Egbu *et al. Agriculture & Food Security (2024) 13:54*
https://doi.org/10.1186/s40066-024-00508-x

Agriculture & Food Security

REVIEW

Open Access

Moringa oleifera products as nutraceuticals for sustainable poultry production

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Abstract

Moringa (*Moringa oleifera*) products hold promise as sources of nutraceuticals in poultry diets due to the presence of proteins, carbohydrates, minerals, vitamins, and polyphenolic compounds with growth-boosting, antimicrobial, and antioxidant activities. Moringa leaves, seeds, or their extracts are among the natural additives that contain polyphenolic substances such as quercetin, catechin, alkaloids, and kaempferol that have been extensively exploited to optimise poultry nutrition. These substances can stimulate fast growth rates, boost the nutritional quality of poultry products, and suppress pathogenic gut microbial proliferation. However, high levels of primary (fibre) and secondary metabolites (tannins, saponins, cyanogenic glycoside, and phytates) in moringa seeds or leaves limit their utilization as nutraceuticals in poultry feeds. Consequently, various conflicting findings have been reported regarding the potential benefits of moringa products in poultry diets. For this review, data from 43 research articles sourced from PubMed, Google Scholar, Web of Science, AGRICOLA, CAB Direct, and Scopus met the inclusion criteria. The review provides an overview of the nutraceutical composition of moringa products and their feeding value in poultry production. The challenges and benefits of adopting moringa products in conventional poultry diets and potential strategies that can enhance their utility in poultry nutrition to warrant a positive impact on food security were discussed. We also delved into the importance of determining optimal dosage levels given that low doses result in limited positive impacts while higher doses may cause debilitating antinutritional effects. We found that tailoring the inclusion dosages based on poultry species, physiological stages, form of moringa products, and bioprocessing techniques can mitigate the impact of antinutrients, thus allowing for higher inclusion rates. Conclusively, the use of moringa nutraceuticals could improve poultry production efficiency and promote food security and sustainable agricultural practices. Policy implications must include establishing clear guidelines for the safe and effective use of moringa products in poultry diets as alternatives to synthetic additives.

Keywords Food security, Moringa, Performance, Phenolic compounds, Poultry, Product quality, Sustainability

Introduction

Globally, there has been an upsurge in the demand of poultry products to cater for dietary protein requirements of a rapidly growing human population. Poultry meat and eggs are the most affordable major animal protein sources making them important contributors to food security [1]. Due to current consumer trends, it is anticipated that consumption of poultry products will increase by over twofold in the next decades [1], which could increase access to animal protein sources and potentially alleviate food insecurity. Over the years,

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increased poultry production has been made possible by the reliance on antibiotic growth promoters (AGP) to improve performance and control disease outbreaks. However, due to safety concerns, the use of in-feed AGP in food-producing animals has been met with serious public displeasure following reports about the development of multi-drug antibiotic resistance by pathogenic bacteria and antibiotic residues in meat products [2]. Recently, it has been reported that antimicrobial resistance could result in the loss of up to 10 million human lives by 2050 [3]. While there has been criticism of such reports, the World Health Organization (WHO) acknowledged the pressing need for a global coordinated strategy to tackle the surge of antimicrobial resistance [4].

Thus, the identification and exploration of natural additives with antimicrobial activities have drawn extensive research attention. Several plants have been investigated for their nutraceutical potential in poultry diets, including neem, pawpaw, bamboo [5], and turmeric [6]. Among these, moringa (*Moringa oleifera*) stands out due to its exceptional nutritional profile and diverse composition of phytochemicals. Moringa leaves and seeds are rich in proteins, carbohydrates, minerals (calcium, phosphorus, iron, and zinc), and vitamins (B-complex, C, and E) [7, 8], which are important nutrients in poultry nutrition. They also contain health-promoting bioactive compounds (quercetin, catechin, alkaloids, kaempferol, chlorogenic acid, and rutin) with antimicrobial and antioxidant activities [9, 10]. These bioactive compounds have been reported to alleviate the detrimental effects of free radicals, reduce inflammations, and improve bird health [11]. Ahmed and El-Rayes [12] observed an increase in performance, nutrient digestibility, and carcass yield in Japanese quail supplemented with 7 g/kg moringa leaf powder in their diets. Another study showed that using *M. oleifera* leaf powder up to 100 g/kg did not compromise the physiological performance of Rhode Island Red layers [13].

However, literature also shows that the utility of moringa leaves and seeds in poultry feeds is restricted by high dietary fibre levels, non-starch polysaccharides (NSP), and antinutrients such as condensed tannins, trypsin inhibitors, oxalates, cyanogenic glycoside, saponins, and phytates [14]. These antinutrients reduce nutrient utilization and digestibility in poultry. For instance, the inclusion of more than 25 g moringa leaf meal /kg diet had detrimental effects on the body weight gain of broiler chickens [15]. Similarly, the inclusion of 50 g moringa leaf meal/kg diet compromised quail performance [16]. These studies confirm that moringa products can produce inconsistent results at higher dietary levels. Thus, to mitigate this, several techniques including heating, blanching, soaking, seed sprouting, fermentation, tanning-binding agents, exogenous enzymes, and extraction of bioactive compounds have been explored [17–21]. Given these conflicting reports and challenges, this review provides a comprehensive overview of the challenges and benefits of adopting moringa products in conventional poultry diets for enhancing food security, while discussing the potential strategies to enhance their utility for sustainable poultry production systems.

Review methods

Search strategy

A comprehensive literature search was conducted across PubMed, Google Scholar, Web of Science, AGRICOLA, CAB Direct, and Scopus. The systematic search was limited to articles published from 2000 to 2024. The following keywords were used in the systematic search: *Moringa oleifera*, moringa, poultry nutrition, nutraceuticals, phenolic compounds, antioxidants, antimicrobial, poultry performance, antibiotic growth promoters, and feed additives.

Articles inclusion and exclusion

The criteria for articles to be included in the database were: studies that investigated the effects of *Moringa oleifera* products (leaves, seeds, pods, roots, flowers, and barks) on poultry; peer-reviewed articles; articles providing data on the bioactive compounds of *Moringa oleifera* and their health benefits; and studies discussing the challenges and benefits of using *Moringa oleifera* in poultry diets. Articles were excluded if they were not written in English, focused on poultry, and had no clear experimental design or results.

Selection process

The initial search yielded a total of 305 research articles. After removing duplicates, 191 articles remained. Following a thorough review of the full texts, 43 articles met the inclusion criteria for use in the write-up of the review.

Data extraction

Data on study design, nutritional composition, phenolic compounds, antinutrients composition, moringa product type and form, dosage, poultry species, growth performance, meat and egg quality, and physiological responses from each study were systematically captured into an Excel spreadsheet. The data were organized into categories for easy comparison across studies, ensuring that variables such as sample size and duration were consistently noted. This approach ensured accuracy of extraction and eliminated any form of bias.

Overview of *moringa* (*M. oleifera*)

Cultivation

Moringa is a fast-growing, drought-resistant plant that grows naturally in tropical and subtropical regions, with India, Ethiopia, and the Philippines being the largest producers [22]. It is also widely cultivated for its numerous health and nutritional benefits [22]. The tree is hardy and adaptable to a wide range of soils and climates. However, it is sensitive to frost and high winds. The plant can be propagated from seeds or cuttings and usually reaches maturity within 6–12 months [23]. One of the key advantages of moringa propagation is that it requires minimal input and resources (i.e., irrigation, fertilizers, pesticides, etc.). The plant is resistant to pests and diseases and can be grown using low-cost, organic farming methods. Moringa cultivation also has environmental benefits through its deep root system that promotes nutrient recycling and organic matter addition, leading to enhanced soil quality and reduced soil erosion. Hence, the minimal input requirement and fast growth (harvest for leaves within 2–3 months and 6–8 months for pods) of moringa, make it a cost-effective and sustainable source of nutraceuticals for poultry production. Its adaptability to various climates could ensure that there is a consistent supply of polyphenolic biocompounds to enhance poultry health and performance.

Harvesting

The harvesting of moringa is a crucial aspect that can affect the quality and yield of the plant. Thus, careful handling of the leaves during harvesting is essential to avoid bruising or damage, which can reduce their quality and shelf life [24]. Generally, moringa is harvested every 2–3 months, depending on the growing conditions and the intended use. For the leaves, harvesting is usually through handpicking of young leaves from the plant, as the younger ones have higher nutrients. The leaves are carefully selected to ensure that only healthy ones are picked.

For large-scale harvesting, machinery is employed to speed up the harvesting process. However, mechanical harvesting combines mature and immature leaves, thus compromising the overall quality of the harvested leaves. For the seeds and pods, harvesting involves manually cutting the pods from the tree with a sharp knife and sun-drying prior to seed removal. Proper drying of the pods is crucial to prevent fungal growth, which can affect the quality of the seeds [25]. Overall, the harvesting of moringa products is a critical step in ensuring that their nutritional and medicinal properties are preserved. The harvesting process ensures the retention of high levels of nutrients and polyphenolic compounds in moringa products that are essential for their efficacy as nutraceuticals in poultry diets. Proper harvesting techniques help maintain the functionality of these compounds, thereby maximizing their benefits when used in poultry diets.

Processing

The processing of moringa products involves several steps that are designed to extract phytochemicals and preserve their valuable nutrients. After harvesting, the leaves, pods, or seeds are washed to remove any dirt or debris and then dried before milling into a fine powder. The powder is then used as a dietary supplement, an ingredient in food products, or as a natural remedy for various ailments [26]. The leaves and pods can also be processed and used as sources of nutrients and phytochemicals. However, the quality of moringa products varies depending on the processing methods used, which affects their composition [14]. Moringa leaves and seeds can also be processed into a liquid extract or oil. The leaves are typically boiled in water to extract nutrients and then strained and bottled for the liquid extract [14, 17]. For the oil extracts, the seeds are pressed to release the oil which is then filtered to remove impurities. Moringa processing requires skills to successfully extract and preserve its valuable nutrients as shown in Fig. 1. Processing methods directly impact the quality and concentration of polyphenolic compounds in moringa products. Effective processing techniques ensure that the nutraceutical properties of moringa are preserved, making them more potent in poultry.

Nutraceutical composition of *moringa* products

Moringa products (leaves, seeds, pods, or their extracts) are used in a variety of traditional medicines, cosmetics, and dietary supplements. They contain high concentrations of carbohydrates, proteins, essential amino acids, vitamins, and minerals as shown in Table 1. Essential amino acids such as lysine, methionine, and threonine are necessary for protein synthesis, immune function, and muscle development. Also, vitamins and minerals play vital roles in metabolic processes, bone development, and immune function. Literature reveals that the nutrient composition of moringa products is highly variable, stemming from differences in growth sites, soil type, climatic conditions, stage of maturity, harvesting stage, and processing methods. The leaves and pods, despite low carbohydrate and crude fat content, have a rich nutritional profile of essential amino acids, calcium, phosphorus, potassium, and vitamins A, C, B2, and E [27]. The leaves are reported to contain higher levels of calcium than milk, higher vitamin C than oranges, higher iron than spinach, and higher vitamin A than carrots [28]. The seeds contain appreciable amounts of phosphorus,

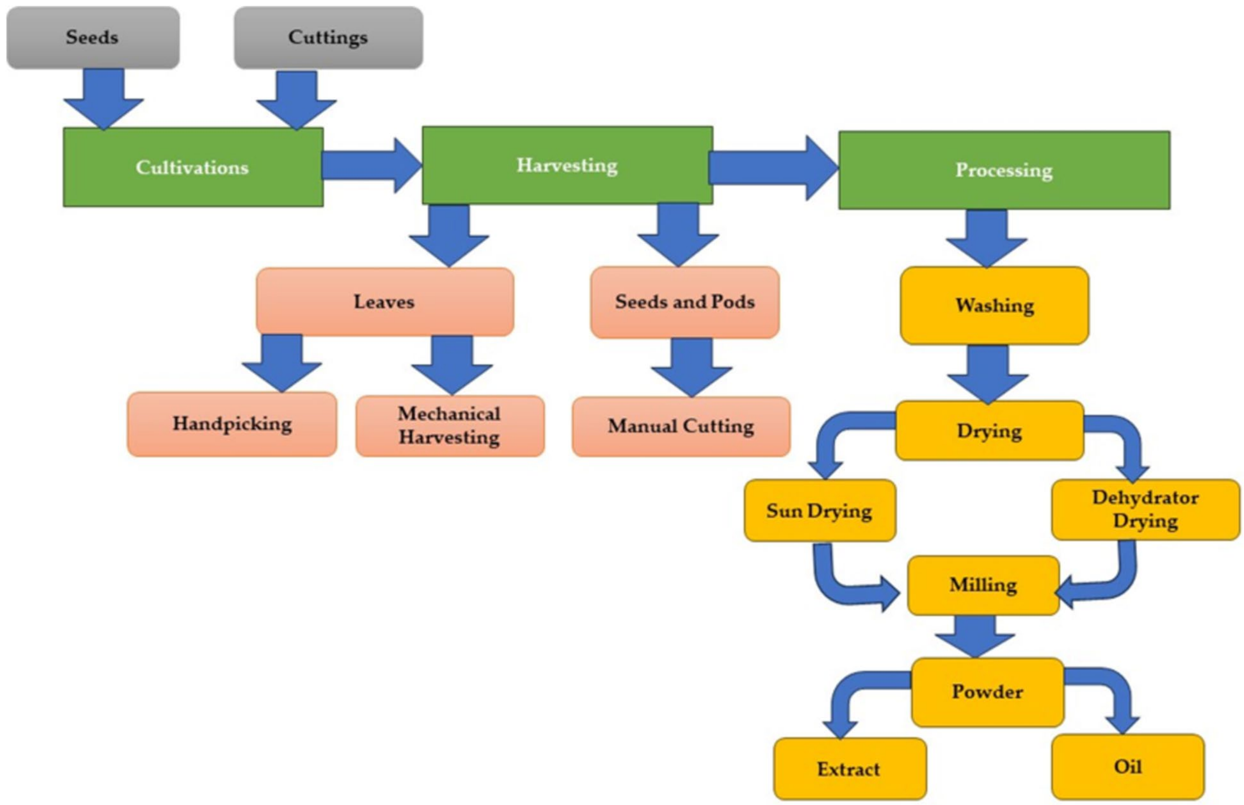

Fig. 1 Cultivation, harvesting, and processing of moringa products

vitamins C, lysine, threonine, and fat [14, 27] that are important for in mitigating food insecurity risks.

Moreover, moringa products contain a myriad of polyphenolic compounds (Table 2) that are imperative for human health and food security. Given the existence of polyphenols such as quercetin, kaempferol, resveratrol, catechin, naringenin, and biochanin A, moringa products have received increasing interest for diverse use in medicine, cosmetics, biofuel, and fertilizer production. These bioactive substances have antioxidant, antibacterial, hypoglycaemic, immunomodulatory, anti-inflammatory, anticancer, growth-stimulating, meat-boosting, and health-promoting activities [11]. Naringin is an active component in moringa products that can improve the absorption of different vitamins, minerals, and other micronutrients in the gastrointestinal tract (GIT) of the host [30]. Furthermore, 200 mg/kg quercetin was reported to reduce inflammation and protect the gut microbiota of Arbor acre broilers by alleviating inflammatory responses induced by lipopolysaccharide injection [32]. Similarly, 200 µg/mL kaempferol inhibits the growth of *Salmonella typhimurium* in the GIT thereby reducing the risk of poultry diseases and improving overall health [33]. Resveratrol included at 500 mg/kg diet enhanced the growth performance, carcass, and meat quality traits in Chinese indigenous broiler chickens [34]. This indicates that the use of natural additives can allow the replacement of synthetic antibiotics and thereby promote sustainable agricultural practices.

Antinutritional factors (ANFs) are secondary compounds that reduce the availability of one or more nutrients when present in animal feed [34]. Moringa products also contain different ANFs, such as tannins, phytate, oxalate, saponins, trypsin inhibitors, and cyanogenic glycoside as presented in Table 3, which affect their utilization, particularly at higher dietary inclusion levels in poultry [16].

The presence of these ANFs causes negative effects on animal performance by chelating or binding nutrients, thus reducing their bioavailability [37]. Tannins are characterized by their aromatic benzene ring structure substituted with hydroxyl groups. These polyphenolic compounds have a molecular weight exceeding 500 and possess the unique ability to bind and precipitate proteins [28]. High levels of tannins are detrimental when included in the diets of young birds with limited protein content. These adverse effects include reductions in feed intake, growth rate, feed efficiency, net metabolizable

Table 1 Nutritional composition (% dry matter, unless stated otherwise) of moringa products

Components	Leaves	Seeds	Pods	References
Carbohydrates	8.10–38.6	8.94–33.6	10.4	[8, 9, 14, 29]
Crude protein	25.4–33.6	26.5–40.3	18.4	[8, 9, 14, 29]
Crude fibre	7.25–33.2	21.0	39.2	[18, 29]
Neutral detergent fibre	16.5–24.4	14.4	53.1	[18, 30, 31]
Acid detergent fibre	11.8–13.4	11.6	49.2	[18, 30, 31]
Acid detergent lignin	6.10	4.30	10.3	[30, 31]
Ether extract	8.40–22.0	33.4–39.1	1.60	[8, 9, 14, 30]
Lysine (g/100 g)	1.4–5.60	4.67	3.30	[14, 18, 26, 27, 31]
Threonine (g/100 g)	1.12–4.2	0.10–4.00	3.30	[8, 14, 18, 27, 31]
Methionine (g/100 g)	0.42–1.80	0.07–1.44	1.49	[8, 14, 26, 27, 31]
Isoleucine (g/100 g)	0.82–4.80	2.03	2.92	[14, 26, 27, 31]
Leucine (g/100 g)	1.83–9.20	7.30	5.64	[14, 18, 26, 27, 31]
Valine (g/100 g)	0.99–5.40	0.13–4.50	3.68	[8, 14, 18, 26, 27, 31]
Phenylalanine (g/100 g)	1.04–6.20	4.52	3.67	[14, 18, 26, 27, 31]
Calcium (mg/100 g)	1439–3650	1.18–3600	30.0	[7–9, 14, 26, 27]
Phosphorus (mg/100 g)	174–340	75.0–520	110	[7, 9, 26, 27]
Magnesium (mg/100 g)	368–561	1.08–635	24.0	[7, 8, 14, 26, 27]
Potassium (mg/100 g)	1324–2530	1.01–8706	259	[7–9, 14, 26, 27]
Zinc (mg/100 g)	2.84–3103	0.84–10.1	3.11	[7, 8, 14, 26, 27]
Iron (mg/100 g)	22.4–490	0.76–3.62	5.30	[7, 8, 14, 26, 27]
Vitamin C (mg/100 g)	17.3–55.3	2.33–4.50	120	[14, 26, 27]
Vitamin B_1 (mg/100 g)	2.64–8.67	0.05	0.05	[26, 27]
Vitamin B_2 (mg/100 g)	6.75–20.5	0.06	0.07	[26, 27]
Vitamin B_3 (mg/100 g)	8.20–22.9	0.20	0.20	[26, 27]
Vitamin E (mg/100 g)	113	0.22–751	–	[14, 27]

energy, and protein digestibility in experimental animals [38]. However, lower doses of tannins have been proven as suitable candidates to replace AGP in animal diets due to their antimicrobial properties, which include deactivating microbial enzymes [39].

Phytates, also known as phytic acid or inositol hexaphosphate, reduce the bioavailability of essential minerals (calcium, phosphorus, zinc, and iron) and amino acids [40]. Phytate molecules present in moringa products are negatively charged and can bind to positively charged enzymes (phytase), amino acids, and minerals to form indigestible complexes. This complexation reduces the solubility and availability of amino acids and minerals making them less absorbable by the bird and limiting the effectiveness of phytase in the GIT. Furthermore, phytates can increase gut acidity, which may interfere with the activity of digestive enzymes and reduce the overall efficiency of nutrient absorption in poultry [41].

The primary concern with oxalates in poultry diets is their ability to form insoluble salts (calcium-oxalate crystals), which reduces calcium bioavailability. Poultry excrete excess calcium-oxalate crystals through their kidneys, which adds significant stress to the renal system under prolonged exposure. Oxalates can also bind with other essential minerals in the diet, such as magnesium, exacerbating mineral imbalances that disrupt the delicate balance of minerals required for normal physiological functions in poultry [42].

Trypsin, a key pancreatic enzyme, is vital for protein digestion into absorbable peptides and amino acids in poultry. Trypsin inhibitors hinder the hydrolysis of peptide bonds by binding irreversibly to trypsin thereby inhibiting the digestion of proteins. This interference leads to reduced protein digestion in the bird's GIT [43], resulting in undigested protein fragments in the lower digestive tract, which are nutritionally poor and potentially toxic. Poor protein digestion results in reduced growth rates, lower feed efficiency, and suboptimal performance in poultry [15]. This can ultimately result in economic losses for poultry producers thereby limiting the sustainable intensification of poultry.

Cyanogenic glycosides are typically present in moringa leaves and seeds in an inert form, however, can be harmful when enzymatically hydrolysed during digestion to release hydrogen cyanide (HCN). Upon release, HCN is absorbed through the GIT and transported to various tissues in the body. Cyanide interferes with cellular respiration by inhibiting cytochrome oxidase [44], which is a critical enzyme in the electron transport chain. This disruption leads to reduced synthesis of adenosine triphosphate. Birds may reduce their feed intake in response to the bitter taste of diets containing cyanogenic glycosides, which can also reduce growth performance due to energy depletion caused by impaired cellular respiration. The disruption of energy metabolism can lead to metabolic disorders, including metabolic acidosis, which can manifest as a drop in blood pH [44]. In cases of extreme exposure, poultry can suffer from acute cyanide poisoning, which may result in sudden death.

Saponins are a class of naturally occurring plant secondary metabolites present in moringa leaves and seeds that bind to dietary proteins and glycoproteins, forming

Table 2 Polyphenol composition (μg/100 g, unless mentioned otherwise) of moringa products

Polyphenols	Leaves	Seeds	Roots	Flowers	Bark	References
Gallic acid	1100	5600	–	–	–	[9]
Chlorogenic acid	1400	6500	–	–	–	[9]
Catechin	25.0	20.0	20.0	12.1	13.0	[10]
Rutin	231	6000	–	–	–	[9]
Vanillin	1100	7500	–	–	–	[9]
Ferulic acid	3800	1000	–	–	–	[9]
Naringenin	14.0	14.0	23.0	14.0	29.0	[10]
Daidzein	5000	2640	–	–	–	[9]
Quercetin	985	600	685	583	870	[10]
Cinnamic acid	3000	6020	–	–	–	[9]
Kaempferol	40.0	25.0	24.0	45.0	23.0	[10]
Coumaric acid	37.0	17.0	15.0	17.0	29.0	[10]
Myricetin	1530	640	1100	890	1360	[10]
Resveratrol	19.0	20.0	19.0	25.0	14.0	[10]
Naringin	22.0	21.0	0.80	12.0	30.0	[10]
Biochanin A	29.0	17.0	45.0	34.0	17.0	[10]

Table 3 Antinutrient (mg /100 g) composition of moringa products

Antinutrients	Leaf	Seed	Pod	References
Tannins	0.22–1.63	1.89–52.0	0.20	[14, 31, 35, 36]
Phytates	0.27–2.23	0.35–115	0.25	[14, 31, 35, 36]
Oxalates	1.42–6.66	0.73–2.21	–	[14, 31, 35, 36]
Trypsin inhibitors	–	0.09–1.20	0.30	[14, 31, 35, 36]
Cyanogenic glycoside	14.8	1.68–8.00	–	[14, 31, 35, 36]
Saponins	2.06–10.9	3.89–29.9	–	[14, 31, 35, 36]

complexes that reduce the digestibility of amino acids. For example, saponin reduces protein digestibility in broilers, resulting in poor growth rates and reduced feed efficiency [45]. Saponins can damage intestinal mucosa due to their detergent-like properties that can lead to increased mucin secretion and reduced absorption of nutrients. Additionally, saponins may lead to mucosal damage and increased secretion of mucin in the GIT [46], negatively affecting gut health in poultry. Overall, high inclusion rates of dietary saponins can impart a bitter taste to feed, potentially reducing feed intake, which leads to reduced nutrient intake and performance.

Current evidence of *moringa* products in poultry nutrition

Poultry products remain affordable sources of animal protein for consumers, hence the poultry industry is the largest and fastest-growing animal agriculture subsector that can help achieve food security. Although the consumption of poultry meat and eggs varies greatly across countries, the poultry market is expected to grow to $493.21 billion in 2026 at a compound annual growth rate of 8.9% [47]. This necessitates the development of sustainable poultry production systems to ensure continuous contribution to food and nutrition security. Thus, nutritional strategies such as the use of moringa products warrant more research exploration. Careful exploitation of the functional properties of moringa products could enhance productive performance, bird health, and product quality while increasing economic returns. Furthermore, moringa bioactive substances with antimicrobial activities could reduce the reliance on AGP, and thus result in the production of safe, antibiotic-free products [48]. This could also reduce the cost of production because the dependence on conventional AGP increases costs. Thus, the incorporation of moringa products in poultry diets could enhance sustainable poultry production and ensure food security given that consumers will have access to high-quality poultry products.

Literature shows that fresh, green, and undamaged mature moringa leaves or seeds can be harvested, processed into powder or extracts, and utilized as a dietary supplement in poultry as shown in Table 4.

From Table 4, it can be confirmed that moringa products have been utilized as a nutritional supplement to improve performance and egg quality in different poultry birds. Similar studies are briefly summarized herein. Onunkwo and George [58] observed that 100 g/kg *M. oleifera* leaf meal in Anak broiler diets reduced the costs of production without affecting growth performance and carcass parameters. The increase in bone weight and ash percentage are indicators of calcium absorption and bone

Table 4 Summarized effects of moringa products on poultry performance, gut health, and product quality

Product type	Poultry	Approach	Findings	References
Leaf extracts	Cobb 500 broilers	0, 60, 90, and 120 ml/L via drinking water	Enhanced growth performance, feed utilization, some haemato-biochemical, carcass yield, meat quality, gut health, and bone parameters	[49]
Seed extracts	Cobb 500 broilers	0, 60, 90, and 120 ml/L via drinking water	The level of 94.75 ml/L enhanced carcass yield, meat quality, gut health, tibia weight, tibia breaking strength, and calcium and phosphorus levels	[48]
Leaf meal	Wenchang chickens × Rugao Yellow layers	0, 25, 50, 75, and 100 g/kg diet for 42 days	Improved yolk colour and antioxidant capacity, and decreased feed conversion ratio and abdominal fat index	[50]
Stem meal	Sansui ducklings	0, 20, and 40 g/kg diet for 63 days	Enhanced performance, shape index, serum superoxide dismutase, and glutathione peroxidase. However, it reduced yolk colour, serum total protein, and albumin but had no improvements in some egg quality parameters	[51]
Leaf meal	Japanese quail	0, 25, and 50 g/kg diet for 35 days	Increased overall weight gain. However, no effect on feed intake, feed conversion ratio, physiological, and meat quality parameters	[16]
Seed meal	Hy-Line layers	0, 10, 30, and 50 g/kg diet for 56 days	Reduced feed intake, body weight, the rate of lay, egg weight, albumen height, and palmitoleic acid. Enhanced yolk colour and linolelaidic acid but had no changes in the saturated fatty acid profile of the eggs	[52]
Leaf meal	Hubbard broilers	0, 60, 90, 120, and 150 g/kg diet for 35 days	Increased meat pH levels, water holding capacity, breast muscle mass, tibia bone weight, ash percentage, and density indices	[53]
Leaf extract	Hubbard broilers	0, 60, 90, 120, and 150 ml/L via drinking water for 42 days	Enhanced weight gain and feed efficiency, with no impact on visceral organs and carcass yield	[54]
Leaf meal	Hubbard broilers	0, 60, 90, 120, 150 g/kg diet for 35 days	Had no impact on feed intake, FCR, and bursa weight, but improved final body weight and intestinal structure	[55]
Pod meal	Hy-Line layers	0, 50, 100, and 150 g/kg diet for 56 days	Enhanced egg yolk β-carotene, quercetin, selenium, crude protein, sodium, potassium, calcium, and phosphorus. However, reduced serum glutamic-pyruvic transaminase, glucose, and cholesterol levels	[56]
Leaf meal	Hy-Line layers	0, 50, 100, and 150 g/kg diet for 56 days	50 g/kg improved yolk colour, albumen height, and Haugh unit during storage but did not affect laying performance	[57]

mineralization, which might be due to the positive effect of moringa polyphenolic compounds on the GIT and decreased excretion of calcium. In another report, the inclusion of moringa leaf meal at 25 g/kg increased fat content in broiler meat [59], which was attributed to the crude fat content of the leaves. However, supplementing moringa leaf meal in Japanese quail diets did not influence meat quality parameters [16]. Also, another study reported no variation in breast meat colour and thiobarbituric reactive substances in heat-stressed Japanese quail fed with diets containing *M. oleifera* essential oil for 42 days [60]. These results indicate that the ability of moringa products to enhance normal oxidative stability for meat quality parameters during storage requires further research.

Furthermore, a study found that supplementing broiler feeds with *M. oleifera* leaf meal at 150 and 200 g/kg reduced overall cholesterol concentration and low-density lipoprotein cholesterol while increasing the concentration of high-density lipoprotein cholesterol in the serum [61]. This effect was attributed to high fibre levels in moringa leaves that could have interfered with lipid metabolism. The utilization of moringa products in poultry diets has shown promise, but some inconsistencies warrant further investigation. Further research is needed to establish optimal inclusion rates that maximize the benefits and minimize adverse effects of moringa products. Moreover, the effect of moringa products on gut microbiota needs further research to fully understand the specific mechanisms and long-term consequences of these changes on bird health and performance.

Enhancing *moringa* products for sustainable poultry production

Physical methods

Drying feed materials by natural means (sun or air drying) is an economic method that is widely used to preserve their quality. In contrast, freeze-drying and oven-drying are common methods to stabilize various products, including food, biological materials, plants, proteins, vaccines, bacteria, and mammal cells. These methods preserve the quality of dried products, including their biological, nutritional, and sensory characteristics. Nonetheless, these methods could have a considerable impact on the levels of bioactive compounds present in moringa products [26]. Drying moringa leaves in an oven, microwave, and freeze dryer enhanced protein, carbohydrate, fat, ash, β-carotene, thiamine, riboflavin, and α-tocopherol contents about 3–4 times as compared to fresh leaves due to increased dry matter content. However, ascorbic acid was reduced in response to the drying methods [26]. Ascorbic acid is often regarded as a marker of dried product quality because of its extremely limited solubility throughout the drying procedures. A study suggested that freeze-drying is the most promising method for preserving the nutraceutical properties of moringa leaves, as it demonstrated the most favourable retention of phytoconstituents and biological activities [62]. However, further research is required to evaluate the optimal drying temperature, duration, and oxygen levels during freeze-drying to maximize the retention of moringa products' phytoconstituents. It is worth noting that the quality of moringa products depends on drying temperature, drying duration, and oxygen levels. For instance, it was demonstrated that roasting moringa seeds enhanced their crude protein content, which was attributed to the reduction of bonded water molecules, thus increasing the relative mass of proteins in the food matrix [36]. Also, the breakdown of protein–antinutrient bonds or the degradation of other compounds than proteins may increase protein content.

In a separate investigation, it was observed that cooking in distilled boiling water for 15 min young leaves and immature pods of moringa reduced crude protein, crude fibre, ether extracts, ascorbic acid, β-carotene, calcium, magnesium, zinc, phosphorus, and potassium contents [37]. However, the authors noted that phytates and trypsin inhibitors remained relatively stable after cooking. Furthermore, a study reported that soaking moringa seeds in tap water or 0.5% NaOH solution for 6 h reduced the fibre, phytate, oxalate, tannin, and saponin contents with tap water soaking being more effective than soaking with 0.5% NaOH solution [63]. Nevertheless, Rayan and Embaby [64] compared the effect of dehulling, soaking, microwaving, autoclaving, and cooking on moringa seeds and dehulling was found to reduce fibre and tannins while soaking decreased fat, minerals, phytate, trypsin inhibitors, and tannins. They concluded that autoclaving and cooking were the most effective methods for reducing ANFs in moringa seeds. These studies show that optimal pre-treatment of moringa products could promote the sustainability of poultry production and, thus, alleviate food insecurity.

Biochemical methods

Biochemical methods are pivotal in elucidating the processes involved in enhancing the nutritional quality of moringa products. The application of various biochemical techniques enables researchers to isolate, quantify, and modify phenolic compounds, thereby optimizing their beneficial effects on poultry nutrition. Biochemical methods are essential for mitigating the negative impacts of ANFs, improving nutrient bioavailability, and maximizing the health-promoting properties of moringa products [21]. However, there are still conflicting reports concerning the biochemical treatment of moringa products in terms of nutrient composition and effect on poultry production.

Fermentation

Fermentation is a biochemical procedure in which microbes such as bacteria, yeast, or fungi alter the nutrient composition of organic material. For instance, the solid-state fermentation of moringa leaf flour with *Aspergillus niger*, *Candida utilis*, and *Bacillus subtilis* at 32 °C for 7 days reduced crude fat, fibre, total sugar, tannins, phytic acid, and glucosinolate contents [18]. The authors also observed an increase in the concentration of total phenolics and flavonoids, along with enhanced antioxidant capacity following fermentation. Similarly, a trial reported a reduction in tannin, phytate, saponins, phenolics, alkaloids, and flavonoids in moringa seed flour wrapped in blanched banana leaves at room temperature for 72 h to ferment but terpenoids were increased [65].

Furthermore, it is important to note that the specific mechanisms involved in antinutrient reduction during fermentation can vary depending on the type of antinutrient and microorganisms involved. The type of microbial strains, fermentation conditions, and food matrix can all influence the extent to which antinutrients are reduced. Overall, the biochemical processes in fermentation act synergistically to reduce antinutrients and enhance the nutritional quality of the fermented product. It was noted that fermenting *M. oleifera* leaf meal with *Aspergillus niger* reduced the levels of crude fibre, phytic acid, saponins, and condensed tannins [66].

Germination

This involves a series of natural biochemical and physiological changes within the seed, ultimately leading to the emergence of a young plant from the seed coat. An earlier study observed a decrease in the saponins, alkaloids, phenolics, phytates, and tannins content of moringa seeds germinated in a dark, temperature-controlled cabinet at 30 °C [65]. Also, enhanced crude protein, fat, zinc, vitamin D, B6, and folic acid content were noted in moringa seeds covered with aluminium foil to exclude light and then allowed for 3 days to germinate [14]. They further observed reductions in phytate, tannin, oxalate, trypsin inhibitors, and cyanogenic glycoside content of the germinated moringa seed but saponin content increased. A study reported enhanced crude protein content of germinated moringa seed, which they attributed to new protein synthesis during sprouting [36]. They also observed a negative effect of germination on the available carbohydrate content of germinated moringa seeds that could have been used as a source of energy during the process. Furthermore, germinated moringa seed flour indicated reduced glucosinolates, saponins, oxalates, phytates, and alkaloids, but total tannin content was elevated [36]. The increase in tannin content of germinated moringa seeds implies polymerization reactions of flavonoids (catechin and quercetin).

Tannin de-activation strategy

The use of moringa leaves as dietary supplements in poultry has been shown to improve growth performance and egg quality [49, 52]. However, the amount of moringa leaf meal that can be added to poultry diets is limited by high concentrations of condensed tannins. Indeed, other scholars have reported that the inclusion of moringa leaf meal in poultry diets should not exceed 25 g/kg due to the presence of tannins [16]. Literature shows that high levels of condensed tannins reduce feed utilization efficiency, growth rates, and protein digestibility in chickens [38]. Moreover, high levels of tannins are harmful to the intestinal mucosa and disturb the normal absorptive function of the gut, resulting in poor performance. Therefore, ameliorating the negative effect of condensed tannins to allow the birds to fully benefit from the bioactive components of moringa leaf meal is necessary. One potential strategy is the use of polyethylene glycol (PEG), a tannin-inactivating compound, which has a high affinity for condensed tannins. Polyethylene glycol blocks the formation of tannin–protein complexes by binding condensed tannins, which increases protein digestibility. However, a trial demonstrated that pre-treatment of moringa leaf meal with incremental levels of PEG did not affect the concentrations of total soluble phenolics, suggesting that moringa has many phenolic compounds other than condensed tannins [67]. Nonetheless, pre-treatment of tannin-rich feeds with PEG reduces the negative effects of condensed tannins in the GIT of birds and improves protein digestibility [21]. This phenomenon makes protein and other nutrients available for utilization and increases the voluntary intake of leaf meals.

Polyvinylpyrrolidone (PVP) is a synthetic polymer known for its ability to form complexes with a wide range of bioactive compounds. In the context of tannins, PVP can bind to them through non-covalent interactions, effectively reducing their negative effects. By forming complexes with tannins, PVP can mitigate their astringency and improve the digestibility of tannin-rich feeds [68]. However, the efficacy of PVP varies depending on factors such as the type and concentration of tannins, animal species, and overall formulation of the feed. While PVP offers potential benefits as a tannin-binding agent, it is essential to consider factors such as cost-effectiveness and potential interactions with other feed components when used to treat tannin-rich feedstuffs. Additionally, further research and field trials may be necessary to optimize its use and ensure its effectiveness in practical feeding scenarios.

Wood ash contains alkaline compounds such as calcium carbonate and potassium carbonate, which can help neutralize tannins by increasing the pH of the digestive tract. An alkaline environment reduces the binding capacity of tannins to proteins, thereby enhancing the digestibility of nutrients. However, despite wood ash tannin binding capacity, its efficacy may vary depending on the type of wood used, the processing method of the ash, and the specific tannin content and composition in the feed [69]. Additionally, excessive supplementation of wood ash may lead to unintended consequences such as mineral imbalances or alterations in the gut microbiota.

Exogenous feed enzymes

Enzyme technology is a principal strategy to improve the digestion of feedstuffs. Enzymes break down plant cell walls resulting in a release of encapsulated nutrients. Exogenous fibrolytic enzymes are synthesized through genetic modification or from microbial sources [70] for use in animal diets. Poultry does not naturally produce sufficient enzymes for the hydrolysis of NSP, which remain mostly unhydrolyzed resulting in poor feed efficiency. Fibrolytic enzymes can be employed to reduce the negative effects of NSP by decreasing intestinal viscosity and improving nutrient digestibility. The ability of fibrolytic enzymes to enhance fibre breakdown and improve weight gain and FCR in broiler chicken diets has been reported [71]. Contrary to these results, previous research reported no improvements in growth performance, blood, and meat quality parameters of Cobb 500 chickens after pre-treating dietary green seaweed with 1.2% fibrolytic enzyme [72]. Similarly, pre-treatment of moringa leaf powder with 1% fibrolytic enzyme did not affect the weight gain and feed conversion efficiency of Jumbo quails [73]. Furthermore, a trial reported no differences in weight gain or FCR in broilers fed with a low-energy diet supplemented with 0.50 g/kg enzyme [74].

The moringa leaf meal contains significant amounts of phytic acid, which may inhibit vitamins, calcium, iron, phosphorus, and protein absorption. Phytate is indigestible to poultry due to the lack of endogenous phytase activity in their digestive system. According to a report, phytase is currently a standard additive in poultry diets [75]. Thus, the addition of phytase in moringa-containing diets would enhance the hydrolysis of phytic acid, breaking it down into inorganic phosphorus and myoinositol. Phytase could therefore increase phosphorus digestibility, making it more accessible for the bird's absorption. Typically, supplementation of the phytase enzyme in grain-based poultry diets has become common practice to increase phosphorus bioavailability by 25–50%, reduce phosphorus excretion by 15–40%, and ensure proper growth and bone development [76].

The pre-treatment of moringa products with exogenous protease may also be an effective strategy to improve growth and increase the digestibility of crude protein in poultry diets. Past experiments indicated that most of the protein in the diets of broiler chickens went undigested as it passed the GIT [77, 78]. This undigested protein may be better utilized in the presence of the exogenous protease enzyme. Therefore, the use of exogenous protease enzymes may optimize protein digestibility and utilization in poultry by inactivating trypsin inhibitors. It was demonstrated that the extraction of antioxidant peptides from moringa leaves with 3,000 U/g alkaline protease, suggests their efficacy in protecting cells from oxidative stress in poultry production [79]. Collectively, these studies demonstrate the ability of enzymes to enhance the various aspects of moringa products for poultry. However, the lack of positive results in some literature is because most of the conventional enzymes are designed for conventional feed ingredients rather than moringa products.

Extraction of *moringa* bioactive compounds

Moringa plant parts contain dietary fibre in the form of cellulose, hemicellulose, and lignin. While dietary fibre is essential for digestive health, high fibre levels can interfere with the utilization of certain nutraceuticals such as protein, minerals, vitamins, and polyphenols. Therefore, extraction methods can be employed to reduce the concentration of these antinutrients and avoid the antinutritional activities of fibre.

Moreover, a study investigated the extraction of *M. oleifera* seed oil using hexane, petroleum ether, and acetone as extraction solvents, where particle size, extraction temperature, and residence time were considered independent variables [80]. The authors posited hexane as the most efficient solvent for oil extraction, with a maximum yield of 33.1%. Additionally, a study examined conventional solid–liquid extraction and ultrasound-assisted extraction, using methanol, ethanol, and acetone as solvents [81]. The authors identified ultrasound-assisted extraction with ethanol–water (50:50) as the most efficient extraction procedure, yielding 47 ± 4 mg of gallic acid equivalents per gramme of moringa leaf. This extract was then characterized using high-performance liquid chromatography coupled with mass spectrometry revealing the presence of 59 bioactive compounds. These findings emphasized the potential of moringa leaves as a nutritional supplement and as a source of bioactive compounds for various applications, including livestock production, food, pharmaceutical, and cosmetics industries. Similarly, the application of microwave-assisted extraction and ultrasound-assisted extraction to improve the extraction of oil rich in bioactive substances from *M. oleifera* seeds was explored [82]. The study demonstrated that microwave-assisted extraction and ultrasound-assisted extraction resulted in higher oil recoveries, ranging from 91 to 94%, in a shorter extraction duration compared to conventional extraction, which achieved a 90% recovery. Importantly, there were no significant differences in the fatty acid composition, acylglycerol profile, or thermal properties of the extracted oils among the different extraction techniques. This research highlights the potential of microwave-assisted extraction and ultrasound-assisted extraction as time-efficient methods for obtaining high-yield moringa oil while preserving oil quality.

A study evaluated the antibacterial activity of aqueous, chloroform, and methanol extracts derived from *M. oleifera* leaves, bark, and roots against four foodborne microbial pathogens [83]. Their findings indicated that all extraction methods showed antimicrobial activity against the tested microorganisms. The results suggested that chloroform extraction was the most effective method for extracting antimicrobial compounds from *M. oleifera* products. Furthermore, the bark of the plant was found to contain a higher number of antimicrobial compounds compared to the leaves and roots. These findings highlight the potential of moringa product extracts in food preservation and the development of drugs against foodborne microbial pathogens.

These studies provide valuable insights into the optimization of extraction processes for antimicrobial, anti-inflammatory, and toxicological properties of moringa extracts. They also demonstrate the effectiveness of various solvents, extraction conditions, and novel extraction methods, which not only enhance the yield of phenolic compounds, but also maintain the quality and stability of the extracted products for a wide range of applications, including in food, pharmaceutical, and livestock industries.

Furthermore, implementing the reviewed methods of incorporating moringa products into poultry production systems presents several practical implications. The feasibility of using moringa as a feed additive is high due to its rich nutraceutical profile which can enhance growth performance and health in poultry. However, scalability may face challenges such as the need for consistent and large-scale cultivation, quality control, and processing to ensure the efficacy of the phenolic compounds. Consequently, while the potential for moringa products as a nutraceutical in poultry diets is promising, careful consideration of these factors is essential for successful commercial adoption.

Conclusions

The nutraceutical composition of moringa products has been demonstrated to contain nutrients and bioactive substances that can be extensively used to promote sustainable poultry production and food security. However, to fully harness the benefits of moringa products, it is essential to address high levels of fibre and secondary metabolites that can inhibit their efficient utilization by poultry birds. This review has explored several methods to mitigate the negative impact of some of the primary and secondary metabolites and enhance the nutritional quality of moringa products for poultry production. Through the proper application of innovative extraction and processing methods, the nutraceutical potential of moringa products can be fully realized. These efforts could contribute to sustainable poultry production and alleviate food insecurity of a growing human population. Evaluating the economic feasibility and cost-effectiveness of incorporating moringa products into poultry diets is essential, which also includes considering factors such as cultivation, processing, and market availability. Future research can focus on investigating novel extraction techniques, exploring synergistic effects of combining different methods, and conducting comprehensive economic analyses. To maximize the benefits of moringa products, we recommend that policymakers and industry stakeholders consider standardizing moringa products dosage for each poultry species based on physiological stages and form of moringa products. Furthermore, some consumers might accept moringa-derived poultry products since moringa is a natural product; however, others may frown at new ideas (neophobia) thereby having significant effects on product pricing.

Acknowledgements

We acknowledge the office of the Deputy Dean of Research and Innovation in the Faculty of Natural and Agricultural Sciences at North-West University for availing the position of a post-doctoral fellowship to the first author.

Author contributions

Conceptualization, C.F.E., A.M., L.E.M., and C.M.M.; validation, C.F.E., A.M., L.E.M., and C.M.M.; writing—original draft preparation, C.F.E., and A.M.; writing—review and editing, C.F.E., A.M., L.E.M. and C.M.M.; visualization, C.F.E., A.M., L.E.M., and C.M.M. All authors read and approved the final manuscript.

Funding

Open access funding provided by North-West University. This research received no external funding.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 24 February 2024 Accepted: 7 October 2024
Published online: 28 December 2024

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