

World's Poultry Science Journal

ISSN: 0043-9339 (Print) 1743-4777 (Online) Journal homepage: www.tandfonline.com/journals/twps20

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To cite this article: Babak Hosseintabar-Ghasemabad, Ambra Rita Di Rosa, Hossein Janmohammadi, Marina Ivanovna Slozhenkina, Ivan Fedorovich Gorlov, Aleksandr Anatolievich Mosolov, Alireza Seidavi & Clive Julian Christie Phillips (2024) The potential of amaranth grain for feeding to poultry, World's Poultry Science Journal, 80:2, 481-509, DOI: 10.1080/00439339.2024.2308228

To link to this article: https://doi.org/10.1080/00439339.2024.2308228

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Published online: 05 Feb 2024.

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WORLD'S POULTRY SCIENCE JOURNAL
2024, VOL. 80, NO. 2, 481–509
https://doi.org/10.1080/00439339.2024.2308228

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SUMMARY

Amaranth is a pseudocereal that has a potentially greater role to play in reducing malnutrition and promoting animal feed security because of its high quality and ability to adapt to environmental stresses. We review the nutrient content and its value for poultry feeding, as well as uses in industry and for human food that might impact on its availability for poultry. Wit effective processing to detoxify antinutritive components by extrusion or autoclaving, it can be incorporated at up to 40% in the diet of broiler chickens without loss of productivity. Its nutritional value is high, in terms of protein, oil, mineral and antioxidant content, as well as its excellent amino acid balance. Amaranth is likely to be most beneficial as feed grain for poultry in extreme climatic regions, such as those that are drought prone, as long as effective processing can be incorporated into the feed production system.

KEYWORDS

Biological value; flock health; food security; global warming; poultry products; pseudocereal

Introduction

Globally about two million square kilometres of agricultural land are currently used to grow feed for poultry (FAO 2018). However, poultry meat has the fastest growth in consumption of any meat worldwide (Whitton *et al.* 2021) and demand for high-quality poultry feeds is expected to increase. At the same time, the growing human population, climate change and wartime export restrictions are increasingly causing concerns about feed security. The predicted effect of an estimated 2°C increase in global temperatures by the end of the century is approximately a 20% reduction in cereal production, dependent on cereal cultivar and species (Fatima *et al.* 2020). Some of this reduction may be avoided by choosing plant species that use C_4 photosynthesis and are tolerant to the predicted extremes of soil moisture and temperature (Janmohammadi *et al.* 2022, 2023; Kianfar

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et al. 2023; Sarker, Oba, Ercisli *et al.* 2022). Amaranth is one such plant species, and it has been successfully grown in Mexico, Guatemala, Nepal, India, Indonesia, China and Nepal (Acar *et al.* 1988).

There is no global data collated for production of amaranth (Aderibigbe *et al.* 2022). A commercial business analyst estimated the global amaranth market to have had a value of USD 1.8 billion in 2020, increasing to USD 3.5 billion by 2030 (Fortune Business Insights 2021). However, the same analyst estimated the US market at $1.48 billion in 2017 (Fortune Business Insights 2018). In the US, amaranth seeds retail at about US $0.88/kg (Iowa State University n.d.), which, if reflected globally, suggests that about 1.5 million tonnes are grown worldwide. China, one of the world's largest producers, was reported in the media as producing 0.8 million tonnes in 2017, but with plans for expansion (Mochan 2017). Amaranth grain has a high nutrient value, and it contains many bioactive compounds, as well as being tolerant of droughts and high temperatures (Baraniak and Kania-Dobrowolska 2022; Oteri *et al.* 2021; Park *et al.* 2020). According to the report of the World Health Organization (WHO 2018; Geneva, Switzerland), amaranth is one of the most neglected and underutilised plant species, in relation to improving feed security, enabling poultry production to be less reliant on dwindling cereal supplies. As such, it is potentially an important tool in combating the effects of climate change (Hosseintabar-Ghasemabad *et al.* 2022; Kianfar *et al.* 2023).

Botanically, amaranth is in the class *Dicotyledoneae*, subclass *Caryophylliid*, order *Caryphyllales*, family *Amaranthaceae* and genus *Amaranthus* (Breus 1997). It is therefore considered a pseudocereal. It is a dicotyledonous plant with an efficient C_4 photosynthetic system due to the presence of phosphoenolpyruvate carboxylase (PEPA) and rubisco enzymes, which are resistant to hot weather and environmental stress. It uses carbon with high efficiency and has low water consumption, as well as having rapid growth and ecological benefits (Jamalluddin *et al.* 2021; Manyelo, Sebola, Hassan, *et al.* 2022; Sarker, Oba, Alsanie *et al.* 2022). There are more than 70 species of *Amaranthus*, many of which are potentially valuable for animal production. Some of the most important are listed in Figure 1, as well as those that are ornamental or weeds (Cai *et al.* 2004; Hosseintabar-Ghasemabad *et al.* 2022). Although outside the scope of this review, it should be noted that amaranth leaf meal can be included in the diet of meat chickens at up to 15% of the diet without loss of productivity or adverse effects on meat quality (Manyelo, Sebola, and Mabelebele 2022).

In poultry diets, amaranth grain can be of similar value to conventional cereals, in terms of energy content, and it can also be used as a protein supplement and a rich source of digestible fibre, antioxidants (vitamins A, C, E, β-carotene, and calcium), iron,

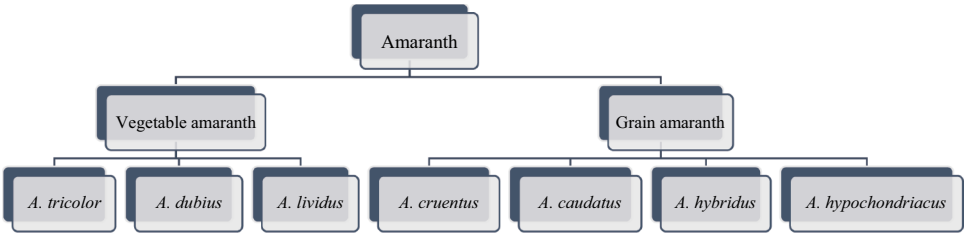


Figure 1. Amaranth species used in nutrition.

manganese and bioactive compounds (carotenoids, flavonoids, polyphenols and phytosterols) (Karamać *et al.* 2019; Nazeer and Firincioglu 2022; Procopet and Oroian 2022). The purpose of this review is to examine the nutritive value of amaranth grain for feeding to poultry.

Methodological approach

The current research was conducted with a focus on the introduction of amaranth nutrients and bioactive substances in poultry nutrition and the effects of these compounds on productivity and health. Since most of the costs in the poultry industry are related to nutrition, and the performance, health and quality of poultry products depend on the composition of the diet, the focus of our searches in Google, Google Scholar, ScienceDirect, Scopus and Web of Science databases used the keywords 'amaranth', 'amaranth grain', 'chemical composition and bioactive compounds in amaranth grain', 'amaranth feeding in broiler chickens', 'amaranth feeding in laying hens', 'amaranth feeding in other poultry'. The methodological recommendations of Park *et al.* (2020), Manyelo *et al.* (2020) and Jimoh *et al.* (2022) were employed in this study.

Carbohydrates in amaranth grain

Whole grain has 7.1–16.4% crude fibre and 7.6% non-starch polysaccharides (NSP) (Cai *et al.* 2004). Mustafa *et al.* (2011) reported total fibre (soluble and insoluble) in the grain of three amaranth species, *A. caudatus*, *A. cruentus* and *A. hypochondriacus*, as between 9.8% and 14.5%. Pedersen *et al.* (1990) found 8–13% crude fibre in amaranth grain, most of which was cellulose and lignin. It is possible to fractionate amaranth grain, which generates a high fibre byproduct, with insoluble and soluble fibre concentrations of 63.9% and 6.86%, respectively (Tosi *et al.* 2001). Neutral detergent insoluble fibre (NDF) and acid detergent insoluble fibre (ADF) concentrations in processed and unprocessed amaranth grains are compared to that in wheat and corn grains in Table 1.

Table 1. NDF and ADF concentrations in amaranth grain, with wheat and corn grains for comparison.

Items	Study reference	NDF (%DM)	ADF (%DM)
Untreated amaranth grain	Janmohammadi *et al.* (2022)	33.9	6.19
Heat-treated amaranth grain	Janmohammadi *et al.* (2022)	34.82	6.84
Raw amaranth grain	Kianfar *et al.* (2023)	34.17	6.25
Autoclaved amaranth grain	Kianfar *et al.* (2023)	35.15	6.92
Raw ground amaranth grain	Jacob *et al.* (2008)	9.53	6.21
Whole raw amaranth flour	Acar *et al.* (1988)	9.59	5.75
Autoclaved whole amaranth flour	Acar *et al.* (1988)	18.12	7.24
Fat-free raw amaranth flour	Acar *et al.* (1988)	8.22	4.29
Fat-free autoclaved amaranth flour	Acar *et al.* (1988)	10.33	4.30
Raw amaranth bran	Acar *et al.* (1988)	20.63	12.73
Autoclaved amaranth bran	Acar *et al.* (1988)	27.05	12.63
Popped grain flour	Acar *et al.* (1988)	23.40	9.80
Wheat	Rostagno *et al.* (2011)	12.26	11.75
Corn	Rostagno *et al.* (2011)	3.19	3.54

Starch is the main component of amaranth grain, and it ranges from 48% to 69% of its dry matter by weight (Cai *et al.* 2004). The starch granules are small, 0.8–2.5 µm, smaller than those in rice (3–8 µm) or potato (15–100 µm) (Cai *et al.* 2004; Corke *et al.* 1997). Light-coloured amaranth grains typically contain more starch than dark-coloured grains (Cai *et al.* 2004; Corke *et al.* 1997). About 86% of the starch is resistant to digestion (Capriles *et al.* 2008). The starch's stable kneading, high viscosity and gelatinous properties, especially after the application of heat (Cai *et al.* 2004; Corke *et al.* 1997, 2016), provide industrial applications in food coating, cosmetic powder, and in making biological and degradable plastic (Karaeva *et al.* 2023; Sayed-Ahmad *et al.* 2022). It is used as a thickener in salad dressings, canned foods, drinks and frozen foods (Cai *et al.* 2004; Dabija *et al.* 2022) and its generally low amylose content and the absence of gluten make it useful in bread and cakes (Balakrishnan and Schneider 2022; Cai *et al.* 2004; Tareh *et al.* 2022). Amylose concentrations vary considerably from 7.8% in *A. hypochondriacus* cultivars to 34.3% in *A. retroflexus* cultivars, with an average in 124 genotypes of 19.2% (Cai *et al.* 2004; Corke *et al.* 1997). The main sugar in amaranth grain is sucrose, which is slightly more than in wheat, triticale and millet (Becker *et al.* 1981; Schmidt *et al.* 2023); however, the amount of monosaccharide and disaccharide in amaranth is low, just 3–5% or less (between 1.8% and 2.2% in *A. cruentus* and *A. caudatus* (Saunders and Becker 1983).

Protein and amino acids in amaranth grain

Amaranth has excellent protein biological value, largely due to its good amino acid balance. Lysine and sulphur-containing amino acids make up 4.4% of the total amino acids of amaranth (Schmidt *et al.* 2023). For human nutrition it is considered second only to eggs, and better than cow's milk (Cai *et al.* 2004; Janmohammadi *et al.* 2022). Since its protein quality is similar to animal sources (Balakrishnan and Schneider 2022; Janmohammadi *et al.* 2023), amaranth grains can be considered an alternative to meat in the human diet (Segura-Nieto *et al.* 1994), not only because of the favourable amino acid composition but also because protein is the second most abundant nutrient (Balakrishnan and Schneider 2022; Cai *et al.* 2004; Segura-Nieto *et al.* 1994). This near perfect balance and quality of amino acids in amaranth grain is due to the existence of simple spherical proteins (Yánez *et al.* 1994). As a proportion of total proteins, albumin is present at 48.9–65%, glutelin 22.4–42.3%, globulin 13.7–18% and prolamin 1–2.3% (Cai *et al.* 2004; Segura-Nieto *et al.* 1994). The first limiting amino acid in amaranth grain has been mainly reported as threonine (Bressani 2003), but also leucine and valine (Bejosano and Corke 1998; Pedersen *et al.* 1987, 1990). The discrepancy may be due to the fact that different genotypes of amaranth have different amino acid profiles. The amino acid profile of amaranth grains is compared to eggs, wheat and corn in Table 2.

Oils and fatty acids in amaranth grain

The oil in amaranth grains is at higher concentrations (5–8%) than cereal grains (Table 3). More than 5% of amaranth oil contains a compound called squalene (2, 6, 10, 15, 19, 23-hexamethyl-2, 6, 10, 14, 18, 22-tetracozahexane), which is widely used in pharmaceutical industries (such as in anticancer, steroid and cholesterol-lowering drugs), cosmetics and health (such as skin and hair softeners), as well as in the

Table 2. Amaranth grain amino acid profile percentage compared to eggs (FAO 1990), wheat and corn (NRC 1994).

Items	Hosseintabar-Ghasemabad *et al.* (2022)	Ravindran *et al.* (1996)	Tillman and Waldroup (1986)	Acar *et al.* (1988)	Tillman and Waldroup (1988c)	Raw (2012)	Egg	Wheat	Corn
Arginine	0.71	1.79	1.43	0.77	1.33	1.06	0.81	0.40	0.38
Histidine	0.23	0.40	0.40	0.23	0.37	0.38	0.32	0.20	0.23
Isoleucine	0.33	0.60	0.57	0.34	0.53	0.58	0.66	0.42	0.29
Leucine	0.62	0.96	0.86	0.50	0.79	0.87	1.11	0.59	1.00
Lysine	0.54	1.01	0.88	0.48	0.81	0.74	0.92	0.31	0.26
Methionine	0.28	0.35	0.35	0.21	0.32	0.22	0.40	0.15	0.18
Phenylalanine	0.43	0.69	–	0.39	0.61	0.54	0.67	0.45	0.38
Threonine	0.38	0.60	0.53	0.31	0.49	0.55	0.55	0.32	0.29
Tryptophan	0.15	–	0.19	–	0.18	0.18	0.19	0.12	0.06
Valine	0.42	0.67	0.64	0.39	0.59	0.67	0.81	0.44	0.40
Alanine	0.41	–	–	0.30	–	0.79	0.72	–	–
Aspartic acid	1.00	1.30	–	0.69	–	1.26	1.30	–	–
Cysteine	0.21	–	0.32	0.23	–	0.19	0.29	0.22	0.18
Glutamic acid	1.61	2.73	–	1.43	–	2.25	1.64	–	–
Glycine	0.72	1.32	1.08	0.65	1.01	1.63	0.43	0.49	0.33
Proline	0.36	–	–	0.35	–	0.69	0.49	–	–
Tyrosine	0.40	–	–	0.35	0.49	0.32	0.53	0.39	0.30
Serine	0.61	0.98	0.81	0.55	0.75	1.14	0.98	0.55	0.37

Table 3. Concentrations of oil and squalene in amaranth grain and other crops.

Items	Study reference	Oil (%)	Squalene in oil (%)	Squalene in 100 g of edible plants
Raw *A. hybridus*	Janmohammadi *et al.* (2023)	5.7	5.14	0.30
Processed *A. hybridus*	Hosseintabar-Ghasemabad *et al.*(2022)	5.2	4.30	0.22
Raw *A. hybridus*	Kianfar *et al.* (2023)	5.5	3.95	0.22
Autoclaved *A. hybridus*	Kianfar *et al.* (2023)	5.4	4.00	0.21
A. cruentus	Cai *et al.* (2004)	5.57–7.72	4.52–5.44	0.25–0.42
A. hybridus	Cai *et al.* (2004)	6.40	5.23	0.33
A. hypochondriacus	Cai *et al.* (2004)	5.35–7.05	3.62–5.01	0.19–0.35
A. tricolor	Cai *et al.* (2004)	5.08	6.14	0.31
Corn	Cai *et al.* (2004)	4	0.03	0.01
Cottonseed	Cai *et al.* (2004)	7	0.01	0.007
Rice	Cai *et al.* (2004)	1–3	0.3	0.003
Olive	Cai *et al.* (2004)	36	0.4	0.14
Peanut	Cai *et al.* (2004)	47	0.03	0.14

aviation and electronic industries (such as airplane fuel, disk cleaners and lubricants in computers) and is currently considered one of the most expensive oils. In addition to amaranth, squalene can be obtained from the oil in the liver of sharks and olive leaves at a high cost. Currently, due to wide range of applications and consequently high price of squalene, many countries cultivate amaranth to extract this oil (phytosqualene) (Cai *et al.* 2004; Sayed-Ahmad *et al.* 2022). The range of fatty acids in amaranth oil in Cai *et al.*'s report (2004) includes palmitic acid (12–25%), oleic acid (35–19%), linoleic acid (25–62%), stearic acid (2–8.6%) and linolenic acid (0.3–2.2%) (Table 4).

In amaranth grain, the ratio of saturated fatty acid (S) to unsaturated fatty acid (U) is 0.1–0.5 (S/U) (Cai *et al.* 2004; León-Camacho *et al.* 2001). The values of C18:1 and C18:2 in amaranth are similar to cottonseed oil and sesame oil (Gamel *et al.* 2007). Phospholipid concentrations in amaranth oil have been measured at 5% (Becker *et al.* 1981) and 3.6% (Opute 1979), with the latter containing 13.3% cephalin, 16.3% lectin,

Table 4. Fatty acid profile in amaranth grain (%).

Items	Hosseintabar-Ghasemabad *et al.* (2020)	Cai *et al.* (2004)	Chung *et al.* (2009)	Palombini *et al.* (2013)
Palmitic acid (C16:0)	7.66	12–25	20.4	15.58
Oleic acid (C18:1, *n*–9)	15.22	19–35	33.3	23.82
Linoleic acid (C18:2, *n*–6)	34.79	25–62	38.2	28.92
γ-linolenic acid (C18:3, *n*–6)	0.30	0.3–2.2	–	0.53
α-linolenic acid (C18:3, *n*–3)	0.37		0.7	0.69

and 2.8% phosphoinositol. Different measurement techniques probably produced these quantitative differences between the various reports (Wirkowska-Wojdyła *et al.* 2022).

Minerals and vitamins in amaranth grain

Minerals in the amaranth plant family vary with species, climatic conditions and soil type, but have been reported to be twice as much as other grains (Gamel *et al.* 2006). Amaranth is rich in calcium and phosphorus, with a Ca:P ratio of 1.2–1.9. In humans, amaranth consumption has been recommended for avoiding osteoporosis and heart disease (Duke 1999). Amaranth is also a rich source of phosphorus, magnesium, potassium, and vitamin C, and has good concentrations of other vitamins. Its concentrations of riboflavin, vitamins C and E, and folic acid compare favourably with wheat (Gamel *et al.* 2006). The amounts of total folate (TF), folic acid (FA), 5-methyltetrahydrofolate (MTHF-5) and 10-formyl tetrahydrofolate (10-CHOTHF) in amaranth grain has been measured at 228 μg/100 g DM, and boiling, steaming and malting reduced TF by 58, 22 and 21%, respectively (Motta *et al.* 2017). According to the European Food Safety Authority (EFSA), a small portion (35 g) of raw amaranth grain provides 25% of the Dietary Reference Intake (DRI) (EFSA 2014) for folate in humans (Motta *et al.* 2017), which suggests that its folate content would be beneficial for poultry diets.

Bioactive compounds in amaranth grain

Amaranth grain has many bioactive compounds with high antioxidant activity, which may be used to improve the health of poultry (Smolentsev *et al.* 2023). They are also beneficial for humans living in semi-arid and arid regions prone to drought who are experiencing malnutrition and metabolic diseases (Sarker, Oba, Alsanie *et al.* 2022). These include phenolic compounds, which exist in grain at a concentration of 168–329 mg/kg, although the extractable compounds are only 70–140 mg/kg (Tang and Tsao 2017). Feeds containing phenolic compounds are valuable for their potential antioxidant properties and strong antimicrobial properties (Ahmed *et al.* 2013). Vitamin E analogs are potent antioxidants with multiple physiological functions, such as regulating metabolic processes, improving anti-inflammatory and anti-cancer properties (Joana Gil-Chávez *et al.* 2013; Tang and Tsao 2017).

There are many other bioactive compounds in amaranth grain, some of which have beneficial effects, such as antioxidants and E group vitamins, and some have anti-nutritional effects, such as saponins and phytates. The bioactive compounds of gallic, protocatechuic and p-hydroxy-benzoic acid are present at 11–440, 4.7–

136 and 5.8–20.9 mg/kg, respectively (Klimczak *et al.* 2002; Woodhead and Swain 1974). The main betacyanin active compounds in amaranth are amaranthine and isoamaranthine, with estimated concentrations of approximately 19 mg/kg (Cai *et al.* 2004; Repo-Carrasco-Valencia *et al.* 2010). Vitamin E homologs include tocopherol and tocotrienols and all four isomeric forms (α, β, γ and δ) have been detected in amaranth grain tocopherols. The highest values have been recorded for γ-tocopherol at 47–53 mg/kg, followed by α-tocopherol at 17–26 mg/kg (Tang and Tsao 2017). β and δ-tocopherol were at trace concentrations. The concentrations (mg/kg) of tocotrienols in amaranth grain have been reported as: α (1.4–31.6), β (0.53–43.86), γ (8.69–0.06) and δ (0.01–48.79) (Bruni *et al.* 2002; Lehmann *et al.* 1994; Tang and Tsao 2017). In the study of Hosseintabar-Ghasemabad *et al.* (2022), amaranth grain had the highest concentration of β+γ tocopherol (293 units), followed by Δ-tocopherol (219 units), with least α-tocopherol (18.60 units). The total content of carotenoids in amaranth has been reported as 17.61–17.69 mg/kg. According to Janmohammadi *et al.* (2023), the most common phytosterol compounds in amaranth grain are β-sitosterol (37%), Δ-5-avena sterol (25%) and stigma sterol (19%). The carotenoids in this category of plants include lutein and zeaxanthin, which have many benefits in improving the health of consumers (Tang *et al.* 2016). An active compound in amaranth, 20-hydroxyacedizone (20HE), present at 148–484 mg/kg), can affect muscle protein synthesis and reduce blood glucose, thus helping to control obesity and diabetes, at least in mice (Foucault *et al.* 2012).

Saponins in amaranth grain have been measured at 0.9–4.91 mg/kg and 0.9–1.0 mg/kg DM, with concentration increasing linearly 24–240 hours after germination of amaranth seeds (Oleszek *et al.* 1999). Several types of saponins have been identified in amaranth grain, and they can be divided into subgroups oleanolic acid, hederagenin or phytolaccagenic acid as aglycones (Junkuszew *et al.* 1998). 3-O-β-di-glucopyranosyl oleanolic acid is a sapogenin with anti-inflammatory activity (Kuljanabhagavad and Wink 2009).

Phytic acid (myinositol hexaphosphoric acid) in amaranth has been reported to be between 2 and 8 g/kg (Breene 1991; Escudero *et al.* 2004; Gamel *et al.* 2006; Kozioł 1992; Tang and Tsao 2017), reduced by 15–20% with thermal processing (Gamel *et al.* 2007). Germination is mainly a catabolic process to deliver nutrients to the growing plant through the hydrolysis of stored nutrients, and phytic acid plays an important role as a source of phosphorus and cations during this process. There is more phytic acid in amaranth than in rice (1–1.4 g/kg), but less than in corn (9 g/kg) or in wheat (9.8–14.3 g/kg) (Cai *et al.* 2004; Lorenz and Wright 1984). In addition to phytic acid and saponin, amaranth has other anti-nutritional compounds such as tannins, oxalate and various inhibitors of trypsin, chymotrypsin and amylase (Chemeda and Bussa 2018). Lorenz and Wright (1984) found the phytate to be between 5.2 and 6.1 g/kg in eight varieties of amaranth grain, higher than rice and millet but less than corn and wheat. *A. cruentus* and *A. hybridus* cultivars have the most tannins (Lorenz and Wright 1984). Dehulling the grain significantly reduces tannin and improves protein digestibility because the amount of tannin in the shell is more than six times that of dehulled grain (Lorenz and Wright 1984).

Table 5. The effect of using different amounts and forms of amaranth grain on bird performance, health, meat and egg quality, listed in chronological order of publication.

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Connor *et al.* (1980)	Broiler chickens	*A. edulis*	Raw	Feeding raw amaranth up to 71% led to a decrease in body weight, feed consumption and feed conversion efficiency.	The feathers were wrinkled and mucous secretions were observed in the mouth, and the head was retracted, as in star gazing.	The presence of anti-nutrients, such as oxalate and nitrate, was noticeable in the amaranth species.	The amaranth species was similar to cereals in terms of nutrient content. However, due to the presence of anti-nutritional compounds and the possible toxicity of the seed in its raw form, high consumption levels were not recommended.
Connor *et al.* (1980)	Broiler chickens	*A. edulis*	Processed	Feeding up to the level of 74% led to a decrease in feed consumption and body weight. Feed conversion efficiency was similar to the control group.	Feathers were ruffled and liver tissue was pale.	Hepatotoxicity was detected	After thermal processing by autoclaving, the desired species could replace up to 70% of grains and protein concentrates.
Laovoravit *et al.* (1986)	Broiler chickens	*A. cruentus*	Raw	Included at 10% and 30% of the diet. No problems were observed at 10%, but at 30% there was reduction in feed consumption and growth	Pallor was noticeable in the liver, although liver cholesterol content was similar to the control group.	Decreased performance at 30% of the diet was attributed to anti-nutritional compounds and reduced availability of nutrients.	Raw amaranth can be included at up to 10% of the diet without loss of performance
Laovoravit *et al.* (1986)	Broiler chickens	*A. cruentus*	Processed	Included at 10% and 30% of the diet. Growth performance was similar to the control group.	Paleness in the liver decreased by autoclaving amaranth. Liver cholesterol contents were similar to the control group.	Despite reduction of anti-nutrients with thermal processing, performance appeared to be restricted by thiamine deficiency at high amaranth inclusion rates.	Autoclaved amaranth could be included at up to 30% of the diet without loss of performance.

(*Continued*)

Table 5. (Continued).

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Laovoravit *et al.* (1986)	Broiler chickens	*A. cruentus*	Processed	Inclusion of amaranth at 78% of the diet did not affect chick growth. On d 17 weight loss was observed.	On day 17 symptoms of convulsions, stargazing, stretched legs and folded heads were observed in the chickens.	At these high inclusion rates, the clinical symptoms were similar to those of thiamine deficiency.	Very high rates of feeding amaranth are likely to lead to thiamin deficiency
Waldroup *et al.* (1985)	Broiler chickens	*A. cruentus* and *A. hypochondriacus*	Raw and autoclaved	Included at 20% and 40% of the diet. Neither raw nor autoclaved forms adversely affected performance at 20%. At 40% weight gain and feed intake reduced, but less after autoclaving.	No pathological lesions or toxicity effects	At levels of more than 20%, the increase of non-nutritive compounds (saponin and phenolic compounds) led to a decrease in growth. In *A. hypochondriacus*, the decrease was greater.	At 20%, inclusion rate, performance was acceptable.
Tillman and Waldroup (1986)	Broiler chickens	*A. cruentus*	Autoclaved and extrusion	Performance was similar to control diet at 20% and at 40% if properly processed.	None reported	Wet extrusion did not work well	Amaranth grain can be used up to 40% in the diet if properly processed by autoclaving and extrusion.
Tillman and Waldroup (1988c)	Broiler chickens	*A. cruentus*	Extruded	At levels of 10–40%, no negative effect on performance was observed. At 50% growth was retarded.	No lesions or fat infiltration in the liver, but some liver and abdominal fat hypertrophy at high inclusion rates. Gizzard weight declined with amaranth inclusion.	At 50 % inclusion, feed refusal or low digestibility reduced growth.	Extruded amaranth feeding up to 40% level can be recommended as a feed source in feeding broilers without negatively affecting performance and carcass characteristics.

(*Continued*)

Table 5. (Continued).

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Acar *et al.* (1988)	Broiler chickens	*A. cruentus*	Raw and autoclaved	In the autoclaved form, growth was significantly greater than the raw form and equivalent to Control diet. Raw amaranth decreased feed conversion efficiency.	None reported	Amaranth flour, fat-free flour, perisperm, bran and popped amaranth in both raw and autoclaved forms were tested. Perisperm increased growth and popping reduced it.	Autoclaved amaranth grain and its fractions can mostly be used like corn.
Ravindran *et al.* (1996)	Broiler chickens	*A. hypochondriacus*	Raw and autoclaved	20% and 40% autoclaved and raw amaranth included. Feed intake increased for raw amaranth and growth reduced, even with amino acids.	No pathological lesions. In the diet containing 60% amaranth, hypertrophy of liver (and proventriculus in some birds), decrease in heart weight and increase in pancreas weight.	The presence of heat-labile anti-nutritional factors in raw amaranth was suspected. of amaranth.	The thermal processed form can be included in the diet of broilers up to 40%.
Kabuage *et al.* (2002)	Broiler chickens	*A. hypochondriacus*	Raw and extruded	40% raw and 60% extruded included. 60% decreased growth unless casein added. Feed intake increased for raw amaranth and growth reduced, even with amino acids. No effect for extruded amaranth.	Mineral availability increased with with extrusion. Zn retention increased.	Casein supplementation allowed 60% amaranth to be included without loss of performance.	Extrusion and fortification with casein improved utilization.
Pisarikova *et al.* (2006)	Broiler chickens	*A. cruentus* and *A. hypochondriacus*	Raw and popped	Trend for reduced chicken weight at end of experiment with popped amaranth, compared with raw, at 10% of diet.	No negative effects on health were reported.	Popped amaranth had reduced CP, EE, NDF, GE, NFE and OM digestibility.	By feeding amaranth, no negative effect was observed on performance, health and meat quality.
Longato *et al.* (2017)	Broiler chickens	*A. caudatus*	Raw	Decreased growth was observed at 5% and 10% amaranth. Meat quality unaffected.	Decreases in serum cholesterol and triglycerides at 5 and 10% amaranth.	Dietary lipid oxidation decreased and antioxidants increased with amaranth.	Amaranth feeding could improve bird health.

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Table 5. (Continued).

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Tillman and Waldroup (1987)	Laying hens	*A. cruentus*	Extruded	Compared with the Control diet, 10% and 20% amaranth in the diet increased egg production rate but reduced egg weight. No effect on daily egg mass.	None reported	With increasing amaranth, yolk were more yellow and less orange; no other effects on egg quality.	If the amaranth grain is properly steam extruded, it can be used up to 30% in the diet of laying hens without any negative effects on production performance and egg quality.
Qureshi *et al.* (1996)	Laying hens	*A. cruentus* and *A. hypochondriacus*	Raw, milled and popped	Compared with Control diet, 20% amaranth reduced serum LDL by up to 70%, but not HDL.	By feeding amaranth grain, apolipoprotein decreased and the activity of 7alpha-hydroxyl cholesterol increased. HMG coenzyme-A decreased in popped, milled amaranth.	Amaranth is rich in tocotrienols and squalene. Serum apolipoproteins reduced. Popped amaranth most effective, maybe due to high squalene content.	In addition to tocotrienols and squalene compounds, amaranth contains strong and other inhibitors against harmful cholesterol, and the effects of reducing cholesterol were beyond expectations.
Króliczewska *et al.* (2008)	Laying hens	*A. cruentus*	Raw	Amaranth at 2%, 5% and 10%.	A decrease in blood cholesterol, triglycerides, LDL, ALT and AST at 10%.		At the highest level, lipid parameters were improved.
Popiela *et al.* (2013)	Laying hens	*A. hypochondriacus*	Extruded	5% and 10% of diet tested. 5% but not 10% increased blood AST, egg production and feed conversion efficiency. Egg quality unaffected.	With increasing consumption of amaranth, in the blood glucose decreased. Fatty acid composition of egg yolks largely unaffected.		5% amaranth more beneficial than 10%.
Rodríguez-Ríos *et al.* (2020)	Laying hens	*A. cruentus*	Autoclaved	15%, 30% and 45% of diet. 45% increased rate of lay, and feed intake, with feed conversion efficiency reduced.	Egg yolk cholesterol unaffected by inclusion of amaranth.		Conclusion that egg yolk cholesterol declined not supported by data provided.

(*Continued*)

Table 5. (Continued).

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Hosseintabar-Ghasemabad *et al.* (2022)	Laying hens	*A. hybridus*	Autoclaved	10%, 20%, 30% and 40% of the diet. 30% and 40% inclusion reduced egg weight, in total and daily, and reduced feed conversion efficiency.	30% and 40% amaranth reduced egg yolk cholesterol. All levels increased antioxidants, triglycerides, total cholesterol and HDL in serum. LDL decreased with amaranth.	Effects attributed to antioxidants, squalene, and reduction in enzymatic activity of cholesterol 7-alpha hydroxylase, 3-hydroxy-3 methylglutaryl coenzyme A reductase in liver.	Amaranth feeding, improved some blood parameters related to the health of birds and also led to the production of low-cholesterol eggs, when included at high levels.
Janmohammadi *et al.* (2023)	Laying hens	*A. hybridus*	Raw	10%, 20%, 30% and 40% of the diet. Decreased egg production, egg mass, yolk cholesterol, and feed conversion efficiency at all levels.	Blood cholesterol declined and HDL increased at all levels.	A 10% reduction in egg cholesterol was observed in birds fed with amaranth. The studied amaranth was known to be a rich source in terms of phytosterol and tocopherol bioactive compounds as well as squalene.	Feeding raw amaranth was able to improve the health of the bird without negatively affecting the egg quality, and at the same time, low-cholesterol eggs were produced.
Kianfar *et al.* (2023)	Laying hens	*A. hybridus*	Raw and autoclaved	5%, 10% and 15% of the diet. Raw amaranth at 15% decreased egg production, yolk cholesterol, blood glucose and feed intake. Amaranth increased linoleic acid and PUFA in eggs.	10% and 15% reduced blood triglyceride compared with 5%. Amaranth reduced blood cholesterol and increased blood antioxidants and glucose.	Blood effects attributed to antioxidants in amaranth	Autoclaved amaranth preferable to raw form and can maintain performance whilst improving egg quality.
Jakubowska *et al.* (2013)	Japanese meat quail	*A. cruentus*	Raw	4% and 7% of the diet. 4% improved breast muscle tenderness, 7% reduced palatability.	No effects reported; no change in chemical composition or fatty acid profile.		The lower dose rate may be more likely to have beneficial effects

(*Continued*)

Table 5. (Continued).

Reference	Poultry group	Specie	Amaranth grain form	Effects on performance	Effects on health	Explanations and reasons	Conclusions
Szczerbinska *et al.* (2015)	Japanese quail layers	*A. cruentus*	Raw	4% and 7% of the diet. Egg production declined at 7%. Amaranth reduced feed consumption. % yolk increased with 4% amaranth. Reproduction improved.	At the level of 7% amaranth feeding, an increase in the concentration of cholesterol, triglyceride, LDL and albumin and the level of liver enzymes in the serum was reduced.	Squalene and PUFAs believed to have improved reproduction	Only 4% level in quail feed was recommended to maintain performance and bird health.

Amaranth grain feeding to the major poultry groups

The effects of incorporating amaranth grain into the diets of the major poultry groups is summarised in Table 5 and detailed below.

Amaranth grain feeding to broiler chickens

It is almost half a century since the first studies of the use of amaranth (*A. edulis*) grain in poultry nutrition (Connor *et al.* 1980), which found that it was rich in the essential amino acids, lysine (0.94%), methionine and cysteine (0.66%), arginine (1.54%), and threonine (0.59%). Thus, it had a better amino acid balance than many cereals. The apparent metabolisable energy contents, corrected to zero nitrogen balance (AME_n), were 3145 and 3475 kcal/kg, for raw and processed grain, respectively. Thermal processing allowed up to 70% of conventional high protein concentrates to be replaced by amaranth grain, without loss of performance.

In the 1980s, many studies were conducted on amaranth grain in poultry diets. Laovoravit *et al.* (1986) found that *A. cruentus* grain, with 13.5% protein and 0.96% lysine (Laovoravit 1982), could be included at 30% of the diet of broiler chickens if autoclaved. Supplementing amaranth-based diets with thiamine sources (diet containing wheat) was recommended, particularly because thiamine is important in regulating chicken growth.

Later, it was confirmed that heat processing can increase protein digestibility (Písaříková *et al.* 2005); however, the amount and duration of heating should be carefully programmed, because protein quality depends not only on amino acid composition, but also on bioavailability and digestibility of protein. The digestibility of protein, available lysine, net protein utilisation (NPU), protein efficiency ratio (PER) or biological value (BV) are very high in amaranth compared to cheese in human nutrition. The average protein digestibility of amaranth is variously reported to be 74% (Bejosano and Corke 1998) and 80–86% (Gamel *et al.* 2006). Roasting at 170–190°C gives the best increase in digestibility (Písaříková *et al.* 2005). However, in the popping process, trypsin inhibitors and other anti-nutritional agents are deactivated, but it also causes the loss of several essential amino acids, especially tyrosine, phenylalanine, methionine, and lysine, and subsequently, a noticeable decrease in protein quality (Gamel *et al.* 2006). This suggests a decrease in the biological value of protein at very high temperatures, and the possibility of denaturation and Maillard reaction, and in parallel, a decrease in the nutritional value of amaranth grain (Bressani *et al.* 1993). Steam dehulling of amaranth grain can also lead to improved performance in broilers (P. G. Peiretti *et al.* 2017).

Tillman and Waldroup (1986) studied the usefulness of amaranth grain (*A. cruentus*), processed either by autoclaving or extrusion, to replace corn/soyabean diets for broilers at 20% or 40%. This study and that of Waldroup *et al.* (1985) indicated that inclusion of amaranth grains at 40% depresses growth rate unless the grain is suitably processed by autoclaving or extrusion. It did not depress growth, even at 40% inclusion rate, if it was properly processed by dry extrusion or autoclaving for 30–45 min. Later work by Tillman and Waldroup (1988c) confirmed that at 50% replacement growth reductions occurred in the finisher period.

Several different forms of raw, autoclaved and processed amaranth grain were evaluated for feeding to broiler chickens by Acar *et al.* (1988). Their control diet of primarily corn and soybean meal contained 3060 kcal/kg of metabolisable energy and 23.6% protein, and all the experimental diets were formulated with similar metabolisable energy and protein contents. The various treatments tested compared whole grain flour amaranth (61.46% of diet), fat-free amaranth flour (62.10% of diet), perisperm (49.50% of diet), amaranth grain bran (35.30% of diet) and popped amaranth flour (61.10% of the diet). Crude protein (CP) contents varied between 9.6% and 29.6% for the different forms of amaranth studied. Ether extract, crude protein, crude fibre and ash in bran were lower than whole grain flour and the lowest values were for perisperm. Autoclaving whole grain flour increased ADF, NDF, cellulose and lignin contents, with new complexes formed after thermal processing. There was no effect on metabolisable energy concentrations, except in the perisperm in which it was reduced. Bran had the highest protein, alanine, arginine, glutamic acid, proline and tyrosine concentrations. Heat-treatment reduced lysine concentrations, but autoclaving improved broiler performance, probably due to reduced levels of antinutritive compounds and improved bioavailability of some nutrients.

In a similar study, Ravindran *et al.* (1996) evaluated the nutritional value of *A. hypochondriacus*, in raw and autoclaved form for feeding to broiler chickens. The raw grain contained 168, 58, 60, 26, 2.2 and 5.6 grams per kilogram crude protein, crude fat, crude fibre, total ash, calcium and total phosphorus, respectively. Replacement of the basal maize/soyabean meal/meat and bonemeal diet with raw amaranth grain depressed growth and increased FCR. However, they were able to overcome these negative effects by autoclaving the grain at 130°C for one hour, suggesting that there were heat-labile antinutritive elements within the grain. The authors suggest that phenolics, in particular tannins, were most likely responsible, though lectins, trypsin inhibitors and troponins may also have been implicated. The authors conclude that processing increased AME from 11.9 to 13.1 MJ/kg DM and confirmed that processed amaranth grain can be included at up to 40% of the diet without loss of performance.

Yaghobfar (2001) determined the chemical composition of amaranth grain as, in g/kg, crude protein 166, crude fat 73, linoleic acid 50.8% of total fat, ash 35, cellulose 250, hemicellulose 45, cell wall excluding hemicellulose 205, lignin 86, protein digestibility 140, lysine 10.3, methionine 3.4, cysteine 2.5, alanine 5.7, arginine 11.0, asparagine 14, leucine 10.4, proline 10.5, phenylalanine 6.4, threonine 5.6, histidine 3.8, glycine 12.0, glutamine 29.5, tyrosine 5.7, valine 6.0, isoleucine 5.5 and glucose 75. The metabolisable energy concentration for raw amaranth was 1805 and extruded amaranth 2275 kcal/kg.

Several studies have found no change in growth of broiler chickens fed unheated amaranth, compared with a control diet Waldroup *et al.* (1985), Serratos (1996), Roučková *et al.* (2004) and Písaříková *et al.* (2005), but this is only when it was included at low rates in the diet. Waldroup *et al.* (1985) found that there was no effect on growth of inclusion of *A. hypochondriacus* or *A. cruentus* grains at 20% of the diet for broiler chickens in the raw and autoclaved forms, but at 40% there was an adverse effect on performance, particularly for *A. hypochondriacus*. Autoclaving reduced these negative effects on the growth of this species. Extrusion, rather than autoclaving, is probably the best method of processing, based on practical considerations and potential benefits (Tillman and Waldroup 1986).

Amaranth grains were able to replace animal origin protein sources, such as meat and bone meal, which are increasingly hard to source, for feeding to broilers (Roučková *et al.* 2004). Amaranth grain is also a suitable substitute for fishmeal (Pisarikova *et al.* 2006), in the raw, heat-processed and dried grains. Pelleting amaranth-containing diets leads to improvement of body weight, feed consumption, feed efficiency and reduction of carcass fat in broiler chickens (Alizadeh-Ghamsari *et al.* 2021). The popping process leads to a change in the content of chemical compounds and protein digestibility, and the differences in nutrient contents between raw and popped amaranth grain were, in g/kg: crude protein 158.1 for raw amaranth, which after popping became 168.5, fat 71.5 for raw amaranth, which after popping became 69.4, NDF 99.2 for raw amaranth, which after popping became 111.8, cellulose 86.6 for raw amaranth, which after popping became 60.0, cysteine 4.2 for raw amaranth, which after popping became 4.1, threonine 6.0 for raw amaranth, which after popping became 6.5, alanine 8.8 for raw amaranth, which after popping became 9.2, valine 6.8 for raw amaranth, which after popping became 7.4, isoleucine 5.2 for raw amaranth, which after popping became 5.6, lysine 9.2 for raw amaranth, which after popping became 8.8, arginine 12.8 for raw amaranth, which after popping became 14.2, *in vitro* protein digestibility 68.1 for raw amaranth, which after popping became 50.6%, respectively (Písaříková *et al.* 2005). Similar improvement was reported by Bressani *et al.* (1993) and Andrasofszky *et al.* (1998). Inclusion at up to 10% was deemed appropriate. Inclusion at 5% and 10% led to some decrease in performance in the work of Longato *et al.* (2017), but the antioxidant in serum increased from 177 (μEq/l) to 219 and 250 units, and lipid peroxidation in the serum of chickens decreased from 700 micromol/ml to 419 and 262 units, respectively. Alizadeh-Ghamsari and Hosseini (2020, 2021) considered that an inclusion at 2% or less gave the maximum performance. Incorporating amaranth grain at 8% of the diet of meat chickens reduced both feed intake and growth rate, but did not affect FCR, in the study of Orczewska-Dudek *et al.* (2018).

Extruded amaranth (*A. cruentus*) grain is reported to contain AME and AME_n values of 3556 and 3415 kcal/kg DM, respectively (Tillman and Waldroup 1988a). The AME_n content of raw and processed amaranth has been determined in Ross 308 broiler chickens (Janmohammadi *et al.* 2022). The main constituents of the basal diet were replaced by between 0% and 60% amaranth, in the untreated or heat-treated form, and with or without an enzyme additive. Total excreta collection was used to create regression models to determine AME_n content, which was estimated at 3260 and 3900 kcal/kg for untreated and heat-treated grain, respectively. Enzyme addition produced a small benefit in AME_n content. These energy concentrations were 230 and 470 kcal/kg more than corn and wheat grains, respectively. In addition, the amaranth grain had about twice the crude protein content of corn.

In the digestibility studies of feeding poultry with amaranth, Tillman and Waldroup (1988b) found that amaranth could be included at up to 40% in the diet, but above this level growth rate was reduced. However, abdominal fat pad, liver and gizzard weight was increased with the proportion of amaranth in the diet.

Amaranth grain incorporation into the diet of meat chickens increased the *n*-3 fatty acid in breast muscle and, amaranth being rich in antioxidants, protects against excessive oxidation of lipids, leading to better sensory properties (Orczewska-Dudek *et al.* 2018). As well, it reduced triglycerides in blood and abdominal and subcutaneous fat content.

Being rich in antioxidants, in particular quercetins such as rutin, amaranth vegetative growth could potentially be used as a phytobiotic replacement for antibiotics in the diet of broiler chickens (Drannikov *et al.* 2021). Quercetin contents vary with amaranth species, being greatest for *A. caudatus* (16 mg/kg DW) and least for *A. tricolor* (<2 mg/kg DW).

Amaranth grain feeding to laying hens

The use of amaranth in the nutrition of laying hens is of special importance due to the risks posed by cholesterol in egg yolks and its challenges to the health of consumers in the form of non-communicable diseases. Some cholesterol is necessary in the human diet – the American Heart Association reported that the consumption of 300 mg of cholesterol per day is sufficient to maintain health, hence a large egg containing 210 mg of cholesterol can be consumed daily provided that other foods consumed do not increase cholesterol intake to dangerous levels (Baghban-Kanani *et al.* 2019, 2020; Rodríguez-Ríos et al. 2020). Several methods can be used to reduce the cholesterol content of eggs: genetic modification (although the cholesterol content is not well inherited), hypocholesterolemic drugs, and flock management (Elkin 2007), but incorporating amaranth into the diet is likely to be one of the most effective.

The ratio of polyunsaturated fatty acids (PUFA) to saturated fatty acids (SFA) in eggs is about 0.5 (Mine 2008). Increasing this ratio can decrease serum cholesterol of egg consumers (Mine 2008). Amaranth reduces cholesterol in eggs through multiple mechanisms, which generates a reduction in cholesterol in consumers' blood and liver (Mine 2008). In particular, compounds such as crude fibre, squalene, phytosterols, tocopherols and tocotrienol found in amaranth can reduce the biosynthesis of cholesterol in poultry (P. Peiretti 2018). Some unique compounds in amaranth grain can limit the production rate of HMG-CoA reductase enzyme in the liver, which will lead to cholesterol reduction. Crude fibre in amaranth reduces cholesterol by binding to it and removing it from the animal's body. Abundant linoleic acid in amaranth grain can play an important role in eliminating bile acids and reducing cholesterol. Also, an exclusive component in amaranth grain is squalene, which, if consumed, is sequestered by the liver with the help of chylomicrons and used to make steroids and bile acids. Bile acids (cholic and deoxycholic) combine with glycine and taurine and produce bile salts, and by increasing the recycling of bile secretions, reduce yolk cholesterol (Kianfar *et al.* 2023). Nutritional modification of cholesterol in chickens'eggs is therefore feasible. Other feeds to reduce egg cholesterol in the diet of laying hens include black cumin (*Nigella sativa*) (Aydin *et al.* 2008), zucchini (*Cucurbita maxima duchesne*) (Orozco-Martínez *et al.* 2012), rapeseed (*Brassica napus*) (Caston and Leeson 1990), chia (*Salvia hispanica*) (Salazar-Vega *et al.* 2009), sunflower meal (*Helianthus annuus*) (Baghban-Kanani *et al.* 2018), seaweed (*Sargassum* spp) (Carrillo *et al.* 2012), Artemisia (*Artemisia annua*) (Baghban-Kanani *et al.* 2019), spirulina algae (*Spirulina platensis*) (Tufarelli *et al.* 2021), and flaxseed (*Linum usitatissimum*) (Tufarelli *et al.* 2022).

Qureshi *et al.* (1996) reported that supplementing the diet of chickens with *A. hypochondriacus* and *A. cruentus* led to a 10–30% reduction in blood cholesterol of birds. LDL decreased by 7–70%. In the control group, a 10–18% decrease in the enzyme activity of cholesterol 7-alpha hydroxylase, 3-hydroxy-3-methylglutaryl coenzyme A reductase was observed in the liver compared to other experimental groups, which

presumably caused the decrease in blood cholesterol in experimental birds. Activation of 7-alpha hydroxylase enzyme leads to the formation of bile acids from cholesterol and increases the catabolism and excretion of cholesterol. It has been shown in hamsters that the cholesterol-lowering effects of amaranth grain were probably due to peptides reducing HMG-CoA reductase enzyme (Mendonça *et al.* 2009; Soares *et al.* 2015). Additional studies showed that the presence of a special phytochemical compound in amaranth grain called 20-hydroxyacedizone (20HE) can lead to increased anti-obesity effects (reduction of triglyceride and cholesterol) and LDL) and even antidiabetic in mice (Foucault *et al.* 2012; Pond *et al.* 1989; Tang and Tsao 2017). Also, the tocopherols in amaranth are more than in cereals, which can reduce the synthesis of cholesterol, low-density lipoprotein and the enzyme lipoprotein lipase, and ultimately regulate and reduce cholesterol in the blood (León-Camacho *et al.* 2001; Qureshi *et al.* 1996; Santiago *et al.* 2014; Schnetzler and Breene 1994; Tang and Tsao 2017). Hood (1998) reported that eight isomers of vitamin E present in amaranth grain oil cause a 30% and 70% reduction of cholesterol and LDL, respectively, in chickens. β-phytosterol in amaranth grain has also a major effect in reducing LDL cholesterol and increasing HDL blood without side effects (Awad *et al.* 2000; Marcone *et al.* 2003; Tang *et al.* 2016).

These theoretical benefits of including amaranth have been repeatedly demonstrated in practice: Króliczewska *et al.* (2008) incorporated 2–10% *A. cruentus* grain into the diet of layers and observed a decrease in blood low-density lipoprotein cholesterol and triglyceride, and an increase in aspartate aminotransferase and alanine aminotransferase activity, compared to the control group. Popiela *et al.* (2013) investigated the performance, blood characteristics, egg quality traits and the composition of egg yolk fatty acids in sixty brown Lohmann laying hens offered diets containing 0%, 5% and 10% extruded amaranth grain. Birds fed with a diet containing 5% amaranth had the lowest FCR and the highest egg production, and birds on this diet had decreased and increased linoleic acid (omega-6) and linolenic acid (omega-3), respectively. Blood glucose, aspartate aminotransferase and alanine aminotransferase decreased with increasing levels of extruded amaranth grain. Tillman and Waldroup (1987) incorporated extruded *A. cruentus* grain in the diet of 20, 65-week-old White Leghorn laying hens at 0–30% of the diet. Inclusion of amaranth tended to increase the rate of lay, but reduced egg weight, whilst improving feed conversion efficiency. Yolk colour declined as the proportion of amaranth in the diet increased. Punita and Chaturvedi (2000) incorporated *A. paniculatus* grain in diet of laying hens and found that the amount of linoleic acid increased by 100% and cholesterol in the eggs decreased by 14%. The highest cholesterol reduction and highest amounts of linoleic acid was observed in a treatment containing mixed red palm oil + popped amaranth grain. Reklewska *et al.* (1995) similarly reported a reduction of triacyl-glycerides and saturated fatty acids and cholesterol in egg yolk. Kianfar *et al.* (2023) including untreated and autoclaved *A. hybridus* amaranth grain in the diet of experimental birds separately, with 0%, 5%, 10% and 15% levels, for six weeks, found that the 5% and 10% levels decreased blood glucose, cholesterol and triglycerides and produced eggs with low cholesterol and triglyceride content. However, the content of omega-6 in eggs and subsequently the ratio of omega-6 to omega-3 in the yolk increased.

No reduction in egg yolk cholesterol was observed when amaranth was included at 15–45% of the diet (Rodríguez-Ríos *et al.* 2020). However, feeding amaranth grain (*Amaranthus hybridus chlorostachys*) that had been thermally processed and included

at up to 40% in the diet did reduce yolk cholesterol (Hosseintabar-Ghasemabad *et al.* 2022), by 10% at a 30–40% inclusion rate. In this study feeding amaranth at 30–40% of the diet reduced egg mass and increased feed conversion ratio; however, inclusion of a multienzyme preparation, including cellulase, xylanase, pectinase, β glucanase, α-amylase, protease and phytase in the diet negated these adverse effects. Amaranth inclusion caused a decrease in triglyceride, cholesterol, LDL, atherogenic index and a parallel increase in HDL and total antioxidant capacity. Janmohammadi *et al.* (2023) confirmed this and attributed egg cholesterol reduction to the abundance of phytosterol and tocopherol bioactive compounds in raw amaranth grain, along with the presence of squalene. More broadly, amaranth inclusion in the diet of poultry can help combat climate stress, because of the drought-resistant properties of the plant, thereby helping to prevent malnutrition and hunger in humans and livestock (Nwadinigwe *et al.* 2019).

Amaranth grain feeding to other poultry

Breeder chickens

Including 3–7% of amaranth grain in the feeding of breeder hens accelerated sexual maturity, increased the number and weight of eggs and the rate of hatchability and chick production (Vishtakalyuk *et al.* 2001). The existence of the desired profile and types of unsaturated fatty acids in amaranth grain, along with significant amounts of squalene, produces a positive effect on sperm motility and can reduce the risk of defects, because omega-3 and omega-6 fatty acids can significantly protect chromosomes against abnormalities, and in parallel, the presence of squalene in amaranth grain sources can neutralise mitochondrial function disorders and assist in sperm development (Singhal and Kulkarni 1988). Also, Vishtakalyuk *et al.* (2001) observed an increase in egg white and yolk %. Khiroug *et al.* (2001) investigated low-cholesterol nutrition of birds, and after adding amaranth grain polysaccharides to the feed of breeder hens, they increased the weight of eggs and white %. Thus, amaranth grain in the feeding of breeder chickens can affect the morphological composition of the egg (Szczerbinska *et al.* 2015).

Cockerels

The AME_n values of amaranth have been determined by feeding amaranth to adult Leghorn cockerels (Hosseintabar-Ghasemabad *et al.* 2020). AME_n values for untreated amaranth with enzyme were 3433 kcal/kg and untreated amaranth without enzyme 3250 kcal/kg. Processed amaranth had similar values, and overall enzyme addition led to a 5–6% improvement in ME value.

Quail

Jakubowska *et al.* (2013) investigated the effects of adding amaranth grain (at 0%, 4% and 7%) in standard isocaloric and isoprotein quail diets, in a study using thirty-six adult female quails (20 weeks). The low level of amaranth led to the improvement of breast muscle tenderness and the high-level reduced breast meat palatability. Szczerbinska *et al.* (2015) investigated *A. cruentus* grain incorporation

at 0%, 4% and 7% in the diet of quail and found that feeding birds with rations containing amaranth had improved egg hatchability. The percentage of yolk in eggs in the group fed with 4% amaranth was more than the other experimental groups, and at 7% there was an increase in the concentration of cholesterol, triglyceride, LDL and albumin, and a decrease in liver enzymes.

Turkeys

Organically grown amaranth has been compared with buckwheat (*Fagopyrum esculentum*), white and yellow corn and wheat for feeding to adult turkeys (Jacob *et al.* 2008). However, in this study the amaranth seeds were not ground because of their small size, whereas the cereal grains were. Although the GE and CP contents of the amaranth were highest, the nitrogen-corrected ME values were less than all the cereals except buckwheat. It was less well utilised by turkeys than chickens.

Conclusions

This review showed that amaranth grain has a favourable content of nutrients, including carbohydrates, protein, fat, minerals and vitamins compared to cereals. In addition, the profile of amino acids, fatty acids and bioactive compounds in the grain indicate potential benefits of including amaranth in feed programmes, provided that it is effectively processed and not included at more than 40% of the diet. Heat processing the grain reduces the effects of anti-nutritive compounds and can improve bioavailability of nutrients. A particular benefit of including amaranth in the diet of layers is the reduction in egg cholesterol content. The antioxidant compounds and squalene, as well as the ideal amino acid balance in amaranth, can be effective in improving the health of the flock, as well as increasing the quality and quantity of poultry products, without affecting the performance negatively.

Acknowledgements

Financial support by Rasht Branch, Islamic Azad University, grant number 17.16.1.575 is gratefully acknowledged. The work was done in accordance with the State task of the State Scientific Institution NIIMMP.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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