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Application of polyphenolic compounds in animal nutrition and their promising effects

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ABSTRACT. Due to the negative impact of antibiotics on human and animal health, they have been banned in animal breeding and substitutes are being explored. Polyphenols – naturally occurring ”plant secondary metabolites” – are one of the best alternatives. They are found in vegetables, fruits, cereals, herbs, legumes, and spices. The main classes of polyphenols include flavonoids, non-flavonoids, and tannins. Polyphenols have been found to exert highly positive effects on both human and animal health. These compounds have been recorded to exert positive influence on growth performance, immune system, antioxidant system, and meat/carcass quality, as well as antimicrobial effects in poultry species. The objective of the ruminant farming system is to obtain high-quality meat and milk and reduce greenhouse gas emissions through improved rumen fermentation and microbial manipulation using phytogenic extracts (polyphenols). Studies have reported that the use of polyphenols in ruminant rations enhances the quality and quantity of meat and meat by-products and reduces the application of synthetic antioxidants and antibiotics, which have been of concern to consumers. Similarly, it has been found that the addition of polyphenols increases oxidative stability, overall acceptability, sensory and nutritional quality, as well as shelf life of meat and its products. However, due to the differences in the chemical composition of 25000 polyphenols identified so far, it is difficult to determine the beneficial effects and optimum dose of all compounds for inclusion in animal and human diets. This review discusses the bioavailability of polyphenols and their growth-promoting, production-enhancing, immuno-modulatory, antibacterial, and antioxidant effects on animals.

Introduction

Recently, the trend of producing healthy animals through diet modulation has been steadily increasing (Jiang and Xiong, 2016). Bearing in mind the health concerns of consumers of the last decade, there is a growing interest in supplementing plant extracts (polyphenols) in animal diets to increase the nutritional value of meat, eggs, and milk. These plant extracts are immune modulators, antioxidants, and growth and feed efficiency promoters that can be found in nature (Nieto et al., 2011). Due to concerns regarding human health and the quality and safety of poultry products, antibiotics have been banned as growth promoters in the European Union countries, hence plant extracts are being increasingly used as an unconventional alternative and safe source of growth promoters in animals

(Tufarelli et al., 2017). Whole vegetables, fruits and grains are considered beneficial to human and animal health, and their properties are associated with non-nutritive and bioactive compounds, commonly known as phytochemicals. The number of these bioactive compounds ranges from 5000 to 25000 in whole foods (Acosta-Estrada et al. 2014; Šaponjac et al., 2016). Polyphenols, in addition to fruits, vegetables and grains, are also found in black and green tea, and in various plant parts such as seeds, roots, shoots and flowers (Surai, 2014). There are many classes of polyphenols, but the major two are flavonoids and non-flavonoids. Polyphenolic compounds are secondary metabolites of plants and a huge body of research work has shown that they exert positive effects on animal performance (Hashemi and Davoodi, 2011), gut microflora development and modulation, immune system, stress mitigation and nutrigenomics (Guo and Langevin, 2002; Bag and Chattopadhyay, 2015; Hashem et al., 2020). Moreover, polyphenolic compounds show antioxidant, antimicrobial, anti-inflammatory, anti-allergic, antimutagenic, and immunomodulatory properties in various organisms (Lipiński et al., 2017). For more than 70 years, antibiotics have been used at low therapeutic levels in poultry and pig diets to improve their growth performance and health (Jin et al., 2020). Along with these beneficial effects of antibiotics, their continuous and excessive use in food-producing animals led to the development of bacterial resistance to antibiotics/antimicrobial growth promoters, as well as raised public health concerns (Mahfuz et al., 2019). Polyphenols have been well known for a long time as an alternative to antibiotics, and can be added to animal diets as effective and natural feed additives. Plants, grains and many agricultural by-products are excellent sources of polyphenols; these plant-based products or their extracts are very effective antioxidants, so they can be used in livestock diets as functional feed additives (Castrica et al., 2019). The mechanism of polyphenol action as growth promoters lies in the fact that they can increase the secretion of endogenous enzymes, bile, mucus and salivary glands, retard the growth of pathogenic microorganisms in the gastrointestinal tract and modulate gut morphology and architecture through their immunostimulatory, anti-inflammatory and antioxidant functions (Costa et al., 2013; Dhama et al., 2014). Furthermore, studies have shown that utilisation of polyphenolic compounds from aromatic plants in animals improved feed intake and growth performance due to their enhancing effect on the flavour and palatability of feeds (Christaki et al., 2020). With respect to the use of polyphenolic compounds in poultry, research has demonstrated that they can alter the surface area of the intestine and enzyme secretion, resulting in improved digestion and absorption of nutrients from the GI tract. These qualities of polyphenolic compounds in poultry resulted in improved feed intake, feed conversion ratio (FCR) and growth performance (Viveros et al., 2011). Studies have found that polyphenols act as natural antioxidants, and are considered to be involved in the protection of polyunsaturated fatty acids (PUFA), proteins, nucleic acids, and carbohydrate moieties from oxidative stress (OS) and damage due to their free radical scavenging and metal (iron and copper) chelation properties (Heleno et al., 2015; Vuolo et al., 2019). Studies have shown that carvacrol and thymol supplementation in the diet of broilers increased the level of antioxidant enzymes, i.e. superoxide dismutase (SOD), glutathione peroxidase (GSH-Px), while reducing malondialdehyde (MDA) levels in serum, liver and thigh muscle samples (Hashemipour et al., 2013). Polyphenols show promising beneficial effects in animals, and the addition of phytobiotics such as seeds, herbal plants, and essential oils (EOs) to ruminant diets improved feed conversion efficiency and production in ruminants. Supplementation of a combination of spices, herbal plants, their extracts and EOs in the diet of ruminants resulted in antioxidant, antibacterial, and antifungal effects; they also increased feed flavour, palatability and animal performance (Kholif et al., 2017). Similarly, Elghandour et al. (2015) showed that the addition of a mixture of herbs and their extracts, seeds, and EOs to ruminant diets improved production efficiency, health, rumen fermentation and beneficial ruminal microflora. These positive changes led to reduced rumen protein degradation and methane production (Hernandez et al., 2017). A similar study was conducted by Kholif et al. (2017), who reported that the use of herbs and EOs in the diet of ruminants led to growth inhibition of pathogenic microorganisms in the intestine, increased nutrient absorption through the gastrointestinal tract (GIT), and improved gut barrier function.

The objective of this review is to highlight the potential effects and applicability of polyphenols as natural feed supplements in poultry and ruminant diets. Furthermore, bioavailability, growth-promoting, production-enhancing, immunomodulatory, antibacterial, and antioxidant effects of polyphenols in animals are discussed.

Distribution of polyphenols in nature

Herbs and spices are generally considered safe and efficient against certain infections and diseases. They have been widely employed as health-promoting plants by many Asian and African nations as well as in other industrialized countries of Europe and America (Polasa and Nirmala, 2003). According to estimates, there are approximately 250000–500000 plant species (Borris, 1996), of which only 1–10% are used for human food and animal feed (Cowan, 1999). Plant-based feed additives, known as polyphenols, are natural, contaminant-free, and considered ideal growth promoters in animal diets compared to inorganic chemicals and synthetic antibiotics (Hashemi and Davoodi, 2011).

Plants use polyphenols as their defence system against diseases, pests, and ultraviolet radiation (Kumar et al., 2020). Polyphenols can be found in roots, shoots, flowers, leaves, seeds, and fruits of plants (Petti and Scully, 2009), but they are not evenly distributed in all parts, as research findings have shown that polyphenol levels are higher in the outer layers than in the inner plant tissues (Wink, 1999). Moreover, various factors such as fruit ripening, temperature, soil type and composition, drought, sun exposure, rainfall, processing, and storage conditions affect the concentration, composition, and proportion of polyphenolic compounds in plants (Manach et al., 2004). Table 1 presents the different classes of polyphenols, their natural sources, and different forms.

Formation of polyphenolic compounds

The phenylpropanoid metabolism of pentose phosphate and skimmic acid in plants results in the secondary metabolites known as polyphenolic compounds. Simple phenolic molecules called polyphenols can also be highly polymerized substances containing benzene rings and one or more hydroxyl groups (Velderrain-Rodrguez et al., 2014). In the presence of the enzyme glucose-6-phosphate dehydrogenase, glucose enters the pentose phosphate pathway (PPP), which produces phenolic compounds. This enzyme generates nicotinamide adenine dinucleotide phosphate (NADPH) utilised in cellular anabolic processes as well as the reversible conversion of glucose to glucose-6-phosphate followed by the irreversible conversion to ribulose-5-phosphate. PPP simultaneously converts glycolysis into erythrose-4-phosphate and phosphoenolpyruvate, which are subsequently used in the phenylpropanoid pathway to synthesise phenolic compounds. PPP exits into the skimmic acid pathway, where it produces phenylalanine, which is transformed into phenolic compounds (Vattem et al., 2005). The synthesis pathway of polyphenolic compounds is shown in Figure 1.

Table 1. Classes, active compounds, and natural sources of polyphenolic compounds (modified from Serra et al., 2021)

Polyphenolic group	Classes	Active compounds	Natural source
	Flavonols	Kaempferol, quercetin	Grape and berry skin, broccoli, onion, lettuce, apple, green tea and wine
	Flavones	Luteolin, apigenin	Red pepper, celery, lemon, onion, rosemary, parsley and oregano
	Flavanols	Proanthocyanidins, epicatechin, epigallocatechin and catechin	Tea, red wine, grapes, apples, apricot, dark chocolate
	Flavanones	Hesperetin, naringenins	Oranges, tangerines, peppermint, lemon, grapefruit
	Anthocyanin	Delphinidin, cyanidin, perlargonidin	Cherries, blackberries, strawberries, raspberries, sweet, potatoes, coffee beans, red cabbage, tomatoes and grapes
	Isoflavones	Equol, genistein, daidzein	Peas, lentils, kidney beans, soybeans
Flavonoids			
	Phenolic acids	Ferulic acid, caffeic acid, chlorogenic acid	Olive, cabbage, apples, tomatoes, pears, coffee beans, ginger and cherries
	Lignans	Stegananic, matairesinol, pinoresinol, podophyllotoxin	Sesame seeds, spices, vegetables, nuts and linseed
	Stilbenes	Pterostilbenes Resveratrol	Red wine, grapes, chocolate, almond, blueberries, raspberries, peanut
Non-flavonoids			
Tannins	Hydrolysable and condensed tannins	Turkish tannin, acer tannin, ellagitannin, tannic acid, chebulagic acid, Chinese tannin	Sorghum, green coffee, bean seed coats, mango kernels, pomegranates, strawberries, almonds, walnuts

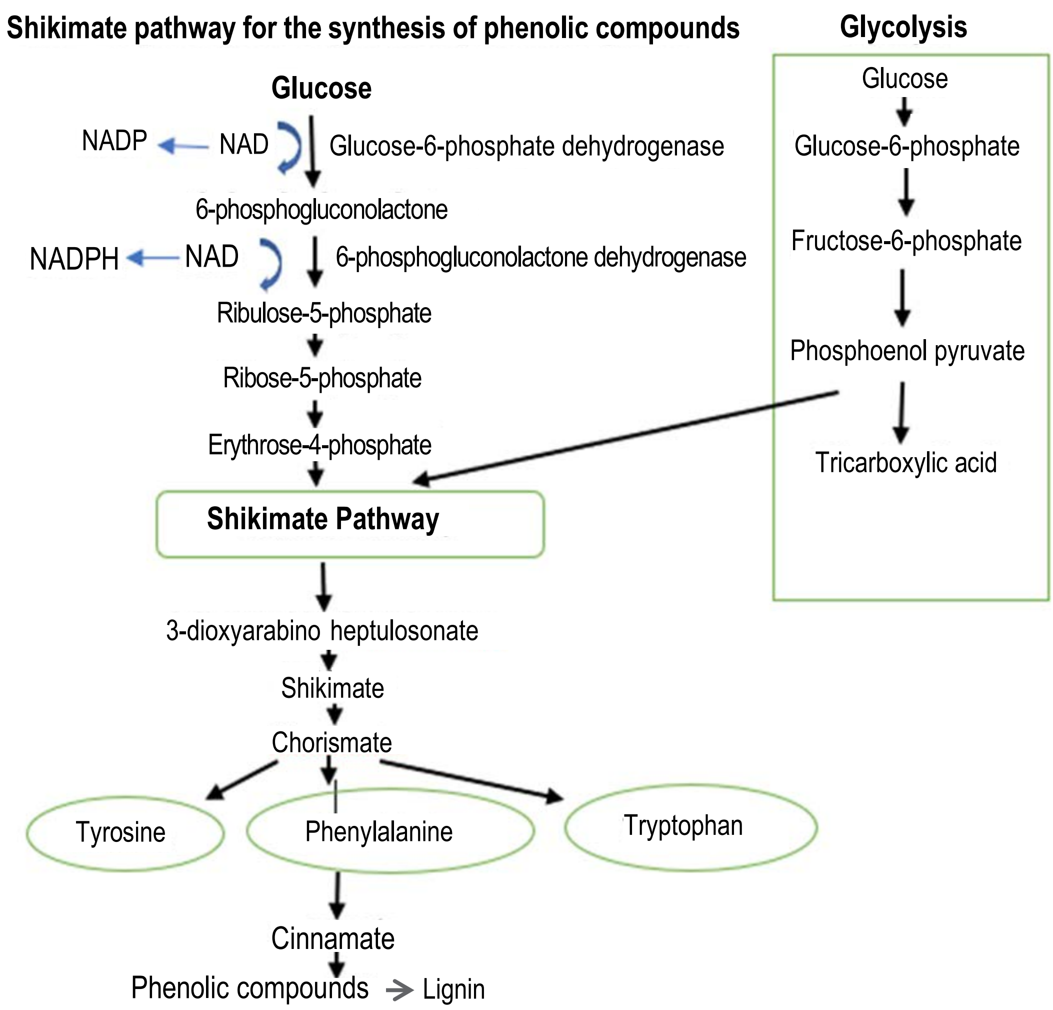

Figure 1. Formation of polyphenols from carbohydrates (glucose) (modified from Lin et al., 2016)
NAD – nicotinamide adenine dinucleotide, NADP/NADPH – nicotinamide adenine dinucleotide phosphate.

Classification of polyphenolic compounds

Plant-derived molecules are divided into numerous classes, but three main types of polyphenols can be distinguished: flavonoids, non-flavonoids, and tannins (Lipiński et al., 2017). Flavonoids, with 4000 molecules, are the most abundant polyphenol group; they have two benzene rings connected by three carbon atoms that form an oxygenated heterocycle (Fraga et al., 2010). Flavonoids are classified into six groups: flavonols, flavones, flavanols, flavanones, anthocyanins, and isoflavones (Gessner et al., 2017). Non-flavonoids are classified into three subclasses: a) phenolic acids, which have two classes: i) cinnamic acids, such as ferulic, coumaric, sinapic acid, and caffeic acid; and ii) less abundant hydroxyl benzoic acids, such as vanillic acid and gallic acid, b) lignans (pinoresinol, syringaresinoland, and secoisolariciresinol), and c) stilbenes (resveratrol) (Serra et al., 2021). Tannins, commonly known as tannic acid, are found in various plant foods and are water-soluble. Tannins are available in condensed and hydrolysable forms. (Piluzza et al., 2014). Figure 2 demonstrates the structure of various phenolic compounds.

Bioavailability of polyphenolic compounds

Successful absorption of a portion of bioactive compounds into the circulatory system for metabolic utilisation and subsequent beneficial outcomes are generally referred to as compound bioavailability (Velderrain-Rodrguez et al., 2014). The availability of polyphenols is determined by the type of compound, its physical and chemical properties, and the presence of functional groups in the structure. Phytogenic polyphenols, like other micro- and

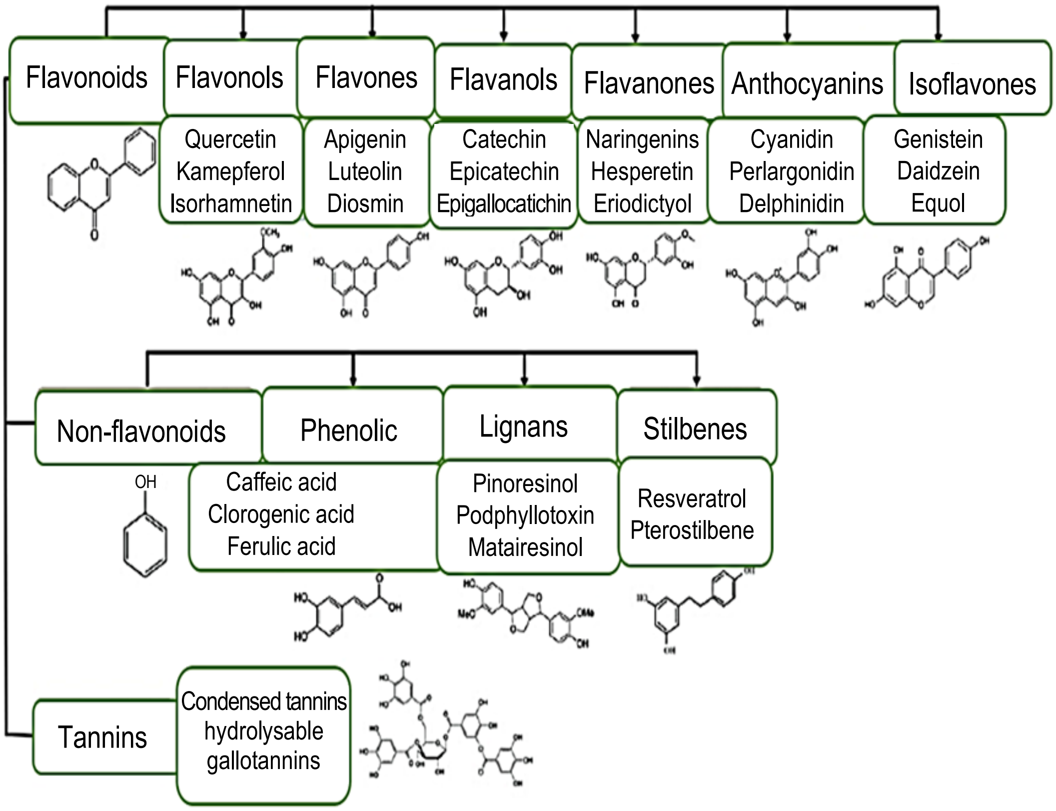

Figure 2. Chemical structure of classes of polyphenolic compounds (modified from Serra et al. 2021)

macronutrients, are not required for life, but can affect specific cells and tissues when come into contact with these structures and trigger a specific response (D'Archivio et al., 2007). According to published studies, only 5–10% of polyphenols are absorbed in the small intestine, while the rest (90–95%) pass into the large intestine and conjugates with bile (Chiva-Blanch and Visioli, 2012); they also undergo enzymatic and microbial breakdown, which converts polyphenols into smaller molecules and facilitate their absorption. Through enzymatic, microbial and biotransformation processes (oxidation, reduction, and hydrolysis), complex polyphenolic structures are converted into simple, water-soluble, and low molecular weight units in enterocytes before entering the liver (Cardona et al., 2013). After the absorption of water-soluble metabolites through the portal system to the liver, they are again subjected to conjugation and biotransformation processes, which improve their absorption by increasing hydrophobicity, and facilitate their elimination. Ultimately, the end products in the form of metabolites enter the systemic circulation and are directed towards the target tissues and organs to perform their specific functions, or are excreted in the urine (Lavefve et al., 2020). Figure 3 illustrates the biological activities of polyphenols, while Figure 4 shows the mechanism of bioavailability.

Health-promoting effects of polyphenols in humans

Polyphenols are naturally occurring compounds and secondary plant metabolites found mainly in fruits, cereals, vegetables and beverages (Scalbert et al., 2005). They are involved in the host defence mechanism against ultraviolet radiation and pathogens (Beckman, 2000). Scientists have explored the protective roles of polyphenolic compounds in neutralising reactive oxygen and nitrogen species (ROS and RNS); these harmful molecules are produced by the body during metabolic processes as by-products and are harmful to human and animal health (Choi et al., 2007). Epidemiological studies have demonstrated that polyphenolic compounds provide marked protection against the development and progression of chronic diseases, such as diabetes, cardiovascular conditions, aging, asthma, cancer and other infectious diseases; these compounds can also act as hypolipidemic agents and exhibit health benefits to humans and animals (Pandey and Rizvi, 2009; Petti and Scully, 2009). Polyphenols reduce the negative impact of oxidative stress on protein, lipid, and DNA caused by oxygen radicals, thereby preventing carcinogenesis (Paszkiewicz et al., 2012). In addition, polyphenolic compounds inhibit cancerous cell proliferation, i.e. anthocyanins

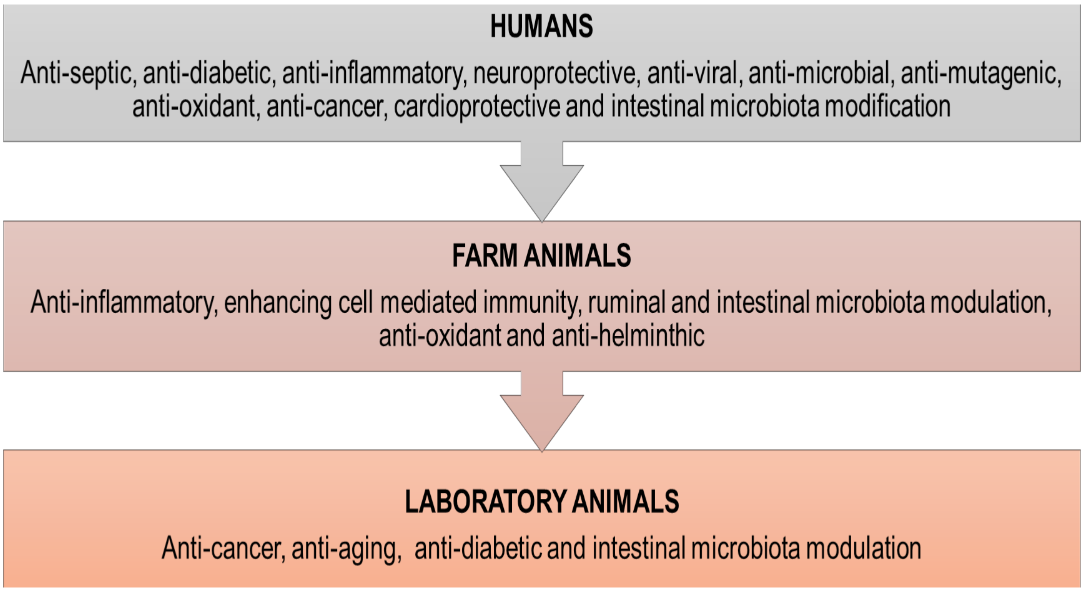

Figure 3. Biological activities of phenolic compounds in humans, farm animals and laboratory animals (modified from Serra et al., 2021)

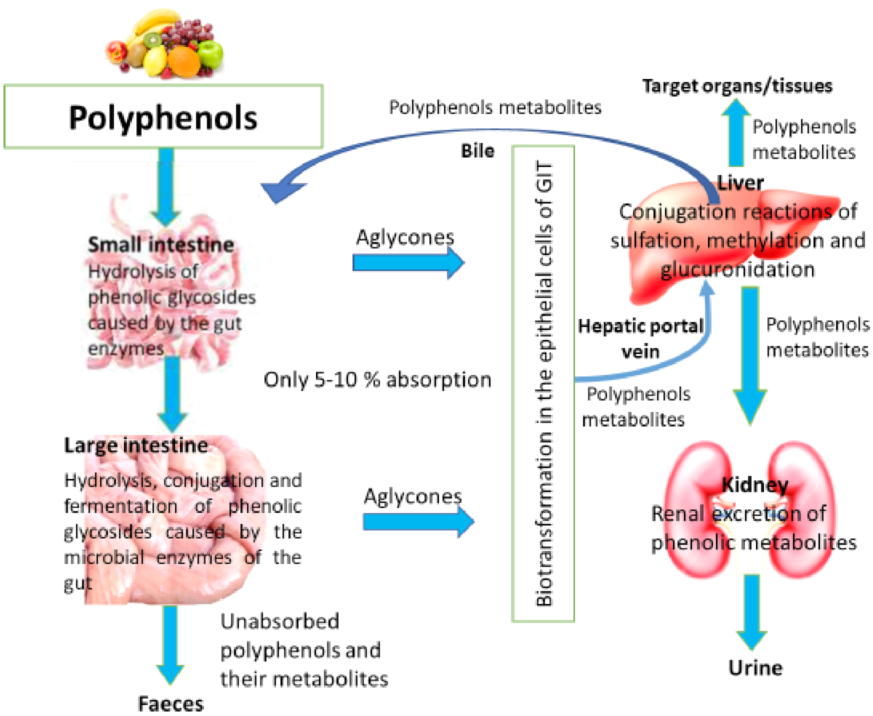

Figure 4. Bioavailability of polyphenols in the body (modified from Bohn, 2014)

supress signal transduction of kinase enzymes, which are involved in cancer cell proliferation, thus polyphenols prevent the cells from entering specific stages of their cycle (G1/S or G2/M) (Lipiński et al., 2017). The anticarcinogenic effects of polyphenolic substances can also be attributed to their role in the apoptosis of malignant cells. One of research studies demonstrated that daidzein and quercetin inhibited

the development of leukaemia, prostate, breast, gastric, and colorectal carcinoma cell lines (Lima et al., 2014; Lipiński et al., 2017). Antioxidant activity of polyphenolics protect against cardiovascular diseases and prevent vascular damage. A previous study has found that resveratrol and catechins have vasodilating effects and help prevent arrhythmias, whereas anthocyanins are able to scavenge ROS and RNS, and protect against plaque build-up in blood vessels; flavonoids in turn are known to reduce oxidation of plasma membrane lipids and low-density lipoprotein peroxidation, thus all these compounds contribute to improved cardiovascular health (Han et al., 2007; Chiva-Blanch and Visioli, 2012). Genistein and daidzein are flavonoids with phytogenic properties that act through their oestradiol entity and bind to oestrogen receptors α in the mammary glands and ovaries, and oestradiol receptors β in the brain, kidneys and lungs (D'Archivio et al., 2007); this property of flavonoids helps in the prevention of osteoporosis and alleviation of menopause symptoms in older women (Kamboh et al., 2015).

Supplementation of polyphenolic compounds in animal diets

Studies have shown promising effects of plant-based polyphenol on food-producing animals. Supplementation of dietary polyphenols improved animals' productivity and performance factors like: feed intake, body weight and FCR, and product quality (Wallace et al., 2010). However, due to the large variety of compounds and their composition, it is difficult to define the optimum dosage level of polyphenols in animal diets. Considering the economics of animal production, low-cost sources of polyphenols include agro-industrial by-products of processing cereal grains, nuts, and seeds (rice husks, wheat bran, etc.), pomace from the brewing, wine and juice industries, as well as peels, stems, and cobs (Serra et al., 2021). Goñí et al. (2007) reported that grape by-product supplementation in the diet of animals delayed oxidation and improved meat quality compared to the untreated group. With respect to farm animal nutrition and better performance, a particular emphasis is placed on other natural sources of polyphenols such as sage, green tea, strawberry, raspberry, oregano, cinnamon, clove, and thyme. These natural herbs exhibit potent antioxidant, antimicrobial, immunomodulatory and anti-inflammatory properties (Chrpová et al., 2010).

Effects of polyphenolic compounds in poultry

Polyphenols as growth promoters

The inclusion of phenolic compounds in animal feeds has been identified as a potential source for improving growth and production performance, and decreasing mortality rate. In addition, most polyphenols originates from aromatic plants that contribute to improved flavour and palatability of feed, resulting in increased feed intake and growth performance of animals (Christaki et al., 2012). Phenolic compounds are potent stimulators of the secretion of saliva, endogenous digestive enzymes, bile, and mucus from the GI tract (Mahfuz et al., 2021). Moreover, these compounds help modulate GIT morphology and reduce the number of pathogenic bacteria due to their anti-inflammatory, antioxidant and antibacterial properties (Lavefve et al., 2020). Phenolics also facilitate fermentation processes in the gut and increase nutrient absorption. These properties improve feed palatability and animal growth performance (Valenzuela-Grijalva et al., 2017). The application of natural phenolic compounds containing substances (clove, paprika, cumin, coriander, thyme and pepper) in the diet of broilers was tested in 1989 and improved body weight and feed conversion were observed (Vogt et al., 1989). Mountzouris et al. (2011) showed in their study that the addition of phenolics to the diet of poultry improved feed conversion ratio and growth performance by stimulating the secretion of digestive enzymes, improving enzymatic activity and modifying the intestinal surface; these alterations caused by phenolic compounds led to a better nutrient absorption and improved bird performance. According to the literature, phenolic compounds contribute to maintaining a proper balance of pathogenic and beneficial bacteria in the gut, and thus gut system homeostasis, resulting in improved growth performance of birds (Wallace et al., 2010). Supplementation of thyme and oregano essential oils to broiler diet at 15 and 20 g/kg resulted in higher average daily gain (ADG) and FCR compared to the control group (Abdel-Wareth and Lohakare, 2021). The addition of curcumin to the diet of broilers from day one at doses of 100, 150, and 200 mg/kg diet showed that the 200 mg/kg dose increased feed efficiency and body weight (BW), while feed intake was unaffected at later stages. At the same time, polyphenols at 150 and 200 mg/kg doses reduced abdominal fat and stimulated apparent metabolisable energy utilisation (Rajput et al., 2013). A study on linoleic acid and gallic acid supplementation (1% and 0.5%) in broilers (aged 22–36 days) found improved feed efficiency (1.95 vs 2.06) and weight gain (80.8 vs 79.6 g/bird/day) compared to the 0.5% level for 1% supplementation compared to 0.5%, respectively (Jung et al., 2010). A study on Ross 308 broilers used naringin and hesperidin supplementation at 0.75 and 1.5 g/kg diet, and showed no significant effect on bird performance (Goliomytis et al., 2015).

In another work, Kamboh and Zhu (2013) used hesperidin at 20 mg/kg broiler diet, and recorded a significant increase in final body weight compared to the control group.

Effect of polyphenols on lipid metabolism

Polyphenol supplementation in broiler diets helps to visualise nutrient metabolism and physiological state of the body by modulating serum biochemical indices (Aghili et al., 2019). Several *in vivo* studies have demonstrated anticholesteremic effects of phenolic compounds. These compounds prevent cholesterol oxidation, resulting in less cholesterol deposition in blood vessels (Yang et al., 2020). Polyphenolics have an effective mechanism for lowering plasma cholesterol levels (Islam et al., 2015), and are thought to inhibit the activity of enzymes regulating lipid metabolism. Cholesterol-7 hydroxylase, fatty acid synthase, 3-hydroxy-3-methylglutaryl-CoA, and pentose phosphate pathway enzymes are all involved in lipid metabolism (Chowdhury et al., 2018). A study was conducted in rats to analyse the effect of tannic acid and rutin on plasma cholesterol levels and lipid metabolism; the results showed a significant decrease in cholesterol levels in the liver and blood plasma (Park et al., 2002). Valenzuela-Grijalva et al. (2017) reported that polyphenol supplementation in poultry diet facilitated faecal excretion of sterols/cholesterol, and reduced cholesterol absorption from the gut, resulting in lower hepatic and plasma cholesterol levels. The addition of tannic acid, gallic acid, and thymol to the diet of broilers resulted in a 12% reduction in total cholesterol levels in the liver and a higher concentration of polyunsaturated fatty acids in breast muscles (Starčević et al., 2015). Supplementation of laying hens' diet with EOs such as nettle *Urtica cannabina*, peppermint oil, hot red pepper or black cumin reduced serum cholesterol levels (Abou-Elkhair et al., 2018; Zhang et al., 2020; Abdel-Wareth and Lohakare, 2020). Various studies in broilers evaluated serum lipid parameters using different sources of phenolic compounds, and lavender essential oil (EO) supplementation was shown to lower LDL-C and cholesterol levels (Barbarestani et al., 2020); oregano, citrus, and anise mixtures were also reported to reduce the concentration of cholesterol (Paraskeuas et al., 2016), while supplementation with *Pulicaria* sp. powder reduced triglyceride and cholesterol levels.

Role of polyphenolic compounds as antioxidant agents

Polyphenols, as antioxidants, protect lipids, DNA, proteins, and sugars from oxidative damage caused by free radical or ROS-mediated reactions (Balasundram et al., 2006). Due to their reducing properties, phenolic compounds act as free radical scavengers. By chelating iron and copper, these compounds inhibit the formation of metal-catalysed free radicals (Vuolo et al., 2019). Phenolic compounds can protect biological molecules from oxidation by donating electrons or hydrogen and delocalising unpaired electrons within the phenolic ring (Giannenas et al., 2020). Research has shown that free radicals and ROS damage the intestinal mucosa and impede nutrient absorption through the GIT, resulting in poor feed efficiency and bird performance (Valenzuela-Grijalva et al., 2017). Carvacrol and thymol supplementation in broiler diets was shown to increase glutathione peroxidase and superoxide dismutase levels and decrease malondialdehyde levels in thigh muscles, serum, and liver samples (Hashemipour et al., 2013). In another study, Wenchang chickens were fed different amounts of turmeric rhizome extract (TRE) (0, 0.1, 0.2, and 0.3 g/kg diet) for 12 weeks. These authors found that TRE supplementation at 0.3 g/kg diet reduced drip loss from thigh and breast muscles and increased breast muscle weight, while dietary TRE levels of 0.1–0.3 g/kg stimulated superoxide dismutase and glutathione peroxidase activities, and reduced malondialdehyde concentrations and abdominal fat ratio (Dong et al., 2015). Inclusion of resveratrol at 0.2 and 0.4 g/kg diet in 5-week-old Japanese quails for a period of 12 weeks demonstrated that the latter improved the antioxidant status in both bird meat and eggs (Sahin et al., 2010). The addition of polyphenolenriched grape seeds to the diet of broilers at 40 g/kg significantly increased the antioxidant capacity (AOC) of antioxidant enzymes (glutathione-S-transferase, glutathione peroxidase, catalase, superoxide dismutase, and glutathione), lowered blood lipids, improved bird performance, and reduced the number of detrimental bacteria in the intestine (Abu Hafsa and Ibrahim, 2017).

Polyphenols and immune functions

Polyphenols have been reported as good anti-inflammatory sources due to their suppressive activity against the production of nitric oxide and prostaglandins, critical players in inflammatory processes (Valenzuela-Grijalva et al., 2017). Phenolic compounds act as immunomodulators of antibody production and cytokine secretion, they stimulate the mechanism of phagocytosis and interferon gamma release (Giannenas et al., 2020). Phenolics increase phagocytosis activity by activating mononuclear cells and stimulating NF-κB and MAPK signalling pathways (Artuso-Ponte et al., 2020). Supplementation of phenolic compounds in the diet of broilers was shown to promote the immune status and growth of birds by modulating duodenal function and intestinal nutrient absorption (Adaszyńska-Skwirzyńska and Szczerbińska, 2017). In another study, broilers challenged with lipopolysaccharide were supplemented with genistein (5 mg/kg) and hesperidin (20 mg/kg) flavonoids, resulting in the stimulation of immune system and improved gut morphology (Kamboh and Zhu, 2014). A polyphenol-rich diet fed to lipopolysaccharide-challenged broilers resulted in a significant decrease in the expression of various types of interleukins (IL-3, IL-4, and IL-8) and interferon-γ. The inclusion of 3 g/kg of thyme essential oil in broiler diets increased serum IgA and IgG antibody titres against Newcastle disease vaccine virus, which eliminated the antagonistic effect of aflatoxins B1 and ochratoxins in mycotoxin-exposed birds (Nazarizadeh and Pourreza, 2019). Quercetin supplementation at concentrations of 0.2%, 0.4%, and 0.6% in the diet of day-old broiler chicks for up to 6 weeks activated the NF-κB signalling pathway, but had no effect on bird growth performance (Yang et al., 2020). Broilers supplemented with genistein and hesperidin at 5 mg/kg diet showed a significant improvement in the antioxidant activity in the form of increased blood SOD concentrations and lower plasma MDA levels compared to the control group (Kamboh and Zhu, 2013). Skrzycki et al. (2009) reported that inflammatory processes could be minimized by flavonoids, as these polyphenols inhibit the signalling of enzymes involved in inflammation, such as 5-lipoxygenase and cyclooxygenase; these enzymes play a role in the synthesis of prostaglandins and leukotrienes from arachidonic acid. Similarly, the immune effect of propyl thiosulfinate (PTS) and propyl thiosulfinate oxide (PTSO), i.e. garlic metabolites, has been evaluated in poultry by Kim et al. (2013). PTS/PTSO supplementation at 10 mg/kg diet in *Eimeria acervulina*-challenged broilers resulted in increased BWG and serum antibody titre against profilin, an immunogenic protein of *Eimeria* protozoa, and reduced excretion of oocysts compared to the control group (Kim et al., 2013). Supplementation of PTS/PTSO in the diet of broilers altered the expression of genes related to innate immunity such as toll like-receptor-3 and 5 (TLR 3 and 5) and NF-κB and down-regulated IL-10 expression compared to the control group (Kim et al., 2013). Poultry diseases such as *Clostridium*-based necrotic enteritis (NE) result in huge economic losses in the poultry industry by causing morbidity and mortality on a massive global scale (Oh and Lillehoj, 2016). The use of phytonutrients in poultry is recommended for the prevention of NE. Research has shown that supplementation with a mixture of XTRACT® (*Curcuma longa oleoresins*) and capsicum increased BW and decreased gut lesion scores of NE-infected birds compared to the non-infected group (Lee et al., 2013). When compared to the control group, birds fed XTRACT® had lower toxin levels in the serum and reduced mRNA expression of IL-8, IL-17A, IL-17F, and lipopolysaccharide-induced TNF in the intestine, but increased cytokine levels in splenocytes. The latter study also found that capsicum and turmeric supplementation could contribute to protective immunity against avian NE due to their stimulating effect on molecular and cellular immunity changes in birds (Lee et al., 2013). Future research is needed to determine the molecular and cellular mode of action of this phytochemical combination in terms of NE control.

Polyphenols and antimicrobial agents

Phenolic compounds have the potential to disintegrate Gram-negative and Gram-positive bacteria due to their lipophilic nature. They can cross the lipid bilayer of plasma and mitochondrial membranes of bacteria, resulting in disruption of normal functions of the microorganism (Giannenas et al., 2020). Phenolic compounds increase the permeability of bacterial cell membranes and disturb cell homeostasis, resulting in cell death due to ion loss and cell denaturation. These compounds also reduce ATP production (necessary for cell functions) and inhibit the activity of DNA gyrase involved in DNA and RNA synthesis (Yang et al., 2015). Moreover, phenolic compounds have an $\bar{O}H$ group in their structure, exhibiting antibacterial/bactericidal properties (Park et al., 2002). Supplementation of broiler diets with carvacrol and thymol (herbal plant extract) polyphenols inhibited *Escherichia coli* and *Clostridium perfringens* colonization of bird intestine due to their antibacterial properties (Steiner and Syed, 2015). The addition of phytogenic feed additives (PFA) to the diet of broilers decreased the pathogenic effects of *Eimeria* infection (coccidial protozoan) (Christaki et al., 2004). Oregano essential oil, obtained from various plant species, proved effective in eradicating the famous gut parasite called *Cryptosporidium*. Similarly, due to its antimicrobial activity, dandelion herb is effective in suppressing *Staphylococcus aureus* and *E. coli* proliferation in the gut of poultry (Qureshi et al., 2017). Genistein, flavonoids, and hesperidin (obtained from *Ginkgo biloba*) were used in the diet of LPS-exposed broilers. These compounds enhanced nutrient absorption by increasing the surface area and improving the structure of the intestine, including the length, width, and depth of the villi (Kamboh and Zhu, 2014). Supplementation of total phenolic compounds at 13.3 mg/kg broiler diet resulted in a significant increase in the height of the intestinal villi (duodenal area), while had no impact on the composition of the ileal microflora (Hong et al., 2012). Some of the studies conducted in poultry using phytogenic additives and extracts are shown in Table 2 and 3.

Table 2. Effects of various polyphenols on broiler performance

Effects in broilers		
Polyphenolic compounds/sources	Effects	References
Chickens supplemented with guava extract at 800 or 1000 mg/kg containing 0.45% phenolic compounds	• Increase in villus height and villus:crypt ratio • No effect on digestibility coefficients of feed nutrients and ME • Positive influence on BW, BWG and FCR of broilers in the period from 1 to 7 days of age • No effect on BW, BWG and FCR of broilers in the period from 1 to 7 days of age	Noleto-Mendonça et al., 2021
Grape pomace (*Vitis vinifera*) in the powder form Dose: 0, 20, 40, 60 g/kg diet duration: 0–24 days	• No effect on FI and ADG and FCR • ↓ Abdominal fat • ↑ Drumstick and thigh weight • ↑ Antibody response • ↑ GSH-Px and SOD in plasma • ↓ LDL, AST, MDA, TC and TG	Hosseini-Vashan et al., 2020)
Hydrolysable tannin from chestnut wood at 1000 mg/kg diet	• ↑ Final body weight, ADG, and improved FCR • ↑ CP retention • ↑ GSH-Px, T-AOC, SOD • ↓ LDL, TC and urea N	Liu et al., 2020
EO from the lavender flower at 0.4 ml/l	• ↑ ADG, final body weight and improved FCR • ↑ Probiotic bacteria and ↓ *Escherichia coli* count in the ileum • No effect on TG, TC, glucose and uric acid level in serum	Adaszyńska-Skwirzyńska and Szczerbińska, 2019
Resveratrol (commercial) at 300 mg/kg diet	• ↑ BWG and improved FCR • ↓ AST and ALT in serum • ↑ Ratio of villus height to crypt depth in the duodenum • ↑ SOD, IgM • ↓ *E. coli* in caecum	Mohebodini et al., 2019
Eucommia ulmoides leaf at 500 and 100 mg/kg feed in birds subjected to heat stress	• Significant improvement in ADG, FI, and FCR compared to heat-stressed control	Zhao et al., 2019
Forsythia suspensa at 100 mg/kg with transport stress (3 h transport at 27 degrees)	• Reduced corticosterone and MDA levels in serum compared to control • Improved ROS scavenging ability	Pan et al., 2018
Cinnamaldehyde from cinnamon at 0.3 g/kg diet	• No effect on TP, TG and glucose • ↑ SOD in serum, ↑ antibody titre against NDV and higher villus height in the duodenum • ↓ Pre-caecal *E. coli* count	Chowdhury et al., 2018
Grape seed extract (catechin, flavonoids and epicatechin) at 25, 50 and 75 ppm/kg diet	• ↑ NDV and IBDV antibody titre • ↓ TBARS in leg and breast muscles • ↑ Total phenolic content in leg and breast muscles	Iqbal et al., 2015
Genistin and hesperidin (1:4 mixture) at 5 mg/kg, 20 mg/kg and thymol at 0.5 g/kg diet	• ↑ SOD, and T-AOC in serum and ↓ LDL-C, TG and TC in serum and muscle • PUFA ratio of n6/n3 was improved • ↓ MDA in serum	Kamboh and Zhu, 2013

ADG – verage daily gain, FI – feed intake, BW – body weight, BWG – body weight gain, FCR – feed conversion ratio, ME – metabolisable energy, CP – crude protein, TP – total protein, ALT – alanine aminotransferase, AST – aspartate aminotransferase, TC – total cholesterol, TG – triglycerides, LDL-C – low-density lipoprotein-cholesterol, LDL – low-density lipoprotein, PUFA – polyunsaturated fatty acids, MDA – malondialdehyde thiobarbituric acid, TBARS – reactive substances, T-AOC – total antioxidant capacity, SOD – superoxide dismutase, GSH-Px – glutathione peroxidase, ROS – reactive oxygen species, IgM – immunoglobulin M, NDV – Newcastle disease virus, IBDV – infectious bursal disease virus

Table 3. Effects of various polyphenols on performance of laying hens and other poultry

Polyphenolic compounds	Effects	References
	Laying hens	
EO from peppermint at 0, 74, 148, 222, and 296 mg/kg (Bovans)	• ↑ FI, egg production, egg mass, EW, HU and eggshell thickness • ↑ TP in serum and ↑ CP, EE and P digestibility • ↓ Cholesterol in serum	Abdel-Wareth and Lohakare, 2020
Carvacrol and thymol at 1000 mg/kg (Bovans White)	• ↑ Egg production and EW • ↓TC and TG in serum • No effect on FCR, eggshell thickness, HU, and yolk colour	Cimrin, 2019
Polyphenols dose: at 0, 0.5, 0.8 and 1.2 g/kg source: eucalyptus leaves	• ↑ Egg mass, egg production and eggshell thickness • ↓ Cholesterol and MDA in the yolk • ↑ GSH-Px, SOD, and AOC in serum • ↓ Drip loss of the meat	Chen et al., 2018
Tea polyphenols and tea catechin at 200 mg/kg (Hy-Line-brown)	• ↑ Egg production and improved FCR • ↑ Albumen HU • ↑ Protein sulfhydryl content of the albumen and ↓ carbonyl content of protein	Wang et al., 2018
Thyme and fennel at 0 and 40 mg/kg	• ↓ Egg yolk cholesterol • ↑ EW, egg mass and yolk colour • Improved egg yolk omega-3 fatty acids	Heravi and Vakili, 2016
	Other poultry	
Oregano essential oil at 100 mg/kg (duckling)	• No effect on ADG, FCR, EE, CP ash and gross energy digestibility • ↓ Lower MDA in liver and serum • ↑ SOD in serum and AOC in the jejunum • ↑ Villus height crypt depth ratio	Ding et al., 2020
Grape seed extract of anthocyanidins and catechins (polyphenols) at 0, 0.1 and 0.2% polyphenols (anthocyanidins, catechins) (Pekin duckling)	• ↑ ADG, final BW and improved FCR • ↓ Abdominal fat • ↑ GSH-Px, SOD, AOC, CAT,IL-2, IgG and ↓ MDA in serum • ↑ ileal *Lactobacillus* count and ↓ *Escherichia coli* count	Ao and Kim, 2020
Saponins and flavonoids (Japanese quail) at 0, 1%, 3% and 5%	• ↑ FI and BWG • ↑ Weight of bursa of Fabricius and thymus • ↑ *Lactobacillus* and *Bifidobacterium* in the intestine • ↓ *E. coli* in the intestine • ↑ GSH-Px, CAT and antioxidant capacity (AOC) • No effect on TC, TG, AST, ALT and TP ↑ IgA, C3 and C4 in serum	Guo et al., 2019
Thymol at 2 g/kg (quail)	• No effect on BW, FI, EW and egg production • No effect on plasma corticosterone level • ↑ H:L ratio and ↑ inflammatory response • ↑ Albumin, globulins, glucose and TP in plasma	Nazarizadeh and Pourreza, 2019
Thymol at 30 mg/kg in turkey poults	• No effect on ADG, *Lactobacillus*, *E. coli* count in the ileum and caecum • Improved FCR • ↑ GSH-Px and GST activity in thigh, breast muscle and liver • ↓ MDA in breast and thigh muscles	Giannenas et al., 2014
Essential oil (mixed) commercial product in powder form at 0.3 g/kg (turkey birds) experiment period for 0–140 days	• No effects on ADG, FCR and carcass weight • ↓ pH of crop content • No effects on SCFA production in the caecum • ↑ α-glucosidase in the ileal digesta	Mikulski et al., 2008

ADG – verage daily gain, FI – feed intake, BW – body weight, BWG – body weight gain, FCR – feed conversion ratio, EO – essential oil, AST – aspartate aminotransferase, TC – total cholesterol, TG – triglycerides, SCFA – short chain fatty acids, EF – ether extract, CP – crude protein, EW – egg weight, MDA – malondialdehyde, TP – total protein, P – phosphorus, TBARS – thiobarbituric acid, AOC – antioxidant capacity, SOD – superoxide dismutase, CAT – catalase, GSH-Px – glutathione peroxidase, GST – glutathione S-transferase, IL – interleukin, H:L – heterophils and lymphocytes, ALT – alanine transaminase, IgG – immunoglobulin G, EW – egg weight, HU – Haugh unit

Beneficial effects of polyphenols on the quality of poultry meat and eggs

Several studies have found that polyphenolic compounds have a significant direct or indirect influence on the quality of poultry meat. Luna et al. (2010) conducted research on the use of carvacrol and thymol at 150 mg/kg in broilers to evaluate their effects on lipid oxidation and thiobarbituric acid reactive species (TBARS) in stored meat, and found lowered TBARS levels in thigh muscle after storage for 5–10 days compared to the untreated group. Flavonoids extracted from citrus fruits, such as naringin and hesperidin, were supplemented in the diet of broilers and after 6 days of storage, lower MDA concentrations were observed in breast muscles. At the same time, breast muscle pH, colour and cooling loss were not affected by this supplementation (Goliomytis et al., 2015). Possas et al. (2017) applied thyme to ready-to-eat turkey meat during the preservation period, which resulted in the inactivation of *Salmonella enteritidis*. Hesperidin supplementation in the diet of laying hens improved the oxidative stability and lowered MDA levels in eggs and egg yolks stored for 30–90 days (Goliomytis et al., 2015). Supplementation of 1% linoleic and gallic acid in the diet of broilers improve water-holding capacity and nutritional value of breast muscles by increasing their DHA and arachidonic acid levels (Jung et al., 2010). Yesilbag et al. (2011) found that dietary addition of essential oil and dry leaves of rosemary (rich in carnosol and carnosic acid polyphenols) to the feed of broilers alleviated oxidative stress, improved meat sensory attributes, and lowered MDA levels in breast muscles of treated chickens compared to the untreated group. Table 4 presents selected scientific studies concerning the quality of poultry meat products in relation to the use of phytogenic additives and extracts (polyphenols).

Use of polyphenols in ruminants

Effects of polyphenolic compounds on nutrient intake and digestibility

Phytogenic products and their extracts have long been used in ruminants to improve health, increase feed intake and digestibility, and milk production (Lillehoj et al., 2018). An increase in dry matter and water intake by 9.2–1.4% was observed in beef cattle supplemented with capsicum (Rodríguez-Prado et al., 2012), while this effect was not observed in dairy cattle (Tager and Krause, 2011). Oh et al. (2021) added dietary rumen-protected capsicum (RPC) and observed enhacement in cattle immunity, with an increase in neutrophil and a decrease in lymphocyte counts. During early lactation, feeding of Nexulin (RPC) at 100 mg/day/cow to dairy cattle reared on pasture grazing led to increased milk production 27.9 vs 26.1 kg/day, and increase in fat (1.397 vs 1.313), protein (1.118 vs 1.014) and lactose (1.409 vs 1.321) (Stelwagen et al., 2016). The inclusion of phytochemical additives in animal diets resulted in higher feed intake and digestibility % on feed palatability and animal performance due to positive effect of these substances caused by enticing flavour (Kholif et al., 2017). Makri et al. (2018) reported that an increase in the digestibility of feed with a phytochemical additive was dose-dependent, as feed intake of sheep administered a dose of 450 mg/kg of the phytochemical additive mixture was lower compared to 150 and 300 mg/kg doses. Christaki et al. (2012) found that essential oil mixtures exerted a modulatory effect on the count of cellulolytic bacteria, enhancing nutrient digestion. The latter authors reported that the addition of essential oils to ruminant diets led to proliferation of fungi and cellulolytic bacteria, including *Ruminococcus albus, Selenomonas ruminantium* or *R. flavefaciens*. Several studies evaluated the effects of phytogenic feed additives on dairy and beef cattle production. Due to variations in animal species, as well as

Table 4. Effect of phenolic compounds on poultry meat products

Phenolic compound source	Poultry product	Days of storage	Effects	References
Grape pomace at 30 g/kg	Egg (layer)	30	• Increased egg production • Reduced egg lipid oxidation • Reduction in the butyric, caproic and margaric fatty acids content	Reis et al., 2019
Grape pomace at 10 g/kg	Breast muscle	10	• Decrease in yolk and albumen pH • ↓ Meat redness and yellowness • Lipid oxidation inhibition	Aditya et al., 2018
Pomegranate pomace at 0.3 g/kg	Minced meat of thigh	11	• ↓ Lower TBARS values and increase in scavenging activity • ↓ n-3 and n-6 ratio	Abdel-aty et al., 2018
Polyphenols from tea at 15 g/kg	Liver, breast muscle and fat	–	• ↓ Abdominal fat and ↓ plasma TG • Reduced liver • Reduced oxidative stress caused by corticosterone	Eid et al., 2003

TBARS – thiobarbituric acid reactive substances, TG – triglycerides phytonutrient dosing and composition, production outcomes are not consistent across studies. Yang et al. (2010a) conducted a study on 70 yearling steers to evaluate the effect of cinnamaldehyde. These authors added cinnamaldehyde to the diet of steers at 400 mg, 800 mg, and 1600 mg per day and observed a quadratic increase in dry matter (DM) and average daily weight gain during the first 28 days. In contrast, Benchaar (2016) carried out a 28-day trial in dairy cattle using cinnamaldehyde supplementation at 50 mg/kg diet (DM) and did not observe any significant increase in dry matter intake (DMI), milk production or milk composition. Table 5 shows some of the research studies conducted in ruminants evaluating performance using phytogenic additives and extracts.

Effect of phytogenic additives on growth performance of ruminants

The best results of supplementing herbs and their extracts on animal performance can be obtained by careful and proper selection of mixtures. These products are very efficient and exert a strong positive effect on animal health and the quality of cattle products (meat and milk). These beneficial effects can be observed with regular and long-term

Table 5. Effects of polyphenols and polyphenol-containing phytogenic feed additives on ruminant performance

Polyphenol source	Species	Findings	References
Finely ground chelated herbs, spices and EOs combination at 3 and 6 g/cow/day	Holstein-Friesian cows	• ↑ Nutrient digestibility • ↑ Milk production • ↑ Milk components • ↑ Ca, Mn, Fe and Zn contents in milk	Kholif and Olafadehan, 2021
Celery and thyme at 20 g/ewe/day	Barki ewes	• ↑ Nutrient intake • ↑ Nutrient digestibility • ↑ ADG • ↑ Final BW • ↑ Milk fat • ↑ Energy-corrected milk	Abd El Tawab et al., 2020
Mixture of extracts of *Amoora rohituka* (rohida), *Punica granatum* (pomegranate), *Dolichos biflorus* (kulthi) and root of *Asparagus racemosus* (shatavari) at 30 g/kg diet	*In vitro*	• Decreased methanogenesis, and reduced fibre degradability	Hundal et al., 2020
Thymol, eugenol and cinnamaldehyde at 1 and 2 g/kg of diet (*in vitro*)	Korean cattle heifers	• ↓ Fibre digestion • ↓ Digestion of readily degradable substrates	Kim et al., 2019
Moringa extract at 10, 20 and 40 ml/goat/day	Nubian goats (lactating)	• ↑ FI • ↑ Nutrient digestibility • ↑ Milk production • ↑ Milk CLA and UFA • ↑ Milk lactose and fat	Kholif et al., 2018
Coriander at 14 ml/cow/day	Friesian cows (lactating)	• ↑ Milk production • ↑ Nutrient digestibility • ↑ Feed efficiency	Kholif et al., 2017
Lemon grass and rosemary at 10 g/goat/day	Damascus goats (lactating)	• No change in FI • ↑ Nutrient digestibility • ↑ Milk yield • ↑ Milk components • ↓ Milk SFA • ↑ UFA and CLA	Hernandez et al., 2017
Oregano (polyphenol) at 8 kg/tonne of diet	Chios lambs (growing)	• No change in FI • No change in DWG • No change in feed conversion • No change in carcass traits yield	Bampidis et al., 2005
Crina ruminants EO at 3.8 mg/l ruminal fluid	Continuous-culture fermenters	• No change in DM, OM, NDF, and CP digestibility	Castillejos et al., 2005

CLA – conjugated linoleic acid, FI – feed intake, BW – body weight, DWG – daily weight gain, ADG – average daily gain, UFA – unsaturated fatty acids, SFA – saturated fatty acids, EO – essential oils, Ca – calcium, Fe – iron, Zn –zinc, Mn –manganese, OM – organic matter, DM – dry matter, NDF – neutral detergent fibre, CP – crude protein use of these products. The supplementation rate with herbs or their extracts ranges from 0.2 to 2% ration DM (Caroprese et al., 2020). Since the use of antibiotics as growth promoters has been banned in European countries, herbs with their therapeutic properties are currently included in the list of alternative and safe feed additives as growth stimulants replacing antibiotics (Bąkowski and Kiczorowska, 2021). Peppermint (*Mentha piperita*) and lemon grass (*Cymbopogon citrullus*) have been identified as herbs of interest for improving the productivity and health of farm animals. Zmora et al. (2012) supplemented these feed additives in the diet of beef and dairy cattle and observed an improvement in the performance of these animals. Similarly, *Fructus Ligustri Lucidi* (Chinese herb) has been reported to help improve the efficiency of dairy production and maintenance of animal health. When this herb was supplemented at a dose of 10 g/cow/day, an increase in ADG, feed efficiency, and digestibility of DM and organic matter was observed (Qiao et al. 2013). The addition of cumin seeds (*Cuminum cyminum*) to the diet of cows at a dose of 200 g/day improved productive performance, had a positive effect on milk yield, and lowered cholesterol levels (Ghafari et al., 2015). Rahchamani et al. (2019) conducted a study in Dallagh sheep using a 10% DMI mixture of licorice and nettle plant powder, and observed an increase in FCR, *Lactobacillus* and somatic cell counts, while there was no significant increase in BW or *E. coli* counts, rumen pH, total protein, triglyceride and cholesterol levels. Hill et al. (2007) conducted a research on Holstein bull calves (40 kg BW, aged less than a week) using 0.05% Apex plant botanicals in a milk replacer and starter feed for calves, and observed an increase in the average daily gain and improved FCR. A study was conducted by Klebaniuk et al. (2016) in Limousine beef cattle (100–650 kg BW) based on adding a mixture of herbs (*Echinacea* + licorice + caraway + garlic + thyme) at 3% DMI, and these authors recorded increased ADG, FCR, as well as higher protein and fat digestibility.

Effect of phytogenic additives on ruminal fermentation

Animal health, a balanced and healthy rumen microbiota, and normal body physiology are important factors in the maximum performance and output of animals. These parameters are of paramount significance for improving growth performance and energy maintenance due to their positive and stimulating effects on carbohydrate and protein digestion, as well as synthesis of volatile fatty acids, vitamins and proteins (Kumar et al., 2021). According to many authors, polyphenols exert antimicrobial effects, and due to this property, they are applied as alternative to antibiotics growth promoters and modulators of rumen microflora (Khiaosa-ard and Zebeli, 2013). Plant-derived polyphenols/phytochemicals exhibit antimicrobial activity to manipulate the rumen microbiota by i) inhibiting the synthesis of bacterial cell wall, ii) nucleic acids, iii) proteins essential for bacterial life, and iv) damaging cell wall structure essential for cell protection. The above mechanisms of action of phytochemicals impair important cell processes leading to their death (Fanning et al., 2014). Therefore, the use of phytochemicals in the ruminant diet increases rumen fermentation by positively altering the rumen microbiota, resulting in improved feed efficiency, average daily weight gain of animals, reduced methane production, and elevated volatile fatty acid production (Cardozo et al., 2006). An *in vitro* study was conducted on garlic oil, and it was observed that it contained anti-methanogenic polyphenols which supressed the proliferation of archaea by inhibiting hydroxymethyl glutaryl coenzyme A (essential for the stability of the cell membrane structure of archaea). This property of garlic phenols help to increase the proportion of propionate and butyrate and reduce the percentage of acetate and branched chain VFAs (Busquet et al., 2005). Similar results were also obtained with the use of eugenol and cinnamaldehyde; these compounds increased the proportion of propionate and butyrate and reduced the percentage of acetate. Busquet et al. (2005) observed that the inclusion of eugenol in the diet of ruminants limited the lysis of large peptides to small peptides and amino acids, while Ferme et al. (2004) showed that cinnamaldehyde reduced the growth of deaminating bacteria like *Prevotella*. Therefore, it has been proposed that using a combination of cinnamaldehyde and eugenol improves microflora and host supply of small peptides and amino acids by reducing deamination and peptidolysis processes. Abd El Tawab et al. (2020) reported that the addition of plant-derived essential oils at 3 g/day/cow improved the post-ruminal digestibility of crude protein and lowered rumen NH_3 levels by reducing the number of hyperammonia-producing bacteria. In the same study, the authors reported that the addition of 3 g/day/cow of compound feed retained rumen pH, which prevented the shift in bacterial population from fibrolytic to amylolytic bacteria, and additionally helped protect against the occurrence of acidosis. Certain herbs like coriander, thyme, cumin, clove turmeric and cinnamon have been reported to significantly decrease rumen gas production by controlling fermentation processes occurring there. Chaudhry and Khan (2012) and Kongmun et al. (2011) investigated the effects of cumin, clove, coriander, cinnamon and turmeric as "natural antibiotics" in *in vitro* fermentation studies. They were found to play a role in eliminating methane-producing bacteria from the intestine, resulting in a 40% reduction in gas production. These herbs also act as natural growth stimulants in ruminant nutrition. Corn spurry, nettle, meadow salsify, caraway and bristly hawkbit were demonstrated to increase milk yields in sheep. Min et al. (2016) conducted a study on the use of condensed tannins (CT) *in vivo* (steers) and *in vitro* from the Quebracho plant at doses of 0, 1, and 2% CT/kg DMI. They found an increase in AWDG at both CT levels, as well as a significant reduction in bloating severity (by 90% at 2% CT, and 40% at 1% CT), which they attributed to a decrease in microbial activity, biofilm and ruminal gas production. In an *in vitro* study, a reduction in the rate of gas production was recorded. Methane production in the rumen was significantly reduced by increasing CT doses, as higher CT levels inhibited microbial activity (Bhatta et al., 2015). Anthocyanins added to ruminant diets were shown to reduce methane production by suppressing the development and activity of methanogens such as *Methanobrevibacter* and *Methanomicrobium*, responsible for methanogenesis (Tayengwa and Mapiye, 2018). Moate et al. (2014) demonstrated that the addition of anthocyanin-rich plants reduced methane (CH_4) emissions and CH_4 yield by approximately 20% in lactating, multiparous Holstein-Friesian cows. Thus, anthocyanins are able to decrease ruminal fluid methanogenesis by acting as H_2 sinks; (2) they can also decrease fibre digestibility in the rumen, resulting in lower methane production; and (3) lastly, these compounds supress methanogens and hydrogen-producing microbial growth and activity (Lazalde-Cruz et al., 2021; Vasta et al., 2019). Representative studies conducted in ruminants to evaluate the effect of phytogenic additives and extracts on rumen methane production and fermentation are listed in Table 6.

Table 6. Effects of polyphenols and polyphenol-containing phytogenic feed additives on methane production and rumen fermentation

Phytogenic plant species	Animal species	Findings	References
Moringa oleifera at 10, 20 and 40 ml/goat/day	Milking Nubian goats	• ↓ CH_4 production	Kholif et al., 2018
Coriander at 14 ml/cow/day	Milking Friesian cows	• No change in VFA ↓ NH_3-N	Matloup et al., 2017
Addition of garlic at 150 g/kg diet	Milking brown Swiss cows	• ↓ CH_4 production	Staerfl et al., 2012
Condensed tannins at 10, 15, 20, 25 and 30 mg/500 mg (*in vitro*)	Kedah-Kelantan cattle	• ↓ Propionate • ↑ Acetate	Tan et al., 2011
Cinnamaldehyde oil at 0.4, 0.8 and 1.6 g/day	Steers	• No change in rumen pH • No change in individual and total VFA production	Yang et al., 2010b
Peppermint oil at 1.0 and 2.0 µl/ml	Buffalo	• ↓ Propionate • ↑ Acetate • ↓ Total VFA	Agarwal et al., 2009
Guaiacol, eugenol, limonene, vanillin and thymol oil at 5, 50, 500 and 5000 mg/l	Dairy cattle	• ↑ Butyrate • ↓ Acetate • ↓ NH_3-N	Castillejos et al., 2006

VFA – volatile fatty acids, CH_4 (methane); ammonia nitrogen (NH_3-N)

Effect of phytochemicals on blood profile, oxidation, and health status of animals

Blood metabolites are used to indicate normal physiology and welfare, and to diagnose and predict diseases. Supplementation of a plant-based additive mixture in the cows' diet reduced blood urea nitrogen and increased serum globulin and total protein levels, indicating proper kidney functions, improved nutritional status, enhanced microbial protein synthesis, and minimum protein catabolism (Giannenas et al., 2011). Lakhani et al. (2019) reported that elevated serum globulin levels could indicate a provoked immune response of the body. The liver plays a vital role in protein metabolism, and any impairment in liver cell function is manifested by higher total serum protein levels

(Mbuh and Mbwaye, 2005). Kholif et al. (2021) conducted a study on phytogenic feed mixture (PFM) (levomenthol, anethole, hexadecanoic acid, b-linalool, and p-menthane) and found that PFM at 3 g and 6 g/cow/day as compared to conrol group improved the antioxidant capacity and total serum protein, and lowered the serum urea nitrogen, lipids, cholesterol, triglycerides and malondialdehyde. Better antioxidant capacity and total serum protein levels, and lower serum urea nitrogen, lipids, cholesterol, triglycerides and malondialdehyde levels indicated improved nutritional status of dairy cows. Lakhani et al. (2019) reported that by supplementing essential oils in ruminants, they observed health improvement due to increased serum glucose levels, higher antioxidant activity (GPx, SOD, and CAT), and lower MDA concentrations. Supplementation of phenolic compound extract from orange peel enhanced the antioxidant capacity of dairy ewes, which in turn improved the welfare, and meat and milk quality (Kotsampasi et al., 2018). Other studies have revealed that phytogenic additives act as prebiotics and bind intestinal cholesterol and neutral lipids, and increase their excretion with faeces, as well as lower the levels of plasma total lipids, cholesterol, and triglycerides, which in turn contributes to reduced risk of atherosclerosis (Fuhrman et al., 2000). Phytogenic mixtures containing polyphenolics and flavonoids also support the reduction of blood plasma cholesterol levels by inhibiting the activity of the liver enzyme 3-hydroxy-3-methylglutaryl-CoA involved in cholesterol synthesis (Lee et al., 2004). Kholif et al. (2020) observed the effect of a phytogenic additive mixture on cation concentrations in dairy cows. These authors noticed that the additive mixture enhanced cation absorption, thereby improving lactation in dairy cows. The addition of essential oil to the diet of dairy cows did not affect the concentration of Ca and other minerals in the blood plasma and prevented metabolic disorders in cows such as hypocalcaemia (Martín-Tereso and Martens, 2014). The latter study was consistent with the results of Lakhani et al. (2019), who reported that essential oil supplementation did not affect plasma Ca and P levels. Braun et al. (2019) observed high serum Ca levels in lactating cows after dietary menthol addition. High OS is commonly found in organs and tissues with high metabolic and energy requirements, such as skeletal muscle and heart, liver or blood cells (Puppel et al., 2015). Dairy cows become metabolically challenged and enter a state of negative energy balance when energy demand exceeds its intake. This in turn activates catabolic pathways, which increase ROS production at the cellular level, resulting in decreased cow performance (Celi et al., 2012). Oxidative stress not only has a negative impact on dry matter intake (DMI), milk yield and composition, and reproductive performance in dairy cows, but also reduces economic benefits (Gorniak et al., 2014; Das et al., 2016). Bagchi et al. (1997) discovered that grape seed anthocyanin extract was a more effective free radical (FR) scavenger than vitamin C or E. At a concentration of 100 mg/l, grape seed anthocyanin extract inhibited O_2 and hydroxyl radical formation by 78–81%. Anthocyanins, a type of antioxidants, can provide electrons to free radicals (FRs), preventing them from oxidizing nearby cells and maintaining FR balance when host animals are in OS; they can also improve the antioxidant potential of animals by increasing hepatic manganese-superoxide dismutase (Mn/SOD), copper/zinc-SOD, and glutathione peroxidase (GPx) mRNA expression (Han et al., 2006). Anthocyanins have an active phenolic hydroxyl structure with an antioxidant mechanism similar to polyphenols, and the following mechanism for improving the antioxidant activity: (1) the phenolic hydroxyl group directly scavenges oxygen FRs through its own structure, improving the body's antioxidant-related enzyme activity and antioxidant capacity; (2) anthocyanin-containing plants inhibit inflammatory processes in the intestinal mucosa by promoting normalisation of the gut microbiota, decreasing pathogen abundance, reducing the permeability of the intestinal barrier, and enhancing the immune system (Sakano et al., 2005; Pieszka et al., 2015).

Effects of polyphenols on milk yield, composition, and efficiency

PFM supplementation at a dose of 3 g/day/cow increased actual milk production by 6% and energy-corrected milk by 13% (Kholif et al., 2021). This improvement in milk yield could be due to improved rumen fermentation and efficient feed utilisation (Kholif et al., 2017). Milk yield can be increased by reducing protein and energy losses during fermentation and improving feed utilisation by the rumen microflora (Salem et al., 2014). Kholif et al. (2021) observed increased milk production due to the addition of PFM in the diet of animals, which led to improved feed intake, nutrient digestibility, and increased propionate production (a precursor of glucose and lactose), as a result of altered rumen microbial fermentation. Similar findings were reported by Santos et al. (2010) in lactating dairy cows. Braun et al. (2019) supplemented menthol (80%) and anethol and eugenol (20%) as a blend of essential oils in the diet of lactating dairy cows and observed improved milk production and yield without changes in feed intake, which could be due to the positive effect of menthol on rumen fermentation. In another study, milk fat percentage was elevated up to 7.2% when cows were fed 3 g/cow PFM, and increased milk fat is associated with higher fibre digestibility (Kholif et al., 2021). The higher fat content in milk is related to higher acetate (a precursor of fat) production in the rumen, and increased acetate production results from improved fibre digestion in the rumen (Santos et al., 2010). Similar results were obtained by Kotsampasi et al. (2018), recorded increased milk fat percentage when the diet of dairy ewes was supplemented with essential oils, while Ca, Cu, Zn, Mn, and Fe concentrations remained unaltered. Ghafari et al. (2015) supplemented cumin seeds at 0, 100, 200 and 300 g/day in the diet of Holstein dairy cows and noticed increased nutrient intake and milk production. According to Matsuba et al. (2019), Holstein dairy cows fed anthocyanin-rich plants had higher milk yield (31.7 vs 29.2 kg/day) and blood SOD levels (9333 vs 8467 U/ml) than those fed a control diet. Furthermore, Matra and Wanapat (2022) demonstrated that Holstein-Friesian crossbred cows fed 400 g/day phenolic-rich dragon fruit peel pellets produced 3.5% fat-corrected milk. Surprisingly, rumen fatty acid biohydrogenation inhibiting *de novo* milk fat synthesis has been proposed as a potential mechanism for reducing milk fat during oxidative stress (OS) (Yoon et al., 2015).The current dominant "trans-fatty acid or biohydrogenation" theory of milk fat depression (MFD) proposes that specific ruminal fatty acid intermediates, particularly trans-10 and cis-12 conjugated linoleic acids (CLA) are biohydrogenated, escape the rumen, and signal a decrease in lipogenic enzyme activity, resulting in reduced mammary gland milk fat synthesis (Sejrsen et al., 2006). As previously stated, feeding anthocyanin-rich diets can potentially increase DMI to reduce negative energy balance, as well as affect rumen fermentation parameters, especially VFAs, to control the fatty acid biohydrogenation pathway in dairy cows. Previous studies have demonstrated that including anthocyanin-containing plants in ruminant diets increased antioxidant activity, improved rumen fluid VFAs, and caused a shift in the structure and relative abundance of the rumen microbiota (Tian et al., 2021). Anthocyanins can influence rumen microorganisms by preventing changes in the biohydrogenation pathway of fatty acids by promoting the development of rumen microorganisms that produce trans-11 fatty acid isomers, or inhibiting the growth and function of rumen microorganisms that produce trans-10 C18:1. As a result, anthocyanins affect the rumen microbiota by altering some biohydrogenation steps (Lazalde-Cruz et al., 2021).

Phytogenic polyphenols and carcass quality of ruminants

The effect of polyphenol/phytogenic mixtures on carcass quality and meat products has also been reported. Considering the sensory meat characteristics, it was observed that the inclusion of hesperidin and cinnamaldehyde in the diet of sheep resulted in a strong meat flavour (Chaves et al., 2011). Another study conducted in steers reported that the addition of citrus pulp (80%) to animal diets did not affect meat texture properties, but rather increased consumer acceptance of the meat (Salami et al., 2020). A study conducted to evaluate the benefits of olive polyphenols added to the diet of goats at 3.2 mg/day found that the addition of the extract led to a decrease in short and saturated fatty acid and MDA levels and increased concentrations of monounsaturated fatty acids in goat meat compared to the untreated group (Cimmino et al., 2018). Supplementation of citrus and wine products, and thus polyphenols present in these by-products, in the diet of lambs at 100 g/kg DM increased meat tenderness by reducing the shear force (Francisco et al., 2018).

Conclusions

The main objective of modern farming systems is to obtain high-quality meat, milk, and egg products. The concept of quality not only includes a safe product for the consumer, but also involves the health and safety of animals. The present review has demonstrated that polyphenols play a vital role in the production of high-quality and healthy meat, milk, and egg products that are safe for human consumption. Furthermore, these compounds also exert profound beneficial effects on performance, digestibility, microbiota, immune response, oxidant status and egg and meat quality of poultry, as well as nutrient intake and digestibility, rumen fermentation, milk composition, blood profile and health status of ruminants. There are about 25000 polyphenolic compounds and comparing them is difficult; however, several studies have reported promising effects of these compounds applied in combination with each other or other organic compounds. Nevertheless, extra attention should be paid to the selection of active compounds for potentially effective blends, and future research should focus on the search for new compounds from agricultural by-products and weeds, supplementation programmes, and dose level determination according to animal species and age. Finally, although these phenolic compounds are considered “natural” products, they should be assessed for adverse effects on human and animal health and possible interactions with other dietary components.

Conflict of interest

The Authors declare that there is no conflict of interest.

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