Upgraded nutritional value of maize - the beneficial effect of phytochemicals

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Abstract

In nature, animals select feeds that contain both nutrients and phytochemicals, compounds that have a beneficial effect on animal and human health. In the sustainable production of farm animals, value-added feeds meet nutrient requirements, and maintain digestive efficiency and metabolic health. Due to high content of phytochemicals such as carotenoids, resistant starch, tocols and phenolics, maize grain is such a feed. These compounds have a beneficial effect on the health and well-being of animals and, if not used for this purpose, are deposited in the tissues. In this way, they improve the quality of meat and egg yolk, but also become sources of phytochemicals in human nutrition. This paper presents the content of phytochemicals in maize grain and their beneficial effects on farm animals.

Key words: maize, carotenoids, resistant starch, phenolics, tocols

Introduction

The challenges in food production system today are to provide an adequate amount of food rich in nutrients and bioactive compounds, meet the demands of the consumers, and at the same time reduce the negative impact on the environment (Viola and Marinelli, 2016). Therefore, feed production and animal feeding are directed towards sustainable animal diets. One of the aspects of sustainable nutrition of farm animals is the use of feeds that meet more than one nutritional requirement of the animals. Although the primary role of diet is to provide the amount of nutrients needed for animal production, it can also affect animal health, behaviour and well-being. In that regard, the main focus is on the adverse effects on animal production, health and well-being due to the presence of pathogens and compounds such as mycotoxins, heavy metals and pesticides, but feeds also contain compounds that have positive effects. These compounds are phytochemicals, bioactive chemical compounds that occur naturally in plants and provide health benefits to animals and humans. A wide range of phytochemicals have been identified in plants; some of the compounds include phenolics, terpenes, carotenoids, alkaloids, fatty acids and polysaccharides (Campos-Vega and Oomah, 2013).

Maize grain is the primary energy source in the diets of farm animals worldwide and its proportion in the diet can be as high as 70%. Among the cereals used in animal nutrition, maize has the highest values of useful energy due to its high starch and oil content (740 and 43 g kg^{-1} DM, respectively) and low content of fiber (neutral detergent fiber, 12 g kg^{-1} DM) and anti-nutritional factors (Eeckhout and De Paepe, 1994; Sauvant et al., 2004). Maize grain also contains a variety of bioactive compounds such as carotenoids, phenolics, tocols and resistant starch (Liu et al., 2007; Siyuan et al., 2018), most of which are in the highest content among cereals. The content of these compounds varies among genotypes, reflecting their different beneficial potential. Due to the high proportion of maize grain in diets of farm animals, these compounds significantly contribute to animal health and affect production performance and quality of animal products.

Of the aforementioned phytochemicals that have been shown to affect animal performance, health and well-being, as well as on the quality of animal products (Mahfuz et al., 2021), only carotenoids and resistant starch have been thoroughly studied in maize. Therefore, this article presents the latest findings on the beneficial effects of carotenoids and resistant starch of maize, while for other phytochemicals, their content and potential beneficial effects are explained. Furthermore, it has to be noted that the content and effect of phytochemicals is presented for minimally processed maize grain, i.e., dried after harvest and milled. Further processing, such as hydrothermal treatment or ensiling, which is often used in the preparation of maize for animal diets, could lead to degradation of phytochemicals, affect their bioavailability, and alter them (Suri and Tanumihardjo et al., 2016).

Carotenoids

Carotenoids are a large group of natural yellow, orange and red pigments that are soluble in lipids and, in addition to their pigmenting properties, possess antioxidant and provitamin A activity. The latter activity is primarily related to the hydrocarbon carotenes, while the pigmenting activity is related primarily to the xanthophylls, oxygenated derivatives of carotenes. The carotenoids present in maize grain are lutein, zeaxanthin, α- and β-cryptoxanthin and β-carotene (Kljak and Grbeša, 2015), and the range of total carotenoid content in commercial maize hybrids is between 14.48 and 32.61 $\mu g\ g^{-1}$ DM (Zurak et al., 2021a). With 84% of the total content, lutein and zeaxanthin, also known as macular pigments, are the predominant carotenoids.

The best known role of carotenoids in animal nutrition is the pigmentation of egg yolk, meat, skin and fat in poultry, whereas these products become a source of carotenoids in human nutrition. In commercial poultry production, maize carotenoids are neglected and pigment additives, usually of synthetic origin, are added to diet. The addition of pigments is most common in egg production, where producers follow consumer preference for intensive yolk colour. However, due to the increasing concern in healthy nutrition, the addition of synthetic pigments has become an issue, and due to the high pigmenting ability of such pigments, the higher colour intensity of the yolk does not imply the higher yolk carotenoid content (Kljak et al., 2021a). As a result, maize regained attention as a natural source of carotenoids in hen nutrition. There is increasing focus on the production of carotenoid-enriched maize, which has been shown to have strong yolk pigmentation ability (Moreno et al., 2020; Ortiz et al., 2021), but Kljak et al. (2021b) showed that commercial maize hybrids could be the only source of carotenoids in the hen diet. In the latter study, the authors evaluated five Croatian maize hybrids that, at a 60% level in hen diet, resulted in yolk colour scores of 10-11 according to the DSM Yolk colour fan scale (Table 1), which are acceptable by consumers in most EU countries (Grashorn, 2016).

In addition, commercial maize hybrids could be used as the only source of carotenoids for pigmentation of breast meat and skin, shank skin and abdominal fat in chicken diets (Kljak et al., 2018). Besides the effect on pigmentation, maize carotenoids have an evident impact on poultry health. Nogareda et al. (2016) showed that chickens infected with *Eimeria tenella* had higher weight, only mild disease symptoms and lower faecal oocyst counts when fed high-carotenoid maize than when fed low carotenoid maize. The authors concluded that high-carotenoid maize could be used as a complementary strategy to boost resistance to coccidiosis.

The carotenoid content of maize represents only a potential that animals can absorb and use for biological functions. Therefore, a prerequisite for the utilisation of maize carotenoids is that they are released from the feed matrix during digestion. Recent findings by Zurak et al. (2021a) have shown that the bioaccessibility of carotenoids differs among different hybrids. Furthermore, in a subsequent study, Zurak et al. (2021b) showed that hybrids with the highest kernel hardness had the highest carotenoid digestibility, implying that kernel structure affects carotenoid digestibility. Therefore, selecting maize hybrids with increased carotenoid digestibility provides a basis for increased carotenoid utilisation. In addition, the use of maize as a carotenoid source in poultry diets would simplify diet preparation and reduce egg production costs due to lower pigment additive costs.

Table 1. The effect of maize hybrid on egg yolk colour and total carotenoid content (Kljak et al., 2021b)

Dietary treatment containing hybrid	TC content in the diet	TC content in egg yolk	YCF Colour
	$\mu g\ g^{-1}$ DM	$\mu g\ g^{-1}$	
Bc 572	17.13	25.99	11
Kekec	13.45	24.47	10
Mejaš	14.78	25.47	10
Riđan	13.86	25.49	10
Pajdaš	14.04	21.97	10

TC – total carotenoids; YCF – DSM Yolk Colour Fan

Maize carotenoids with provitamin A function are β-cryptoxanthin and β-carotene, and although their content is up to 15-fold lower than that of lutein and zeaxanthin (Kljak and Grbeša, 2015), there are hybrids with increased content. Such hybrids contribute to the vitamin A status of farm animals. Feeding chickens with high-carotenoid maize hybrids resulted in accumulation or increased accumulation of retinol in the liver and increased retinol serum concentrations compared to chickens fed low-carotenoid maize (Díaz-Gómez et al., 2017; Nogareda et al., 2016). Furthermore, piglets born to vitamin A-deficient sows fed high-carotenoid maize continuously during lactation were found to have increased accumulation of retinol in the liver compared with sows given retinyl palmitate orally (Heying et al., 2013).

In ruminants, the effect of maize carotenoids has not been studied because maize has a much lower carotenoid content than forages (Pickworth et al., 2012). However, maize carotenoids contribute to carotenoid concentrations in plasma, liver and subcutaneous fat, especially in rations high in maize. Cattle have a higher capacity to absorb carotenoids compared to sheep and goats (Yang et al., 1992), and bovine milk is the only one that contains appreciable levels of carotenoids (Álvarez et al., 2015), resulting in pigmentation of dairy products. For example, 95% of β-carotene and 64% of xanthophylls, initially present in milk fat, were found in cheese fat (Nozière et al., 2006).

Resistant starch

Based on nutritional properties, i.e., the extent to which starch is digestible, starch is classified into digestible and resistant starch in monogastric animals (RS; Sajilata et al., 2006). Digestible starch is further subdivided into rapidly and slowly digestible starch (RDS and SDS, respectively; Englyst et al., 1992), which differ in the rate of starch digestibility, although both fractions are digested in the small intestine. The RS fraction escapes digestion in the small intestine and could be fermented by the resident microbiota in the colon. Thus, RS is considered as dietary fiber and acts as a prebiotic. On the other hand, RS in ruminants is the starch fraction that is not fermented in the rumen and is digested in the small intestine of the animal.

Maize, like other cereals, contains RS_1-type starch, i.e., physically protected RS, which is a result of inaccessibility of starch to amylolytic and digestive enzymes; this starch can be digested in the small intestine only if it is thoroughly milled (Raigond et al., 2015; Sajilata et al., 2006). The digestibility of starch in maize is influenced by numerous intrinsic factors that include amylose content, amylose-to-amylopectin ratio, starch granule size, starch and non-starch lipid content, and zein content (Kljak et al., 2019; Zurak et al., 2020). The results of these studies show that the starch digestibility rate in maize decreases with increasing content of zein, amylose, starch, and non-starch lipids and with decreasing granule size. These properties negatively affect the intestinal digestibility rate of starch and contribute to an increase in SDS and RS content. Furthermore, these properties differ among maize genotypes, resulting in a wide range of content of starch fractions (Table 2). The content of RS in maize also varies depending on the determination method; it can be determined using an analytical method or estimated using *in vitro* procedure for starch digestibility. The latter method, originally proposed for humans (Englyst et al., 1992), was tested for poultry, and Weurding (2002) showed that digestion coefficients after 2 and 4 hours of incubation in the *in vitro* digestibility procedure could be estimated for starch digested to the posterior jejunum (i.e., RDS) and posterior ileum (i.e., SDS), respectively, whereas RS can be calculated as the difference from 100% starch. However, it should be noted that the analytical method could result in lower values because it is not based on the gastrointestinal digestion of starch, thus excluding a possible interaction between the cereal matrix and intestinal enzymes.

Table 2. Range of contents of rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) in commercial maize hybrids estimated from starch digestion coefficients in *in vitro* procedure for poultry using equations by Weurding (2002)

Starch fraction	Hybrids used in study by Zurak et al. (2020)	Hybrids used in study by Kljak et al. (2019)
	g kg^{-1} DM	
RDS	306.2 – 594.8	486.3 – 527.5
SDS	24.5 – 256.5	90.1 – 124.5
RS	81.4 – 148.3	103.7 – 145.4

In monogastric animals, fermentation of RS in the colon leads to the production of short-chain fatty acids (SCFA), which lower intestinal pH that suppresses the growth of pathogenic microorganisms but enhances the growth of beneficial microbes (Tan et al., 2021). In addition, RS modulates the gut microbiota and enhances the animal immune response. However, SCFA are a less efficient energy source than glucose from the small intestine. An excessive amount of RS in the diet, for example, above 30% in finishing pigs, may reduce feed intake (Tan et al., 2021). Inclusion of high-amylose maize, maize abundant in RS, in the diet of pigs alters fermentation in the colon and results in higher production of propionate and butyrate. Butyrate is the most beneficial, it serves as an energy source for normal colonocytes and has a beneficial effect on reducing the risk of diseases such as colorectal neoplasia (Bird et al., 2007). In addition, He et al. (2017) have shown in an *in vitro* experiment that increasing the content of maize RS reduces protein fermentation in both the cecum and colon, thereby reducing ammonia production.

For poultry, even lower levels of RS are required in the diet to avoid negative effects on animal production. This is most likely due to the shorter colon and the reduced possibility of utilisation of RS by the gut microbiota. Liu et al. (2020) have shown that a level greater than 4.18% of maize RS results in lower nutrient retention, weight gain and feed efficiency in broilers. However, a possible health effect is more than evident; for example, the addition of 5 g kg^{-1} high-amylose maize in the diet provided protection similar to antibiotics in chickens suffering from necrotic enteritis (when inoculated with sporulated oocysts of each of *Eimeria maxima*, *Eimeria acervulina*, and *Eimeria brunetti* at 9 days of age and *Clostridium perfringens* at 10 days of age) without negatively affecting feed intake and weight gain in broilers (M'Sadeq et al., 2015). In addition, maize RS at up to 12% in the diet reduced the abundance of caecal Firmicutes which decreased fatty acid synthesis in the liver and suppressed abdominal fat deposition in broilers (Zhang et al., 2020). Excessive fat deposition decreases feed efficiency and waste during meat processing.

In ruminants, since RS is digested in the small intestine, it reduces the availability of starch for microbial degradation in the rumen and helps prevent rumen acidosis. Compared to the rumen, where fermentation of starch leads to the production of SCFA, digestion in the small intestine leads to a direct supply of glucose that can be used more efficiently by the animal compared to hepatic gluconeogenesis of propionate (Deckardt et al., 2013). However, rumen degradable starch is required for normal rumen conditions, digestion and animal production. For example, Matthé et al. (2001) recommended feeding no more than 1.3-1.8 kg RS per cow per day to avoid reducing starch utilisation efficiency. Furthermore, the introduction of maize high in RS into ruminant diets, as Wang et el. (2016) showed in goats, shifted the fermentation of starch in the rumen toward increased production of acetate, butyrate and isobutyrate and decreased production of propionate and total SCFA. In addition, the increase in starch flow into the small intestine has positive effects on metabolic health status in terms of haematocrit and levels of albumin, C-reactive protein, growth hormone, interleukin-2, oxaloacetate transaminase and creatine kinase in the blood.

Other phytochemicals present in maize

Phenolics are the largest natural phytochemicals whose structure consists of an aromatic ring with one or more hydroxyl substituents; they can range from simple phenolic molecules to highly polymerized compounds (Vuolo et al., 2019). Phenolics are potent antioxidants, and their beneficial effects include anti-inflammatory, antidiabetic, cardioprotective, neuroprotective, antitumor and anti-ageing properties. Cereals are among the richest sources of phenolics, with compounds from the phenolic acid and flavonoid subgroups. They can be present in free and conjugated forms and are mainly found in aleurone. Grbeša and Kljak (2017) showed that Croatian maize hybrids contain between 3735 and 4715 mg/kg of galic acid equivalents of phenolics, of which on average 81% are bound. Furthermore, about 40% of maize phenolics are released during digestion in the small intestine and can be absorbed, while the remaining phenolics enter the colon, where they are released by fermentation and can counteract the prooxidants (Kljak et al., 2009).

Due to their antioxidant, antimicrobial and anti-inflammatory properties, phenolics are considered a natural alternative to antibiotics in animal production. Numerous studies have been conducted so far on a wide range of herbs and plant extracts rich in phenolics from different subgroups (Hashemzadeh-Cigari et al., 2014; Mahfuz et al., 2021; Maggiolino et al., 2021). Thus, maize phenolics could contribute to the health status and well-being of animals. In addition, farm animals can deposit phenolics in meat and egg yolks, where they improve quality by improving oxidative stability. This effect has also been demonstrated for maize. Duvnjak et al. (2018) demonstrated that maize phenolics reduce the formation of malondialdehyde in yolks exposed to induced lipid oxidation.

Naturally occurring vitamin E (tocols) consists of eight vitamers (α-, β-, γ-, and δ-tocopherols and their corresponding unsaturated tocotrienols). Of them, α-tocopherol has the highest vitamin E activity, which is why the term vitamin E is used synonymously for this tocol. The activity of the other tocols compared to α-tocopherol is 50% for β-tocopherol, 10% for γ-tocopherol, 3% for δ-tocopherol, 30% for α-tocotrienol, 8% for γ-tocotrienol, and 5% for β-tocotrienol, while it has not been demonstrated for δ-tocotrienol (Szewczyk et al., 2021). Maize contains α-, γ- and δ-tocopherol and α- and γ-tocotrienol, and their average contents in 105 commercial maize hybrids were 4.1, 25.0, 0.7, 0.9 and 2.2 $\mu g\ g^{-1}$ DM, respectively (Zurak et al., 2021). Additionally, increased tocol content is accompanied by increased content of unsaturated fatty acids in grain (Goffman and Böhme, 2001).

Tocols have anti-inflammatory and antioxidant functions, while their non-antioxidant functions are possible through specific interactions with enzymes, structural proteins, structural lipids, and transcription factors (Szewczyk et al., 2021). In addition, the antioxidant activity of individual tocols varies. In some biological processes, tocotrienols are more effective than tocopherols, while, compared to α-tocopherol, γ-tocopherol, the most abundant tocol in maize, has the ability to scavenge reactive forms of nitrogen (Jiang, 2014; Sen et al., 2006). In addition, tocols can be further metabolized, and the resulting metabolites affect the activity of transcription factors (Szewczyk et al., 2021). The combination of supplemental vitamin E and selenium has been shown to ameliorate oxidative stress in animals exposed to heat stress or contamination with mycotoxins (He et al., 2013; Zhang et al., 2020). Apart from health effects, tocols can also be deposited in meat and egg yolk and improve their quality (Zhang et al., 2020). Although maize has moderate tocol content, it can undoubtedly strengthen the immune system of farm animal and improve the quality of their products.

Conclusions

Maize is a rich source of phytochemicals in animal nutrition. While some of them have been studied and shown to have beneficial effects, others contribute significantly to animal health status and production performance due to the high proportion of maize grain in the diet. In addition, all maize phytochemicals could have additive and synergistic effects and improve animal health status to a greater extent than any single compound (Siyuan et al., 2018). Moreover, if these phytochemicals are not used to improve the health status of animals, they are deposited in the tissues and improve the quality of meat and egg yolk. These products also become their sources in the human diet. Therefore, maize should not be considered only as a source of energy in the diet of farm animals, and further studies on its beneficial effects are needed. In addition, breeding maize hybrids should also improve the content of phytochemicals, not only yield and pest resistance, so that the potential of maize to enhance animal health and well-being could be used to reduce the cost of additives in compound feed production.

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Unaprijeđena hranidbena vrijednost kukuruza - blagotvorni utjecaj fitokemikalija

Sažetak
U prirodi, životinje biraju krmiva koja sadrže i hranjive tvari i fitokemikalije, spojeve koji imaju blagotvoran učinak na zdravlje životinja i ljudi. U održivoj proizvodnji domaćih životinja, krmiva dodane vrijednosti zadovoljavaju potrebe za hranjivim tvarima i održavaju učinkovitu probavu i metaboličko zdravlje. Zbog visokog sadržaja fitokemikalija poput karotenoida, rezistentnog škroba, tokola i fenola, zrno kukuruza je takvo krmivo. Ove fitokemikalije imaju blagotvoran učinak na zdravlje i dobrobit životinja, a ukoliko se ne iskoriste za tu svrhu, životinje će ih deponirati u svoja tkiva. Na taj način poboljšavaju kvalitetu mesa i žutanjka jajeta, ali i postaju izvori fitokemikalija u prehrani ljudi. U ovom radu prikazan je sadržaj fitokemikalija zrna kukuruza te predstavljen njihov potencijalan blagotvoran učinak na domaće životinje.

Ključne riječi: kukuruz, karotenoidi, rezistentni škrob, fenoli, tokoli