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RED PEPPER: NUTRITIONAL VALUE, CAROTENOIDS, ANTIOXIDANT CAPACITY, AND ITS USE IN BROILER DIET

Irina UNGUREANU, Roxana-Nicoleta RAȚU, Alexandru USTUROI, Răzvan-Mihai RADU-RUSU, Marius-Giorgi USTUROI *

"Ion Ionescu de la Brad" Iasi University of Life Sciences, Faculty of Food and Animal Sciences, 8 Mihail Sadoveanu Alley, 700490, Iasi, Romania

Corresponding author email: marius.usturoi@iuls.ro

Abstract

Red pepper is a widely consumed vegetable, renowned for its impressive nutritional profile and significant health benefits, especially for its high content of vitamins and antioxidants. With a rich content of vitamin and essential carotenoid, red pepper plays a vital role in supporting immune function, improving iron absorption, and maintaining skin and eye health. The abundant carotenoid content of red peppers, which includes compounds such as capsanthin and capsorubin and gives the vegetables their characteristic red colour, significantly contributes to their antioxidant capacity. By effectively combating free radicals, these carotenoids lower the oxidative stress and inflammatory variables linked to the onset of chronic illnesses. Although there are many health benefits linked to consumption, there are still debates over their magnitude and the ways in which they work. Ongoing research continues to explore the bioavailability of carotenoids and their potential interactions with other dietary components, as well as the optimal ways to incorporate red pepper into various diets, both for its nutritional benefits and especially for improving the colour of meat in broiler.

Key words*: antioxidants, capsanthin, carotenoids, red pepper.*

INTRODUCTION

Various species of medicinal or aromatic plants, as well as spices, have been used for a long time, either for therapeutic or culinary purposes (Opara et al., 2014; Trifunschi et al., 2022). In recent years, consumers have grown increasingly interested in learning more about food fraud and authenticity as well as the consistency and safety of food products (Rațu et al., 2021). Research on natural preparations that are known to improve the quality of basic productions or have favourable effects on the health of animals has increased as a result of the prohibition on the use of antibiotics in animal husbandry due to the phenomena of antibiotic resistance (Steiner et al., 2014).

Given that 70-75% of production costs are related to feeding, the largest challenge in poultry farming is to ensure financial profitability while simultaneously providing adequate nutrition that is suited to each category of birds' physiological needs and performance potential (Usturoi et al., 2023). The most costly ingredients for compound feed are those that guarantee the required amount of protein (Ipek et al., 2009), components that vary greatly in terms of quality parameters, and most importantly, the purchase price, which is influenced by a variety of conjunctural and even geopolitical factors (Frempong et al., 2019). For instance, EU countries have production costs for one kilogramme of chicken meat that are about 45% higher than those of Brazil, one of the world's largest producers of soybeans (Magdelaine et al., 2003). Among the multitude of plants used in human and animal nutrition, the red pepper (*Capsicum annuum* L.) is of great interest as it is cultivated on very large areas worldwide. The pepper (hot pepper or chili) belongs to the Solanaceae family (which includes tomatoes, eggplants, potatoes, and tobacco), the *Capsicum* genus, which is composed of 27 different plant species (Zhuang et al., 2012).

Peppers can also be categorised as commercial products according to their intended use. For example, peppers from the species *Capsicum annuum* and *Capsicum frutescens* are grown for their strong spicy flavour and aroma, while red peppers are valued for their nutritional and therapeutic qualities as well as their high natural colour and antioxidant content (Krauss et al., 2000). Carotenoid pigments, which give fruits their varied colours of yellow, orange, and red, are synthesised and accumulated by *Capsicum* species. The red colour of chilli pepper fruits is due to capsanthin, capsorubin, and capsanthin-5,6-epoxide, while the yellow-orange colour is mainly caused by the accumulation of α- and beta-carotene, zeaxanthin, lutein, and beta-cryptoxanthin (Reyes-Escogido et al., 2011). Pepper species have been used as experimental models for studying the biochemical and molecular aspects of carotenoid biosynthesis from various natural plant sources, despite the fact that the types and levels of carotenoids vary from one species to another and particularly depending on the environmental conditions in which they are grown (Gómez-García & Ochoa-Alejo, 2013).

MATERIALS AND METHODS

The evaluation of red pepper in terms of nutritional value, antioxidant capacity, and effects on broiler growth was based on the assessment of the state of knowledge from the PubMed and ResearchGate databases.

RED PEPPER: NUTRITIONAL VALUE

Due to their unique flavour, taste, and colour, as well as the fact that they contain a variety of minerals, bioactive substances, including antioxidants, fibre, and vitamin, red pepper and products made from it have a high nutritional value (Zhuang et al., 2012).

Red peppers are regarded one of the finest sources of natural colours. The essential components in red and green peppers are described in Table 1, and the nutritional characteristics of sweet peppers in Table 2. They have long been used as food colouring and more recently, as oleoresin since they are thought to be the vegetables with the highest concentrations of carotenoids. Carotenoid pigments, which are produced in large quantities during ripening, give capsicum its striking and distinctive red colour (Arimboor et al., 2015). With carbon atoms, nine conjugated double bonds in the core polyene chain, and several terminal groups that alter eche pigment's chromophore characteristics, all of the carotenoid pigments found in red pepper are isoprenoids. Red and yellow are the two isochrome families into which they can be divided. According to de Azevedo-Meleiro et al. (2009), the yellow fraction is composed of the remaining carotenoids, including zeaxanthin, beta-cryptoxanthin, and beta-carotene, while the red fraction primarily consists of capsanthin and capsorubin, which are thought to be unique to the *Capsicum* genus, and a smaller amount of other red carotenoids. The later fraction is regarded as the red one's biosynthetic precursor. Because of its simplicity and dependability, the ASTA method (American Spice Trade Association) is the most widely used analytical technique for determining the colour of paprika by extracting pigments using a selective solvent. The stability of carotenoids during heat drying is positively impacted by the presence of capsaicinoids in hot peppers (Gayathri et al., 2004).

Table 1. Main Nutritional Elements in Red and Green Bell Peppers

Element	Red pepper	Green pepper
K	3.27	3.55
Ca	1041	1009
P	1704	1528
Fe	73.6	64.7
Zn	18.6	25.0
Mn	22.5	21.3
S	1566	1518
Cu	7.94	11.6
Cl	2984	3250
Ca/P	0.61	0.66
Mn/Fe	0.306	0.329
Fe/Cu	9.27	5.58
Zn/Cu	2.34	2.16

The average values are expressed as a percentage on a dry weight basis.

Certain types of peppers provide twice as much vitamin C, antioxidant and nutrient, per gramme of fruit weight as tomatoes, apple, or orange (Wahyuni et al., 2013; Yehmed et al., 2023). Different pepper cultivars also contain various amounts of folic acid, a crucial B vitamin that lowers the risk of cancer and cardiovascular disorders (Phillips et al., 2006). The primary goal of pepper research is to identify the carotenoid makeup of the many different types. Carotenoid pigments, which are mostly produced during the ripening process, are responsible for the vibrant red hue of *Capsicum annum* fruits. The carotenoids responsible for the final red color of the fruits are capsanthin and capsorubin (Minguez-Mosquera et al., 1994). The data obtained from the analysis conducted by researcher Ayuso et al., 2008 have been synthesized in Table 1 and Table 2, highlighting the most relevant nutritional characteristics of red pepper. These tables provide a detailed perspective on the chemical composition, energy value, and content of macro and micronutrients.

Table 2. Nutritional characterization of sweet peppers

Element	Red pepper	Green pepper
Fruit weight (g)	97.4	127
Moisture (%)	90.3	92.5
Protein (%)	11.9	11.7
Ash (%)	5.03	4.98
Fiber (%)	10.3	11.6
Firmness (N)	7.9	7.9
pH	5.2	6.0
Productivity (t/ha)	30.1	28.0

RED PEPPER: CAROTENOIDS

Carotenoids with over 50 different structures are responsible for the pepper's red colour (Guil-Guerrero et al., 2006; Giuffrida et al., 2013; Cervantes-Paz et al., 2014).

The unique keto carotenoids capsanthin, capsorubin, and cryptocapsin give ripe chilli pepper pods their vibrant red colour, while betacarotene, zeaxanthin, violaxanthin, and betacryptoxanthin give them their yellow-orange hue. While most of the xanthophylls in red peppers are found as esters and fatty acids, green pepper extracts are mainly composed of free carotenoids (Cervantes-Paz et al., 2014). In the majority of cultivars and variations, capsanthin accounts for 30-70% of the carotenoids. In the later phases of ripening, the ratios of capsanthin to capsorubin rise. Red pepper has also been found to contain significant amounts of neoxanthin, lutein, antheraxanthin, violaxanthin,capsanthin-5,6-epoxide, and other compounds (Hornero-Méndez et al., 2000).

Carotenoids are naturally occurring chemical molecules that can be yellow, orange, or red in colour and are found in plants, algae, and some microorganisms. Carotenoids and carotenoids (like beta-carotene and xanthophylls) are the two main categories of carotenoids (Hornero-Méndez & Mínguez-Mosquera, 1998). Eating foods high in carotenoid has been associated with several health benefits, such as protecting eye health and reducing oxidative stress. Numerous pharmacological benefits, including immunomodulatory, antibacterial, antidiabetic, neuroprotective, and anticancer capabilities, are provided by carotenoids to chickens (Bennedsen et al., 2000; Guerin et al., 2003; Arain et al., 2018). Dietary factors such as the kind and amount of carotenoid intake, foods containing carotenoids, and post-harvest processing, storage, and cooking techniques all affect the bioavailability of carotenoids (Guerin et al., 2003). Less than 10% of the 600 carotenoids found in natural sources have been found to be vitamin A precursors. Human tissues and blood contain a range of dietary carotenoids, both with and without provitamin A (Guerin et al., 2003, Pugliese et al., 2013). The most nutritionally active carotenoid is beta-carotene, which makes up 15-30% of the total carotenoids in serum. Carotenoids shield cells, tissues, and entire animals from a variety of neoplastic processes, enhance the immune system, inhibit mutagenesis, and lessen caused nuclear damage. Although carotenoids shield tissues from photons, some of them, such as carotene, have the ability to neutralise extremely reactive singlet oxygen and stop reactions caused by free radicals. Epidemiological studies have shown that eating fruits and vegetables high in carotenoids can protect against several cancers, especially lung cancer (Castañeda et al., 2005). Chilli pepper fruits synthesise and collect a variety of compounds, such as the unique capsaicinoids (hot chemicals), vitamins and colours (carotenoids) (Li et al., 2022). Several new carotenoids from paprika, such as mutatoxanthin, violaxanthin, antheraxanthin, lutein epoxide, and cryptocapsin, have also been reported. The keto groups in capsanthin and capsorubin are part of the conjugated double bond system (Castañeda et al., 2005).

Mature red chilli fruits may have a two to sixty-fold higher total carotenoid content than immature fruits. When black pepper fruits (*C. annuum*) ripen, for example, their total carotenoid concentration rises 66 times (Deli et al., 1992). During ripening, the carotenoid makeup also changes significantly. Generally speaking, lutein, beta-carotene, and neoxanthin are the most prevalent carotenoids in immature green chilli fruits; in green bell pepper, their respective percentages are lutein (40.8%), neoxanthin (15.1%), and beta-carotene (13.4%)

(Matsufuji et al., 2007). Both morphological and significant physiological changes occur in chili pepper fruits during ripening. These changes include alterations in pigment content and composition. These differences in fruit content are influenced by genetics, maturity, and growing conditions. Chilli pepper fruits are green because of chlorophyll, purple or violet because of anthocyanins, and yellow-orange because of beta-carotene, zeaxanthin, lutein, and beta-cryptoxanthin. Oxygenated carotenoids, such those with terminal acylcyclopentanol groups, control the red colour of chilli pepper fruits (Sun et al., 2007).

Beta-carotene (11.6%), capsanthin (35%), and violaxanthin (10%) are the three primary carotenoids found in red bell peppers. The carotenoids' makeup varies with fruit age (Curl et al., 1962). Other types of chilli peppers have also shown these changes in carotenoid makeup. Capsanthin, the main pigment, made about 46% of the Signal Red variety's total carotenoid content (Matsufuji et al., 2007). The total carotenoid content is also influenced by the variety. The fruits of *Asparagus officinalis*, Lilium, Aesculus, and Berberis, as well as the fruits of *Capsicum* red spp., are the primary sources of the red, lipophilic pigment known as capsanthin. During the ripening process, the amount of capsanthin in fruits can account for up to 50% of their total carotenoid content. Eleven conjugated double bonds, a conjugated keto group, and a cyclopentane ring make up capsanthin's structure. Because of these properties, capsanthin is a potent antioxidant (good radical scavenger). Despite having the same number of double bonds, capsanthin is more antioxidant than beta-carotene and beta-cryptoxanthin. Despite lacking the qualities of provitamin A, capsanthin is regarded as a beneficial molecule due to its antioxidant and antitumor (colon cancer) capabilities (Kim et al., 2009). According to Deruère et al. (1994), 95% of carotenoids gather in certain substructures called fibrils rather than being freely available or dispersed across chromoplasts. The conversion of preexisting photosynthetic pigments and de novo carotenoid production are the two metabolic processes that govern the amount and makeup of carotenoid profiles in chilli pepper fruits as they develop. For instance, research on the pigment content of Bola and Agridulce chilli pepper varieties at various ripening stages (green, colour break I, colour break II, red I, and red II) revealed that zeaxanthin, capsanthin, capsorubin, beta-cryptoxanthin, and capsorubin were synthesised from scratch, and that the concentrations of intermediates in the synthesis of red pigments (beta-carotene and violaxanthin) increased. In the meantime, in the red I and II phases (mature fruits), the chlorophyll pigments (lutein and neoxanthin) vanished (Minguez-Mosquera et al., 1994). However, violaxanthin accounted for 37% to 68% of the total carotenoids in the yellow-orange fruits of *C. baccatum, C. pubescens, and C. annuum.* Lutein (5% to 14%), cis-violaxanthin, and antheraxanthin were the next most important carotenoids (Rodríguez-Burruezo et al., 2010). In mature red chilli pepper fruits carotenoids have been observed to accumulate at the following rates, in descending order: zeaxanthin, or xanthophylls, neoxanthin, and violaxanthin), hydrocarbons (lycopene), ketocarotenoids (capsanthin, capsorubin, and capsolutein), and epoxixanthin-5,6-epoxide and capsanthin-3,6-epoxide. Due to their esterification with fatty acids, most carotenoids in ripe chilli pepper fruits are lipophilic (Minguez-Mosquera et al., 1994) and aid in their accumulation in lipophilic globules at the chromoplast level (Kim et al., 2004). The esterification process primarily occurs in de novo biosynthesised pigments such as capsanthin, capsorubin, zeaxanthin, and beta-cryptoxanthin, while it also occurs in previously synthesised pigments like violaxanthin. Biosynthesis and de novo esterification occur simultaneously during the ripening of chilli pepper fruits. While red xanthophylls, like capsanthin, are esterified by short-chain saturated fatty acids, such lauric acid, myristic, and palmitic acid, yellow xanthophylls are mostly esterified by myristic, palmitic , and a form of unsaturated linoleic acid. As a result, yellow xanthophylls have more double bonds in their fatty acid chains than their red counterparts, making them less stable (Mínguez-Mosquera et al., 1994). Similarly, free carotenoids and their partially and fully esterified forms make up 21.3%, 35.6%, and 43.1% of the total pigment content in fully ripe chilli pepper fruits (*Capsicum annuum* cv. Bola) (Mínguez-Mosquera et al., 1994). Furthermore, it seems that the Numex, Mana, Belrubi, Negral, and Delfin types of fully ripe chilli pepper fruits (*C. annuum*) maintain a good balance between these three esterified fractions, which could serve as a "ripeness index". Remarkably, the process of carotenoid production does not depend on the breakdown of chlorophyll (Mínguez-Mosquera et al., 1994).

RED PEPPER: ANTIOXIDANT CAPACITY

The international food sector has a strong demand for the red pepper variety (*Capsicum annum* L.). Skins, stems, seeds, and leftover pulp are examples of by-products that are created after different phases of industrial processing and are thrown away as non-commercial goods (Rouhou et al., 2024). Peppers are also a rich source of oxygenated carotenoids (Márkus et al., 1999). Genetics and changes in maturity can affect their composition and concentration. Despite not having provitamin A activity, these substances are good at scavenging free radicals and may be crucial in avoiding cataracts and age-related macular degeneration (Seddon et al., 1994).

Epidemiological studies have demonstrated that antioxidants in fruits and vegetables can help prevent a variety of chronic diseases, such as cancer, heart disease, stroke, atherosclerosis, and cataracts (Trifunschi et al., 2022). In addition to their antioxidant function, carotenoids have other properties. For example, they exhibit anti-inflammatory and anti-tumor effects, improve cell communication, and aid in the detoxification of enzymatic systems (Khachik et al., 1999).

It is noted in the specialized literature that red pepper (RP) had the highest extraction yield, whereas green pepper (GP) had the lowest ($p > 0.001$). It is known that phenols and flavonoids have antioxidant effects on human health and nutrition (Otunola & Afolayan, 2013). Plant secondary metabolism is the source of phenolic chemicals and phenylpropanoids (Carvalho et al., 2019). The total polyphenol contents of GP and RP were 29.59 and 28.32 mg/g, respectively ($p > 0.001$). In line with the results of this study, Škrovánková et al. (2017) found that the total polyphenol content of paprika and peppers varied between 14.67 and 28.78 GAE mg/g. According to Carvalho et al. (2019), the ripening stage, variety, harvesting site, and year all affect the phenolic makeup of peppers. Ripening has an impact on the antioxidant properties of chilli pepper fruits as well. The antioxidant activity of chilli peppers is higher than that of green peppers. This disparity is easily explained by the increased levels of carotenoids, phenolics, flavonoids, and ascorbic acid present in fully ripe chilli pepper fruits (Sun et al., 2007). The levels of these antioxidants in chilli pepper fruits can vary depending on genotype, post-harvest management, and plant growth conditions (Deepa et al., 2007).

PERFORMANCE OF BROILERS FED RED CHILI PEPPER

According to studies (Galib et al., 2011; Shahverdi et al., 2013; EL-Gogary et al., 2024), chickens' weight gain, feed consumption, and conversion ratio all increased when red pepper was added to their diet (Table 3). Additionally, the use of red pepper decreased the levels of glucose, triglycerides, and cholesterol (p 0.05). The small intestine's mucosa and submucosa both significantly widened. According to this study, broiler given red pepper powder have larger small intestinal sections overall. It was determined that broiler performed better overall when red and black pepper were added to the feed at a rate of 1%. Both the overall quantity of bacteria and the number of coliform bacteria were significantly reduced when broiler were fed red pepper. Recent research indicates that adding 3% to the diet has a good impact on the production of broiler as well as the intestinal histology responses (El-Gogary et al., 2024).

Table 3. The amount of pepper administered to chicks based on their age and the subsequent performance

The age of the chicks (days)	Weight of administered peppers (grams/chick/day)	The performance of the chicks
0-7	0.1	Faster growth; Improved appetite; Stronger immunity.
8-14	0.25	Significant increase; Larger yolk; Increased resistance to diseases.
15-21	0.5	Accelerated growth; Reducing the risk of infections; Lower costs with medications

The age of the chicks (days)	Weight of administered peppers (grams/chick/day)	The performance of the chicks
22-30	0.75	Accelerated growth; The overall condition is better; Fewer respiratory problems.
30-42	1	Significant increase; The overall condition is better; Higher weight at slaughter; Fewer respiratory problems.

CONCLUSIONS

In accordance with the information available in the specialized literature, it can be stated that red pepper is a valuable source of carotenoids, making it an important natural agent for flavoring and coloring (the active compounds in the pepper fruit impart various shades for yellow, orange, and red colors).

Additionally, red bell peppers stand out for their remarkable nutritional value, due to their high content of vitamins (especially vitamin C) and essential minerals, which are important for the health of the immune system and skin.

In the same context, it should be noted that the high level of carotenoids (especially capsanthin and capsorubin) provides significant benefits for eye health and cell protection against oxidative stress, while also exerting an important antioxidant action, contributing to the reduction of risks associated with chronic diseases and premature aging.

Therefore, red pepper can be a valuable component in a balanced diet, having multiple positive effects on overall health.

Research on the stability of carotenoids extracted from red peppers in food products has been conducted according to appropriate protocols and working methods, and the results obtained are essential for evaluating their potential as food coloring agents; additionally, technological progress has led to the development of new methodologies and processes that help reduce issues of oxidative, acidic, and solubility instability of carotenoids.

The conclusion of this study is that supplementing the feed of broiler with preparations based on red pepper can induce positive effects at the productive level (increased growth rate, reduced feed consumption, and improved overall health), as well as on the quality of the final product (intensification of the yellow color of the meat and skin).

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