REVIEW PAPER

Health Prob Civil. 2025, Volume 19, Issue 4
ISSN 2353-6942, eISSN 2354-0265

PART III. OTHER

CAROTENOID CONTENT IN SWEET CORN KERNELS: IMPLICATIONS FOR HUMAN HEALTH AND FOOD SECURITY

Alicja Baranowska[1(A,B,C,D,E,F,G)], **Marcin Weiner**[1(A,B,C,D,E,F,G)]

[1] Department of Agriculture, Faculty of Technical Sciences, John Paul II University in Biała Podlaska, Poland

Authors' contribution:

A. Study design/planning
B. Data collection/entry
C. Data analysis/statistics
D. Data interpretation
E. Preparation of manuscript
F. Literature analysis/search
G. Funds collection

Summary

Sweet corn (*Zea mays* ssp. *saccharata*) is a vegetable of high nutritional value, important for human health and food security. Its kernels contain carotenoids: plant pigments that play significant health-promoting roles, including functioning as natural antioxidants and serving as precursors of vitamin A. The aim of this study was to provide a synthetic overview of the current state of knowledge regarding the carotenoid content in sweet corn kernels, their significance for human health (particularly in the context of preventing civilization diseases), and food security. Scientific studies retrieved from electronic databases using MeSH terms related to sweet corn, carotenoids, health-promoting properties, and food security were analyzed. It was demonstrated that lutein and zeaxanthin are the predominant carotenoids in sweet corn kernels, contributing to its health-promoting value (e.g. protection of vision). The content of these compounds may vary significantly depending on genotype, cultivation conditions, and environmental factors. Achieving consistently elevated levels of provitamin A in corn kernels is of particular importance from a public health perspective: biofortification of corn varieties may help reduce the phenomenon of hidden vitamin deficiency and ensure food security.

Keywords: zeaxanthins, sweet corn, lutein, carotenoids, food security

Tables: 1
Figures: 0
References: 58
Submitted: 2025 Oct 1
Accepted: 2025 Oct 16
Published Online: 2025 Oct 24

Introduction

Maize (*Zea mays* L.) is one of the most versatile cereal crops. It is cultivated in temperate, tropical, and subtropical regions worldwide, covering over 197 million hectares in 160 countries. Annual maize grain production exceeds 1.1 billion tons [1-3]. Maize is among the staple cereals (alongside wheat and rice) that constitute the main component of the human diet, accounting for approximately 42% of caloric intake and 37% of protein in global food consumption. It plays a crucial role in ensuring global food security [4,5]. Often referred to as the "grain of the poor", maize is the dietary staple for about 4.5 billion people in 94 developing countries, providing around 30% of their daily caloric requirements.

Baranowska A, Weiner M. Carotenoid content in sweet corn kernels: implications for human health and food security. Health Prob Civil. 2025; 19(4): 466-475. https://doi.org/10.5114/hpc.2025.155347

Address for correspondence: Alicja Baranowska, Department of Agriculture, Faculty of Technical Sciences, John Paul II University in Biała Podlaska, Sidorska 95/97, 21-500 Biała Podlaska, Poland, e-mail: a.baranowska@dyd.akademiabialska.pl, phone: +48 83 344 99 00

ORCID: Alicja Baranowska https://orcid.org/0000-0002-0558-4194, Marcin Weiner https://orcid.org/0000-0001-9288-0823

It is also a primary source of oil, starch, biofuels, and animal feed [6]. The United States (361 million tons annually) and China (259 million tons annually) dominate in global maize production, together accounting for 54% of the world's maize output. Other major producers include Brazil, Argentina, Ukraine, Indonesia, India, and Mexico [2,3,5]. It should be noted that *Zea mays* L. exhibits considerable diversity in botanical and utilitarian traits. Among its many subspecies, sweet corn (*Zea mays* L. ssp. *saccharata*) is the most well-known, primarily cultivated as a vegetable [7,8]. Sweet corn (*Zea mays* ssp. *saccharata*) was distinguished as a subspecies of maize in the 19th century; its kernels are intended for direct consumption (harvested at the milk stage) and for processing industries [8]. Due to its high adaptability (hybrid varieties), sweet corn cultivation is possible in various climatic zones, including temperate, tropical, and subtropical regions [3]. Globally, sweet corn ranks among the eight most consumed vegetables, with production reaching approximately nine million tons annually. The United States is the largest producer (over three million tons per year), where sweet corn is considered a "national vegetable", and per capita consumption exceeds 11 kg annually. Cultivation is also expanding rapidly in Asia (notably China and Japan) and Europe. Average sweet corn yields reach ~8.5 t/ha, and the area under cultivation continues to grow in response to consumer demand. Other significant producers include Mexico, Nigeria, France, and Hungary [9-11].

The increasing popularity of sweet corn is attributable to its high nutritional value and health-promoting properties. Young kernels, consumed at the milk stage, are rich in readily assimilable carbohydrates (simple sugars and dextrins) and high-quality plant protein. They also contain lipids, vitamins (A, B-group, E, and K), and mineral compounds (especially potassium, magnesium, and phosphorus). Interest in sweet corn consumption is also rising due to the absence of gluten in the kernels. Among the bioactive phytochemicals present in sweet corn, carotenoids, polyphenols, and phytosterols are particularly noteworthy for their antioxidant and health-promoting effects [10,12,13]. Sweet corn kernels are characterized by a substantial carotenoid content, with xanthophylls (lutein and zeaxanthin) predominating and imparting a yellow color to the kernels. Thus, sweet corn varieties with yellow or orange kernels are an important dietary source of these compounds, especially in countries where corn is a popular and widely consumed vegetable. Carotenoids are compounds with health-promoting properties. Their most important feature is antioxidant activity against reactive oxygen species and free radicals. Lutein and zeaxanthin accumulate in the retina, protecting the macula from degeneration, while β-carotene (present in smaller amounts in corn) serves as a provitamin A; its intake contributes to vitamin A synthesis in the body [14-16]. Deficiency of vitamin A and other micronutrients is a serious public health issue worldwide, classified as "hidden hunger". According to the World Health Organization (WHO), 190 million preschool children and 19 million pregnant women globally are at risk of vitamin A deficiency. Ensuring adequate dietary intake of provitamin A is therefore crucial for human health [17]. Biofortification of corn varieties with carotenoids (e.g. through breeding for increased β-carotene content) is considered a sustainable strategy to prevent vitamin A deficiency in developing populations [18]. Currently, sweet corn provides significant amounts of lutein and zeaxanthin in the diets of many populations, and potentially increasing β-carotene levels would make this crop an even more valuable component of functional foods.

Aim of the work

The aim of this work is to provide a synthetic overview of the current state of knowledge regarding the carotenoid content in sweet corn kernels and the significance of these compounds for human health and food security.

Methods

This work is a review article. The material was collected based on scientific literature from electronic databases: Wiley Online Library, Elsevier, PubMed, SpringerLink, Taylor & Francis; the Science Alert scientific portal; the MDPI journal publisher platform; and the Google Scholar search engine. The data collection period covered the months from February to September 2025. The literature review included monographs and articles in English and Polish published in recent years. The selection process involved meticulous examination of titles, abstracts, and full texts. Sources related to the research topic were chosen.

Literature review results

Plant carotenoids: functions and properties

Carotenoids are a group of organic bioactive compounds, fat-soluble derivatives of unsaturated hydrocarbons with antioxidant properties. Carotenoids are the most important isoprenoid (terpenoid) biopigments, responsible for the yellow, orange, and red colors found in nature. By imparting color to flowers and fruits, they also attract insects, aiding in pollination and seed dispersal. In plants, carotenoids are synthesized in the plastids of photosynthetic organs (chloroplasts) and storage tissues (e.g. plant juices). Carotenoids perform many essential functions in the plant kingdom; they are indispensable molecules for photosynthesis, pigmentation, protection against harmful UV radiation, synthesis of phytohormones, and signaling [19,20]. Carotenoids were first isolated and characterized in the early 20th century. A key figure in carotenoid research was the German chemist Richard Willstätter, who in 1910 distinguished two main groups of carotenoids: carotenes, which include hydrocarbons such as β-carotene and lycopene ($C_{40}H_{56}$), and xanthophylls, which, in addition to hydrogen and carbon, contain oxygen ($C_{40}H_{56}O_2$). Xanthophylls are oxidation products of carotenes and include lutein, zeaxanthin, canthaxanthin, and β-cryptoxanthin [21]. To date, approximately 850 carotenoids have been identified, of which 60 are present in the daily diet, and 12 can be detected in the blood. The most common dietary carotenoids are α- and β-carotene, β-cryptoxanthin, lutein, lycopene, and zeaxanthin. Carotenoids are absorbed through the intestines into the bloodstream, which transports them to various tissues via lipoproteins [22-27]. The normal fasting concentration of β-carotene in blood is 0.9-5.58 µmol/L (50-300 mg/dL) [28]. Carotenoids, especially β-carotene, are precursors of vitamin A (retinol) and constitute an important source of this vitamin in the human diet. In the digestive tract, β-carotene is converted to retinal, which can then be reduced to retinol or oxidized to biologically active retinoids [29]. Carotenoids are synthesized by all photosynthetic organisms, as well as many non-photosynthetic species. These natural pigments are responsible not only for the yellow or orange color of plant foods (e.g. corn, carrots, peppers, papaya, tomatoes) but also for the red color of certain fish (e.g. salmon) and crustaceans (e.g. cooked lobster, crab, and shrimp). The carotenoids responsible for the color of corn kernels also determine the color of egg yolks. It should be emphasized that carotenoids are not biosynthesized in the human body and must be supplied through food or supplements; plant carotenoids present in fruits and vegetables are the main source of natural carotenoids available to humans [30,31]. The primary dietary sources of carotenoids are yellow and red vegetables and fruits, as well as dark green leafy vegetables. Rich natural sources of carotenoids include kale, red pepper, spinach, carrot, and tomato (Table 1).

The recommended daily intake of carotenoids is not strictly defined, but it is recommended to consume at least 400-800 g of vegetables and fruit per day, which promotes an adequate supply of carotenoids and other beneficial compounds. However, it should be emphasized that excessive consumption of β-carotene supplements may be detrimental to our health.

Table 1. Content of selected carotenoids in edible portions of vegetables (mg/100 g of edible portion) [16,22,32]

Vegetable (common name / Latin)	α-Carotene	β-Carotene	Lycopene	Luteoline Violaxanthin	Cryptoxanthin Zeaxanthin	Total
Kale / *Brassica oleracea* L. var. *sabellica* L.	0.15	7.3	-	24.4	0.2	34.7
Spinach / *Spinacia oleracea* L.	0.04	3.2	-	12.4	-	17.3
Lettuce / *Lactuca sativa* L.	-	1,3	-	5.3	0.03	8.5
White head cabbage / *Brassica oleracea* L. var. *capitata* L.	-	0.02	-	0.15	-	0.25
Brussels sprouts / *Brassica oleracea* L. var. *gemmifera* (DC.) Zenker	0.05	0.53	-	3.8	-	6.2
Broccoli / *Brassica oleracea* var. *italica* Plenck	-	0.28	-	0.98	0.02	1.6
Red bell pepper / *Capsicum annuum* L.	0.5	3.2	0.13	-	3.3	30.4
Green bell pepper / *Capsicum annuum* L.	0.01	0.1	-	0.53	0.07	0.7
Tomato / *Solanum lycopersicum* Mill.	0.15	0.9	11.4	0.21	-	12.7
Carrot / *Daucus carota* L. subsp. *sativus* L.	4.9	9.2	-	0.36	-	15.9

Due to the high global consumption of sweet corn, it is also a rich source of these compounds [16,22,32]. However, it should be noted that carotenoid content in plants depends primarily on species, variety, climatic and soil conditions, agronomic practices, and post-harvest processes [22,33]. The method of preparation for consumption has a significant impact on the carotenoid content in fruits and vegetables. For example, removing the outer leaves of white cabbage deprives it of a substantial amount of lutein and β-carotene (the outer leaves contain approximately 150 times more lutein and about 200 times more β-carotene than the inner leaves). In contrast, the skin of a tomato contains about 5 times more lycopene than the pulp. The lycopene content in tomatoes is also influenced by the temperature at which the fruit develops [16].

It should be emphasized that carotenoids present in food are susceptible to degradation. Among the many factors affecting carotenoid degradation are food processing procedures, elevated temperature, oxidation, exposure to light, and changes in pH [34,35]. In addition to their health-promoting properties, carotenoids are also gaining increasing interest as nutricosmetics (products combining the features of dietary supplements and cosmetics), as it has been demonstrated that they provide cosmetic benefits when consumed in appropriate amounts [28].

Carotenoids in sweet corn kernels: health-promoting properties

Sweet corn kernels provide many valuable nutritional and health-promoting components. Sweet corn contains an elevated level of carotenoids compared to the grains of other cereal species [36].

Carotenoids perform various biological functions beneficial to human health. As potent antioxidants, they neutralize reactive oxygen species and protect cells against oxidative stress. Oxidative stress is associated with numerous diseases, including cardiovascular diseases, neurodegenerative disorders, and cancers. Carotenoids can protect cellular components from oxidative damage, potentially mitigating the progression of these diseases. Carotenoids, especially xanthophylls, also exhibit anti-inflammatory effects [37-39].

Therefore, a diet rich in carotenoids correlates with a reduced risk of developing chronic diseases, such as certain cancers, cardiovascular diseases, and eye disorders. Epidemiological studies have demonstrated a correlation between high dietary carotenoid intake and a decreased risk of breast, cervical, ovarian, and colorectal cancers, as well as cardiovascular and ocular diseases. It is believed that carotenoids act in a time- and dose-dependent manner [40].

The carotenoids most frequently studied in this context are β-carotene, lutein, zeaxanthin, and lycopene. β-carotene is the most effective precursor of vitamin A (12 mg of β-carotene provides approximately 1 mg of retinol). Scientific studies indicate that lutein and zeaxanthin are present in many tissues of the human body and are concentrated in the retina and lens of the eye. It has been shown that in the eye, lutein and zeaxanthin filter high-energy wavelengths of visible light and act as antioxidants, protecting against the formation of reactive oxygen species and subsequent free radicals. Thus, they potentially play a role in the prevention and treatment of certain eye diseases, such as age-related macular degeneration, cataracts, and retinitis pigmentosa. Scientific studies have also shown that lutein and zeaxanthin are present in the skin, and animal studies have provided evidence for the effectiveness of these carotenoids in preventing light-induced skin damage, especially from ultraviolet radiation [41-45]. Kopcke et al. found that dietary supplementation with β-carotene provides protection against sunburn in a time-dependent manner (protection required at least 10 weeks of supplementation) [46].

Recent studies conducted among American adults have shown that higher dietary carotenoid intake is associated with a lower prevalence of metabolic dysfunction-associated fatty liver disease. However, this relationship varied depending on age, gender, and lifestyle factors of the study population [47]. In contrast, studies by Lin et al. indicate that lower serum concentrations of α-carotene, β-carotene, β-cryptoxanthin, lycopene, and lutein/zeaxanthin were associated with higher all-cause and cardiovascular mortality risk among American adults with metabolic dysfunction-associated fatty liver disease [48].

Studies by Deng et al. demonstrated that American adults with optimal sleep duration were associated with higher dietary carotenoid intake compared to those with short or long sleep duration [49]. Among American adults, higher intake of β-cryptoxanthin was associated with less frequent anxiety symptoms [50]. Thus, optimal carotenoid intake may be associated with a reduced risk of many civilization diseases. Moreover, recent studies suggest that carotenoids may be important for mental and metabolic health and are also important during pregnancy and early life [51,52].

Carotenoid content in sweet corn and food security

The global population continues to grow, and it is anticipated that providing future generations with fresh and healthy food in a sustainable manner will become increasingly challenging. Nutritional deficiencies are already a widespread problem, estimated to affect around two billion people worldwide. Malnutrition leads to deteriorating health, reduced work productivity, and is associated with high rates of mortality and morbidity [53]. Vitamin A deficiency is one of the major nutritional deficiencies globally. It is particularly prevalent among individuals living in underdeveloped and developing countries, especially in Central and West Africa and South-Central Asia. Vitamin A deficiency can led to impaired immune function, is the leading cause of preventable blindness in children, and increases the risk of death from severe infections; it is also a potential risk factor for cognitive disorders and mental illnesses [54-56].

To help combat vitamin A deficiency in the diet, efforts are underway to biofortify crops that serve as staple foods, one of which is maize. Maize is one of the primary cereals (alongside wheat and rice) that constitute the main dietary component for approximately 4.5 billion people in 94 developing countries [6]. Thus, maize plays a significant role in ensuring global food security. Maize has been identified as one of the promising crop species for carotenoid biofortification due to its importance as a major food crop worldwide. Maize biofortification is being conducted, among others, within the framework of the International HarvestPlus Program, which aims to reduce nutrient deficiencies by increasing the content of vitamins and minerals in staple crops. Maize biofortification has led to the development of maize varieties with high β-carotene content, known as orange maize, which are being implemented in Sub-Saharan African countries [57].

Recent work in China has also demonstrated the possibility of introducing genes that enhance β-carotene synthesis into elite sweet corn lines using marker-assisted selection, resulting in sweet corn lines with significantly increased provitamin A content in the kernels. This may mean that in the future, sweet corn varieties with more intense orange kernel coloration and even higher carotenoid content will become available on the market [58].

It should be noted that traditional staple cereals (rice and wheat) are poor in carotenoids, which promotes the occurrence of hidden vitamin hunger in populations whose diets are based on these products. In this context, sweet corn and colored maize varieties (yellow, orange) are valuable dietary supplements. Including these crop species in the daily diet alongside other vegetables and fruits increases dietary diversity and the supply of micro- and macronutrients, which is one of the pillars of food security, understood as ensuring not only caloric intake but also nutritional quality of food. In the context of sustainable food systems, the cultivation of sweet corn enriched with carotenoids has a dual significance: on one hand, it provides local markets with a high-value vegetable, and on the other, it can serve as a raw material for the food industry to produce fortified products (e.g. purees, porridges, whole grain snacks) targeted at vulnerable groups (children, pregnant women). Consumer education regarding the preparation of corn to maximize carotenoid utilization is also important; for example, the addition of a small amount of vegetable oil to corn dishes significantly increases the absorption of lutein and β-carotene in the digestive tract. In summary, ensuring consistently high carotenoid content in sweet corn through breeding efforts, appropriate variety selection, and agronomic practices aligns with the goals of food security by ensuring the availability and bioavailability of key nutrients.

Conclusions

Sweet corn is not only an economically important vegetable but also a valuable source of carotenoids in the human diet. Its kernels contain lutein and zeaxanthin compounds essential for eye health and exhibiting antioxidant activity. Although the proportion of provitamin A (β-carotene) in the total carotenoid pool of sweet corn is lower than in many other vegetable species, this plant constitutes an element of strategies to improve vitamin A supply in the diet, especially in combination with biofortification efforts.

From the perspective of food security, the stable supply of sweet corn rich in carotenoids to consumers is of significant health-promoting importance. Regular consumption of this vegetable may support the prevention of diseases associated with vitamin A deficiency and oxidative stress. Including sweet corn alongside other vegetables and fruits in our diet contributes to increasing the supply of key micro- and macronutrients, which is one of the elements in combating hidden hunger. Further research should be conducted on breeding sweet corn varieties with increased carotenoid content and improving agronomic practices to maximize the nutritional value of sweet corn. Therefore, sweet corn may, to an even greater extent than before, combine the characteristics of a high-yield crop with the role of "functional" food, supporting human health and the achievement of global food security goals.

Disclosures and acknowledgements

The authors declare no conflicts of interest with respect to the research, authorship, and/or publication of this article.

This research was funded by the Research Development Fund of John Paul II University in Biała Podlaska, Poland, the project number PB/26/2020.

Artificial intelligence (AI) was not used in the creation of the manuscript.

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