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Review

Antioxidant and Antimicrobial Properties of Selected Phytogenics for Sustainable Poultry Production

Caven M. Mnisi [1,2,*], Victor Mlambo [3], Akho Gila [1,2], Allen N. Matabane [1,2], Doctor M. N. Mthiyane [1,2], Cebisa Kumanda [4], Freddy Manyeula [5] and Christian S. Gajana [6]

[1] Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho 2735, South Africa
[2] Department of Animal Science, School of Agricultural Sciences, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho 2735, South Africa
[3] School of Agricultural Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Mbombela 1200, South Africa
[4] Department of Animal Sciences, University of Pretoria, Pretoria 0028, South Africa
[5] Department of Agriculture and Animal Health, College of Agriculture and Environmental Science, University of South Africa, Florida 1710, South Africa
[6] Department of Livestock and Pasture Sciences, University of Fort Hare, Alice 5700, South Africa
* Correspondence: 23257539@nwu.ac.za; Tel.: +27-18-389-2738

Abstract: The use of antibiotic growth promoters (AGP) in poultry production not only promotes the emergence of pathogenic multi-drug resistant bacteria, but it also compromises product quality, threatens animal and human health, and pollutes the environment. However, the complete withdrawal of AGP without alternatives could result in uncontrollable disease outbreaks that would jeopardize large-scale poultry intensification. Thus, the use of phytogenic products as potential alternatives to in-feed AGP has attracted worldwide research interest. These phytogenic products contain numerous biologically active substances with antioxidant and antimicrobial activities that can enhance poultry health, growth performance, and meat quality characteristics. In addition, the incorporation of phytogenic products as feed additives in poultry diets could result in the production of high-quality, drug-free, and organic poultry products that are safe for human consumption. Thus, this review examines the current evidence on the antioxidant and antimicrobial properties of a selection of phytogenic products, their effects on nutrient utilization, and physiological and meat quality parameters in poultry. The paper also reviews the factors that could limit the utilization of phytogenic products in poultry nutrition and proposes solutions that can deliver efficient and sustainable poultry production systems for global food and nutrition security.

Keywords: antibiotic growth promoters; bioactive compounds; phytogenics; poultry; sustainability

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1. Introduction

Poultry is a major contributor to human nutrition through the provision of high-quality protein, lipids, and other nutrients. However, the future of the South African poultry industry is faced with a lot of uncertainties and sustainability challenges owing to the unsustainability and high market cost of some conventional feed ingredients, including synthetic antibiotics. Thus, to deliver sustainable production systems, phytogenic products can be used to enrich poultry diets with nutrients and bioactive compounds (phytochemicals). These phytogenics are naturally endowed with a milieu of bioactive chemicals that account for their antioxidant and antimicrobial activities in poultry. Most of these phytochemicals are components of essential oils, which include carvacrol, capsaicin, cineole, cinnamaldehyde, eugenol, flavonoids, isoflavones, polyphenols, resveratrol, thymol, and many others that are well known for their potent antioxidant and antimicrobial properties [1,2]. Consequently, dietary supplementation with plant essential oils or their botanical components has the potential to boost the birds' antioxidant and antimicrobial systems, thus improving feed utilization, growth performance, and meat quality and stability. Some studies have demonstrated positive effects of phytogenic products on antioxidant systems that are critical for the protection of birds from the negative effects of lipid peroxidation [3,4]. However, in a few instances, phytogenic feed additives have been unable to prevent meat lipid peroxidation in chickens [5]. Another demonstrable benefit of phytogenic bioactive compounds in poultry diets is their ability to improve the quality and shelf-life of poultry meat through their ability to modify its fatty acid composition [6,7]. The fatty acid composition of meat is an important quality parameter in this era of prevalent non-communicable chronic metabolic diseases afflicting humanity in southern Africa [8] and globally [4]. On the other hand, Puvača et al. [9] reported that phytogenics used as natural antimicrobial growth promoters act as biochemical elements of numerous pathways involved in growth, development, and health, where they participate in the modulation of physiological and immunological processes in poultry. Through these pathways, phytochemicals exhibit various antimicrobial activities [10]. This paper, therefore, presents a review of the antioxidant and antimicrobial properties of phytogenic products used in poultry production. It further presents an overview of selected plant sources of beneficial compounds and their contribution to food and nutrition security and sustainable poultry production. We also explore the challenges and possible solutions surrounding their use in practical poultry diets. Unlike existing reviews on this topic, this offering provides the reader with broader perspectives on the utility of phytogenics as mitigators of contemporary economic, environmental, and social challenges that face poultry producers. This review not only characterizes the beneficial compounds and their modes of action but also addresses how they impact the entire poultry production chain and associated sustainability hurdles.

2. Antioxidant Properties of Phytogenic Products Used in Poultry Production

Phytogenics are very rich in bioactive compounds with potent antioxidant properties that can modulate the immune system, reduce oxidative stress, and thus improve growth performance and meat quality [11]. Due to their ability to shield lipids and proteins, antioxidants are frequently and effectively used as natural additives in poultry feed. They are increasingly becoming popular as alternatives to synthetic antioxidant additives, such as butylated hydroxytoluene and tocopheryl acetate. Their beneficial effects are mediated through the improvement of the antioxidant status of poultry [12,13], including increasing the activities and gene expression of antioxidant enzymes [3] whilst decreasing lipid peroxidation [14]. In addition, the phytochemicals can modulate the antioxidant status of poultry through their alteration of meat fatty acid composition from the saturated (lauric, myristic, palmitic, and stearic acids) to the monounsaturated (e.g., oleic acid) and polyunsaturated (PUFA) (long-chain) fatty acid lineages [4,7]. Saturated fatty acids are undesirable in meat due to their association with hypercholesterolemia and other chronic metabolic diseases in humans [4,7] whilst PUFAs, particularly omega-3 fatty acids, are associated with good health [15]. Furthermore, some of the antioxidant bioactive compounds in phytogenics, such as anthocyanins, polyphenols, retinol, and tocopherol, have good pigmentation-imparting effects [16,17], with the potential to enhance meat color. These compounds also have the potential to enhance meat stability by delaying the oxidation of stored meat.

According to Dyshlyuk et al. [18], the antioxidant defense and immunity-boosting qualities of dietary plant polyphenolics help maintain a balance between the generation of free radicals and their neutralization by supporting the antioxidant system along the gut lining. The significant antioxidant activity of polyphenolics is attributed to the presence of hydroxyl groups, which function as hydrogen donors to surrogate radicals created during the initial stage of lipid oxidation, thus delaying the generation of hydroxyl peroxide. Indeed, the intake of phytogenic products in poultry results in an increase in serum antioxidant enzyme activities and a decrease in the malondialdehyde level [15–18]. The antioxidant properties of phytogenic compounds, such as α-tocopheryl acetate or butylated hydroxytoluene, are useful in the protection of dietary lipids from oxidative damages [19]. Plant oils containing natural antioxidants contribute to the improved oxidative stability of meat and meat products containing higher levels of polyunsaturated fatty acid. Accordingly, antioxidants in phytogenic products have the potential to improve meat quality [16]. This is achieved when plant-derived antioxidants scavenge excess oxygen free radicals and chelating metals [20] or by increasing the activity of antioxidant enzymes, thereby reducing oxidative damage [21] in meat products. Furthermore, the protective effects of most dietary phytochemicals are a result of multiple distinct mechanisms [22], and hence, meat quality is affected by protecting muscle function in a live animal body. In addition, phytochemicals have been shown to benefit animals in terms of improved performance, meat quality [23], and an enhanced endogenous antioxidant system. This is possibly done by directly affecting specific molecular targets or indirectly as stabilized conjugates affecting metabolic pathways [24]. As a result, both external and endogenous stimuli activate and deactivate critical events in intracellular relays, allowing proper signaling to diverse downstream target molecules in a highly sophisticated manner to fine-tune cellular homeostasis [25]. Thus, the use of these plant-derived phytochemicals (e.g., carvacrol, thymol, catechins, quercetin, oregano, curcumin, and cinnamaldehyde) is regarded as an ingenious strategy to adopt in livestock production as antioxidant agents for enhancing the antioxidant capacity of the body and relieving oxidative stress, thus improving their growth performance and meat quality [26]. The ability of phytoproducts to act as antioxidants is mostly attributed to the existence of antioxidant compounds. However, their level mostly depends on the type of plant [27] as well as the growth environment. Since the primary roles of polyphenols in the plant relate to how it responds to challenging environmental conditions, Borguini et al. [28] demonstrated a stronger antioxidant potential of plants produced in an organic system compared to conventional ones.

3. Antimicrobial Properties of Phytogenic Products in Poultry

Although there is still much to learn about the mechanisms by which plant-derived phytochemicals exert their antimicrobial effects on various microbial populations, on target sites, in a feed matrix, and in the presence of other phytochemicals with opposing effects, their antimicrobial effects in animal health and nutrition have been extensively studied. Phytogenics are widely known for their ability to combat infections on a microbiological level. Additionally, purging of the digestive tract helps reduce ATP or energy losses during inflammation and immune responses, prevents diseases, promotes feed and nutrient digestion, and enhances growth performance and production. Transit time, digestive secretions, and the activity of digestive enzymes are some of the mechanisms known to affect gut function, and their combined effects have an impact on nutritional digestibility. Indeed, poultry performance is directly correlated with gut health and function, which is influenced by constant interactions amongst nutrition, intestinal integrity, gut flora, and the immune system. A favorable enhancement of the eubiosis could be how phytogenic compounds might selectively affect microorganisms. This leads to better utilization and absorption of nutrients, resulting in higher performance. Numerous phytogenics have positive effects on the digestive system, including spasmolytic, laxative, and antiflatulent properties. Phytogenics have attracted a lot of attention because they contain a variety of beneficial compounds, such as flavonoids and isoprene glucosinolate derivatives, which have antimicrobial properties. Lee et al. [29] showed that phytogenic compounds enhanced the intestinal activities of trypsin, lipase, and amylase in broilers. At a dose of 0.6 mL/L, oregano and thyme essential oils were found to have a bactericidal action on *E. coli* [30]. Mathis et al. [31] showed that walnut leaves (*Juglandaceae*) slowed the spread of *Clostridium perfrengens* in hens while improving weight gain. Likewise, pomegranate (*Punica granatum*) and green tea (*Camellia sinensis*) products were shown to alter the intestinal microbiota by promoting the proliferation of non-pathogenic bacteria in the digestive system [32]. Broilers fed diets supplemented with the extract of green tea leaves and pomegranate rinds promoted a greater relative abundance of lactic acid-producing bacteria [32]. The in vitro effectiveness of certain berry, date, and thyme extracts against chicken-derived *E. coli* and Salmonella isolates was demonstrated in a 2009 study by Dhifi et al. [33]. Cinnamon extract, thyme, and clove stimulated the digestive secretions of bile, mucus, and saliva and improved enzyme activities, which are of great nutritional interest [34]. In addition, some oils extracted from plants positively influenced the activity of trypsin and amylase in chickens and had a stimulatory effect on the intestinal mucus in chickens, maintaining an equilibrium in the microflora present in their gut [35]. Oladeji et al. [36] claimed that phytogenics significantly increased poultry production performance in terms of weight gain and the feed conversion ratio. This improvement was attributed to the high nutrient availability due to changes in the intestinal ecosystem, such as the increase in the population of lactic acid-producing bacteria.

Lactic acid-producing bacteria have a positive impact on the lower gastrointestinal tract by regulating the composition of intestinal microflora, promoting intestinal immunity, and developing intestinal health. This could be the reason why several researchers have concluded that phytogenic feed additives improve nutrient digestibility, growth performance, and gut health in poultry [37]. Aksit et al. [38] reported earlier that phytogenics' antibacterial effect may help to improve the carcass's microbiological freshness. According to Ganguly [39], the phytogenic growth promoter remains active throughout the gastrointestinal tract, where it exerts broad-spectrum antimicrobial action, improves broiler overall growth performance, and further improves nutrient utilization by enhancing gastrointestinal histomorphology and host immunity. Mohebodini et al. [40] reported that the inclusion of resveratrol from grape by-products in broiler diets increased the levels of immunoglobulin G (IgG) and immunoglobulin M (IgM). These antibodies provide specific immunity to prevent the adhesion of pathogenic microbes and some viruses on the intestinal wall [41]. Therefore, a healthy gut composed of beneficial microbiota is very important for poultry performance and welfare and can be achieved by incorporating phytogenic products into their diet.

4. Selected Plant Sources of Antimicrobial and Antioxidant Compounds

4.1. Moringa oleifera

Moringa oleifera is a medium-sized perennial, evergreen, and deciduous tree from the family *Moringaceae* that grows quickly in a variety of soil types and hot, humid, and dry tropical and subtropical climates [42]. Out of the 13 species in this family, *M. oleifera* is the most popular and widely utilized species [43]. Owing to its nutritional profile, *M. oleifera* is prized globally for its contribution to the livestock industry and food and pharmaceutical sectors [44]. *M. oleifera* is rich in essential nutrients, such as lipids, proteins, minerals, and vitamins [45]. Reports have indicated that the leaves have the highest protein value (250 to 270 g/kg CP) [42], with some protein being available in the seeds, roots, and flowers [46]. Furthermore, *M. oleifera* is also a great source of well-balanced amino acids and vitamins, of which the amount of vitamin A is about 10 times more than in carrots and pumpkins and the amount of vitamin C is 7 times more than in oranges [47]. According to Mbikay [48], moringa leaves contain vitamins A, B and B-Complexes, C (ascorbic acid), E (α-tocopherol), K, and pro-vitamin A in the form of beta-carotene, along with minerals such as sulfur, calcium, phosphorus, potassium, manganese, and iron. Moringa products are also rich in monounsaturated fatty acids [45] and polyunsaturated fatty acids, such as linoleic acid, α-linolenic acid, arachidic acid, stearic acid, oleic acid, and palmitic acids [49].

In addition, *M. oleifera* contains a myriad of phytochemicals, such as flavonols, quercetin, apigenin, kaempferol, luteolin, myricetin glycosides, and polyphenols, which exhibit antioxidant, antimicrobial, anticarcinogenic, anti-inflammatory, and medicinal activities [50,51]. However, the leaves also contain antinutritional substances, such as alkaloids, carotenoids, glucosinolates, isothiocyanates, saponins, tocopherols, tannins, oxalates, phytates, trypsin and amylase inhibitors, lectins, and cyanogenic glucosides [52], which may affect their utility in poultry diets and induce different responses. For example, Kakengi et al. [53] found that adding 10% and 20% *M. oleifera* leaf meal in place of sunflower seed meal enhanced feed intake and dry matter intake while lowering the egg mass output in laying hens. However, Khan et al. [54] also reported that the inclusion of 1.2% *M. oleifera* leaf powder in broiler feeds improved the intestinal microarchitecture and cellular count, which in turn promoted gut health.

4.2. *Lippia javanica*

Lippia is a genus that belongs to the family *Verbenaceae* [55], which is distributed in the tropics of Africa and South America [56]. There are more than 200 species in the genus *Lippia* (*Lamiales: Verbenaceae*), many of which are aromatic [55]. According to Viljoen et al. [57], *Lippia javanica* (*Burm. f.*) *Spreng*., often known as fever tea, is a perennial, erect, woody shrub that is rich in nutrients and bioactive compounds. The plant has been used to treat various ailments such as colds, cough, fever, influenza, malaria, measles, rashes, stomach problems, and headaches [58]. Nutritionally, *L. javanica* possesses varying amounts of essential nutrients, such as protein, fats, carbohydrates, minerals, and vitamins [59]. It is a good source of cobalt, cadmium copper, chromium, iron, magnesium, calcium, manganese, zinc, selenium, potassium, phosphorus, and lead [60,61]. Bio-compounds, such as caryophyllene, carvone, ipsenone, ipsdienone, limonene, linalool, myrcene, myrcenone, ocimenone, p-cymene, piperitenone, sabinene, and tagetenone, are abundant in the volatile oil of *L. javanica* [59]. *L. javanica* also contains alkaloids, amino acids, flavonoids, iridoids, triterpenes, and other volatile and non-volatile secondary metabolites. Furthermore, *L. javanica* contains phytochemicals, such as anthocyanins, anthraquinones, coumarins, saponins, flavones, alkaloids, flavonoids, tannins, phenols, cardiac glycosides [55], and phenylethanoid glycosides (isoverbascoside and verbascoside) [62]. From the essential oils extracted from *L. javanica*, Pascual et al. [63] reported the presence of p-cymene, camphor, limonene, β-caryophyllene, linalool, α-pinene, thymol, carvone, ipsenone, myrcenone, myrcene, piperitenone, caryophyllene, and tagetenone, which give the plant antiseptic, antibacterial, and antiviral properties [64]. Varied results have been reported from feeding trials involving *L. javanica* leaf meals depending on the amount used and the bird species. For example, the inclusion of *L. javanica* in broiler diets at a rate of 5 g/kg had positive effects on the growth performance, carcass characteristics, and fatty acid profiles of broiler meat [65]. However, Mnisi et al. [66] reported that the inclusion of *L. javanica* at a rate of 25 g/kg feed promoted similar growth performance, health status, and carcass and meat quality traits as the commercial grower diet containing antibiotics in Japanese quail.

4.3. *Camellia sinensis*

Camellia sinensis, commonly known as green tea, is an evergreen shrub that belongs to the family *Theaceae* [67]. The *Camellia* genus comprises over 200 species, with a majority being native and adapted to China [68]. The green tea plant is the most grown for its buds and leaves, which are used to make tea [69]. Green tea leaves have a crude protein content that ranges from 18.15 to 22.9% and metabolizable energy between 11.3 and 14.6 MJ/kg [70]. The leaves are rich in vitamins (A, C, E, K, and B complex), lipids (linolenic and linoleic acids), pigments (carotenoids and chlorophyll), and minerals [71]. Green tea contains beneficial compounds that have stress-reducing functions and antioxidant activities with neurological effects and anti-inflammatory properties [72]. Its polyphenols account for up to 35% of the dry weight of the leaves [73]. However, the majority of the antioxidants are catechins, which make up about 10 to 20% of dry leaves. The major catechins identified in the plant are (-)-epigallocatechin gallate, (-)-epicatechin (EC), (-)-epigallocatechin (EGC), and (-)-epicatechin gallate (ECG) [63], which have potential health benefits [74].

Furthermore, it contains 26 different amino acids, alkaloids (caffeine, theobromine, and theophylline), carotenoids, lipids, L-ascorbic acid, carbohydrates, methylxanthines, minerals, chlorophyll, saponins, organic compounds, and volatile organic compounds [74,75]. Other important bioactive compounds that have been isolated in the plant are flavonoids such as kaempferol, myricetin, and quercetin, which account for 2–3% of the dry leaves [76].

Mahlake et al. [77] indicated that replacing the antibiotic zinc-bacitracin with green tea leaf powder in the diets of Jumbo quail boosted the overall feed intake but had no effect on weight gain or feed conversion efficiency. Additionally, 10% aqueous green tea extract and other antibiotics had comparable antibacterial effects on the antibiotic-resistant *S. pyogenes*, *P. mirabilis*, and *S. aureus* species [78].

4.4. *Allium sativum* L.

Garlic (*Allium sativum* L.) is a bulbous plant that belongs to the *Anaryllidaceae* family [79]. It is believed to have originated in Asia, although it is now utilized throughout the world [80]. Garlic is globally used as a nutraceutical, containing carbohydrates, protein, amino acids, lipids, fiber, vitamins, minerals, organic acids, saponins, phenolic compounds, and a large group of organo-sulfur compounds [81], along with phytochemicals (saponins, tannins, alkaloids, and flavonoids) [82]. Additionally, garlic has enzymes, minerals, vitamins [83], and moderate sulfur content but little B vitamin [84]. Garlic bioactive compounds are organosulfur compounds, which are responsible for its smell, flavor, and antioxidant and medicinal properties [85]. Sulfur compounds, such as trisulfides, thiosulfinates, tetrathiol, sulfates, scordinine, pseudoscordinine, methyl sulfides, methionine, glutathione, disulfides, dimethyl sulfides, diallyl sulfides, cystine, cysteine sulfoxides, cysteine, cycloalliin, allyl trisulfides, allyl sulfides, allyl disulfides, alliin, allicin (thiosulfonate), and ajoene, have all been reported in garlic [80,86].

Other reported phytochemicals are flavonoids (flavones and quercetins) [87], phenolic compounds, saponins, and sapogenines [88]. These bioactive compounds have antibacterial, hypo-cholesterolemic, antioxidant, and growth-promoting qualities, which are beneficial to livestock and poultry [83]. For example, the addition of 0.5 kg/ton garlic meal in diets as an alternative to antibiotics promoted the high live weight in broilers [89]. According to Eltazi et al. [90], supplementing a standard diet with 3% garlic powder promoted higher body weight gain, higher feed intake, and an improved feed conversion ratio, along with higher dressing and breast percentages in broilers.

4.5. *Allium cepa*

Allium cepa, commonly known as an onion, is a member of the *Liliaceae* family, which is currently grown all over the world and has its roots in central Asia [91]. The onion is an important source of nutritional components, such as proteins, carbohydrates, sugars (arabinose, fructose, galactose, glucose), vitamins, lipids, minerals, and some flavonoids and polyphenols components [92]. Onions are a rich source of vitamin A (β-carotenoid), vitamin B (B1, B2, B3), vitamin E (α-tocopherols), and vitamin C (ascorbic acid) [93,94], which exhibit antioxidant activities. They are also a good source of diverse dietary flavonoids, phospholipids, and glycolipids, along with organosulfur compounds, such as allicin, alliin, diallyl disulfide, S-methyl-L-cysteine S-oxide, propanethial S-oxide, and 3-mercapto-2-methypentan-1-ol [95]. Furthermore, Metrani et al. [96] reported that onions contain various sulfoxides, which include (+)-S-(1-propenyl)-L-cysteine sulfoxide, (+)-S-methyl-L-cysteine sulfoxide, S-propyl-L-cysteine sulfoxide, S-methyl-L-cysteine sulfoxide, and S-propenyl-L-cysteine sulfoxide, which exhibit antibacterial and antioxidant activities. In addition, onion bulbs are said to be a good source of phytonutrients and antioxidants due to the presence of organosulfur compounds, such as cysteine sulfoxides, quercetin, quercetin glucosides, and allicin [97,98].

Onion bulbs' saponins have been shown to have biological effects, including antifungal and anti-inflammatory properties [97]. These substances stimulate the digestive and immune systems, which in turn enhance growth performance and general health in birds [99]. It has been claimed that onion extracts or powder used in drinking water or livestock feed have both growth-promoting and anti-pathogenic properties [100]. The phytochemicals in onions alter the gut flora and immune system and encourage the growth of colonic and mucosal microflora, which function as a barrier to prevent microbes from entering the gastrointestinal tract [101]. Aditya et al. [102] found that adding 5 or 7.5 g of onion to broiler diets increased the overall feed intake and body weight of the hens without affecting the feed conversion ratio. Supplementing drinking water with up to 1% onion extracts during the starter and grower periods increased the average daily feed without compromising broiler chickens' feed conversion ratio [100]. Muscovy ducks fed diets containing 1% onion meal had an enhanced feed conversion ratio, live body weight, and weight gain [103]. Dosoky et al. [104] found that Japanese quail hens fed diets with 800 g of dried onion per kg DM had increased body weight.

4.6. *Mentha piperita*

Peppermint (*Mentha piperita*) is a perennial herb that belongs to the *Lamiaceae* family [105]. *Mentha piperita* is one of the most commonly used medicinal plants in the world [106]. This is mainly because of the presence of phytochemicals that have anti-inflammatory, anti-aging, antimicrobial, antioxidant, emmenagogue, antinociceptive, and rubefacient properties [107]. Bio-compounds, such as proteins, carbohydrates, lipids, minerals, vitamins, alkaloids, saponins, glycosides, steroids, and tannins, have been extracted from the plant [105,108]. Peppermint products have high concentrations of minerals, such as P, K, Na, Ca, Mg, and Zn, and vitamins A, C, and E [105]. The leaves contain flavonoids and phenolic acids, along with acetaldehyde, amyl alcohol, cadinene, caffeic acid, cardiac glycosides, dimethyl sulfide, limonene, menthol, menthone, menthyl esters, phellandrene, pinene, and pugelone [2,109], which have antioxidant and antimicrobial activities.

Furthermore, the plant contains mint oil, which is composed primarily of linoleic, palmitic, and linolenic palmitic acid [110]. About 0.5 to 4% of the essential oils found in peppermint leaves are composed of menthol (25–78%), menthone (14–36%), isomenthone (1.5–10%), menthyl acetate (2.8–10%), and cineol (3.5–14%) [111]. Due to its bioactive substances, peppermint is frequently used in the poultry industry to boost the immune system, in addition to its potent antibacterial and antioxidant capabilities [112]. According to Khempaka et al. [113], peppermint leaves had positive impacts on broiler ammonia generation, abdominal fat deposition, and antioxidant activity. Early in a broiler's life, peppermint leaves are effective at promoting growth [114]. When added to broiler diets in various concentrations (0, 5, 10, or 15 g/kg), peppermint leaves significantly boosted their body weight and daily body weight gain compared to a control diet [115].

4.7. *Aloe vera*

Aloe vera is one of over 420 species in the genus *Aloe*, which has been variously categorized as belonging to the *Asphodelaceae*, *Liliaceae*, or *Aloaceae* families [116]. It is a succulent, perennial xerophyte with thick, fleshy, pointed leaves that cluster at the stem. *Aloe vera* is ubiquitous in components with biological activity, such as polysaccharides, phenolic compounds, minerals, water- and lipid-soluble vitamins, organic acids, and lipids [117]. It is made up of 96% water and 4% dry matter, containing protein, fat, dietary fiber, and 75 other biologically active compounds [118,119]. Anthraquinones, saccharides, vitamins, enzymes, and low-molecular-weight compounds are the main components of *A. vera* and are responsible for its anti-inflammatory, immunomodulatory, wound-healing, antibacterial, antiviral, antifungal, anti-tumor, anti-diabetic, and antioxidant properties [120].

In addition, other phytochemicals, such as alkaloids, anthraquinones, anthrones, chromones, coumarins, flavonoids, lignin, naphthalene, saponins, sterols, pyrans, and pyrones, have been isolated from the plants of the genus [121]. In poultry nutrition, the incorporation (1.5, 2, 2.5%) of *A. vera* gel in broiler feed reduced the *Escherichia coli* count [122]. Similarly, Dai et al. [123] found that *A. vera* products increased *Lactobacillus spp.* and *Bifidobacteria* while decreasing the amount of *E. coli*. In another study, Darabighane and Zarei [124] reported improved feed utilization efficiency upon adding 1.5%, 2%, and 2.5% of *A. vera* gel to the diet of broilers with coccidiosis. The authors stated that this could be attributed to the potential of *A. vera* to enhance the intestinal health and immune system response in the birds.

4.8. Seaweeds

Seaweeds are macroalgae that grow in the littoral zone of aquatic systems. They consist of green (*Chlorophyceae*), red (*Rhodophyta*), and brown (*Phaeophyceae*) algae. There are 10,100 different kinds of seaweeds that have been identified worldwide. Seaweeds can be found in all types of marine settings; hence, their nutritional value varies greatly depending on the species, habitat, geographical origin, production region, season, harvest time, environmental and physiological fluctuations, and water temperature [125]. Seaweeds contain polysaccharides, proteins, amino acids, minerals, vitamins, and antioxidant chemicals [125]. Stengel et al. [126], reported that seaweeds are a rich source of bioactive compounds, such as polyphenols, which have antioxidant and antimicrobial properties and thus, can be used as a nutraceutical additive in poultry production [127].

Choi et al. [128] demonstrated that adding seaweed supplements at a rate of 5 g/kg improved the feed conversion efficiency. According to Abudabos et al. [129], adding seaweed to broiler diets improved the quality of the meat by reducing the number of microorganisms in the digestive tract and boosting immunological function. Nhlane et al. [130] investigated the impact of green seaweed (*Ulva* sp.) meal on native chickens and found that its dietary addition boosted native chickens' feed intake and overall body weight gain but not their ability to convert feed into energy. Broiler hens supplemented with green seaweed at doses of 10 or 30 g/kg did not alter the growth or feed efficiency; however, birds given the higher dose (30 g/kg) showed increased dressing percentage and breast muscle yield compared to those given the control or 10 g/kg dose [131]. In another study, the inclusion of seaweed up to 150 g/kg in the diets of ducks had no negative impacts on the growth rate or carcass quality [132].

5. Contribution of Phytogenics to Environmental Health and Food Security

Food security has four dimensions, including (1) availability—national, (2) accessibility—household, (3) utilization—individual, and (4) stability. To achieve full food security, all four dimensions must be intact [133], which is still a major challenge in most low- and middle-income countries (LMICs). Rapid human population growth, poverty, the COVID-19 pandemic, and climate change, with its concomitant recurrent droughts [134], are among the major factors that exacerbate food insecurity. Ironically, over 80% of households in Sub-Saharan Africa (SSA) practice poultry farming with predominantly indigenous poultry breeds [135]. However, they have not yet been sufficiently exploited to alleviate food insecurity. This current scenario, therefore, provides an opportunity to explore sustainable strategies to ensure poultry intensification in the sub-continent. To meet the increasing global demand for nutritious food, the poultry industry, which contributed 40.6% of total meat production (337.3 million tons) in 2020 [136], must be sustainably intensified.

However, poultry intensification raises significant concerns about environmental sustainability. This is because intensive poultry production depends on external inputs, primarily comprising monoculturally produced feed ingredients such as maize and soybean, whose production is associated with serious environmental impact issues, including climate change, deforestation, and loss of biodiversity [137]. In addition, broiler chickens excrete enormous amounts of unutilized nitrogen and phosphorus into the environment annually, which, if mismanaged, leads to environmental manure [138], atmospheric ammonia pollution [139], and eutrophication and its induction of aquatic hypoxia and harmful algal blooms [140]. Thus, improved nutrient utilization efficiency in birds consuming diets with phytogenic products could have positive environmental consequences by reducing the nutrient pollution of poultry wastes. Furthermore, the use of phytogenic plants as feed additives results in improvements in protein digestibility, which further leads to the greater utilization of dietary amino acids and a reduction in the excretion of nitrogenous compounds [141]. As a result, the use of phytogenic feed additives lowers the emissions from poultry production. In addition, the anti-microbial effects of phytogenic feed additives result in lower ammonia release. This is achieved by a reduction of Gram-negative bacteria and an increase in the beneficial bacterial activities in the hindgut of poultry, leading to increased formation of volatile fatty acids in excreta, a lower slurry pH, and consequently, the reduction of ammonia emissions [142].

In addition, the usage of antibiotics in intensified poultry farms can accelerate the spread of antibiotic resistance genes in the environment [9,10,142,143]. Therefore, sustainable poultry intensification could be a strategy to enhance food security, particularly in SSA, without causing catastrophic damage to the ecosystem, such as the feeding of phytogenic feed additives. The use of phytogenic compounds could provide a more environmentally friendly, lower-cost solution for improving food and nutrition security while also benefiting poultry consumers' health. This will, in turn, meet the demand for animal protein and, ultimately, reduce hunger and food insecurity, even in low-income countries. This would also ensure that consumers have access to healthy poultry products that are free of antibiotic residues, and as such, comply with the goal of achieving good health and well-being. The antimicrobial properties of these phytogenics could also reduce the amount of carbon and methane that is released into the environment, which could contribute to the goal of combatting climate change. Moreover, phytogenics have probiotic, prebiotic, and antibiotic activities that can reduce pathogenic bacterial infections and help reduce disease outbreaks, thus promoting food safety. This is very important, given that most of the recent pandemics have been of animal origin [144].

6. Anti-Nutritional Factors as Constraints to the Use of Phytogenics in Poultry Nutrition

The incorporation of phytogenic products in poultry diets is known to improve the performance and health of birds, but their widespread adoption could be limited by the presence of anti-nutritional factors (ANFs) (Table 1). Anti-nutritional factors have been reported to reduce nutrient utilization or feed intake when included in animal feeds [145]. Several studies have reported the toxicological effects of ANFs in poultry [146,147]. For example, phytates, tannins, and phytosterols in *M. oleifera* reduced weight gain in Arbor Acres broiler chickens by reducing the digestibility of amino acids [148]. In addition, reductions in crude protein digestibility, metabolizable energy utilization, feed intake, weight gain, and feed conversion efficiency were observed in broilers fed a diet with cassava pellets containing cyanogenic glycosides in place of maize [149,150]. Feed intake, weight gain, and carcass traits were reduced in chickens fed a diet containing 40 g/kg of polyphenol-rich *C. sinensis* [151]. Hassan [152] observed poor growth in broiler chicks fed 3 g saponins/kg diet due to a depressed feed intake. Farhadi et al. [153] reported that tannins from eucalyptus leaf powder reduced body weight and the overall feed conversion ratio in broilers because tannins bind proteins and form indigestible complexes. With phytogenics used as whole plant parts, it was shown that the high fiber content reduced the performance of the birds by increasing the passage rate [154]. Similarly, Nduku et al. [155] found that feeding one-week-old broiler chicks a diet containing *M. oleifera* high in fiber reduced the daily weight gain and impaired the feed conversion ratio. This is because simple non-ruminants such as chickens have a limited capacity to utilize high-fiber diets due to a lack of microbial digestive enzymes.

Table 1. Anti-nutritional factors present in selected plants used in poultry diets.

Phytogenics	Anti-Nutritional Factors	References
Moringa	Tannins, oxalates, phytate, saponins, cyanogenic glycosides, alkaloids, flavonoids	[156]
Lippia	Tannins, oxalates, saponins, phytate, alkaloids	[157]
Camellia sinensis	Flavonoids, phenolics	[158]
Garlic	Alkaloids, tannins, saponins	[159]
Onion	Alkaloids, tannins, flavonoids, total phenolics	[159]
Peppermint	Alkaloids, saponins, glycosides, tannins, flavonoids	[108]
Aloe	Flavonoids, tannins, alkaloids	[160]
Artemisia afra	Flavonoids, alkaloids, phenolic acids, lignans, proanthocynidins	[161]
Carpobrotus edulis	Saponins, flavonoids, alkaloids, cyanogenic glycosides, tannins	[162]

Table 1. *Cont.*

Phytogenics	Anti-Nutritional Factors	References
Eucalyptus	Tannins, phytate, oxalates, saponins	[163]
Seaweeds	Flavonoids, phlorotannins	[164]

7. Amelioration of Antinutritional Effects in Poultry Consuming Phytogenics

As aforementioned, the utility of phytogenics is hindered by the presence of ANFs, which could be ameliorated using a variety of techniques. Solid-state fermentation, alkali treatments, tannin-binding agents, thermal processes, exogenous feed enzymes, and plant breeding are some of the strategies that can be used to ameliorate ANFs. Solid-state fermentation (SSF) is a process that takes place in a solid matrix in the absence or near absence of free water with the aid of the metabolic activity of microorganisms [165]. When fermenting phytogenics to reduce ANFs, it is also important to use microorganisms, such as lactic acid bacteria, that will promote beneficial intestinal microbiota while acting against pathogenic enteric microbes [166]. Microbial activity during SSF can reduce the levels of ANFs in potential phytogenic substrates. Indeed, Olukomaiya et al. [167] reported a significant reduction in the phytic acid content in fermented lupins flour using *Aspergillus sojae* and *A. ficuum*. Similarly, Shi et al. [168] reported a reduction in the concentrations of crude fiber, tannins, hemicellulose, and phytate in fermented *M. oleifera* inoculated with *A. niger*, *Candida utilis*, and *Bacillus subtilis* at a ratio of 1:1:2. Similarly, *M. oliefera* seed flour was reported to have reduced tannin, phytic, phenol, flavonoid, saponin, and alkaloid contents after fermentation and germination processes compared to unprocessed flour [169].

Thermal processing is also an effective means of inactivating thermo-labile ANFs in phytogenic products [170]. Heat-based methods include autoclaving, pressure cooking, microwaving, extrusion cooking, and toasting. Batista et al. [171] reported that autoclaving reduced the contents of trypsin and α-amylase inhibitors and resistant starch in *Phaseolus vulgaris*. Toasting the seeds from *Senna obtusifolia* at 80 °C for one hour significantly lowered the hemagglutinin, phytate, oxalate, saponin, and tannin contents [172]. Thermal application has been shown to partially hydrolyze tannic acid and release gallic acid molecules, and these newly produced gallic acid and galloyl groups had enhanced antimicrobial and antioxidant effects compared to fresh tannic acid [172]. Moreover, boiling, steaming, stir-frying, and roasting were reported to decrease the total polyphenols contents of *Capsicum annuum* L. [173].

Exogenous enzymes have the potential to improve the utility of phytogenics for sustainable poultry production [174]. Proteases and carbohydrases (xylanases and cellulases) are exogenous enzymes commonly used in poultry feeds. Costa et al. [175] successfully used exogenous *ulvan lyase* to boost the meat nutritional value of birds by feeding them *Ulva lactuca* supplemented with carbohydrases. Abou-Arab and Abu-Salem [176] treated *Jatropha curcas* seeds with sodium bicarbonate ($NaHCO_3$) and sodium hydroxide (NaOH) and successfully inactivated the phytic acid, trypsin inhibitors, total phenols, and saponins. This review shows that ANFs in phytogenic products could hinder their utility as sources of beneficial bioactive compounds. However, there are several methods that could be used to reduce the ANF content of phytogenic products and improve their utilization in poultry nutrition. Nonetheless, factors such as costs and the ease of application often guide the preferable processing method of farmers.

8. Prospects and Conclusions

The use of phytogenic products as functional feed ingredients in poultry diets could allow for AGP-free large-scale sustainable production of poultry products in the agro-food value chain. This paper presents evidence that the incorporation of phytogenic products in poultry diets can boost feed utilization efficiency, reduce feed-food competition, and enhance their contribution to eradicating hunger and food insecurity. However, there is also evidence that their utilization can be limited by the presence of plant secondary metabolites, particularly when higher dietary inclusion levels are used. Thus, it is important to establish their maximum tolerance level in poultry diets and, thereafter, develop strategies to ameliorate any antinutritional activities should higher dietary inclusion levels be desired. Such practical strategies would ensure the large-scale adoption of phytogenic products by farmers and feed manufacturing companies.

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