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REVIEW

THE ROLE OF CAROTENOIDS IN AVIAN NUTRITION: IMPACT ON MEAT QUALITY AND COLOR

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Abstract: Carotenoids are natural pigments found in various plant sources that not only give color to food, but also possess antioxidant properties and nutritional benefits. This paper analyzes the natural sources of carotenoids and their effect on the color of chicken, in the context of the importance of this sensory attribute in consumer perception.

Carotenoids are absorbed in the small intestine and transported throughout the body, where they are stored in adipose tissue and skin. They integrate into the lipid matrix of muscle tissue, thus influencing the color of the meat and, at the same time, improving the immune response due to their role as precursors of vitamin A. Diets high in carotenoids can also affect the composition of meat fats, contributing to a more balanced nutritional profile. Interest in the use of carotenoids as feed ingredients has increased significantly due to their bioactive properties and beneficial effects on health. Currently, a wide range of products are available on the market, offered in the form of additives, supplements or food colorings

Keywords: *broiler, carotenoids, meat color, natural pigments*

INTRODUCTION

Poultry meat enjoys great popularity all over the world, due to its high nutritional value and low lipid content, but also for the special quality of the muscle fibers and special sensory properties [1]. For a long time, the induction of attractive colors/shades in the various animal products was based on the use of synthetic dyes, and the maintenance of animal health was achieved by the administration of antibiotics [2].
Such practices are increasingly challenged today, as consumers prefer healthy food, free of chemically synthesized products and obtained under sustainable production systems [3].
In this context, the research focused on studying the effects generated by the various natural sources on the productivity and health of farm animals, but also on the quality of the products obtained from them. The therapeutic effect of plants has been known for a very long time, which is why they are increasingly used in livestock production, even if there is an opinion that the total exclusion of antibiotics can lead to a significant increase in health problems and a reduction in the overall performance of animals [4]. Most classes of natural pigments obtained from plants are used in different fields of activity, from the food industry and pharmacology to animal husbandry. Carotenoid coloration has been studied since the beginning of the nineteenth century, when the crystalline-yellow pigment in the carrot was isolated by Wackenroder and the xanthophylls-yellow pigment in the autumn leaves, by Berzelius; At present, more than 750 carotenoid pigments have been identified [5].
In poultry, carotenoid substances have been shown to act as stimulants of endogenous antioxidants by facilitating nutrient metabolism and improving meat quality by reducing cholesterol content [6]; The main antioxidants in plants are polyphenolic flavonoids, which can be easily added to the diet of broilers, as they have no adverse effects [7, 8].
This paper addresses an important topic in the field of animal nutrition, namely, the use of natural sources of carotenoids in birds to improve the quantitative and qualitative production of meat. From this point of view, we aimed to carry out a global analysis of the research aimed at administering natural preparations to the chicken broiler in order to improve the color of the meat, but also their effects on growth performance and health; The results of studies on the impact of poultry meat color on consumer acceptability will also be presented.
The study will corroborate the different scientific approaches in the field of nutrition, physiology and breeding technologies, to develop a unitary strategy for the management of natural products in birds, in a framework that respects both the requirements of economic performance and those of sustainability and food safety.

MATERIAL AND METHODS

To carry out this review, scientific articles, specialized books and official reports published between 1978 and 2025 were consulted, available in databases such as Google Scholar, Scopus and on the websites of recognized institutions (EFSA, USDA, ISO). The keywords used in the search included: *"broiler"*, *"carotenoids", "natural pigments", "meat color"*. The selection of papers was based on their relevance to the proposed theme, taking into account both experimental studies and synthesis articles. Only materials that directly analyzed the importance of phytoadditives and their effect on chickens (health effects, effects on meat and egg quality, on general welfare) as well as food safety aspects were included. The extracted information was then grouped and synthesized according to the categories of factors presented in the text, in order to provide a clearer and more accessible picture of the main conclusions in the literature. Graphical schemes and illustrative images were generated using Canva to support the presentation of the reviewed information.

CHEMICAL STRUCTURE, CLASSIFICATION AND ROLE OF CAROTENOIDS

Carotenoids are natural pigments responsible for the yellow, orange, and red coloration, of many plants and microorganism and are increasingly used in poultry nutrition due to their antioxidant and pigmentation properties [2]. In poultry production, carotenoids contribute to meat and egg pigmentation, oxidative stability and overall product quality.
Chemically, carotenoids belong to the terpenoid family and are mainly composed of isoprene units. Most carotenoids are tetraterpenoids with the general molecular formula $C_{40}H_{56}$ [9, 10]. Their molecular structure determines their antioxidant activity and biological functions [10, 11].
Carotenoids are generally classified according to chemical composition, natural origin, and biological function (Figure 1). Based on chemical composition, they are divided into carotenes and xanthophylls, compounds commonly used in poultry diets for their provitamin A activity and antioxidant effect. Depending on their origin, carotenoids may derive from plant or microbial sources, while functionally they are involved in light absorption in natural carotenoid supplementation in poultry feeding strategies.

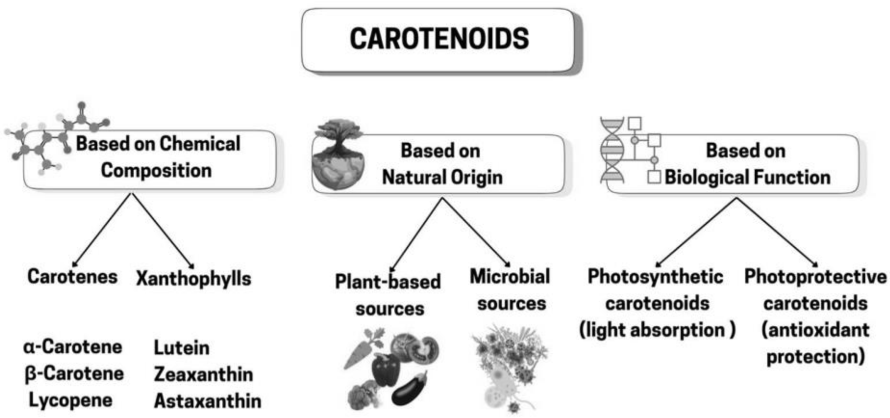


Figure 1. *Classification of carotenoids*

Figure 1 illustrates the main classification criteria of carotenoids based on their chemical composition, natural origin and biological function. According to their chemical structure, carotenoids are divided into carotenes (a-carotene, b-carotene, lycopene) and xanthophylls (lutein, zeaxanthin, astaxanthin). From the perspective of natural origin, carotenoids may be derived from plant or microbial sources, both of which are increasingly used in poultry nutrition as natural feed additives. Functionally, carotenoids play important roles in photosynthesis and antioxidant protection against oxidative stress.

This classification highlights the diversity of carotenoids and support their relevance in poultry production, particularly regarding antioxidant activity, pigmentation, and improvement of meat quality.
Depending on the chemical composition, carotenoids can be classified into two main groups, as follows:

Xanthophylls (oxygen-containing carotenoids):

-*Lutein:* An essential carotenoid, known for its role in maintaining eye health. Lutein is made up of 40 carbon atoms, 56 hydrogen atoms, and two oxygen atoms ($C_{40}H_{56}O_2$). It is known to protect vision and reduce the incidence of age-related macular degeneration by decreasing oxidative stress in the retina [12, 13].

-*Zeaxanthin:* Structurally similar to lutein, zeaxanthin also has the molecular formula $C_{40}H_{56}O_2$. This carotenoid plays a complementary role in maintaining eye health by protecting retinal cells from light-induced oxidative damage [14].

-*Astaxanthin:* It is a pigment that belongs to the family of xanthophylls, oxygenated derivatives of carotenoids whose synthesis in plants starts from lycopene. In addition to its effect on color, one of the most important properties of astaxanthin is its antioxidant activity, which has been reported to surpass that of β-carotene or even α-tocopherol [15].

Carotenes (Hydrocarbon Carotenoids):

-*Beta-carotene and alpha-carotene:* This carotenoid acts as a precursor to vitamin A due to its ability to form two retinal molecules following enzyme cleavage. Its molecular formula remains consistent with the overall structure of carotenoids ($C_{40}H_{56}$), emphasizing its importance in human nutrition and health as a source of vitamin A [16].

-*Lycopene:* It is a predominant carotenoid, widely found in fruits and vegetables, tomatoes and products derived from them being the main sources. Lycopene may reduce the risk of developing various types of cancer, including ovarian, breast, prostate, cervical, and liver. Increased concentrations of lycopene protect the skin against oxidative damage caused by UV radiation [7, 17, 18].

The main botanical families from which the natural sources of carotenoids originate, together with the plant organs that are used as a food product are shown in Figure 2.

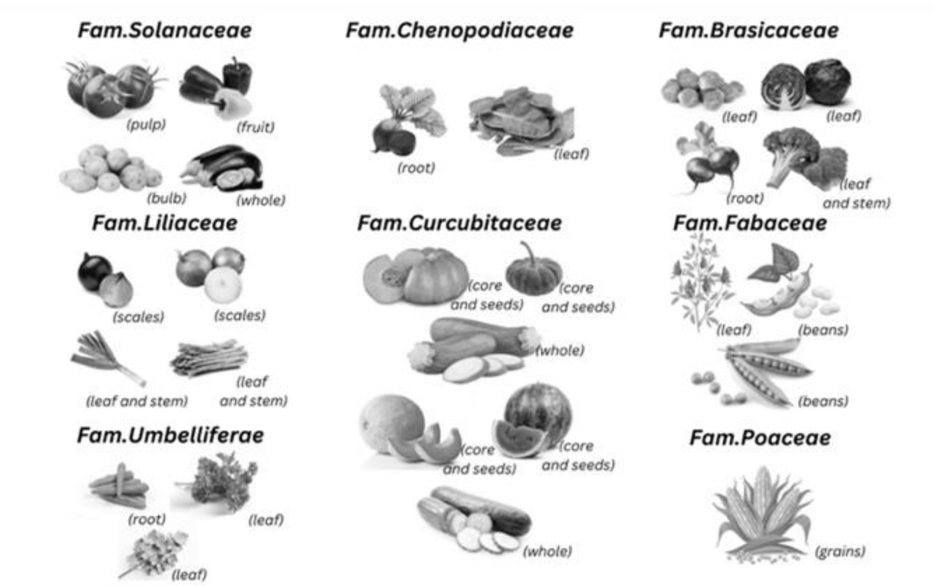


Figure 2. *Carotenoids : Plant-Based Sources classified by Botanical categories*

Figure 2 illustrates the main botanical families that represent natural sources of carotenoids with potential applications in poultry nutrition, as well as the plant organs commonly used as feed ingredients. The figure includes representatives from the families *Solonaceae*, *Liliaceae*, *Umbelliferae*, *Chenopodiaceae*, *Curcubitaceae*, *Brassicaceae*, *Fabaceae* and *Poaceae*, highlighting the diversity of fruits, leaves, roots, bulbs, seeds, grains, and steams that may serve as natura carotenoid sources. Plants belonging to the *Solanaceae* family, such as tomato and pepper, are important sources of lycopene and β-carotene, while members of *Brasicaceae* family provide lutein, zeaxanthin, and other antioxidant compounds. Leafy vegetables from *Chenopodiaceae* family and cereals from the *Pomaceae* family are frequently used in poultry feeding due to their pigmenting and antioxidant properties. Similarly, plants from the *Curcubitaceae* and *Fabaceae* families contribute bioactive compounds that may support bird health and productive performance. The inclusion of these plant-derived ingredients in poultry diets is of increasing interest because they provide natural alternatives to synthetic pigments and antioxidants. Their use may improve meat and egg pigmentation, oxidative stability, immune response, feed efficiency and overall product quality. Therefore, Figure 3 emphasizes the wide availability of botanical carotenoids sources and their relevance in the development of sustainable and functional poultry feeding strategies. Carotenoids play important and varied roles in the human body (Figure 3) as is the case of canthaxanthin and astaxanthin considered as neuroprotective agents [9], which is why the consumption of carotenoids is associated with reduced risk of cardiovascular diseases, muscle degeneration and even cancer [19].

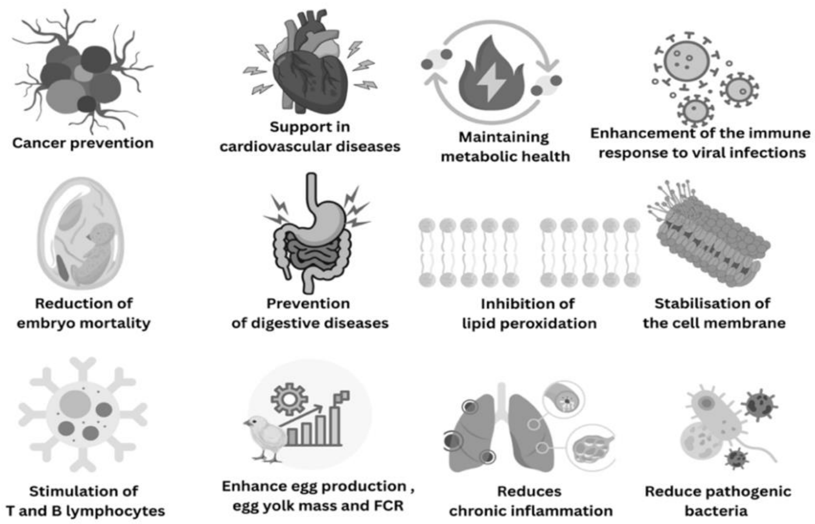


Figure 3. *General effects of carotenoids*

Figure 3 summarizes the main biological effects of carotenoids relevant to poultry nutrition and health. Carotenoids exert strong antioxidant and anti-inflammatory activities, contributing to the inhibition of lipid peroxidation, stabilization of cell membranes and reduction of oxidative stress. In poultry production, these effects are associated with improved immune response, reduced pathogenic bacteria, better metabolic health, and lower embryo mortality. In addition, carotenoids may positively influence productive performance by enhancing egg production, egg yolk quality, and feed conversion ratio (FCR). Therefore, the figure highlights the multifunctional role of

natural carotenoids as feed additives in improving poultry health and production efficiency.
Carotenoids can improve the immune response, reduce mutagenesis, and protect cells and tissues from damage caused by neoplastic agents; It also provides protection against light radiation and, under certain conditions, neutralizes singlet oxygen – a reactive form of oxygen – and inhibits free radical-induced reactions [20].
The results of various studies have shown that preparations rich in carotenoids exert a whole series of biological and therapeutic effects, being credited with anticancer, immunomodulatory, anti-inflammatory, antibacterial, antidiabetic and neuroprotective activities [17 – 21].
Carotenoids protect against oxidative stress as an adaptation to extreme conditions, but they also participate in the modification of cell membranes [22]. Clinical trials have shown that regular consumption of carotenoid-rich fruits and vegetables is epidemiologically correlated with a lower risk for certain types of cancer, especially lung cancer; Although these associations do not prove a causal relationship, they support the interest in long-term interventional studies, especially those involving supplementation of daily diets with beta-carotene [23]. Due to its content of active phenolic compounds, cinnamon helps maintain hemostasis [24].

BIOACTIVITY AND BIOAVAILABILITY OF CAROTENOIDS

Similar to vitamins, carotenoids are sensitive compounds that can be affected by water, heat, etc., hence the high risk of being distorted in the manufacturing process of animal feed [25,26]. The bioavailability of carotenoids is influenced by various factors, such as the type and number of carotenoids ingested, the food matrix in which they are incorporated, post-harvest processing methods, storage conditions, etc. [21].
For a long time, the extraction of carotenoids from plants was based on the use of different solvents (hexane, acetone, methanol, etc.) [27]. Against the background of research that has shown that the stability of carotenoids in these solvents is poor [28], testing of new extraction methods and more efficient solvents has begun, so that at present, the chemical industry only works with environmentally friendly extraction methods [29]. From this point of view, it is considered that the most efficient extraction method (economical and high-yield), is the ultrasound-assisted one (UAE), most often used in combination with DES as a solvent [30 – 32]. The stages of technological flow specific to the ecstasy of carotenoids in the raw material (vegetables/fruits/other plants: peppers, tomatoes, corn, algae, marigold flowers, etc.) are presented in Figure 4.

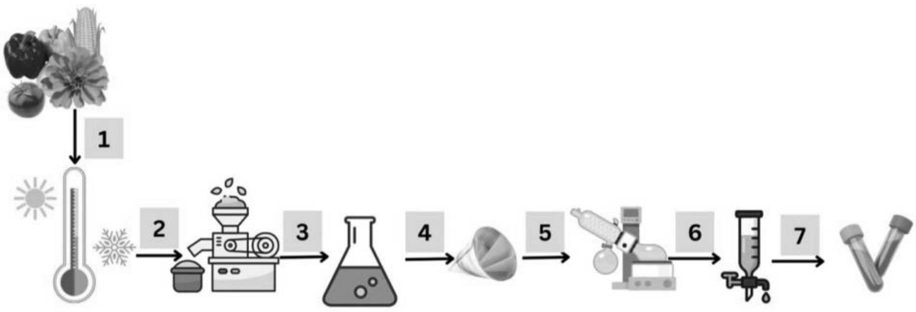


Figure 4. *Extraction of Carotenoids from Plant Material- Schematic Diagram*

In the initial phase, the compounds are stabilized, which can be done by drying in the oven (40 - 60 °C) or by freeze-drying (for thermolabile products). Next, the dry product is ground until a fine powder is obtained that mixes with the appropriate solvent (acetone, ethanol, hexane, ethyl acetate, mixes or antioxidants). This is followed by filtration, through which the solid phase is separated from the liquid with carotenoids, after which the solvents evaporate under vacuum, at a temperature of 35 - 40 °C, thus obtaining the extract, which can be in the form of concentrated liquid, powder or matrix. Purification (step 6) is optional and involves saponification, to remove lipids or esters. Several methods of stabilization of crystalline carotenoids in carrots during drying and storage have been tested, concluding that the spray drying method provides superior protection against oxygen under aerobic storage conditions [33]. In a study that looked at the stability and bioaccessibility of carotenoids from green oil extracts using oil-in-water emulsions, significant improvements were achieved in terms of carotenoid bioactivity, effective prevention of degradation and increased bioaccessibility *in vitro* [34].

The storage of carotenoids can generate various problems, caused primarily by temperature (above +37 °C major degradations occur), but also by the quality of the packaging used [35].

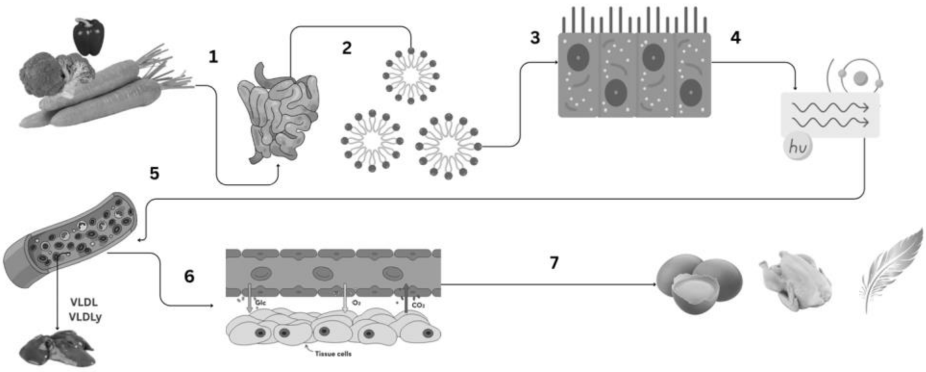
Carotenoids dried and stored at room temperature lose more than half of their initial level in the first 3 - 6 months, while those dried by freezing at -80 °C are much better maintained; if carotenoids are dried at +90 °C and stored at room temperature, they have the same stability as those obtained by the freezing method [36].

The storage and processing conditions of raw materials intended for the manufacture of feed are another important factor in the active maintenance of carotenes, in the sense that storage at high temperatures favors the oxidation of carotenoids, a phenomenon that can also occur against the background of high temperatures during the granulation stage of the combined fodder [37 – 39]. *In vitro* analysis of the bioaccessibility and carotenoid content of egg yolk has led to the conclusion that some of the physical traits (hardness) of maize grains administered to birds, affect the availability and/or deposition of carotenoids [40]. The formulation of carotenoids with the help of nanotechnology is a solution for the future, which can ensure the improvement of bioavailability and the protection of active compounds, essential components for health [41, 42]. This practice offers possible solutions to the challenges of low bioactivity and bioavailability associated with traditional carotenoid formulations [43, 44]. Research in this regard highlights the fact that complexing carotenoids with water-soluble molecules leads to a very high solubility in water, but also to the improvement of the stability of lutein and zeaxanthin, which showed deceleration of oxidation under stress conditions [42].

Absorption and bioavailability in the body can be significantly improved by reducing carotenoid particles to nanometer sizes [45], as nanometric carotenoid particles exhibit much higher solubility and stability, resulting in easier absorption in the gastrointestinal tract [46]. The conclusion of a study on the impact of lipid content in excipient nanoemulsions on carotenoid bioavailability, using *in vitro* and in vivo models, was that the bioavailability of carotenoids increases with increasing lipid content [47]. Nano systems (nanoemulsions, liposomes, polymeric nanoparticles and lipid nanoparticles) significantly improve the bioaccessibility and bioavailability of carotenoids compared to free forms [44].

USE OF CAROTENOIDS IN THE POULTRY SECTOR

Improving breeding performance and optimizing feed conversion rate is of major interest in the livestock sector, especially under intensive farming conditions [48]. The use of carotenoids in animals is arousing increasing interest, due to their bioactive properties and positive effects on health, so that a multitude of products have appeared on the market, available in the form of feed additives, nutritional supplements or natural dyes [49].
The interest in medicinal plants is due to the multiple benefits they have on animal health and implicitly their productivity, due to their high content of active compounds with different actions, including antioxidants as is the case with polyphenolic flavonoids [50]. Therefore, the use of natural pigments in the poultry sector makes it possible to obtain healthier meat, eggs whose yolk is richer in nutrients, but also intensely colored carcasses [51].
Studies conducted on broilers have shown that lutein esters are hydrolyzed in the intestinal tract, while free lutein is absorbed at the level of the duodenum and jejunum [52]. Some authors point out that β-carotene in biofortified corn is preferentially converted into retinol in the intestine, while β-cryptoxanthin accumulates more in the liver [53] (Figure 5).



1. Ingestion and Release from Feed Matrix -in the gizzard and small intestine, mechanical grinding and enzymatic digestion release carotenoids from plant or feed matrices.
2. Emulsification and Micelle Formation- Carotenoids are incorporated into mixed micelles (fat-soluble transport particles), which improve their solubility and bioavailability.
3. Transport to the Intestinal Epithelium - carotenoids are absorbed into enterocytes via passive diffusion and/or facilitated transport (e.g. SR-BI, NPC1L1 transporters).
4. Intracellular Processing in Enterocytes - Carotenoids are then packaged into lipoprotein particles (portomicrons or other avian equivalents of chylomicrons).
5. Transport into Circulation - Carotenoids circulate in the lymhatic and venous system to the liver.
6. Liver – Central Metabolic Hub - Repackaging into VLDL and VLDLy (very low-density lipoproteins for yolk deposition).
7. Distribution and Deposition in Target Tissues- Yolk deposition is mediated by VLDLy particles, which selectively transport lipids and carotenoids to the developing oocyte, vitals.

Figure 5. *Diagram of the absorption and integration process into tissues*

The presence of zeaxanthin can interfere (although not significantly) with the absorption of β-carotene, while the absorption of β-carotene depends on the presence of fats, the activity of organs – especially the liver and kidneys, and the intensity of metabolism [54]. The importance β-carotene derives from the fact that it is involved in improving intestinal morphology, IgA levels (serum and mucous membranes) or markers of the intestinal barrier (MUC2, ZO1, OCLN, etc.), but also for its role in decreasing *E. coli* infestations and increasing the concentration of *Lactobacillus* [55] (Figure 6).

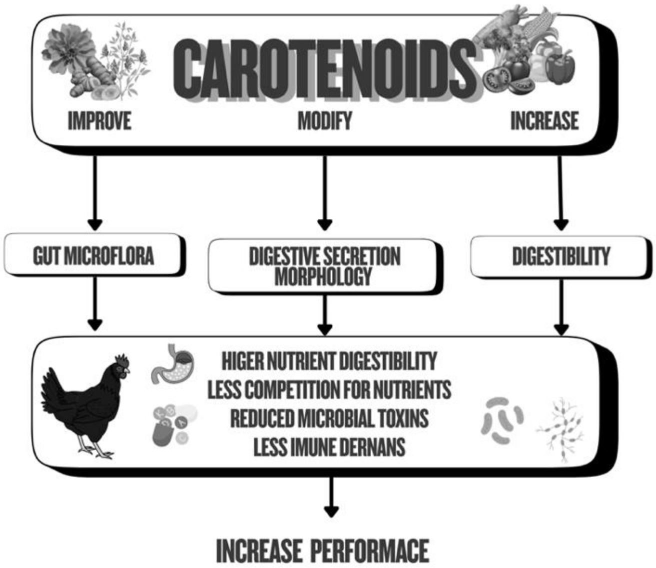


Figure 6. *Mechanism of operation of carotenoids on growth and health performance in chicken broiler*

Dietary carotenoids and carotenoid-rich phytogenic additives are extensively studied in poultry nutrition due to their role’s oxidative stability, immune modulation and tissue pigmentation. Carotenoids such β-carotene, lutein zeaxanthin and lycopene are efficiently absorbed and deposited in tissues and egg, contributing to oxidative protection and pigmentation [57].

Lutein esters from plant sources are hydrolyzed in the intestine prior to absorption, ensuring systemic distribution without re-esterification [58].

Marigold extract supplementation at 200 mg for 42 days improved immune response and preferences [59]. Dill supplementation improved gut health, whit leaf inclusion enhancing intestinal function [60] and 3 % dill powder increasing hematological parameter [61].

Chicory improves mineral absorption and gut microbiota integrity; supplementation at 250 - 350 - mg·kg^{-1} enhance performance and reduce blood lipids [62, 63]. Disease conditions significantly reduce carotenoid absorption and tissue disposition [64].

Lutein from Chlorella showed efficient deposition serum, liver, and oocytes, improving yolk pigmentation [65, 66].

Phytogenic additives demonstrate dose-dependent effects: moringa at 0.3 % reduced mortality under heat stress [33]; garlic at 3 %, ginger at 2 %, and red pepper at 1.5 - 2.25 % improve immunity, digestions, and serum parameters [67 – 70]. Turmeric at 0.5 % enhance broiler performance [72, 73].

Capsanthin, β-glucan and carotenoids modulate inflammation and growth performance [74]. β-carotene improves redox balance [75], while ginger oil reduces lipid peroxidation [76, 77].

Moringa at 0.5 - 0.75 % reduce lipid levels under stress [78]. Black cumin improved oxidative resistance, trough doses above 6 g·kg^{-1} may impair welfare [79,82]; 1 % oil improved performance under heat stress [81]. Cinnamon increase growth performance [80].

Lycopene at 100 - 200 mg·kg^{-1} (day 21 - 42) reduce MDA and improve growth and feed efficiency [83], also enhancing antioxidant enzyme activity and fertility via antioxidant pathways [18, 84, 85].
Oregano at 150 mg·kg^{-1} improved egg production [86], grape seed extract at 100 mg·kg^{-1} increased body weight [87], and ginger powder (1 %) showed similar effects [67]. Wormwood at 20 - 40 mg·kg^{-1} enhance antioxidant capacity and growth [88].
Carotenoid-rich diets improve performance and product quality, particularly through pigmentation and oxidative stability [14]. Lutein, zeaxanthin and canthaxanthin enhance meat color and antioxidant resistance [89 – 91].
Meat quality is defined by physicochemical and sensory trains [92 – 93]. Carotenoids and phytogenic supplementation improve growth, feed intake, and carcass trains, including reduced fat deposition [74, 94, 95]. Breeder supplementation improves immunity and hatchability [96].
Basil at 0.5 g·kg^{-1} improved performance and reduced mortality [97]. Chicory at 3 g·kg^{-1} reduced feed intake and mortality [98], while chili pepper at 0.50 - 1 % improved performance [99, 100].
Natural carotenoid sources include corn, corn gluten, red pepper, marigold and algae meal [90, 101]. Sargassum supplementation at 3 - 6 % increased carotenoid content in tissues [102, 103].

CHARACTERISTICS OF MEAT AND CONSUMER PERCEPTION

Carotenoids play an important role in influencing the visual and sensory characteristics of meat, having a direct impact on consumer perception and product acceptability. Meat color is one of the main factors evaluated by consumers at the time of purchase, being associated with freshness, quality, nutritional value. In this context, the use of carotenoids in animal nutrition can contribute to the modification and stabilization of meat color through pigment accumulation in tissues and through their antioxidant effects on lipids and myoglobin. These effects can improve the visual appearance of the product and reduce oxidative changes responsible for discoloration during storage. Furthermore, consumers' positive perception of products obtained using natural compounds, such as carotenoids, supports the growing interest in integrating these substances into modern animal production systems. Therefore, the relationship between meat properties, color, and the use of carotenoids should be analyzed in an integrated manner, highlighting both the technological implications and the impact on consumer preferences.
Consumers' perception of poultry meat includes ethical, sensory and sustainability factors, which requires adequate cooperation between production farms and the marketing service, which ensures the market value of the commodity, but also customer confidence in poultry products (Figure 7).

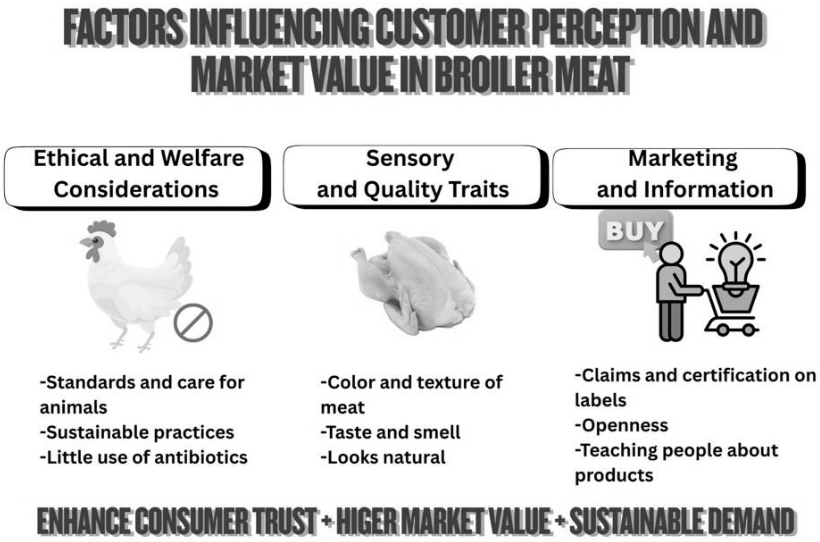


Figure 7. *Factors influencing consumer perception of meat quality*

Texture has been considered one of the most important attributes of poultry meat, with a direct influence on consumer satisfaction [104].

In 2009, Fletcher said that the chicken broiler industry had begun to dominate the poultry meat market, but also that the new genotypes no longer present the problem of meat hardness, even at older slaughter ages.

On the other hand, there are also authors who have found higher values of shear force with the increase in the life span of the broiler and a corresponding decrease in the tenderness of the meat [105].

A comparative study between Ross 308 and Cobb 500 indicates that the first of the hybrids tested exhibited firmer meat texture, higher chewiness, and better muscle elasticity [106].

Another essential element in the purchase of poultry meat is its color, with the specification that preferences differ depending on the geographical area; for example, consumers in Europe opt for a yellowish white to pink meat, those in Brazil prefer a meat with pale pink shades, those in Asia prefer meat with white shades, while in Africa red shades are more desired (Table 1).

Since color represents one of the first parameters evaluated by consumers at the time of purchase, adapting product pigmentation to market requirements has major economic and commercial importance. The Table 1 demonstrates that consumer preferences regarding meat color differ considerably among geographical regions and food cultures. For example, in some country’s consumers prefer meat with yellow shades, which are associated with natural feeding practices and superior quality, whereas in other regions white or pale pink meat is preferred, being perceived as fresher or less processed. These differences justify the need to adjust the level and type of carotenoids used in poultry feed according to the target consumer market.

Table 1. *Consumer preferences for chicken meat color (2005-2025)*

Location	**No. of subjects**	**Favorite shade**	**References**
United Kingdom	-	Light yellow	[107]
France	356	Yellow	[108]
Guinea	130	Yellow	[109]
Romania	-	White	[110]
Spain	-	White / Yellow	[111]
Albania, Bosnia and Herzegovina, Bulgaria, Serbia, Croatia, North Macedonia, Montenegro	2369	Uniform and clean color	[112]
Ethiopia	217	Red	[113]
Germany	95	Uniform and clean color	[114]
Indonesia	100	White / Yellow	[115]
Northern Ireland/Brazil	37	Less pigmented shade/ Pale pink	[116]
Poland	793	Light pink	[117]
Global, but also includes studies from Europe	-	Pink/ slightly pigmented yellow	[116]
Italy	84	Pink	[118]
Romania		White	[119]
Asia	400	White	[120]
Belgium	275	Yellow	[121]

Furthermore, the table support the idea than use of carotenoids has not only a biological and antioxidant role, but also a technological and marketing function. By influencing the color of meat and skin, carotenoids may contribute to increasing product acceptability and improving market competitiveness. Therefore, the inclusion of this table in a scientific paper provides context for interpreting the effects of carotenoids on product quality and highlights the practical relevance of their use in the poultry industry.

Consumer perception of poultry meat is strongly influenced by color, which is commonly associated with freshness, taste, and overall product quality. Studies show that most consumer associated white meat with freshness and better taste, while dark meat is less preferred, even when its sensory qualities may be superior [122]. A survey involving 400 consumers demonstrated that color is one of the most important factors influencing poultry meat purchasing decision, with while meat being the most preferred, followed by yellowish-white meat, whereas intensely yellow meat was the least accepted [120]. These findings are highly relevant to poultry production because pigmentation can be influencing through dietary carotenoids. Different carotenoid sources produce specific pigmentation effects; for example, b-carotene contribute to yellow coloration, whereas capsanthin is associated with red pigmentation [2]. In addition, carotenoids have been shown to influence broiler skin color, an important quality parameter affecting consumer preference [21, 123]. Consumers are increasingly interested in poultry products with attractive and natural color shades, often associated them with freshness and superior quality.

Meat color is a complex characteristic defined by three main parameters: brightness, tonality, and intensity, each contributing differently to consumer perception and product attractiveness [125]. Color tonality depends largely on the ratio of red and white muscles fibers and on the chemical state of myoglobin and hemoglobin, the main pigments responsible for meat coloration [126].

Furthermore, pigment stability is influenced by oxidative reactions, interactions between myoglobin and iron ions, and storage conditions, all of which may lead to changes in meat color during preservation [127 – 129]. The intensity of meat color is determined primarily by the concentration and saturation state of myoglobin content [132]. Brightness is also an important quality attribute and is influenced by factors such as bleeding efficiency, freshness, muscle-to-fat ratio, oxidative status of pigments, and the specific color shade of meat [127 – 135]. Overall, poultry meat color may vary from pale pink to bright red or dark purple depending on these physiological and biochemical factors [135].

Several studies have demonstrated that dietary carotenoids can effectively modify meat and skin pigmentation in broilers. In Langshan broilers, lutein was identified in subcutaneous and abdominal fat as well as in breast and leg muscles, while lutein, a-carotene, and b-carotene were detected in heart tissue [130]. Supplementation with red pepper improved appetite and enhanced meat and egg color parameters [99]. Similarly, carotenoid supplementation intensified yellow pigmentation across the entire broiler skin surface [131]. Different carotenoids also produce distinct pigmentation profile, with curcumin generating dark yellow shades and lutein producing yellow-orange coloration [23, 103]. Diets rich in corn and natural pigments increased yellow pigmentation of skin and meat, whereas wheat-based diets had limited effects on meat color intensity [136]. However, despite reports that corn-fed chicken meat was more appreciated for taste, consumer still preferred lighter-colored meat over intensely yellow meat, suggesting that excessive pigmentation may negatively influencing purchasing behavior [107].

In addition to nutrition, genetic background and production systems may also affect meat color characteristics. Comparative studies between Ross 308 and Cobb 500 broiler showed no significant differences in meat color between the two genotypes [133]. In contrast, production systems increased redness and brightness while reducing yellow pigmentation compared with slow-growing chicken [134]. Environmental conditions may also contribute to meat appearance, for example, LED lighting improved meat color parameters in Ross 308 broilers without affecting carcass yield [137].

Overall, these findings indicate that meat color is a multifactorial characteristic influenced by diet, genetics, oxidative processes, and environmental conditions.

Therefore, carotenoids should be considered not only as natural antioxidants, but also as important nutritional tools capable of modulating poultry meat pigmentation and improving consumer acceptance according to market preference.

REGULATORY STANDARDS FOR CAROTENOIDS IN POULTRY DIETS

The administration of carotenoids in the livestock sector is strictly regulated in many jurisdictions to guarantee the safety of animals, consumers and the environment. In the European Union, Regulation (EC) No 1831/2003 establishes a comprehensive framework for the use of additives, labelling and authorization, according to which all additives – including b-carotene, lutein, zeaxanthin and canthaxanthin – must go through an authorization process before they can be used on the market [138].

EU Regulation 1097/2020 on the use of extracts rich in lutein and zeaxanthin sets the maximum level of carotenoids in feed at 80 $mg \cdot kg^{-1}$ feed for fattening and laying birds, and 50 $mg \cdot kg^{-1}$ for lutein/zeaxanthin extracts, respectively. As regards the administration

of canthaxanthin in poultry feed, the Regulation imposes doses of 25 $mg\cdot kg^{-1}$ for broilers and 8 $mg\cdot kg^{-1}$ for breeding and laying hens; The same regulation prohibits the use of carotenoids in drinking water due to the risk of exceeding the authorized doses [139].
EFSA's opinion (2024) for turkey broiler confirms that the dose of 80 mg carotenoids$\cdot kg^{-1}$ feed is safe and does not pose a risk to consumers or the environment [140, 141].
The European Food Safety Authority (EFSA) has suggested changing the wording of the provisions regarding mixing with other carotenoids. Thus, from 2025, EU Regulation 1486/2015 had some changes regarding the production of canthaxanthin, if in the old annex canthaxanthin could not be mixed with a quantity greater than 5 % carotenoids, in the new regulation the allowed amount is 80 $mg\cdot kg^{-1}$. Fermentation with Yarrowia lipolytic CBS 146148 has been authorized as a source to produce canthaxanthin and the new (fermentative) method is only used in the form of a preparation. Non-EU countries follow the same general pattern of additive use [142 – 145].
Carotenoids must be evaluated for safety, maximum defined content in feed or premixes, efficacy as well as environmental impact [146].
According to data provided by Grand View Research, Industry Report 2033, Mordor Intelligence, Trends & Industry report 2030, Globe Newswire, Trends Analysis Report 2024-2030, Coherent Market Trends Share and Forecast 2025-2032, Reanin, Carotenoids Market Size 2031, most of the carotenoid products manufactured in 2025 ended up in animal feed (37.98 %) and the food industry (29 %), compared to only 12 % used in cosmetics and 6 % in pharmaceuticals (Figure 8) [146].
As illustrated in Figure 8, the animal feed sector is the primary economic driver of carotenoid market, holding the largest share at 37.98 %. This confirms a massive demand in livestock production and aquaculture, where carotenoids are critical components rather than mere additives. In poultry nutrition, they are indispensable for the pigmentation of egg yolk and skin.
The food and beverages industry ranks second (29 %), reflecting a consumer shift toward “clean label” products and natural alternatives to synthetic colorants. The dietary supplements segment follows with 18 %, driven by the nutraceutical market’s expansion and the demand for specific compounds targeting ocular health and antioxidant support.
Conversely, the personal care and cosmetics (12 %) and pharmaceuticals (6 %) sector show the lowest shares. Despite the recognized anti-aging and therapeutic properties of carotenoids, their growth in these fields is constrained by high ingredients costs, competition from other active molecules, and stringent pharmaceutical regulatory frameworks.
The data in Figure 8 reveal that animal feed and human food collectively account for approximately 67 % of the global market, proving that primary industrial value carotenoids is rooted in nutrition and natural pigmentation. For the poultry industry, these figures validate the significance of current research: optimizing dietary carotenoids directly addresses a major economic demand, linking livestock efficiency with the global consumer market for functional foods.

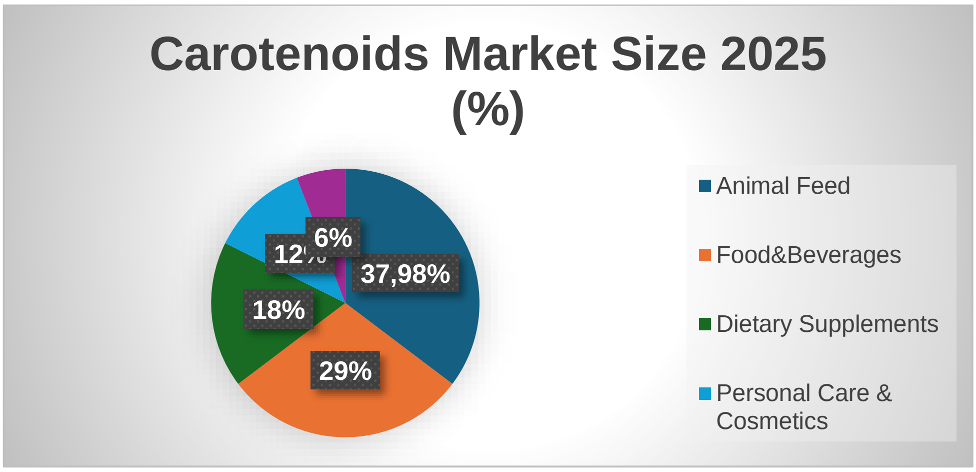


Figure 8. *Carotenoids Market Size 2025*

In 2024, the global carotenoid market was dominated by Europe, with a revenue share of 28.2 % (Germany held 32.6 % of the European industry), the best-selling product being astaxanthin with a revenue share of 42.2 %; The livestock segment reached a market share of 27.3 %. The global carotenoids market stood at a level of USD 0.893 billion and is projected to grow to USD 1.218 billion in 2034 (an annual growth rate of 3.5 %) [147].
This situation is due both to consumers' awareness of the beneficial effects of natural products – without synthetic additives – on health, and to the growing interest of farmers of the effects that carotenoids have on animals (they improve immunity, quality of the final product, powerful antioxidant, precursor of vitamin A, substitute for antibiotics.

DISCUSSION

Despite increasing interest in the use of carotenoids in animal nutrition driven by consumer demand and industry acceptance, their practical application remains constrained by several critical limitations, including high production and extraction costs, chemical instability, variable bioavailability and uncertainty regarding optimal dosing strategies across species and production systems.
Although a substantial body of in vivo and *in vitro* evidence reports enhanced bioavailability and biological activity of carotenoids trough different dietary and technological strategies, the current literature is fragmented and largely non-comparative. This limits translational relevance, particularly in poultry nutrition, where species-specific metabolic responses remain insufficiently characterized.
A major bottleneck is the lack of standardized experimental frameworks for assessing absorption kinetics, metabolic conversion, and intestinal transport. The absence of harmonized methodologies for carotenoid quantification further hampers cross-study comparability and precludes robust meta-analytical integration.
Recent technological advances in green extraction and formulation have partially addressed these limitations. Techniques such as supercritical CO_2 extraction, ultrasound- and microwave- assisted extraction, and NaDES-based systems improve yield, purity, and environmental sustainability. However, scalability and cost-effectiveness at industrial level remain insufficiently validated.

Overall, while technological progress is evident, the field is still characterized by methodological heterogeneity and limited translation validation, highlighting the need for standardized, comparative, and application-oriented research frameworks.

CONCLUSIONS

In the last decade, consumer preference for “clean label” products has increased significantly, with growing demand for foods with simple ingredient lists and minimal use of synthetic additives such as dyes and preservatives.
This shift in consumer expectation represents a relevant constraint for poultry meat producers, who are increasingly required to reformulate feed strategies by incorporating natural carotenoid sources and to adapt production systems in line with sustainability and animal welfare principles.
Natural carotenoid supplementation in broiler diets aligns with clean-label requirements, particularly when derived from plant, algal, fruit or vegetable sources perceived as natural by consumers and when used as substitutes for synthetic pigments, thereby contributing to consumer acceptance of poultry products.
However, current research is predominantly focused on dietary supplementation and tissue deposition of major carotenoids (*e.g.*, β-carotene, lutein, zeaxanthin), while comparative studies addressing different chemical forms (free, esterified, encapsuled), remain limited. This represents a significant gap in understanding carotenoid bioavailability and functional efficiency.
Overall, carotenoid supplementation constitutes a promising strategy to improve product quality and market value by balancing technological, nutritional and consumer-driven requirements. Nevertheless, existing evidence remains largely descriptive, and further mechanistic studies are required to elucidate carotenoid metabolism at the molecular level and to better define their functional potential in poultry nutrition systems.

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