 billion USD by 2032; hence, the compound annual growth rate will be 9.2% from 2024 to 2032 (20). India dominates in the International moringa and caters to approximately 80% of the global demand (25).This review covers information on the multiple utilities of moringa and the way forward for its exploitation.

Moringa: The crop value

Nutraceutical values

The nutritional requirements of humans are fulfilled through fruits, vegetables, cereals, meat and milk, but most of these nutrient-rich products are not affordable. At this juncture, moringa plays a vital role due to its richness in nutrition and affordability (Tables 1 - 4). Moringa leaves are more nutritious due to their high levels of proteins, vitamins and minerals. The 92% of available proteins are digestible in moringa. It has higher vitamin A than carrots, vitamin C than radish, tomato, pea and carrots and possesses a higher level of calcium and magnesium (26). It contains several amino acids, namely lysine, histidine, arginine, phenylalanine, tryptophan, methionine, threonine, isoleucine, leucine and valine (27). The concentration of vitamins, nutrients and polyphenols in *M. oleifera* leaves varies based on the potential of the plant, method of drying, environmental conditions and analytical techniques.

Contributory benefits

Moringa in the human diet

Moringa leaves and pods are used as vegetables since they are rich in protein, calcium, iron, vitamins (A, C, B, D, K and E) and phosphorus. Moringa leaves are used as a green leafy vegetable, mainly during the lean season. *M. oleifera* is one of the most nutrient-dense plant sources. It has different nutrients totaling 90, 46 antioxidants and 18 amino acids (inclusive of eight essential amino acids). In developing countries, moringa is widely used to alleviate malnutrition among children and improve milk secretion in breastfeeding women.

Moringa oil

Ben oil or moringa oil is extracted from seed**.** Moringa seeds possess an oil content of 35 to 40%, of which 76% are polyunsaturated fatty acids (28). It can be used as vegetable oil since it has numerous essential fatty acids. This oil contains a good amount of oleic acid (70%), sterols and tocopherols, which possess antioxidant, antiviral and anti-inflammatory properties. Ben oil has good amounts of palmitic acid, linolenic acid, stearic acid, linoleic acid and behenic acid (29). The colour of the oil is brilliant yellow. It has been utilized in cosmetics, medicines and perfume industries to stabilize scents and lubricants (30).

Biofuel production

The energy produced from the anaerobic digestion of biomass is called biogas, a kind of renewable energy**.** Biogas potential in moringa was analyzed in their pods and leaves with two different ratios (75% moringa pod and 25% moringa leaves). The proximate composition was good in both pods and leaves. Hence, it has been concluded that the co-digestion of moringa pod and leaves provides a higher biogas yield than the first composition of only 100% moringa pod. In addition**,** biodiesel is produced from its oil through transesterification. The methyl esters of biodiesel from moringa oil exhibit a cetane count of 67, which is highest in moringa since it has a higher oleic acid count (31).

Biocontrol agent

Overusing pesticides and fungicides in agriculture has increased detrimental effects (cancer or allergies) on humans. This negative impact urgently requires exploring biocontrol agents with minimal adverse effects. Moringa leaf and seed extract have been reported as effective and inexpensive bio-control agents to control soil, plant and foodborne pathogens (32). Also, it controls the soil-borne pathogens *Fusarium solani* and *Rhizoctonia solani* at a maximum of 50%. It minimizes the pest-induced damage and increases the yield by 20% to 35%. The use of moringa leaf and seed extract ensures a safer environment and exhibits effective management of pathogens and insect pests; hence, it has been included in the integrated pest management (IPM) strategy (33).

Plant growth enhancer

Moringa leaf extract is a source of vitamins, cytokinin, IAA (indole -3 - acetic acid), zeatin, gibberellins and macro and micronutrients that enhance crop growth. In beans (*Phaseolus vulgaris*), the crop yield has been increased by the exogenous application of moringa leaf extract (33). With the application of moringa leaf extract in linola (*Linum usitatissimum*), the crop yield has increased under saline conditions (34). It is an alternate approach to synthetic sources, reduces the cost and improves soil health. The organic matter of moringa residue improves soil properties like porosity, structure, water-holding capacity (thereby reduces the frequency of irrigation which reduces the soil salinity issues) promotes root development and makes the plant resist to abiotic stresses (drought, salinity).

Green manure

Owing to its biomass and nutritional supremacy, in some countries, moringa is used as green manure or green compost.

Imparting abiotic stress tolerance

In plants, abiotic stress is an unfavourable condition induced by several factors, such as drought, flood, salinity, extreme temperatures, ultraviolet radiation and heavy metals. It reduces the yield by up to 50% worldwide since the plants divert their energy towards combating these stresses instead of producing yield (35). It primarily alters physiological and biochemical processes. Abiotic stresses in plants induce oxidative stress by overproduction of reactive oxygen species (ROS), which damage proteins, lipids, carbohydrates and DNA (deoxyribonucleic acid). The primary sites for producing ROS are the chloroplast, mitochondria, peroxisomes, apoplast and plasma membrane with the chloroplast being the major site for ROS production (36). Abiotic stress affects the photosynthetic process through the production of ROS (37). Moringa is an organic biostimulant that protects plants under various stresses and is considered an eco-friendly and sustainable approach.

In *Ocimum basilicum*, the moringa leaf extract altered the expression of the gene under 1000 ppm of salt stress. This altered gene expression enhances growth and yields under salt stress through the induction of high estragole and eucalyptol content (38). In plants, drought stress affects many crucial cell functions and thereby reduces performance. Under drought, the foliar or root application of moringa leaf extract enhances the leaf area, plant height, biomass production, relative water content, water use efficiency and chlorophyll content of maize, soybean and squash (39). During heat stress, moringa leaf extract reduces oxidative damage and increases the antioxidant properties of total phenolic contents, niacin and riboflavin and enhances superoxide dismutase in maize and catalase activity in cotton. It improves the levels of various growth-promoting substances such as GA^3 (gibberellic acid), IAA, ABA (abscisic acid), benzyl adenine and kinetin in common beans thereby mitigating the heat-induced growth inhibitions (40). Under heavy metal stress, moringa leaf extract enhances cadmium stress tolerance and increases photosynthetic pigments, proline content and water use efficiency in common beans (33).

Phytoremediation

Air

Moringa can remove the pollutant (benzene, xylene, trichloroethylene and toluene) in air by absorption.

Plants and soil

Heavy metals like cadmium in soil and plants affect the whole ecosystem. It mediates the damage to the cell by inhibiting enzyme activity in the Calvin cycle, affects antioxidant enzymes, stimulates nitrogen fixation and stimulates reactive oxygen species, thereby causing oxidative damage in membranes and nucleic acids that finally lead to cell death (41). It was studied in *Lepidium sativum* under cadmium stress, in which the application of moringa leaf extract reduced the cadmium concentrations by increasing the non-enzymatic antioxidant content of glutathione and ascorbic acid (42).

Water

Drinking water before usage is purified to remove the silt particles, solids, heavy metals (cadmium, zinc, arsenic, manganese, copper and chromium) and microorganisms. The hardness of water is mainly caused by calcium, magnesium, iron, manganese, strontium and aluminium ions. Softening is the process of removing these ions. Softening is required if the hardness is greater than 150 mg/L of water. Usually, the water purification industries add chemical coagulants for purification, which are more expensive and less available all the time. Alternatively, in an eco-friendly way, pounded moringa seed or oil-extracted seed cakes have been used for water purification in small-scale industries (43). Moringa seed extract absorbs metal ions through ion exchange and forms complexes since it is one of the absorbents of the lingo cellulosic group (Fig. 2). The press cake is a byproduct obtained during oil extraction and is rich in protein with active polyelectrolytes (cationic). In dirty water, the colloids are negatively charged, which can be neutralized by the cationic polyelectrolytes. It can, therefore, be used for sedimenting mineral and organic particles in water and fibers. Moringa root powder significantly reduces the contamination of *Escherichia coli* bacteriain the contaminated water by 87% at a concentration of 600 mg/L (44).

The seed extract of *M. oleifera* and *Moringastenopetala* possess water purification properties at a rate of 200 mg and 100–150 mg/L water, respectively. Among the two species, *M. stenopetala*i s more effective in the water purification process. The seeds of *M. oleifera* can remove humic acid, alkalinity,

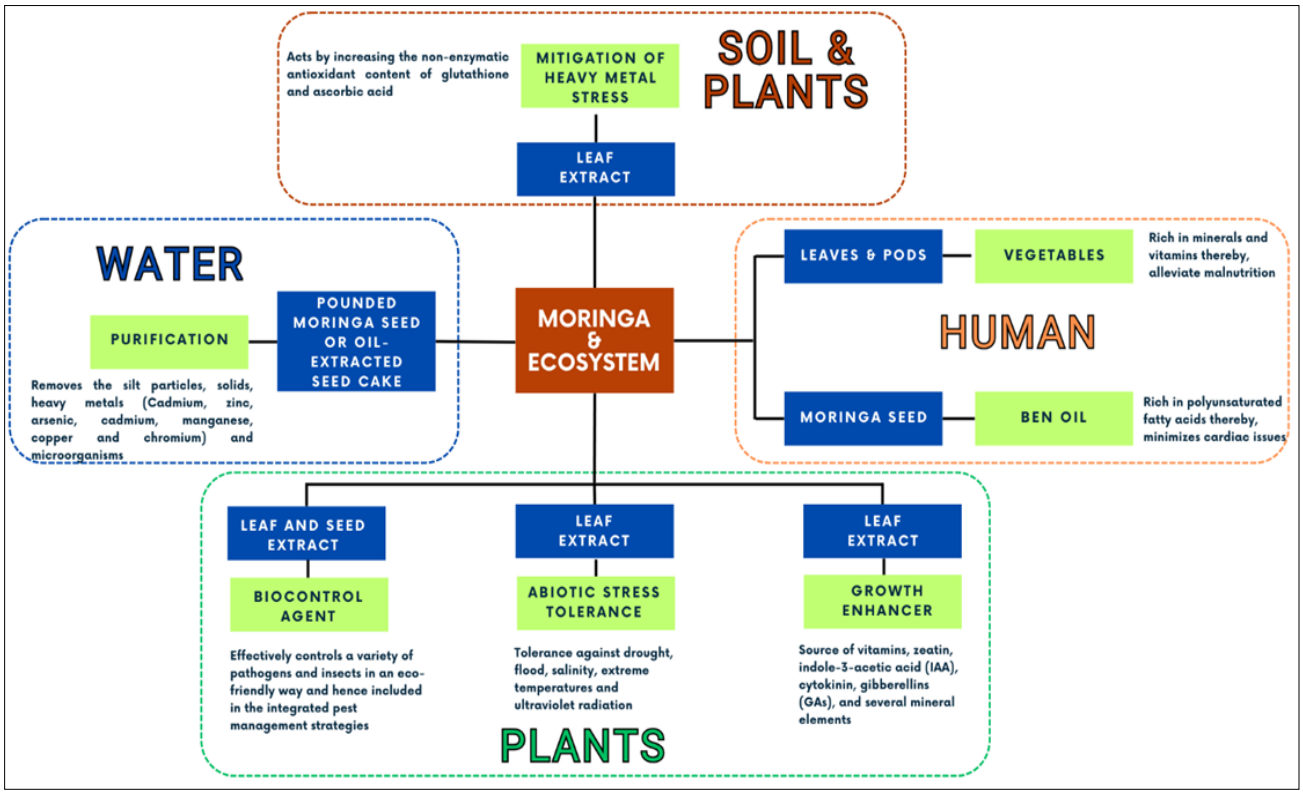

Fig. 2. Moringa and its eco-remedial values.

turbidity and dissolved organic carbon (45). Microorganisms (*E. coli* and *Staphylococcus aureus*) present in the river of African countries, such as Nigeria, Rwanda, Malawi, Egypt and Sudan, were reduced by 90% and 95%, respectively, through the usage of moringa extract (46). The moringa seed extract removes heavy metals such as 60.2% arsenic (III), 85.06% arsenic (IV), 85.10% cadmium, 90% nickel and copper, 80% lead and 50% of zinc and chromium. Moringa is also used to treat the dairy industry and palm oil effluent waste (45).

Animal feed

At the global level, the consumption rate of meat products increased by 1.2% in 2017, necessitating an increase in the production of animal feed (https://www.fao.org/markets-and-trade/en/). In human consumption, the major sources of animal protein are large ruminants, poultry and pigs. The production of animal feed with reduced methane emissions is a significant challenge, as methane gas is released *via* belching during ruminal fermentation. Moringa appears to be a viable and eco-friendly option in dairy sector, as it enhances animal growth performance while also reducing methane production. This reduction is attributed to its bioactive compounds, saponins and condensed tannins, which decreases microbial activity in the gut and improve fermentation efficiency. In lambs, the inclusion of moringa meal in the diet lowers the cost per kilogram of body weight gain. The total cost per kilogram of body weight was Rs. 105.44 for moringa meal-included diet, compared to Rs. 131.34 for diet without moringal meal (47).

In India, agriculture and animal husbandry have been interwoven as mixed farming systems since ancient times. According to the 20th livestock census report, India holds the world's largest livestock population of 536.76 million (48), it ranks first in cattle, second in goats and third in buffalo. The average milk production per cow per year in the USA is 9000 Kg, whereas in India, it is only 1000 Kg. This low productivity can be attributed to factors such as malnutrition, undernutrition or both. Feeding is a major component of livestock production, accounting for 55-60% of the total cost of milk production. In India, the green fodder requirement is 827.19 million tonnes, whereas the availability of green fodder is 734.2 million tonnes, leaving a deficit of 92.99 million tons (11.24%). In the case of dry fodder, the requirement is 426.1 million tons, while the availability is 326.4 million tons. For concentrates, the requirement is 85.78 million tons, while the availability is 61 million tons (49). This gap in green fodder availability is ecpected to widen further due to the increasing livestock population and the conversion of productive agricultural land into non-agricultural purposes. To address these challenges, alternative fodder resources must be explored. Under these circumstances, tree fodder has been considered a viable alternate source of fodder for the livestock. It could enhance the availability of quality green fodder due to its high protein, vitamins and minerals. Among the tree fodders, moringa is one of the popular tree fodders in the dairy industry due to its high level of nutrition in leaves and reduces the methane emission from the rumen by 17% (50). On average, moringa can produce a green fodder yield of 100-120 tonnes per hectare per year with 4 to 5 cuttings. One accessions of *M. stenopetala* called 'Gamolle' produces higher biomass than *M. oleifera*. In general, the leaf twigs ratio is higher in *M. oleifera* (2.3:1) than in *M. Stenopetala* (1.5:1). Regarding nutrient content, crude protein is higher in *M. Stenopetala* whereas calcium is higher in *M. oleifera.* Moringa and its associated products can be used as feed for a variety of animals and birds, as detailed below for a comprehensive understanding.

Ruminants: Initially, for milch animals, moringa seed was used as feedstuff and later the young branches, leaves and seed cake were fed in a different ratio. The fodder values of moringa, including crude protein (8% to 23%), crude fat (2% to 6.5%), crude fibre (4.5% to 26.5%), acid detergent fibre (6% to 13.5%), neutral detergent fiber (8% to 36 %) and dry matter (7.6% to 9.2%) at different stages were estimated and suggested as a quality fodder crop in the previous research (24). In cattle, immature moringa leaves and twigs are utilized as fodder to increase milk secretion which improves the microbial protein synthesis inside the animal rumen by consumption (51). For ruminants, it acts as a good alternative to soybean and rapeseed meal. In goats, the antioxidant compounds and vitamin C in the milk and serum increase, if they were feed with 25% *M. oleifera* or *M. peregrina* and therefore, moringa, can be considered as an alternative to alfalfa during lean seasons (52). The moringa can partially or completely replace the berseem fodder in Friesian cow feeding schedules because it increases the milk yield and composition due to its higher crude protein, total phenolic compounds, condensed tannins, essential amino acids and minerals, such as calcium, magnesium, phosphorus, iron, manganese and zinc. The feeding efficiency of animals is improved by the supply of *M. oleifera* leaves. The ensiled *M. oleifera* exhibited higher antioxidant levels due to the accumulation of amino acids and low molecular weight peptides. Thus, the moringa silage can replace maize silage by 263 g/Kg of diet in dairy cows (53). During the lean season, maize and rice feed are replaced by *Tephrosia* spp. and *M. oleifera* in Nigeria (54). Buffaloes supplied with 50 g per Kg of *M. oleifera* leaf powder resulted in an increased milk yield, milk composition, nutrient digestibility and antioxidants. In bulls, the quality of semen in terms of volume, colour, viscosity, mass movement, sperm motility and sperm concentration increased with the inclusion of moringa leaf in their diet. In ewes, the supply of *M. oleifera* leaves resulted in increased milk composition, body weight, red and white blood cells, protein, blood urea nitrogen and ovarian follicle development (55). Thus, the moringa can be used as an alternate protein source in ruminants significantly reducing the production cost.

Poultry: In the poultry industry, antibiotics are used to increase feeding efficiency, growth and productivity in birds. However, an alternative, eco-friendly approach involves the use of phytobiotics, which are derived from plants and used to enhance animal productivity at a low cost (56). One such phytobiotics is moringa leaves, which enhance growth rate and productivity due to their richness in vitamins and minerals and the absence of heavy metals (57). For egg-laying hens, the inclusion of 1% *M. oleifera* in their diet is recommended (58). In poultry increased body

weight is observed when soybean meal is supplemented with moringa leaves due to the presence of active compounds. Additionally in poultry, a reduction in cholesterol content and an increase in yolk pigmentation in eggs are observed with the moringa leaves supplementation, as it has hypocholesterolemic effects and a significant carotene content (59). It also reduces *E. coli* levels, thereby improving the immune system. Furthermore, it enhances intestinal levels of *Lactobacillus*. In chickens, increased growth (chick weight) and reproductive performance (motility and velocity of sperm cells and hatchability) are observed with the inclusion of moringa leaf (60). In broilers, an increase in gut microflora and growth is noted with the inclusion of moringa in the diet (Abo).

Newcastle Disease Virus (NDV) is a highly contagious and infectious viral disease that causes severe economic losses worldwide in poultry worldwide. It can be prevented through vaccination, which is expensive. Moringa, with its powerful antiviral properties, offers a cost-effective alternative to combat NDV by modulating the immune system through its bioactive compounds (61). Generally, synthetic antibiotics are used in poultry to impart resistance against microorganisms, raising concern about public health hazards. Alternatively, food supplements containing moringa improve poultry resistance to microorganisms and contribuite to the production of healthy, antibiotic-free meat and eggs. In poultry, economic losses also occur due to bacterial pathogens, such as *E. coli, Salmonella* spp. and mycoplasma, which can be controlled by supplementing the diet with moringa extract (leaf, seed and root) due to its antibacterial properties. The recommended dosage of moringa extract against bacterial diseases is 15 g/L of water (62). However, excess moringa meal inclusion in poultry feed may negatively affect egg-laying capacity due to its anti-nutritional factors. Therefore, the permissible limit of moringa leaf meal in the poultry diet should be maintained from 1% to 5% (63).

Pigs: Pork is a nutritionally complete food that is widely consumed globally. It contributes to increased the omega-3 fatty acid intake in humans. The inclusion of 6% moringa leaf meal in pig diets enhances body weight and total unsaturated fatty acids. The benefits of the incorporating moringa meal into pig diets include (i) increased carcass yield, higher meat weight in the leg and reduced rib fat (64). Moringa leaf meal reduced production costs and a lower incidence of piglet scours by stimulating the immune system and improved digestion process and higher level of unsaturated fatty acids. It is recommended that the proportion of moringa in pig diets be formulated based on their growth stages.

Rats: Moringa leaf extract improves liver and kidney function as it contains several bioactive compounds. In Wistar rats, the leaf and stem extracts of moringa reduce the fatty liver due to three antioxidant compounds, namely caffeic acid, quercetin and gallic acid, which help eliminate free radicals. The free radical scavenging action ensures the hepatoprotective activity of moringa. It also increases the haemoglobin content in rats (65). Due to the hepatoprotective mechanism, moringa protects the liver from the oxidative damage caused by diclofenac sodium (66). Moringa meal exerts antidiabetic or hypoglycaemic properties in Wistar rats due to the presence of streptozotocin (67).

Aquatic animals: The feed formulations for aquatic animals, especially fish, are prepared in such a way as to supply all the nutrients and minerals required for their growth and reproduction. A study on the effect of fermented and non-fermented moringa leaf meals on the growth performance of fish revealed that the inclusion of 4.4% fermented *M. oleifera* leaf meal has beneficial effects on crude protein, free amino acids, muscle lipid and antioxidant levels. In addition, increased liver anti-inflammatory properties are observed in fish fed with a diet supplemented with fermented *M. oleifera* leaves (68). Better growth performance is observed in *Labeo rohita* with a 10% inclusion of *M. oleifera* in their diet, while a reduced growth rate was noted when this limit was exceeded (69). In male rainbow trout broodstock, a feed containing 8% moringa leaves increased sperm quality and reproductive efficiency. The supplementation of moringa leaves in the diet of carnivorous fish (10-20%) and herbivorous and omnivorous fish (10-30%) is encouraged to ensure better growth and reproduction efficiency without any adverse effects (70).

Rabbit: Continuous usage of antibiotics in animals creates a harmful effect on human health upon consumption. Natural feed additives such as moringa, eucalyptus, propolis and yucca enhanced the antimicrobial, anti-inflammatory, antioxidant and immune-stimulant properties in rabbits, especially under heat stress conditions. They also improve the growth and reproduction efficiency of rabbits (71).

Moringa leaf extract or nano-formulized version has a positive effect on growing rabbits after weaning or prenatal treatment of their dams in terms of increased intake of feed, decreased oxidative stress and enhanced liver and kidney function. Moringa leaf meal can replace soybean meal by up to 20% during lean seasons while increasing haemoglobin content by 29% in rabbits. A recent study has concluded that the rabbit diet supplemented with 70% moringa leaves resulted in an increased growth rate, feed conversion ratio and functional attributes of meat in rabbits (72). In rabbits, severe economic losses occur due to the parasitic disease called coccidiosis which is caused by *Eimeria* spp. It destroys the intestinal epithelial cells. The natural anti-coccidial activity is identified in *M. oleifera* and *Vernonia amygdalina* (73). The utility of moringa from an animal perspective is furnished in Fig. 3.

Based on the above facts, moringa can be included in the diet of animals to increase milk and meat production as well as quality. The concentration of moringa feed varies based on the type of animal since it contains the least amount of anti-nutritional compounds. Hence, it serves as an alternate feed during the lean season.

Pharmacological properties

The products derived from moringa possess varied medicinal properties such as antioxidant, anticancer, antiulcer, antidiabetic, anti-inflammatory, immunomodulatory and antimicrobial agents since it is rich

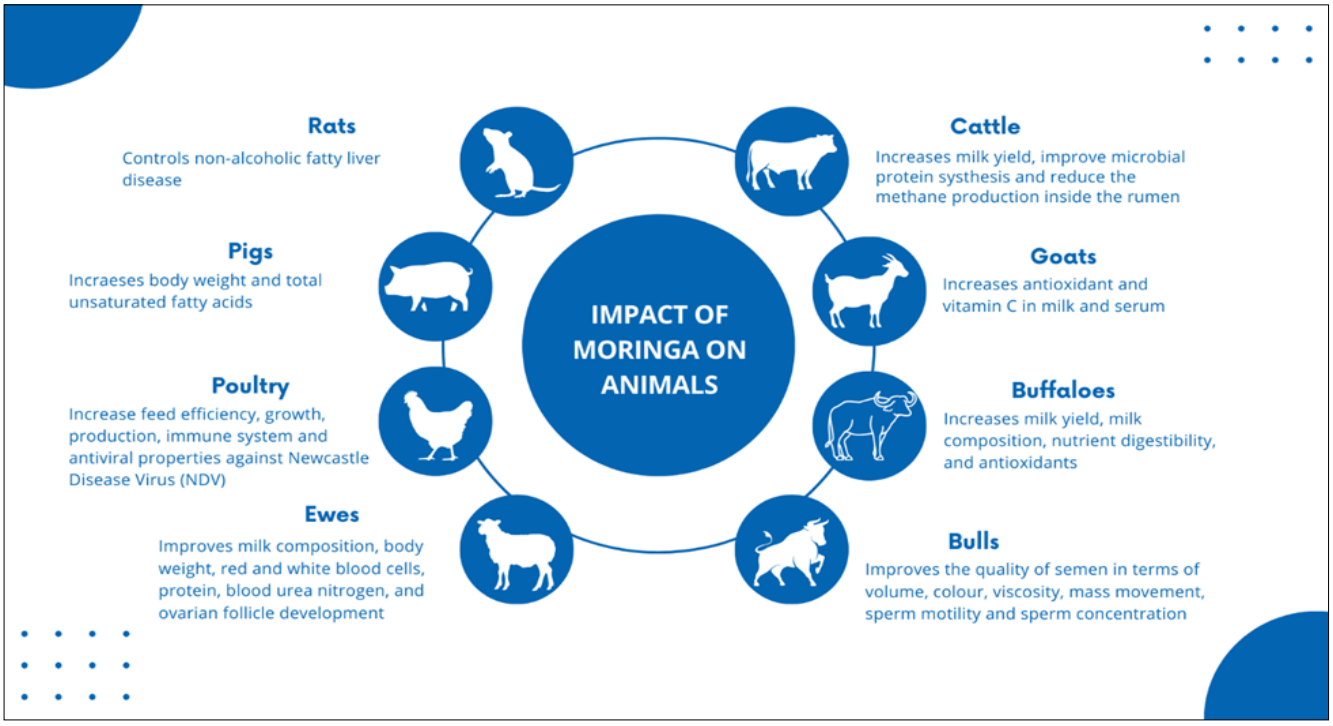

Fig. 3. Impact of moringa on animals.

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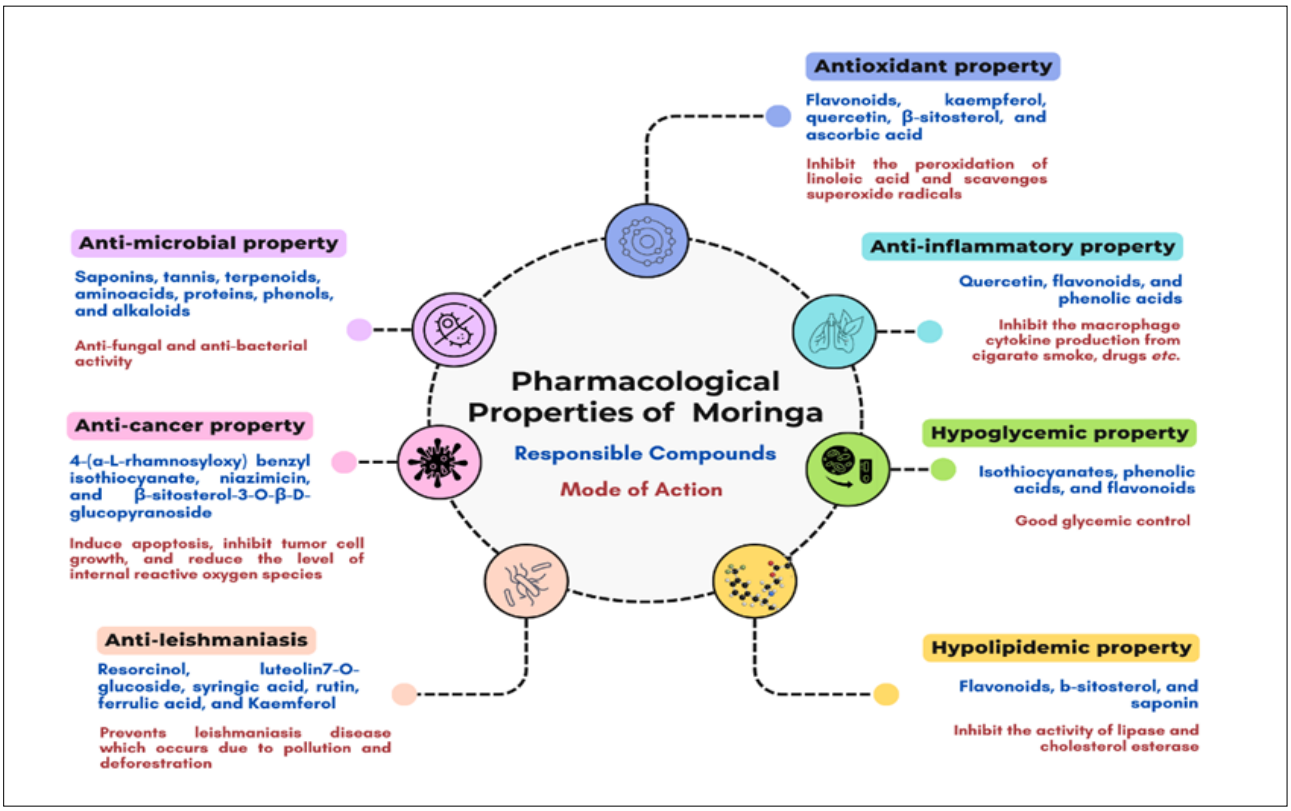

Fig. 4. Pharmacological properties of moringa.

phytochemical compounds. The supremacy of moringa for its pharmacological properties in comparison to other medicinal plants is well documented (https://cb.imsc.res.in/imppat/basicsearch/therapeutics). The concise information is furnished in Fig. 4. In general, moringa has been used to treat lifestyle-related diseases since it has bioactive elements. Including moringa in the diet, especially for anaemic patients, improves haemoglobin in humans. The ayurvedic medicine sector states that it can prevent or cure 300 diseases (cancer, diabetes, arthritis, heart problems etc.) in humans (26). Nearly 5,000 years ago, it was documented in Indian Vedic literature due to its massive pharmacological properties (74).

Moringa seed powder is used in the curing of breast and colorectal cancer, heart diseases and thyroid disorders. Crushed leaves are used to treat conjunctivitis, diarrhoea and scorpion bites. The flowers and roots of moringa are used to treat cholera since they contain the compound pterygospermin and have also been recognized as antibiotics. The leaves are used to treat malaria, skin problems, influenza, arthritis, hypertension and diabetes. The oral intake of moringa leaf powder in humans exhibits significant benefits of anti-hyperglycaemic, anti-

dyslipidaemia and antioxidant properties without any adverse effects.

No adverse effects have been reported in humans with dosages of leaf powder up to 8 g per day. The roots treat ulcers, scurvy, toothache, colds and asthma. The root bark is mainly involved in preventing kidney problems, ulcers and enlargement of the spleen. Stem bark is used to cure eye diseases. Gum is used to relieve headaches (mixed with sesame oil), earaches, dental caries, dysentery, asthma and rheumatism. Seeds are used to treat fevers and abdominal tumours. Seed oil is used to treat skin diseases, scurvy, bladder troubles, tumours, ulcers, bacterial and fungal infections and stomach disorders. The flowers are used to treat inflammations, colds, tumours and cholera.

Antioxidant properties: The compounds that inhibit the action of free radicals and thereby protect the cells from oxidative damage are called antioxidants (75). In general, there are 46 antioxidant compounds found in moringa such as flavonoids, kaempferol, quercetin, β-sitosterol, ascorbic acid, etc. Kaemferol and quercetin exhibit higher antioxidant activity than ascorbic acid (76). Moringa seed contains ferulic acid, epicatechin, gallic acid, protocatechuic acid, catechin, caffeic acid, vanillin, cinnamic acid, quercetin, phytosterol, quercetin rhamnoglucoside and chlorogenic acid, whereas the young flowers and pods contain carotenoids. The phenolic compounds in moringa exhibit antioxidant properties through metal chelation and scavenging of free radicals. The total phenol and flavonoid contents in moringa reduce free radical activity (77). Chlorogenic acids are the major phenolic compounds in moringa, which are responsible for antiradical capacity and possess anti-herbivorous properties (78).

Moringa's antioxidant properties inhibit the peroxidation of linoleic acid and scavenges superoxide radicals. Environmental factors like temperature, season, soil properties and crop growth stage influence the concentration of antioxidant properties in moringa (79). Winter samples exhibited higher antioxidant activity (DPPH-radical scavenging EC_{50} = 200 µg/mL) compared with the summer samples (EC_{50} is 387 µg/mL). Leaf growth stages also affect antioxidant activity (80). Mature and tender leaves showed slight but significant differences for DPPH-scavenging activity, nitric oxide scavenging activity (EC_{50} = 56.77 and 65.88 µg/mL, respectively), superoxide scavenging activity (EC_{50} = 12.71 and 15.51 µg/mL, respectively) and lipid peroxidation inhibition (EC_{50} = 25.32 and 30.15 µg/mL, respectively).

Anti-inflammatory and immunomodulatory properties: In moringa, approximately 36 anti-inflammatory compounds such as quercetin, flavonoids and phenolic acids are abundant in the seeds and leaves. In mice, moringa seed extract with a dosage of 3 mg/Kg of body weight reduced hind paw oedema inflammation by 85% when induced by carrageenan. In humans, the production of macrophage cytokines, which triggered by external factors such as cigarette smoke, drugs and lipopolysaccharides, is inhibited by the ethyl acetate-based extraction of bioactive compounds from moringa leaves (81). Cyclophosphamide-induced immune deficiency in mice was alleviated through an increase in white blood cells, neutrophil percent and immunoglobulin levels in serum following the injection of leaf extracts of *M. oleifera* (82).

Hypoglycemic properties: Worldwide, the common metabolic disorder is diabetes which results in hyperglycaemia. Tablets or insulin therapy are commonly utilized to treat diabetics, but they are very expensive and produce several side effects. Searching for an alternate herbal medication is highly preferable. The extracts of the seed, root and stem bark of *M. oleifera* control the blood sucrose levels due to a good glycaemic index. *Moringa* leaves possess the property of glucose homeostasis. The identified bioactive compounds are isothiocyanates, phenolic acids and flavonoids have mechanisms of insulin resistance and hepatic gluconeogenesis. These compounds have hypoglycaemic properties in various cells of the pancreas, liver, skeletal muscle and adipose tissue. The effect of moringa as an herbal drug on diabetic patients depends on their age, sex, nutritional level and dietary habits. The anti-diabetic properties of *M. oleifera* leaves were tested on rats. Alloxan (120 mg per Kg of body weight) was used to induce hyperglycaemia in rats. The leaf extract at different concentrations of 100 mg per Kg, 200 mg per Kg and 300 mg per Kg showed a remarkable reduction in blood glucose. The reduction percentages were 33.29, 40.69 and 44.75 respectively (83). The antibiotic properties of moringa flower were tested on rats by inducing type 1 diabetes using streptozotocin at a concentration of 65 mg per Kg and type 2 diabetes using alloxan at a concentration of 120 mg per Kg. The flower extract reduced the glucose level in both treatments and determined the phytochemicals responsible for this antidiabetic property (flavonoids and tannins).

Hypolipidemic properties: The moringa leaves have lipid homeostasis capacity. The bioactive compound consists mainly of flavonoids involved in lipid regulation (84). It has been influenced by the inhibition of lipase and cholesterol esterase. Various bioactive compounds responsible for lipid-lowering capacity are reported. B-sitosterol lowers the plasma cholesterol of rats (85). Saponin is also involved in reducing plasma cholesterol by increasing bile acid excretion.

Anti–leishmaniasis: It is a parasitic disease caused by the *Leishmania* genus (Intracellular protozoan parasites). It affects millions of people in Asia, Africa and South America owing to pollution, deforestation and migration. So far, no vaccine has been developed to combat this disease. The following six compounds with anti-leishmanial activity are reported in moringa, namely resorcinol, luteolin7-o-glucoside, syringic acid, rutin, ferulic and kaempferol 3-o-rutinoside. Among these, the first three are more active than others (86).

Anti-cancer properties: Moringa leaves protect the cells from oxidation-induced DNA damage caused by cancer and other degenerative diseases (80). In *M. oleifera*, niazimicin, 4-(a-L-rhamnosyloxy) benzyl isothiocyanate and β-sitosterol-3-*o*-β-D-glucopyranoside are the major biomolecules involved in anti-cancerous activity (87). The mechanisms involved in the anticancer properties of *M. oleifera* are apoptosis and reduction of internal ROS level. It inhibits the tumour cell growth, without causing any damage to the normal cells (88). A decrease in glutathione, simultaneous ROS increase and ATP decrease with increasing *M. oleifera* extract concentration indicated that moringa induces cell death (apoptosis). It was analysed and proved in animals, not in

humans. Hence, further studies on humans are needed.

Antibacterial and antifungal activity: *M. oleifera* has antimicrobial activity, which can be influenced by the compounds saponins, tannins, terpenoids, amino acids, proteins, phenols and alkaloids. The leaf extract of *M. oleifera* showed antibacterial properties against *Salmonella* species. The concentration of leaf extract at 5mg /mL showed resistance against a variety of microorganisms like *Salmonella typhi* (89). The fresh leaf juice, leaf extract and leaf powder of *M. oleifera* showed antibacterial activity against four Gram-negative bacteria. Antifungal activity was observed against *Penicillium* spp., *Mucor* spp., *Candida albicans* and *Trichoderma harzianum* (90). The highest antifungal activity was observed against *Aspergillus flavus* which produces aflatoxin B1. Thus, the pharmacological properties of *M. oleifera* were confirmed and recommended for medication with various studies on animals under *in vitro* and *in vivo* conditions and a few studies on humans.

Moringa extracts: An alternative to chemical fungicides to control postharvest diseases

Moringa is a multipurpose tree with high potential in the agriculture, pharmaceutical and food industries due to its phytochemical content. It is a rich source of vitamins, minerals, proteins, β carotene, phenolic acids, flavonoids and other bioactive compounds. The higher concentration of phenolic acids and flavonoids in moringa leaf extract contributed to its good antioxidant activity both *in vitro* and *in vivo*. The plant extracts can be widely utilized for post-harvest pest and disease control (Fig. 5). Moringa leaves could be used as a functional additive in edible coating formulation to improve the postharvest quality of citrus fruits. Its antimicrobial properties make it possible to use them in preparing organic edible film to enhance the shelf life of horticultural perishables and improve the antimicrobial activity of edible coating. Plant extracts are an effective alternative to synthetic fungicides as they are safe, eco-friendly and affordable with less negative impacts and control postharvest fungal rots in horticultural perishables.

Moringa plant extracts can be utilized to increase the shelf life of the cut flowers. Moringa leaf extract was used as an additive in vase life solution to extend the shelf life of gladiolus spikes and can be used as an eco-friendly novel floral preservative (91). The antimicrobial properties of the extract can be used to prevent post-harvest losses. Moringa extract has bio-pesticide action and has antibacterial, antifungal and insecticidal properties contributing to plant disease management (92).

Postharvest disease management and shelf-life extension

Moringa leaf extract as an additive in gum arabic edible coating inhibited the mycelial growth of pathogens causing postharvest disease in avocados. It extended the shelf life by reducing the respiration rate and ethylene production with better firmness. Moringa leaf, bark and seed extracts inhibited the growth of soil-borne fungi and were found effective against *Rhizoctonia* and *Pythium* spp. The unique combination of caffeoylquinic acid, quercetin, beta-sitosterol, zeatin and kaempferol in moringa extract contributed to its antibacterial and antifungal activities (93). The postharvest diseases of papaya are mainly caused by *Colletotrichum gloeosporioides, Rhizopus stolonifer, Phytophthora palmivora* and the moringa leaf and seed extracts, which effectively controlled these pathogens. An *in vitro* study revealed that the ethanolic extract of moringa leaf and aqueous extract of moringa seeds recorded 100% suppression of mycelial growth. The aqueous extract moringa leaf (30%) was effective for *P. Palmivora* and *R. stolonifer,* recorded inhibition of 71.28% and 33.71%, respectively. The ethanolic extracts of moringa leaf and

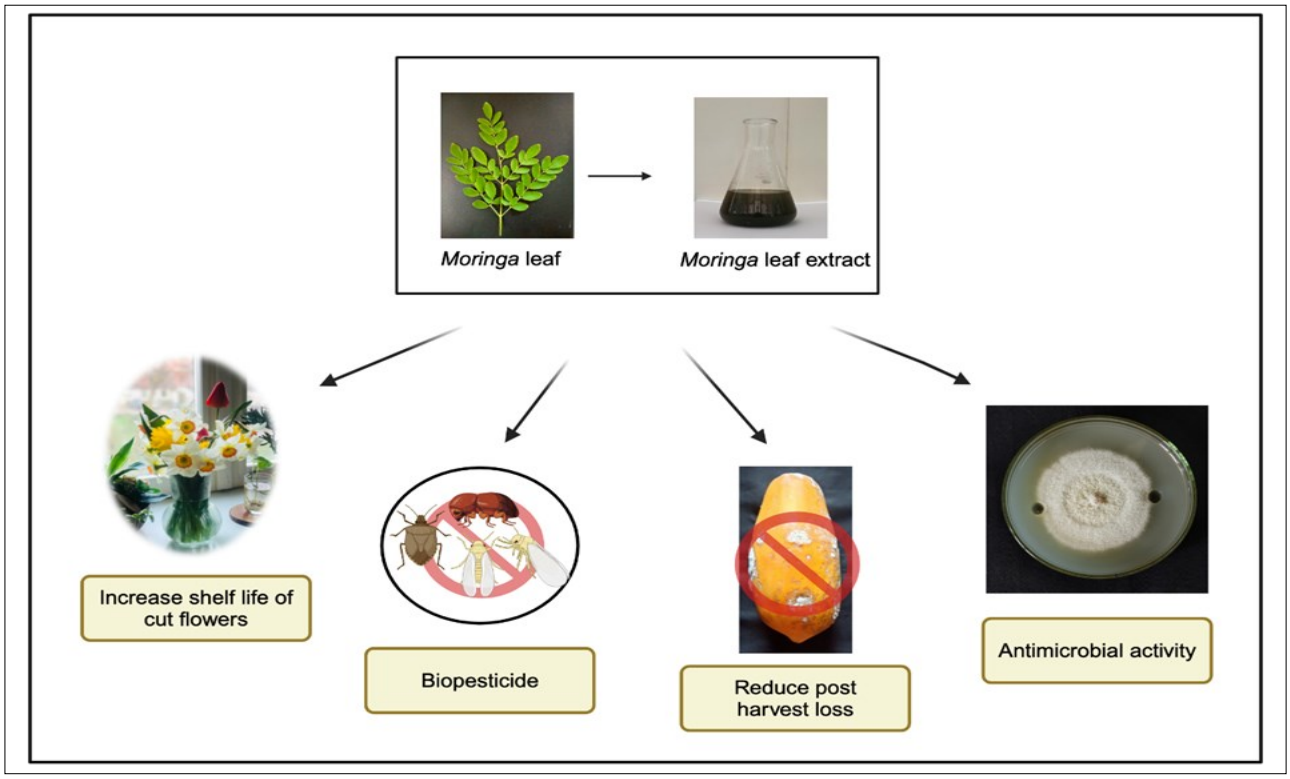

Fig. 5. Role of moringa plant extracts in post-harvest disease management.

seeds recorded higher antifungal activity and effectively suppressed mycelial growth by breaking and shrinking the hyphal strands and reducing spores. Hence, moringa extracts can be an environmentally friendly alternative to synthetic fungicides to control postharvest diseases. Moringa leaf extract as seed treatment also effectively controlled the soil-borne fungi (94).

The acetone extract of moringa leaves recorded antibacterial activity. In contrast, both acetone and aqueous extracts (10 mg/mL) have not exhibited any antifungal activity against *C. albicans, Penicillium notatum, Aspergillus flavus* and *Aspergillus niger* (93). The extract (20%) of moringa roots and leaves could be used as a potent bio-fungicide and recorded reduction in radial growth, spore/sclerotia and dry mycelia weight when tested for its antifungal effect *in vitro* against *Fusarium oxysporum, F. solani, Alternaria solani, A. alternata, R. solani, Sclerotium rolfsii* and *Macrophomina phaseolina* (95). The aqueous extract of moringa leaves (100 mg/mL) exhibited variable antifungal activity against *A .niger, A. flavus, P. italicum, F. oxysporum, R. stolonifer, Alternaria* spp*., C. albicans, C. parapsilosis* and the mean growth inhibition percentage was reported as 75.2 ± 0.55%, 59.4 ± 0.75%, 58.2 ± 0.63%, 46.5 ± 0.63%, 62.5 ± 0.77%, 24.5 ± 0.65%, 20.3 ± 0.75% and 80.00 ± 0.70%, respectively.

In vitro studies were conducted using moringa leaf and stem extract to control pathogens causing onion rot. The moringa stem extract inhibited the growth of *A. niger* var. *tieghem* at all concentrations of 12.5%, 25%, 50% and 75% and the inhibition increased progressively with the concentration. Whereas moringa leaf extract exhibited no inhibition at lower concentrations and slight inhibition was noticed at 75% concentration. Moringa extract was recommended as a bio-protective agent to control onion rot. *M. oleifera* extracts at 2.25 to 3.00 g/L concentration completely inhibited the growth of *C. gloesporioides* in both *in vitro* and *in vivo.* Spore shredding, cytoplasmic discharge and mycelial blast were vividly observed when *C. gloesporioides* was treated with moringa extract. The minimum effective concentration of moringa extract was recorded at 2.25 g/L and could be applied as a curative, protective and simultaneous treatment to inhibit anthracnose disease in mangoes. The postharvest application of moringa leaf extract (10%) on mango cultivar 'Zebda' reduced the postharvest fruit weight loss, decay percentage, total acidity and lipid peroxidation. Higher retention of total soluble solids (TSS), sugar-acid ratio, vitamin C, antioxidant activity (as DPPH radical scavenging assay) and total phenols were reported for fruits under cold storage of 6 weeks than the untreated mango fruits, which indicated the extended shelf life of mango with better retention of nutritional quality (96).

The 'Fuerte' and 'Hass' avocado fruits coated with moringa leaf extract (2%) and a combination of moringa + 1% carboxy methyl cellulose lowered respiration rate, moisture and firmness loss during the storage. They enhanced the postharvest storage life. The moringa leaf extract (10%) with 10% gum arabic and 10% moringa leaf extract with 1% carboxy methyl cellulose as postharvest treatment of avocado cultivar Maluma effectively controlled the *C. gloeosporioides* up to 33% and reduced weight loss, firmness loss and delayed the colour changes. The postharvest treatment of plum cultivar 'Golden Japan' with salicylic acid, putrescine and moringa leaf extract (10%) played an effective role in controlling the fruit weight loss, decay, softening and other compositional changes such as titratable acidity, total soluble solids, total carotenoids, total phenolics, total flavonoids and antioxidant activity during cold storage. Edible coating of guava (cv. Maamoura) with 10% gum arabic + 10% moringa leaf extract reduced postharvest weight loss, decay and *Rhizopus* rot infection, delayed fruit softening under cold storage conditions and increased marketability (97). The 'Cavendish' banana coated with chitosan nanoparticles (2%) and moringa leaf extract (10%) recorded the lowest weight loss (23%), respiration rate (18 mg/Kg/h) with higher retention of soluble solids, fruit firmness and peel colour with improved shelf life and marketability (98).

The effect of methanolic (15 g/250 mL) and aqueous (20 g/250 mL) moringa leaf extract on postharvest stem-end rot in mango was assessed. The methanolic extract recorded the highest inhibitory rate (65.45%) compared to the aqueous extract (42.44%), significantly reducing the stem-end rot in mango (99). The moringa extracts (10% concentration) recorded a 100% fungicidal effect against *Botrytis cinerea* and *C. gloeosporioides* in an *in vitro* study. The *in vivo* evaluation revealed that the hexane extract of moringa completely inhibited *Botrytis* incidence and ethanolic extract recorded only 1% disease incidence for *C. gloeosporioides*. These findings indicated that *M. oleifera* extracts could control major postharvest diseases in blueberries and extend their shelf life. Applying 6% moringa leaf extract on strawberry fruit cultivar, Chandler exhibited the lowest respiration rate and ethylene production, malondialdehyde and total soluble solid accumulation compared to untreated fruits during five days of storage in ambient conditions. Moringa leaf extract was used as an additive in the vase life solution to extend the shelf life of gladiolus spikes. The moringa leaf extract at 1% concentration recorded a shelf life of 10 days, 14 days for 2%, 17 days for 3% and 16 days for 4% concentration, whereas the control recorded only seven days of vase life. The study revealed the potential of moringa leaf extract as a promising environmentally friendly novel floral preservative for future applications in the floral industry (5).

Plant extract can be used as biopesticides, a non-toxic, biodegradable alternative to chemical fungicides. Moringa extracts exhibited antifungal activity to major postharvest disease-causing fungi and extended the postharvest storage life of highly perishable horticultural crops. Even though its effectiveness is proven against many fungi *in vitro* studies, *in vivo* evaluation still needs to be improved in many crops. The parts of moringa, such as leaf, seed, fruit, bark and its proportion used for extraction and medium or procedure for extraction (aqueous, methanolic, ethanolic, hexane) need to be standardized for various postharvest diseases. However, the effectiveness of moringa-derived products can vary depending on preparation methods and environmental conditions, which may limit their use compared to synthetic fungicides. Also, scalability and chemical stability can be a concern as their efficacy might be reduced over time. Therefore, more comprehensive research is needed to better understand the disease-inhibiting

mechanisms of different moringa-derived products. This understanding can help develop moringa-derived products as natural alternatives to chemical fungicides and their applications in postharvest disease management, leading to safer and more sustainable agricultural practices.

Bio- accessibility and bioavailability

Upon digestion, the food-originated compounds readily available for absorption is called bio-accessibility and the amounts of digested compound absorbed and metabolized are called bioavailability. In moringa, caffeic acid, gallic acid, kaempferol, morin and oligosaccharides (mannose and stachyose) showed high bio-accessibility (6–10%). The higher bio-accessibility in the stomach was observed for gallic acid, chlorogenic acid, vanillin and rutin, whereas in the small intestine, it was observed for *p*-coumaric acid and quercetin. The Fe bioavailability from moringa is low due to its high phytic acid levels, but the bioavailability of folate is high with a value of 81.9% (100). Comprehensive information on bio-accessibility and bioavailability will help nutritionists develop meal plans for needy people. Newer experiments are warranted on these aspects of different food formulations of moringa to develop food plans aimed at nullifying the ill effects of malnutrition from a global perspective.

Ethical and sustainability considerations

Large-scale moringa cultivation requires a few Government initiatives like a protected moringa cultivation zone, the Government must ensure the minimum support price for moringa products and the government has must create special economic zones to facilitate moringa processing and export.

Conclusion

The Heaven's Tree, moringa, has multiple utilities in human and animal health, environmental cleansing, eco-friendly plant protection and pharmacological applications. It offers the potential to:

(i) alleviating human malnutrition due to its nutritional significance,

(ii) maintain animal health through a balanced diet,

(iii) protect the environment utilizing its remediating properties,

(iv) cure human ailments arising from mineral deficiency,

(v) reduce the use of plant protection chemicals, thereby benefiting the environment. A comprehensive understanding and dissemination of knowledge regarding these multifaceted benefits of moringa are essential, as they will significantly impact both human health and the environment. Further, an interdisciplinary research approach (like classical plant breeding, molecular biology, biochemistry, microbiology and environmental science) is required to

(i) harness genetic gains in yield and quality traits,

(ii) study medicinal properties and assess their efficiency,

(iii improve palatability while minimizing antinutritional properties,

(iv) enhance the bioavailability of nutrients,

(v) document and promote the environmental cleaning properties of moringa products.

Acknowledgements

The authors are thankful to the Director, Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University.

Authors' contributions

SK[1], SM, AM and GLPR drafted the manuscript. SL, PG, SDS, CB and KNG provided the technical inputs. BK created the illustrations. SK[2] and SR drafted and corrected the manuscript. All authors read and approved the final manuscript. (SK[1] stands for Shamini Karunagaran and SK[2] stands for Selvaraju Kanagarajan)

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

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