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Nutraceuticals as components of sustainable poultry production systems for food and nutrition security in Africa: a review

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Abstract

Poultry production plays a key role in reducing food and nutrition insecurity in developing countries. However, as the poultry industry continues to grow, its future is in doubt due to economic, environmental, and social sustainability challenges. To address these challenges, poultry production practices must be optimized for food security, human health, economic viability, and environmental stewardship. At the core of this sustainability endeavour are the substantial nutritional and health requirements of birds that are raised intensively. Nutrient-dense feed resources such as maize and soybeans are indispensable in most poultry production systems in Africa, yet these grains are also direct nutrient sources for humans. This has increased their demand and prices on the world market. In addition, frequent disease outbreaks pose viability challenges that are traditionally mitigated using antibiotic growth promoters (AGPs). However, this practice has led to the undesirable propagation of antibiotic-resistant microbes and production of antibiotic residue-containing poultry products. Alternatives to AGPs such as phytogenic products are required to address some of these challenges. Phytogenics contain nutraceuticals that can boost feed efficiency, bird immunity, and product quality without the negative outcomes associated with AGPs, thus promoting sustainable poultry production. However, phytogenics have not been widely adopted in the poultry industry for a variety of reasons, which are interrogated in this review. The objective of this paper is to explore and evaluate the role of nutraceuticals in sustainable poultry production systems and how they can be used to enhance food and nutrition security in Africa. Optimal usage of phytogenics has the potential to sustain poultry meat and egg production as primary animal protein sources for a growing global human population, especially in developing countries.

Keywords Food security, Health, Nutraceutical, Poultry, Product quality, Sustainability

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Introduction

The demand for meat and eggs will continue to increase in response to human population growth, increased incomes, and a changing diet [1]. The United Nations provides an estimate of 9.7 billion people on the planet by 2050, with a large proportion of this increase occurring in developing countries [2]. Indeed, it is estimated that close to 1.5 billion people will be living in African cities by 2050 [2]. Consequently, urban areas are expected to consume approximately 70% of total meat and milk products, requiring an additional 28 million metric tonnes (Mt) of meat and 47 Mt of milk compared to 2020 consumption figures [3]. The poultry industry's growth has mirrored that of the human population since it is the main source of dietary animal protein [4]. The popularity of chickens as a source of animal protein rests on relatively lower capital and operational costs as well as a short generation interval. It is for this reason that in developing countries, the poultry industry is the fastest growing terrestrial food animal production sector [5], a feat achieved through high levels of intensification. Clearly, poultry production is a major mitigator of food and nutrition security risks in Africa [6], despite the many sustainability challenges it faces. These include inefficient resource utilization, disease outbreaks, suboptimal bird welfare, poor product quality and safety, and environmental pollution. Sustainable poultry production systems are important if households are to have access to adequate, safe, and highly nutritious food to support a productive and healthy lifestyle. Such systems must rely on locally available, easily accessible, and inexpensive sources of nutrients and bioactive substances for poultry production. Reliance on local sources of nutraceuticals in place of AGPs and other chemotherapeutics could address economic, environmental, and social sustainability challenges facing poultry production [6]. This review discusses the concept of nutraceuticals and their potential in addressing the challenges faced by poultry production systems. Nutraceuticals have medicinal and nutritional value with the potential to modulate the bird's immune system, prevent disease, improve health, and ultimately increase production [6]. They have multiple roles that include promoting bird health and growth performance, enhancing nutritional quality of poultry products, reducing environmental pollution, and minimizing antibiotic residues in products destined for human consumption. The primary objective of the review paper is to explore and evaluate the role of local sources of nutraceuticals in sustainable poultry production systems, with a focus on enhancing food and nutrition security in Africa.

Poultry production systems

Chickens account for a large proportion of poultry species [7] that are reared in a variety of production systems. These production systems vary in terms of inputs, outputs, bird health and welfare, and their effects on the environment [8, 9]. In developing countries, the subsistence poultry production system is the most prevalent, where households provide labour and feed from locally available resources [2]. However, high mortality rates due to lack of housing, adverse weather conditions, theft, predation, inadequate feeding, and lack of health management, are common in this system. On the contrary, commercial production systems tend to be high-input large operations that require high levels of expertise to produce large quantities of poultry products. Birds are sometimes reared in environmentally controlled houses while management practices are designed to maximize production [10]. While the importance of these two production systems to combat food and nutrition insecurity in developing countries remains unequivocal at present, the future of commercial poultry production is less assured due to socio-economic and environmental sustainability challenges. Despite the substantial quantitative and qualitative gains that have been realized in different sectors of this industry, these challenges have led to wavering social acceptance of intensively farmed birds as protein sources. These challenges include high feed costs [11], indiscriminate use of antibiotics [12], high stocking densities, restricted natural behaviours, practices such as debeaking [10], safety of poultry products for consumption, disease outbreaks, and environmental pollution caused by greenhouse gas emissions and waste disposal (excretion of nutrients leading to soil and water pollution).

Towards sustainable poultry production in Africa

Poultry production is the most efficient livestock subsector in providing dietary protein to meet an increasing global demand. Poultry plays an important role in achieving food and nutrition security by providing both macro- and micro-nutrients to humans [13]. In addition, poultry are sources of income because they can be sold to acquire cash for basic human needs [9]. While the African continent has the lowest meat consumption rate with an average *per capita* of 13 kg per year for the period 2018–2020 [14], chicken meat is still the most consumed at 5.75 kg *per capita* yearly. This is because of its affordable prices, product consistency, higher protein, and lower fat content than red meat [15]. Despite these advantages, the poultry industry still faces several sustainability challenges that could hinder its growth and development. If not optimized, the African poultry industry could fail

to meet the demand for poultry products given that it is currently facing a myriad of nutritional, technical/extension, financial, market and infrastructure-related challenges. Of major concern is the continent's continued dependence on imports for hybrid birds and raw materials (mostly soybeans and maize grains), which renders the industry unsustainable [6]. For example, the continuous reliance on maize and soybean, whose production has negative socio-economic and environmental consequences due to the use of large acres of arable land, water, chemicals (pesticides, fertilisers, etc.), and fuel, could in the future restrict large-scale poultry intensification. The importation of large quantities of these ingredients, which are subjected to customs duties and high tariffs increases the costs of poultry feeds. Indeed, current estimates put feed costs at more than 70% of total production costs, making it the largest cost item [4]. Further, the use of in-feed AGPs is costly notwithstanding the risk they pose to human health. Therefore, the use of inexpensive and locally available phytogenics, which are plants that are rich in nutrients and bioactive substances, could reduce feed costs and improve growth performance, and product quality [7, 16] and safety. Given that phytogenics have no or limited direct food value for humans, their use would reduce feed-food competition and ensure that crop production systems complement animal production systems in alleviating food and nutrition insecurity.

Nutraceutical value of local phytogenics

The African continent is home to many terrestrial phytogenics including those from the genera *Moringa*, *Acacia*, *Allium*, *Lippia*, *Aloe*, *Camellia*, *Eucalyptus*, *Artemisia*, and *Ziziphus* among others. Marine phytogenics commonly known as macro algae or seaweeds including the red, brown, and green species are also ubiquitous along the coastal shorelines of Africa. These phytogenic products are usually used across African countries as dietary supplements in a form of herbs, spices, or extracts, but this is mostly influenced by their nutrient level or the concentration of bioactive compounds. Phytogenic products have varying levels of nutrients, which can still be exploited to meet the nutritional requirements of poultry. Although, their protein and energy levels are lower than those of soybean and maize, their incorporation in poultry diets can supply some dietary nutrients. In addition to macro-constituents (Table 1), these plants also contain bioactive substances with health-promoting, growth-stimulating, and meat-enhancing properties that are necessary for sustainable poultry production systems in Africa.

Table 1 Some examples of local phytogenic sources and their proximate components (%)

	Proximate components					
	Moisture	**Protein**	**Lipid**	**Ash**	**Carbohydrates**	**References**
Seaweeds	12.9	10.12	1.3	26.2	34.6	[17, 18]
Moringa oleifera	9.5	30.3	6.5	7.6	*	[19]
Red grape pomace	*	13.3	8.4	19.4	4.5	[20]
Green tea	*	15.0	7.0	5.0	7.0	[21]
Amaranths	85.4	3.9	0.3	3.9	6.7	[22]
Lippia	90.4	1.22	0.2	1.6	6.6	[23]
Garlic	3.4	8.4	0.9	3.6	*	[24]

* = not reported

Table 2 Bioactive compounds in locally available phytogenic plants

Plants	Bioactive compounds	References
Seaweeds	Fatty acids, sterols, carotenoids, fibres, polysaccharide, agar, carrageenan, alginate and phycocolloids	[27]
Amaranthus	Polyphenols, β-xanthin, betalain, β-cyanin, flavonoids, vitamin C, β-carotene, carotenoids	[22]
Lippia javanica	Verbacoside, isoverbacoside, sterols, carotenoids, flavonoids, icterogenin	[28]
Garlic	Saponin, phenols, polysaccharides, organosulfur compounds, alliin, polysaccharides	[29]
Grape pomace	Flavanoids, proanthocyanidins, anthocyanins, stilbenes, tannins, hydroxycinnamic and hydroxybenzoic acids	[30]
Green tea	Catechins, flavanols, epigallocatechin gallate, L-theanine and caffeine	[31]
Olive pomace	Polyphenols, vitamin E, tyrosol, oleoside, pinoresinols, palmetic acids stearic and oleic acids	[32]

These phytogenics consist of a wide range of bioactive compounds (Table 2) that can improve growth performance and prevent diseases because they exhibit antioxidant, immunomodulatory and antimicrobial activities in the lower gastro-intestinal tract (GIT) [25]. Nutraceuticals are plant-derived substances that have nutritional and medicinal properties [26]. However, they differ from typical nutritional supplements in several aspects, including their capacity to promote animal health and well-being without leaving any traces in meat products. In poultry, nutraceuticals are used to maintain gut microflora and the immune system, as well as control gut architecture and increase growth rate [25]. The use of phytogenics in poultry feeds could promote the production of high-quality poultry products, which are essential for achieving food and nutrition security in Africa.

Bioactivities of phytogenics used in poultry diets

Generalized potency

Bioactive compounds found in phytogenic products have the potential to increase nutrient digestibility, GIT motility, and bile acid function, all of which can aid poultry feed efficiency. In addition, bio-compounds like phenolics (flavonoids, thymol, eugenol, carvacrol), alkaloids (capsaicin), terpenes, lectins, aldehydes (cinnamaldehyde), polypeptides or polyacetylenes have a variety of biological effects that result in improved poultry performance, high immune cell proliferation and antibody titers, relief from intestinal upsets, reduced oxidative stress, and low mortality rates [24]. Essential oils from the genera *Eucalyptus*, *Citrullus* and *Artemisia*, to mention a few, have been reported to improve the flavour and fatty acid profile of poultry products and stimulate digestive enzymes, thus improving nutrient utilization [26]. Some phytogenic products such as quercetin from *Citrus sinensis* peel extracts and *Camellia sinensis* (green tea) boost the immune system, reduce stress levels, and increase overall health and performance of poultry birds [33]. Likewise, green tea products contain antioxidants that improve poultry health status by reducing oxidative stress while increasing antioxidant activity in numerous tissues [34]. Immunomodulatory effects of phytogenic products include increased immune cell proliferation, modulation of cytokines, and an increase in antibody titers [24, 32], which allows the birds to perform normal physiological and metabolic activities that stimulate optimal performance and health. According to a growing body of scientific research, phytogenics have health-promoting properties that can boost poultry defence against microbial infections [35] and inhibit inflammatory prostaglandins.

Putative roles as antimicrobial agents

Due to growing awareness regarding food safety and the hazards of indiscriminate antibiotic usage, dietary incorporation of phytogenic products (herbs, spices, and their extracts) as organic alternatives has attracted worldwide research interest, with positive results being reported by several scholars [24, 34]. This is attributable to phenolic compounds in phytogenic products that have strong antimicrobial activities. These phenolic compounds also have beneficial effects on GIT microbial activity and gut functionality [35]. Due to their direct antibacterial activities on various pathogenic bacteria, the incorporation of phytogenic products in poultry diets could enhance intestinal microbiota by reducing microbial toxic metabolites in the gut and alleviate intestinal challenges and immunological stress, resulting in improved performance by increasing nutrient utilisation and digestibility. Ayachi et al. [36] discovered that various extracts of berries, date palm, and thyme had an in vitro effect against *E. coli* and *Salmonella* isolates from chicken. Their antibacterial action enhances bird performance by reducing growth-depressing metabolites produced by Gram-positive bacteria, reducing the incidence and severity of subclinical infections, preventing microbial nutrient-use, and improving nutrient absorption due to intestinal thinning [37].

Putative roles as antioxidants

An antioxidant is a substance that inhibits the oxidation of a sensitive substrate [38]. Local phytogenic sources like tea plants (*Camellia* spp.), Lippia, Moringa, seaweeds, carrots (*Daucus carota*), among others, produce numerous antioxidants including carotenoids, flavonoids, tocopherols, tocotrienols, and cinnamic, benzoic, folic, and ascorbic acids [38]. Natural antioxidants include vitamins (A, C, and E) and carotenoids like lutein and beta-carotene [39]. Due to their importance in the food and pharmaceutical industries, phenolics and flavonoids have attracted global attention as natural antioxidants and free radical scavengers. Antioxidants are also recommended for use in poultry diets to prevent oxidative damage caused by free radicals. Ahmed et al. [40] found that sulphur components in garlic and onion reduce the oxidation of low-density lipoproteins in poultry. Abdel-Moneim et al. [41] concluded that dietary polyphenols are powerful antioxidants that can be utilized in poultry to boost health and improve growth performance and product quality. Under oxidative stress, birds are unable to effectively neutralize excess free radicals such as reactive nitrogen and oxygen species, which damage chromosomes, modifying encoded amino acids and, therefore, affecting a variety of cellular activities [39]. This is because free radicals are highly reactive and have

detrimental effects. Thus, phytogenic antioxidants can be used as natural free radical scavengers during digestion, to reduce the production of lipoxidation and glycation end-products by detoxifying reactive oxygen species. Under conditions of oxidative stress, the accumulation of reactive oxygen species induces lipid peroxidation and glycoxidation reactions, whose end-products are known to have pathogenetic roles in the development of various oxidative-related diseases.

Phytogenics in practical poultry diets

Local phytogenic products are inexpensive, readily available, and easily accessible, hence their incorporation in poultry diets is gaining worldwide popularity. Low cost and accessibility allow for the wider adoption of phytogenic products into poultry diets, even by resource-limited farmers. Some of these nutraceutical plants grow naturally and are well-adapted to local growing conditions, making them a low-cost alternatives to antibiotic growth promoters and other feed additives. Existing literature shows that phytogenics contain bioactive substances with antimicrobial, anticarcinogenic, antimutagenic, anti-inflammatory, and antioxidant properties that have positive effects in poultry (Table 3). For example, Nhlane et al. [42] reported that the incorporation of 3.5% seaweed in Boschveld indigenous chickens increase feed intake and overall weight gain. In another study, the inclusion of 70% *Moringa oleifera* leaf meal in diets of Potchefstroom koekoek chickens improved semen quality parameters, hatchability traits and chick weight [43]. Moreover, Alagawany et al. [44] observed that the inclusion of *Glycyrrhiza glabra* products in chicken feed resulted in chicken products that are high in functionally active components such as polyunsaturated fatty acids, microelements, and vitamins. Overall, there are more studies reporting beneficial effects of phytogenic products on a wide range of response parameters in poultry than those reporting negative or no changes. Indeed, Helal et al. [26] reported that phytogenic products from local medicinal plants result in increased nutrient bioavailability and feed utilization efficiency and are necessary to sustain poultry health and productivity. Thus, there is convincing scientific evidence that optimal incorporation of phytogenic products in poultry diets can boost performance metrices, physiological responses and health status of the birds and therefore contribute to sustainable poultry production.

Factors limiting utilization of phytogenic products

The use of local phytogenic products in poultry feeds is limited by the presence of anti-nutritional factors (ANFs) such as tannins, saponins, oxalate, phytate, alkaloids, and fibre or non-starch polysaccharides that negatively affect nutrient utilization and poultry performance (Table 4). Buyse et al. [50] showed that tannins from chestnut wood lowered growth traits in broiler chickens. In another study, Marzo et al. [51] reported that trypsin inhibitors found in soybean expellers

Table 3 Poultry responses to dietary inclusion of selected local phytogenic plants

Plants	Study design	Main findings	References
Seaweed	Boschveld chickens from 4 to 14 weeks. Inclusion rates: 0, 20, 25, 30 and 35 g/kg (seaweed meal)	i) Linearly increased feed intake and overall weight gain ii) No effects on apparent nutrient digestibility and feed conversion efficiency	[42]
M. oleifera	Hy-line brown hens, 64–74 weeks old. Inclusion rates: 0, 3, 6, and 9 g/kg (leaf meal)	i) Increased egg production and some egg quality parameters ii) Decreased triglycerides, serum cholesterol, and the concentrations of excreta ammonia	[45]
Green tea	Female Huiyang Bearded chickens. Inclusion rate of 2% leaf meal	i) Promoted lactobacillus and inhibit the proliferation of *E. coli* in the lower GIT ii) Increased leg meat and meat calcium contents	[46]
Amaranth	Ross 308 male broilers from 1 to 42 days old. Inclusion rates: 0, 4 and 6% (grains)	i) Improved body weight and European broiler index ii) Reduced blood cholesterol, abdominal fat and low-density lipoprotein levels	[47]
Lippa javanica	Male Japanese quails from 1 to 9 weeks old. Inclusion rate: 25 g/kg (leaf meal)	i) No effects on growth performance, blood parameters, and meat quality traits	[48]
Garlic and onion	Layers from 30 to 60 weeks old. Inclusion rates: 0.5 or 1% garlic and onion powder, respectively, and the mixture (1% garlic + 1% onion)	i) Improved egg production, egg mass/hen, and feed conversion ratio ii) Decreased high-density lipoprotein iii) Reduce blood cholesterol	[24]
Pumpkin leaf	Arboc acres from 28 to 42 days old. Inclusion rates: 0, 15 and 30% (extracts)	i) Improved packed cell volume, haemoglobin concentration, and red blood cell counts ii) No mortality recorded	[49]

Table 4 Negative effects of some anti-nutritional factors present in phytogenic products on poultry performance

Substances	Negative effects	References
Tannins	i) Bind proteins and inactive digestive enzymes resultant in reduction of protein digestibility ii) Increase liver proteolysis activity and reduced body weight	[53]
Trypsin inhibitors	Promote loss of amino acids and pancreatic enzymes lead to suppression of growth performance in chickens	[51]
Fibres	i) Reduce the digestibility of nutrients and increase the sizes of gastro intestine tract ii) Increased digesta viscosity by causing gelling in gut	[54]
Saponins	Inhibit digestive enzymes lead to reduction in nutrients absorption and indigestion-related health disorders	[55]
Oxalate	i) Reduce bioavailability of minerals be it calcium ii) Impaired protein and energy digestibility	[56]
Phytate	Affects bioavailability of calcium and micronutrients (iron, copper, and zinc)	[57]
Non-starch polysaccharides	Increase viscosity of small intestinal chyme especially on growing or fattening chicken resulting in reduced nutrient utilisation, depress weight gain, and promote wet and sticky droppings	[58]

reduce essential and non-essential amino acids digestibility in broiler diets. Further, Nguyen et al. [52] found that non-starch polysaccharides and fibres in wheat depressed bird performance and nutrient utilization. In most studies, negative results are common when phytogenic products are incorporated at higher inclusion levels, especially in the form of unextracted plant powders. Some phytogenic products contain substances that impede the digestive system of birds, often due to a lack of endogenous enzymes needed to break them down. It is, therefore, important to determine an optimum inclusion level for each local phytogenic product to avoid compromising poultry health, performance, and product quality. Determination of optimal levels is important because low doses result in limited positive impacts while higher doses may introduce debilitating levels of antinutrients including fibre. This is especially important given that most producers tend to use whole plants rather than extracts to reduce cost. Thus, it is important for poultry producers or feed manufacturers to quantify the level of antinutrients in each phytogenic product and explore strategies to negate their antinutritional activities.

Strategies to improve the utilisation of phytogenic products

Incorporating phytogenic products as sources of nutraceuticals into poultry diets could be an ingenious strategy to build long-term sustainable poultry systems that can deliver global food and nutrition security. However, their utility can be limited by the presence of plant secondary metabolites as outlined in Table 4. Thus, this section explores various strategies that can be used to ameliorate the antinutritional activities of plant metabolites and enhance the utilization of phytogenic products in poultry diets.

Exogenous fibrolytic enzymes

Some phytogenic waste by-products like apple, grape and tomato pomaces have high levels of fibre or non-starch polysaccharides that require pre-processing with exogenous fibrolytic enzymes prior to incorporation into poultry diets. These enzymes can be used to decrease the fibre content of phytogenic products and reduce intestinal viscosity leading to improved nutrient digestibility [30] and bioavailability of beneficial bioactive compounds. Other exogenous enzymes such as proteases, lipases and phytases are commonly used to improve protein, lipid, and phosphorus digestibility in poultry, respectively. Since multi-enzyme mixtures target several substrates, Bedford et al. [59] stated that employing enzymes in animal feeds improves nutrient utilization more effectively than using a single enzyme. Indeed, the addition of multi-enzymes (Optizyme® p-5) to green tea-containing diets in broilers stocked at 18 birds/m^2 improved growth and feed conversion ratio by 2.5 and 1.7% [60]. Matshogo et al. [61] also reported higher carcass weights after feeding broiler chickens with diets containing green seaweed pre-treated with fibrolytic enzymes (Viscozyme® L). However, Mulaudzi et al. [62] found that pre-treating *Moringa oleifera* leaf meal with 1% fibrolytic enzymes (Viscozyme® L) had no improvement in feed utilization and weight gain of Jumbo quail.

De-tannification

Phytogenics also contain low molecular weight phenolic compounds such as condensed tannins, which could be mitigated using a variety of pre-processing techniques. The techniques involve the use of enzymes, thermal processing, soaking, drying, wood ash, cutting and storing, urea, solid-state fermentation, acetic acid, sodium hydroxide, and tannin-binding agents such as polyethylene glycol (PEG),

polyvinylpyrrolidone, and polyvinyl polypyrrolidone [20, 63]. For instance, tannase enzyme has been used to increase the bioavailability of total polyphenols to broiler chicks fed with grape pomace-containing diets [64]. Pre-treatment of grape pomace with PEG also ensured that dietary inclusion of the pomace did not compromise the health status of broiler chickens by inactivating the antinutritional activities of condensed tannins [20]. Similarly, Saeidi et al. [65] concluded that pre-treatment of 150 g/kg oak acorn with PEG could be included in broiler diets without adverse effects on performance or the tibia traits. Overall, literature shows that the use of PEG reduce the negative effects of dietary tannins [63] resulting in improved protein digestibility.

Heat treatment has also been demonstrated to reduce the bioactivity of tannins. For example, heat treatment of fluted pumpkin (*Telfaria occidentalis*) leaves' extract demonstrated the effectiveness of heat against tannins and other antinutritional compounds by increasing broiler performance [66]. Wood ash is another low cost, widely available source of alkali that is recommended for inactivating tannins. Soaking is yet another strategy that can reduce the concentration of antinutritional compounds such as tannins in phytogenic products. Singh et al. [67] showed a reduction in phytic acid, tannins, and trypsin inhibitors by 59.9, 10.8, and 14.0%, respectively, after soaking chickpea seeds in water for 12 h. Heat treatment, wood ash and soaking in water are cost-effective approaches that can easily be applied by farmers who wish to include tannin-rich phytogenic products in poultry diets, but more research is needed to test the efficacy of these strategies.

Solid-state fermentation

Solid-state fermentation (SSF) is a biological method that allows microorganisms to grow on solid substrates with little or no free water. Interestingly, there is growing research in using solid-state fermented feeds in broiler diets to improve performance and gut health [68]. This is because this technique promotes nutrient bioavailability and inhibits gut pathogenic bacteria [69]. Furthermore, Alshelmani et al. [68] found that SSF increases nutrient composition and ileal amino acids digestibility of palm kernel cake in broilers. Overall, the adoption of various nutritional solutions to improve the utility of feed ingredients have garnered worldwide recognition. Thus, it would be critically important to employ some of the strategies, including those not presented in this section, to improve the feeding value of phytogenic products in poultry diets.

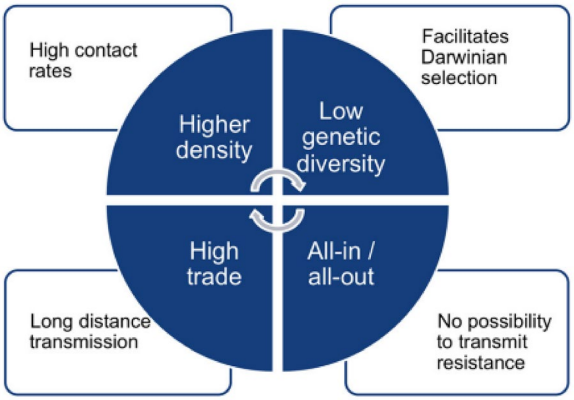

Fig. 1 Characteristics of intensive poultry systems and their consequence on the spread and evolution of emerging infectious diseases. Source: Gilbert et al. [70]

Phytogenics and poultry health

Role of poultry intensification on transmission and evolution of diseases

Poultry intensification is very common in commercial high-input production systems. It is globally considered as one of the most profitable farming systems. However, the level of intensification may impinge on poultry health due to the transmission and emergence of diseases through various mechanisms (Fig. 1). This is because intensification uses high stocking densities, which predispose poultry to stress and contribute to higher contact rates among birds leading to widespread disease outbreaks. For instance, the avian influenza in China has been associated with high intensification in poultry [70]. Given that phytogenic products contain antioxidant bioactive compounds (flavonoids, anthocyanidins, flavanols, etc.) that can boost the immune system and reduce stress by modulating immune-related signal transduction pathways, their use in poultry diets coupled with good management practices may offer a solution to heat, oxidative and nitrosative stresses, while reducing mortality rates. Thus, the use phytogenic products rich in antioxidants in intensive farming systems could alleviate intensification stressors by eliminating free radicals, and improve poultry performance and product quality.

Phytogenics and the control of poultry disease

Diseases cause slow growth and high morbidity and mortality rates, which eventually lead to economic losses in poultry. To control disease outbreaks, poultry farmers rely on conventional antibiotics to prevent and treat diseases, while enhancing feed efficiency and growth [71]. The use of AGPs such as coccidiostat, salinomycin, and zinc bacitracin is common in intensive

poultry production systems. However, these AGPs exert selection pressure on gut microbes, which lead to the development of antimicrobial resistance by pathogenic bacteria. In addition, AGPs alter gut microbiota, resulting in necrotic enteritis and diarrhoea in poultry [72]. Thus, the use of AGPs has led to public concerns due to possible transmission of multidrug resistant pathogens and antibiotic residues in meat products, that could potentially harm human health and increase pressure on health care systems [71]. Consequently, many jurisdictions have outlawed the use of antibiotics in food producing animals [72]. This has necessitated the use of natural and safe alternatives including phytogenic products in poultry to benefit from their bioactive compounds with antimicrobial, antitoxigenic, antioxidative, anti-inflammatory and immunomodulatory properties [73]. Given these attributes, phytogenic products have been considered as potential alternatives to conventional antibiotics [73]. These phytogenics may have direct and indirect benefits on the chickens' health (Fig. 2).

Unlike AGPs, phytogenic products do not destroy gut microbiota, but supress the growth and adhesion of multi-drug resistant pathogens such as *Clostridium jejuni*, *Escherichia coli* and others in the GIT [71]. This reduces microbial competition and thus increase the population of beneficial microbes in the GIT. Mohebodini et al. [74] have indicated that inclusion of phytogenic products in broiler diet increases *Lactobacillus* and *Bifidobacterium* species and reduces proliferation of coliforms, *Achyranthes bidentate*, and *Salmonella* species. Synergetic effects of phytogenic products and beneficial bacteria such as *Clostridium perfringens* may reduce *necrotic enteritis* in poultry [75]. This signifies that the inclusion of phytogenics in poultry diets may reduce the incidence of gut infections.

Phytogenics and the one health concept

One Health is a concept that accepts that the health of animals, whether domestic or wild, plants, environment, and humans is closely inter-twinned, and those linkages should be simultaneously considered when addressing public health challenges. This is even more relevant when addressing the challenge of antimicrobial resistant pathogens, which have emerged as a serious threat to human health [71]. According to O'Neill [76], antimicrobial resistance (AMR) accounts for 700 000 annual deaths worldwide and this figure is projected to increase to 10 million deaths per annum by 2050. The misuse and overuse of antibiotics in food producing animals is a major contributing factor to the emergence of AMR [77]. Interestingly, these antimicrobial resistant pathogens form part of the gut microbiota. Thus, this has necessitated a need for intervention strategies, which are in line with One Health approach to curb the development of antimicrobial resistance in animals, especially poultry. Phytogenic products can be used to mitigate the development and the spread of antimicrobial resistance in poultry farming as part of the green technology. The inclusion of phytogenic products in poultry diets can reduce pathogenic microbes before, during, and after slaughter. In addition, application of phytogenics can improve carcass hygiene, product quality and extend meat shelf life. There is currently no scientific evidence that implicates phytogenic products in inducing the development of antimicrobial resistance, which indicates that food derived from poultry reared on these products may have no antimicrobial resistant determinants and antibiotic residues. This approach will reduce foodborne diseases related to AMR in humans and health care costs associated with the treatment of infections caused by multi-drug resistant pathogens. Given that most farmers use poultry litter to improve soil fertility for crop production, the application

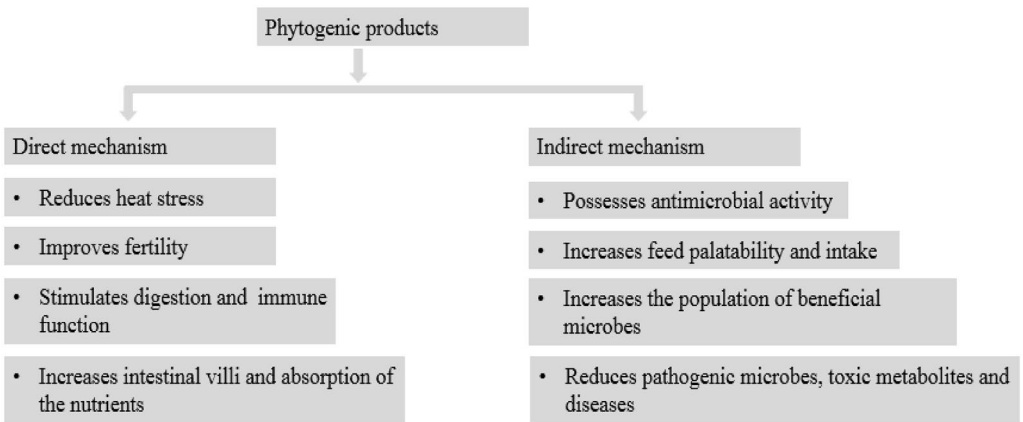

Fig. 2 Direct and indirect effects of phytogenic products on poultry health

of a litter from birds raised on diets containing phytogenics can potentially protect the environment by reducing the load of antibiotic residues and multi-drug resistant pathogens. This will also comply with the One Health concept that advocates for the use of eco-friendly and natural products for food production.

Environmental benefits of phytogenics as feed ingredients

Poultry intensification results in the generation of greenhouse gases (GHGs) such as methane, nitrous oxide, carbon dioxide, hydrofluorocarbons, and sulphur hexafluoride that contribute to global warming [78]. Feed production, on-farm energy usage, post-farm processing, transportation, and manure storage and processing are the major contributors of GHGs in poultry production [79]. Further, the consumption of feed results in the production of carbon [78], which is broken down under anaerobic conditions to produce methane. Thus, the use of phytogenic products that contain polyphenols and saponins with anti-methanogenic activities could potentially reduce the production of methane and ultimately lower the amount emitted to the environment. The ability to reduce enteric gas production and increase nutrient digestibility is one of the major desirable attributes of phytogenics because an increase in nutrient utilization indicates low nutrient excretion, meaning less environmental pollution [6].

Another environmental issue that requires urgent attention is the over-reliance on AGPs in animal husbandry, which find their way into the environment through urine and faecal excreta resulting in agro-ecosystem contamination. The use of contaminated manure on agricultural soils delays plant germination, which has a negative effect on farmland productivity and profitability [80]. The authors further reported that antibiotic residues are increasingly found in terrestrial and marine environments due to poor regulations by policymakers. Thus, the use of phytogenic products as alternatives can be a sustainable strategy to completely withdraw the use of antibiotics in animal feeds, reduce environmental contamination and promote better health for the environment, humans, and animals. Moreover, the use of phytogenic products in poultry nutrition as natural alternatives to AGPs conveys a positive public image [81] and social acceptance of the industry.

Conclusions

Poultry products provide high-quality macro- and micronutrients required to prevent malnutrition and suboptimal development in humans, especially vulnerable groups such as children and pregnant women. However, nutritional, welfare, environmental, and health challenges continue to bedevil this industry. The welfare and health challenges negatively affect social acceptance of intensive poultry production as a source of food, whereas the nutritional and health challenges have adverse effects on productivity and profitability of the industry. This review presented a variety of locally available phytogenics with the potential to enhance nutrient utilization, combat pathogens, and improve immunity in poultry. The optimism around phytogenics is based on their bioactive compounds with antimicrobial, antioxidant, growth-stimulating and health-promoting functionalities that have been proven beneficial in poultry nutrition. Despite the benefits of incorporating phytogenics in poultry production systems, their adoption faces numerous challenges that need to be resolved. Some solutions to these challenges including pre-processing techniques have been proffered suggesting that phytogenics can be used to improve sustainability of the poultry industry. This would ensure that poultry meat and eggs continue to be the major animal protein sources for a rapidly growing human population, especially in developing countries.

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