Multifunctional Applications of Moringa oleifera in Sustainable Agriculture, Livestock Nutrition, and Environmental Management: A Comprehensive Review

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Abstract

Moringa oleifera, a popular "miracle tree" is known for its various practical uses and is of agricultural and animal feed interest among others. This plant is a sustainable-eco friendly tool for boosting crop productivity, for the management of plant diseases in ecological manner, and for upgrading quality of animal feed. Its nutrient-dense composition packed with proteins, core vitamins (C and A) and minerals (iron and calcium), and rich in powerful phytochemicals like quercetin and kaempferol means it has value for animal health and plant performance. Further, Moringa's bactericidal and antioxidant properties make it suitable for water filtration and soil amendment, furthering environmental health as a whole. In this review article, the multifaceted properties of Moringa, particularly its efficacy in animal feed, sustainable agriculture, water purification and plant protection programs are discussed.

Keywords: Moringa oleifera, Phytogenic Feed Additives, Sustainable Agriculture, Natural Water Purification, Soil and Plant Health, Livestock and Poultry Nutrition

1. Introduction

Over the past decade, plant-derived feed additives including essential oils and phytogenic compounds have attracted great interest for their potential uses in the nutrition of both livestock and poultry [1–4]. These natural feed additives have been investigated in order to improve feed quality, animal health, and provide cheaper substitutes for synthetic chemicals. Also, due to bioactive molecules such as thymol, carvacrol and rosmarinic acid, they can inhibit growth of mycotoxigenic fungi [5, 6], enhance the antioxidant and antibacterial activity of feed.

Moringa oleifera has attracted the researchers in this aspect due to its profile of bioactive phytochemicals and capacity to suppress fungal pathogens i.e., Aspergillus flavus, A. parasiticus and Fusarium moniliforme, which generally inhabit stored grain [7, 8]. The rising concern on the adverse health effects of synthetic pesticides, such as carcinogenity, teratogenity, and other health impacts [9], has also underscored the want for safe natural alternatives [10]. Against this background, Moringa oleifera, provides a potential eco-friendly approach for controlling agricultural pests and diseases [11].

M. oleifera (Family: Moringaceae) flourishes in the tropics and subtropics. And its potential uses are endless; the plant is valued in herbal medicine, nutrition, soil enrichment and water treatment. Moringa possesses anti-inflammatory, antimicrobial, antioxidant and anticancer properties, likely due to its high content of vitamins A, B, C, amino acids, calcium and iron [12, 13]. Its immunomodulatory effects in animals have been clinically studied with results showing it has the potential to influence the immune system, reduce pathogenic intestinal microflora, like E. coli, and MBTU can also promote the propagation of beneficial intestinal germs, such as Lactobacillus species [14].

Aside from animal health, Moringa leaf extract (MLE) has been shown to promote initial vegetative growth in many other species like tomatoes, maize, peanuts, and wheat. Another reason for integrating this natural biopesticide in Integrated Pest Management (IPM) programs comes from its biological control activity [15, 16]. Use of MLE has been reported to provide a higher yield up to 35% and a better resistance to pests and diseases [17]. It is an affordable and sustainable crop enhancer in poverty and food-insecurity stricken areas due to its rich supply of Moringa [18].

In general, Moringa's good balance between the practical nutritional density and versatility in application it easy to be used as animal feed, green manure, medicinal extract, and natural coagulant. In this review, an attempt is made to compile reports on the phytochemicals, nutritional values, and diverse applications of Moringa oleifera in soil, water, and animal systems.

2. Nutrient Contents

All parts of the Moringa oleifera tree are edible and vitamin rich. Its leaves in particular are a good source of digestible nutrients and can be eaten fresh, cooked, processed into powder, etc. They are promoted as a food supplement in many developing countries owing to the high protein, vitamins (A & C) calcium and iron content [22]. Animal studies have suggested that Moringa may have potential to promote nutrition and immune function [23].

Whether green or dry, it is equally useful as a food." They consist of 30–40% sweet oil (by weight), of which ~76% is composed of polyunsaturated fatty acids that lower cholesterol [73]. Both leaves and seeds are good source of antioxidants such as carotenoids, vitamin E, flavonoids and phenolics [24], [25]. The leaves of moringa also contribute all the essential amino acids such as lysine, leucine, threonine, valine, etc which make them great for food supplementation as well [25].

Moringa leaves have also been incorporated in animal feed (as feed additive) to enhance growth and feed efficiency or as an alternative to conventional crops for sustainable farming by local farmers [26], [27]. Their nutritional profile like NDF, ADF, CP and EAA values are suitable for increasing digestibility and animal performance in ruminants [28].

However, there are anti-nutritional or toxic compounds in certain parts of the epigeal (bark, roots). Root bark also contains alkaloids (moringinine, moringine), tannins, and saponins that can stimulate uterine contractions or hypotensive activities [29]–[33]. Alterations in cardiovascular and hepatic indicators were observed in animal experiments which were performed with ethanolic root extract [34], [35]. A toxic effect due to excessive consumption may be induced by spirochin, an alkaloid present in the flesh, which causes nerve paralysis [35], [36].

In addition, there are pthylates in the leaves (3.1%) that might inhibit mineral bioavailability, particularly in monogastric animals [30]. The nutritional content of wasabi also varies widely depending on the location, type of soil, and climate [25]. They should be taken into consideration when incorporating Moringa into human or animal feeding to prevent excessive use and possible health hazards.

3. Phytochemistry

Its nutritive importance and medicinal application is primarily due to rhamnose (monosaccharide), glucosinolates and its hydrolysis product isothiocynates, which have shown significant hypotensive and spasmolytic effects [13], [37], [38]. The main bioactive components are benzyl glucosinolates and benzyl isothiocyanate derivatives, which have been described for activities such as anticancer, antibacterial, and hypotensive effects [13].

The flavonoids kaempferitrin, rhamnetin, kaempferol, isoquercitrin, and quercetin are highly concentrated in moringa flowers and show powerful antioxidant activity [13], [37]. Eighty percent ethanol leaf extracts also contain cytokininlike hormones and exhibit anticancer activity, especially against leukemia cell lines [29], [39], [40].

When it comes to antioxidants, Moringa wins hands-down compared to the greenest green vegetables you can think of. Its phenolic content is known to be between 74 and 210 μmol/g, its content of vitamin C runs from 70 to 100 μmol/g, β-carotene from 1.1 to 2.8 μmol/g, and α-tocopherol – from 0.7 to 1.1 μmol/g [42], which puts it at levels significantly higher than those reported for common sources of antioxidants such as strawberries, soybeans, carrots, and hot peppers [43].

Other studies have found that moringa's total phenolic and flavonoid content are two to three times higher than what's found in, say, broccoli, spinach, and peas. Its leaves also possess kaempferol and quercetin with antioxidant activity stronger than that of ascorbic acid [40, 45].

Seeds are rich in a variety of phytochemicals (ferulic acid, vanillin, gallic acid, chlorogenic acid, quercetin, phytosterols (sitosterol, stigmasterol), etc.) that play a role in hormone regulation and lactation [25, 48]. These compounds also exhibit immunomodulatory, anti-oxidant, and antidiabetic properties which make them even more beneficial as medicine.

Such phytochemicals have immobilized applications that represent a plethora of pharmacological activities, such as antitumor, antimicrobial, hypolipidemic, immune regulating effects, etc [13, 25, 46, 47]. They influence a variety of physiological systems (digestive, hormonal, neural) lending support to the relationship of moringa with herbal medicine and functional foods.

4. Its Applications and Utilization in Soil and Plant Health

The use of moringa in soil and plant health is in the rise in many parts of the world especially in the area where moringa is cultivated. Moringa oleifera is a plant that is revered for its economic, nutritional, and medicinal value, and it also serves as a major crop that has received high commodity as a soil fertility enhancer and disease suppression. One of its most relevant agronomical applications is based on its use as moringa leaf extract (MLE) and natural biostimulant. The aqueous and ethanolic extracts of moringa leaves, which are enriched with antioxidants and secondary metabolites like of ascorbic acid and polyphenols [49, 50] have demonstrated great potential in improving plant productivity. MLE is also beneficial in enhancing plant tolerance to abiotic stress such as drought and salinity [51].

Being tolerant to drought it can grow in almost all soils [52]. When grown as green manure, this plant's growth can be worked into the soil, nourishing it with organic material and essential elements. It is common practice to plant moringa (at 10 × 10 cm planting distance) in relatively high densities, let it grow for some time and then cut the seedlings down and incorporate them within 15 cm depth prior to sowing the main crop [53–55].

In particular, MLE is abundant with active phytochemicals such as plant hormones (cytokinins, gibberellins, and indole-3-acetic acid), vitamins (ascorbic acid, zeatin), and minerals such as phosphorus, calcium, potassium, magnesium, iron, and zinc [56, 57]. These properties contribute to its function as a natural growth stimulant and soil amender. The utilization of the tree in less developed regions is crucial, with its cultivation able to support the requirement for low-cost agricultural inputs in high poverty and food insecure areas [58].

MLE is also a universal promoter of hormones of many plants. Foliar application or seed soaking with MLE has been reported to promote chlorophyll content, photosynthetic capacity, plant growth and yields of numerous plants such as canola, field beans, maize and linseed [59–61]. For example, in crops affected by high salinity or nutrient deficiencies, the priming of seed or the foliar application of MLE can enhance parameters (i.e., shoot length, leaf area, dry biomass, and pod development) by approximately 50–60% when compared with control plants [50, 62, 63].

The enhancement in growth may mainly be due to the existence of zeatin, auxins, and gibberellins content in MLE, which is responsible for cell division, cell elongation, and metabolic activity [64, 65]. When applied as pretreatment or foliar spray under salinity stress, MLE significantly improves plant growth and yield, as it alleviates the detrimental effects of salt-stress [51, 66, 67].

Field experiments have showed that MLE applications can enhance crop yield by 20–35% [29, 68, 69]. It also diminishes stressor effects, such as NaCl and $CaCl_2$, which are toxic for root and shoot growth and for pod setting in legumes [56]. For example, under saline condition, treated bean plants with MLE resulted in significant enhancement in the number of pods, protein content and plant biomass of bean comparing them with the untreated control.

The role of MLE in alleviating drought and salt stress can also be due to its high cytokinin contents, especially zeatin that delays leaf senescence and maintains the content of chlorophyll [61, 70]. In drought-stressed soybean (Glycine max) plants, MLE treatment increased shoot and root growth and significantly increased dry matter production over water-stressed, untreated plants [71].

5. Influence on Plant Growth, Yield and Physiological Attributes

The use of Moringa oleifera leaf extract (MLE) showed significant enhancement in plant growth attributes and yield parameters in several crops. MLE is particularly rich in macro- and micro-nutrients, carotenoids, phenolics, antioxidants, and plant hormones which include cytokinins and gibberellins and these chemical compounds are responsible for its potency as natural plant growth stimulant [29, 61].

Researches have evidenced increase in various parameters like plant height, number of branches, pod number, seed yield and total biomass, in canola and common bean (Phaseolus vulgaris L.) from application of MLE on the foliar area, or the seed soaking on experimental assays [59, 56, 57]. These benefits are associated to the MLE ability to modulate the photosynthetic apparatus and the metabolism of the plant. By enhancing chlorophyll and carotenoid contents, MLE enhances more efficient photosynthesis, leading to growth vigor, stimulating the vegetative stage and enhancing the development of the fruit [61].

It has also provoked mobilization of important metabolites including ascorbic acid, calcium, potassium and zeatin (compounds involve in rapid growth process at early germination stages) [62, 63] to augment seedlings vigor. Pre-treatment of linseed (Linum usitatissimum L.) with MLE under saline environment also brought about robust enhancement in germination than hydroprimed and untreated controls indicat- ing that the MLE could be a potential stress alleviator under salinity [50].

In addition, the MLE-treated plants have demonstrated an enhanced resistance to salt-stress. The root and shoot length, dry matter yield and number of pods of plants are usually inhibited by salinity. However, when MLE was introduced (by see soaking or foliar spaying) the tensile moduli of the plant increased in length and a greater coverage area and dry mass (even under stress conditions) was observed on the surface of the plant [56, 66, 67].

MLE also has a positive effect on many important physiologic and biochemical indexes. In salt-stress pea plants (Pisum sativum L.), foliar application of MLE increased the contents of chl a and b, carotenoids and soluble sugars, whereas it markedly decreased the electrolyte leakage (EL) as an indicator for membrane injury [61, 66]. The decrease in EL may be attributed to increased stability of the membrane and to the order of integrity and metabolism of the plant [73].

In addition, the use of MLE increased the relative water content (RWC) in plant tissues – an important indicator hydration and cell health states. The highest RWCs in plants under the combined seed soaking and foliar MLE application indicated continued osmotic regulation and water holding capacity [66, 67, 74]. These effects may be related with the increase in osmoprotectants and antioxidants produced by the extract.

In the mineral nutrients of plants, the MLE treatment could enhance the absorption and transport of N, P and K and maintain the ionic balance under salt stress, such as K/Na and Ca/Na ratios that play important roles in saline environments [66]. It also increased the activity of antioxidant enzymes and the levels of ascorbic acid (vitamin C), and thus strengthened the plant's resistance against reactive oxygen species (ROS) [75–78].

One of the main factors that drives effectiveness of MLE is its high cytokinin concentration, especially zeatin. This hormone retards leaf senescence, maintains high chlorophyll content and prolongs the productive life of foliage [57, 80]. Therefore MLE-treated plants are able to maintain higher photosynthetic rates and accumulate more energy for growth and reproduction.

In conclusion, the leaf extract of Moringa oleifera can be used as a multi-purpose plant growth promoter, stress alleviator and physiologically strengthen. As a seed pre-treatment or as a foliar application, MLE provides a sustainable option to increase productivity and stress tolerance of plants in adverse agricultural conditions.

6. Applications in Water Treatment and Purification

Moringa oleifera serves not only as a nutrient, but as an agronomic boon and water purifier. Its seeds were also found to contain proteins that serve as potent natural coagulants, which allow for their potential use as water treatment substitutes for traditional chemical re-agents (e.g., alum) especially in low-resource settings [81, 82]. This is crucial for underprivileged societies in the developing world where coagulant chemicals are costly or unavailable.

The main mechanism is related to a water-soluble protein present in the moringaseeds, acting as a cationic polyelectrolyte. This protein, on injected, into turbid water, complexes with suspended particles and impurities, forming clusters and settling out of solution [84]. The reduction in water hardness using moringa seed powder has been found to be 50–70% (depending on dosing and initial hardness) [85, 86].

Its efficacy has been demonstrated at different water qualities. It has been demonstrated that this treatment can substantially lower turbidity, alkalinity, DOC, as well as reduce the presence of HA and heavy metal levels [87–90]. The clarification of turbidity or removal of various pathogens such as Escherichia coli were observed in raw water samples collected from various water sources by applying moringa seed powder, which averaged above 90% and greater than 95%, respectively [84, 96, 97].

Reduction of color for agro based industries using moringa has been confirmed by other reports too. In one such study in distillery effluent treatment system, moringa seeds resulted in a color removal efficiency of 56–67% with the aid of NaCl/KCl as an additional additive in the process [94]. Analogous achievements have also been reported in the removal of cheese whey and POME, where the moringa seeds extract facilitated the removal of suspended solids and pollutants [89, 95].

In particular, seed extracts of moringa have been found to have good antimicrobial action as shown by a drastic reduction in the population of fecal coliforms, S. aureus and other waterborne pathogens [96, 97]. Efficiency up to 99.5% of bacteria removal was achieved in some circumstances [96]. Not only do these qualities make it a water purifier, but they also act to combat waterborne diseases, making moringa a useful tool in public health.

Moringa has also been proved effective for the removal of heavy metals such as: iron, copper, zinc, manganese lead, chromium and cadmium from water [98, 112]. These are widespread in polluted water bodies and are associated with substantial risks to human and ecological health. The proteins and polyphenolics present in moringa seeds chelate with the cations producing insoluble complexes which are filtered easily [113].

There are many factors that influence the efficiency of coagulation of moringa seed powder, these include; pH, temperature and contact time. Its optimum pH ranges between 6.5 and 9 and coagulating activity has been found to reduce at temperature below 15 °C [84, 96, 100]. Hence the use of moringa for water treatment, there is need to ensure that environmental conditions are controlled in order to achieve maximum efficiency [101, 102].

In general, eco-friendly, non-toxic, and biodegradable nature of Moringa oleifera offers an interesting option to the synthetic water treatment agents. It is not only effective for the elimination of physical and chemical contaminants, but also significant in enhancing the microbiological quality of water, which is of particular benefit to those rural communities without safe water supplies [104–106].

7. Influence on Soil and Water Heavy Metal Concentration

Heavy metals, including arsenic, cadmium, lead, zinc, nickel, and chromium, are the priority environmental contaminants in industrial and agricultural areas. The effects of these pollutants on soil quality, water quality, human health, and aquatic organisms can be severe. Moringa oleifera seed extract (MSE) has gained interest as a biodegradable and natural alternative for the removal of heavy metal contamination from the soil or aqueous environment [89].

This was probably due to a phenomenon called biosorption which occurred when bioactive components and specific functional groups in Moringa seed extracts combined with metal ions in the solution to form insoluble and metal-bacteria stable complexes. These are carried out through processes like ion exchange, complexation, chemisorption, and surface adsorption [89, 107]. Cell wall constituents such as cellulose and lignin exert important effects because they provide the hydroxyl and carboxyl groups capable of coordinating with metal ions [89].

Moringa's ability to detoxify heavy metals from water supplies has been demonstrated by other researchers. For example, batch sorption experiments revealed that moringa seed powder removed approximately 85.06% of arsenic (V) and 60.21% of arsenic (III) from polluted water [89, 111]. The cadmium and nickel showed the similar results of 85.1% and 90% removal efficiency, respectively [89, 108]. For moringa the percentages were 90% (copper), 80% (Pb), 60% (Cd), 50% (Zn), and 50% (Cr) [112].

Applying the MSE directly to soils for instance, it has been demonstrated that the ability of MSE to bind heavy metal preventing it to be taken up by plants. At soil pH levels of between 6 and 8, moringa proteins chelate metal ions, resulting into complexes that are not easily taken up by the plant roots [113]. This mechanism serves to conserve crops from exposure of metals toxicity and also to prevent it from entering the food chain.

Field and laboratory trials in the Sudan and UK illustrated the potential of moringa in mitigating groundwater contamination from heavy metals [96, 114, 115]. In one research, the utilization of moringa seeds resulted in 98% removal of copper, significant removal of cadmium and 78% removal of lead in samples of water [116].

This may be due to the complex biochemistry of moringa that enabled to use of moringa to remove or immobilize these metals. Its seed comprise a blend of proteins, polyoses, lignin and fatty acids, as well as the various functional groups—carboxylic and amine groups—that allow for the strong coordination of metal ions [117–119]. This feature makes Moringa oleifera an effective low-cost biosorbent, which could be used on a large scale in contaminated areas.

In conclusion, Moringa oleifera seed extract provided an environmentally acceptable and efficient technique for controlling heavy metals in aquatic systems as well as in agricultural soils. Its application may promote food safety, restore soil health and reduce latent hazards of environmental pollution in the long run.

8. Applications in Management of Plant Diseases

Moringa oleifera has attracted a great attention as a possible natural biocontrol agent for plant diseases. Although the plant is already known for its antimicrobial effects in humans and animals [38], its use for the protection of crops (antagonistic activity against plant-pathogenic species, specifically for soilborne infections) has only recently attracted attention and research [16].

The excessive use and misuse of chemical pesticides has caused numerous environmental and health problems such as ecosystem unbalance, pest resistance, pesticide residue in food and water. Therefore, it is highly desirable to develop environmentally friendly and sustainable substitutes for disease management. The moringa has antimicrobial, antifungal property and insecticidal activity, therefore can serve as a possibility [15, 47].

A number of in vitro assays have shown that moringa extracts are effective against common plant pathogens. For example, the use of moringa leaves in the soil has been reported to have suppressed the occurrence of seedling damping off due to Pythium debaryanum [22]. In the same vein, foliar application of ethanol extracts from moringa leaves improved the resistance of the plant to pests and diseases, which led to more firm and healthier crops [126]. These results justify moringa to be part of IPM approaches.

Aside from soil application, Moringa leaves extracts (MLE) has been reported to enhance the health and productivity of fruit crops. For instance, pre-harvest foliar MLE application in Hollywood plum decreased fruit drop and increased yield, improved fruit color and firmness, and the levels of antioxidants and vitamin C [127]. These effects make MLE an interesting biostimulant, especially in organically-managed agricultural systems.

Seed priming with MLE has also demonstrated its potential to minimize seed-borne fungal infection. A germination rate of 92% was observed in MLE-treated seeds in one study, whereas seeds in the non-treated control germinated at a rate of only 66%. Furthermore, the infection rates of seeds treated with MLE was significantly (p10%), it enhances body weight gain, egg quality and immune functions with no side effects [144], [146]. It also has the potential as a natural and safe remedy for common avian diseases such as Eimeria spp., NDV, E. coli and Salmonella, owing to its myriad of phytochemicals and immune-stimulatory effects [157], [140], [166].

You should be cautious though whenever you mix moringa with feeds and water. High levels or the use of particular plant pieces (e.g., roots and bark) could include antinutritional factors and even toxicological risks [30], [35]. More studies are required to standardize dosage, extract formulation, and application to different agricultural and veterinary environments.

In nutshell, Moringa oleifera is an excellent natural resource that can be harnessed to enhance sustainable agriculture, animal productivity, and environment health. Its adoption in agricultural systems would be beneficial for food security, public health and environmental preservation, particularly in developing countries.

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