FoodAfrica, Internet Forum 31 March – 11 April
Internet Paper for Food, Nutrition and Health Theme

Enhancing the carotenoid levels of foods through agriculture and food technology

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Abstract

Aside from increased food production, efforts should be taken to optimize the levels of health-promoting compounds in foods. In order to do this, the compositional variation throughout the food chain must be known. The composition of carotenoids differs qualitatively and quantitatively between foods. It also varies in a given food due to factors such as cultivar or varietal differences, stage of maturity, climatic or geographic effects, part of the plant consumed, conditions during agricultural production, post-harvest handling, processing and storage. Based on this variability, measures can be taken to offer the population foods with the highest carotenoid concentrations. This effort includes selection of carotenoid-rich foods and cultivars, consumption or preservation of fruits and vegetables at the mature or ripe stage, use of whole rather than peeled fruits, optimization of cooking, processing and storage conditions. The tropical climate also promotes greater carotenoid biosynthesis. This article focuses on carotenoids but the lessons learned with these bioactive phytochemicals can be applied to other food components.

Introduction

There is growing recognition that optimization of the nutrient/phytochemical contents and profiles of foods, through conventional plant breeding and agronomic practices or genetic manipulation, is a viable strategy (Lindsay, 2000; Parr and Bowell, 2000; Schneeman, 2000; Scott *et al*, 2000; van den Berg *et al*, 2000; Miettinen, 2001). Parr and Bowell called attention to the possibility that manipulation of phytochemical metabolism by expensive molecular techniques might give little improvement than that achieved by traditional agricultural procedures. Moreover, the full potential of this strategy can be materialized only if the benefits of agriculture are reinforced by food technology.

Carotenoids are responsible for the pleasing yellow, orange or red color of many foods. The role of some of these compounds as provitamin A precursors has been known for years. Other beneficial effects to human health have been more recently attributed to carotenoids, such as enhancement of the immune response and reduction of the risk of degenerative diseases such as cancer, cardiovascular diseases, cataract and macular degeneration, these actions not being restricted to the provitamins A (Krinsky, 1993; Bendich, 1994; Olson and Krinsky, 1995; Mayne, 1996; Olson, 1999). Thus, the consumption of carotenoid-rich foods is widely recommended.

The principal carotenoids of foods are β-carotene, β-cryptoxanthin, lycopene, lutein and violaxanthin. Except for violaxanthin, these are also the principal carotenoids found in the human plasma, and together with zeaxanthin, are the carotenoids most studied in terms of human health.

β-Carotene and β-cryptoxanthin are provitamins A. Lycopene is vitamin A inactive but is a more efficient antioxidant than β-carotene (Di Mascio *et al.*, 1989). It has been linked with reduction of the risk of cancer, especially lung, stomach and prostate cancer (Giovannucci, 1999). Lutein and zeaxanthin are the carotenoids associated with lowered risk of macular degeneration and cataract (Moeller *et al.*, 2000).

Variation in the carotenoid composition

Foods vary qualitatively and quantitatively in their carotenoid composition. Dark green leafy vegetables, palm oil, palm fruits, carrot, orange sweet potato, mature squashes and pumpkins, tomato, yellow, orange and red tropical fruits are rich sources of carotenoids (Rodriguez-Amaya, 1997, 1999a)

In a given food, qualitative and especially quantitative differences also occur due to factors such as cultivar or variety, stage of maturity, climate or geographic site of production, part of the plant utilized, farming practice, processing and storage of food.

Differences among cultivars of the same food are well documented. An example is shown in Table 1. The red-fleshed papayas Solo, Formosa and Tailandia, produced in the Brazilian State of Bahia, differed particularly in the lycopene content with the Tailandia papayas having twice as much as the other two cultivars. The orange-fleshed common papaya is devoid of lycopene.

Table 1. Cultivar and geographic effects on the principal carotenoids (µg/g) of papaya (*Carica papaya*).

Carotenoid	Common	Solo	Formosa	Formosa	Tailândia
	SP	BA	SP	BA	BA
β-carotene	1.2	2.5	1.4	6.1	2.3
β-cryptoxanthin	8.1	9.1	5.3	8.6	9.7
lycopene	-	21	19	26	40

SP – São Paulo, BA – Bahia
Reference: Kimura et al. (1991)

Maturation of a vegetable or ripening of a fruit is usually accompanied by enhanced carotenoid biosynthesis. This is shown in Table 2 for Tommy Atkins mangoes, in which the major carotenoids increased from the mature-green to the ripe. The same trend was observed in the cultivar Keitt (Mercadante and Rodriguez-Amaya, 1998).

Table 2. Principal carotenoids (µg/g) of Tommy Atkins mangoes (*Mangifera indica*) at three stages of maturity.

Carotenoid	Stage of maturity		
	Mature-green	Partially ripe	Ripe
β-carotene	2.0 ± 0.8	4.0 ± 0.8	5.8 ± 2.5
violaxanthin	6.9 ± 3.0	18 ± 7	22 ± 9
cis-violaxanthin	3.3 ± 1.3	9.0 ± 3.2	14 ± 5

Reference: Mercadante and Rodriguez-Amaya (1998).

In the same lot of acerola, ready for consumption, the firm ripe (red-orange) and fully ripe (dark-red) fruits were separated and analyzed separately. The composition differed especially in β-carotene, which was only 2.2 µg/g in the firm-ripe fruits and much higher (12 µg/g) in the fully ripe fruits (Porcu and Rodriguez-Amaya, unpublished results).

Greater difference would be expected when comparison is made from the immature stage. This was indeed the case with *Cucurbita moschata* cultivar Menina Verde (Table 3). α-Carotene and β-carotene increased dramatically during maturation.

Table 3. Principal carotenoids (μg/g) of *Cucurbita moschata* Cv. Menina Verde at two stages of maturity.

Carotenoid	Stage of maturity	
	Immature	Mature
α-carotene	0.1	23
β-carotene	1.5	39

Reference: Arima and Rodriguez-Amaya (1988).

The β-carotene content of mature leaves of lettuce (12 μg/g) and endive (14 μg/g) were about three times those of the young leaves (3.5 and 4.2 μg/g, respectively) (Ramos and Rodriguez-Amaya, 1987).

While fruits from cold regions are generally colored by anthocyanins, tropical and subtropical fruits owe their color mainly to carotenoids. Climatic effects are also seen in fruits of the same cultivars produced in regions of differing climates, elevated temperature and greater exposure to sunlight increasing carotenogenesis. Comparing papayas of the cultivar Formosa produced in the hot Northeastern state of Bahia with those produced in the temperate Southeastern state of São Paulo, the former fruits presented higher β-carotene, β-cryptoxanthin and lycopene contents (Table 1).

In Keitt mangoes, those produced in Bahia had more of the major carotenoids, especially β-carotene (Mercadante and Rodiguez-Amaya, 1998). In acerola, β-carotene and β-cryptoxanthin were much lower in the São Paulo fruits, compared to those from the neighboring hot Northeastern states of Pernambuco and Ceara which had similar composition (Cavalcante and Rodriguez-Amaya, 1992).

Comparing kale at the same stage of maturity, produced in neighboring farms, all constituent carotenoids were significantly higher in samples collected from an organic farm than in those taken from a conventional farm using agrochemicals (Mercadante and Rodriguez-Amaya, 1991). This indicated that one of the chemicals used in the latter farm, probably herbicide, inhibited carotenoid biosynthesis in the leaves.

In many fruits, carotenoids are more concentrated in the peel than in the pulp. In S*pondias lutea*, for example, although β-carotene appeared slightly higher in the peeled fruit, β-cryptoxanthin was twice as much in the whole fruit (Table 4).

Table 4. Effect of peeling on the principal carotenoids (μg/g) of *Spondias lutea* and guava (*Psidium guajava*).

Fruit/Carotenoid	Whole fruit	Peeled fruit
Spondias lutea		
β-carotene	1.6 ± 0.2	2.6
β-cryptoxanthin	16 ± 2	8.3

Reference: Rodriguez-Amaya and Kimura (1989)

Effects of processing and storage

Many carotenogenic foods are seasonal and preservation at peak harvest is necessary to minimize losses, make the products available all year round and permit transportation to places other than the site of production. Processing and storage of foods should, however, be optimized to prevent carotenoid losses (Rodriguez-Amaya, 1997, 1999b, 2002). Although industrial processing is more often focalized, losses on home preparation can also be, at times even more, considerable.

Retention or loss of carotenoids during processing and storage of food has been reported in numerous papers. The data are somewhat conflicting and often difficult to interpret. However, some conclusions can be drawn (Rodriguez-Amaya, 1997):

- The tropical climate enhances carotenoid biosynthesis. On the other hand, this same ambient conditions may hasten destruction of carotenoids during post-harvest handling and storage.
- Carotenoid biosynthesis may continue, raising the carotenoid content, in fruits, fruit vegetables and root crops even after harvest, provided they are kept intact and not treated in any way that would inactivate the enzymes responsible for carotenogenesis. In leaves and other vegetables, post-harvest degradation of carotenoids appears to prevail, especially at high storage temperature and under conditions that favor wilting.
- Carotenoids are naturally protected in plant tissues; cutting, shredding, chopping and pulping of fruits and vegetables increase exposure to oxygen and bring together carotenoids and enzymes that catalyze carotenoid oxidation.
- The stability of carotenoids differs in different foods, even when the same processing and storage conditions are used. Thus, optimum conditions for carotenoid retention during preparation/processing differ from one food to another. Carotenoids *per se* have different susceptibilities to degradation.
- The major cause of carotenoid destruction during processing and storage of foods is enzymatic or non-enzymatic oxidation. Isomerization of *trans*-carotenoids to the *cis*-isomers, particularly during heat treatment, alters their biological activity and discolors foods, but not to the same extent as oxidation. Enzymatic degradation of carotenoids may be a more serious problem than thermal decomposition in many foods.
- In home preparation, losses of carotenoids generally increase in the following order: microwaving < steaming < boiling < sautéing. Deep-frying, prolonged cooking, combination of several preparation and cooking methods, baking and pickling all result in substantial losses of carotenoids.
- Whatever the processing method chosen, retention of carotenoid decreases with longer processing time, higher processing temperature and cutting or puréeing of the food. Reducing processing time and temperature, and the time lag between peeling, cutting or puréeing and processing improve retention significantly. High temperature, short-time processing is a good alternative.
- The heat treatment in blanching may provoke some losses of carotenoids, but the inactivation of oxidative enzymes will prevent further and greater losses during holding before thermal processing, slow processing and storage.
- Freezing and frozen storage generally preserve the carotenoids, but slow thawing can be detrimental, particularly when the product has not been properly blanched.
- Peeling and juicing result in substantial losses of carotenoids, often surpassing those of heat treatment.
- Traditional sun-drying, although the cheapest and most accessible means of food preservation in some regions, causes considerable carotenoid destruction. Drying in a solar dryer, even of simple and inexpensive design, can appreciably reduce losses. Protecting the food from direct sunlight also has a positive effect.

- Exclusion of oxygen (e.g. through vacuum or hot filling, oxygen-impermeable packaging, inert atmosphere), protection from light and low temperature diminish carotenoid decomposition during storage.

Alteration or loss of carotenoids during processing and storage of foods thus occur through physical removal (e.g. peeling), isomerization and enzymatic or non-enzymatic oxidation, the last two reactions being due to the many double bonds in the carotenoid molecules.

In programs designed to promote production and consumption of carotenoid-rich foods, the following measures have been recommended (Rodriguez-Amaya, 1997):

- Identify locally available or potentially available food sources of carotenoids.
- Select and promote greater production of rich sources, which also have good agronomic, technological and sensory properties.
- Process carotenoid-rich food cultivars at optimum maturity/ripeness, stage at which they are both appropriate for processing and contain high levels of carotenoids.
- Avoid peeling foods. Losses during juicing should also be minimized.
- Consume or thermally process foods immediately after cutting, chopping or macerating. Consider blanching to inactivate the enzymes.
- Advocate simple measures such as avoiding prolonged cooking, cooking with the lid on, washing before peeling and cutting, avoiding cutting or macerating into very small pieces, keeping the food intact during storage, storing at low temperature in the dark and keeping storage time at a minimum.
- Optimize cooking, processing and storage conditions. Minimize cooking/processing time and temperature.
- Use solar-drying, in which the food is protected from direct sunlight, instead of traditional sun-drying.

For a long time the major concern about processing in relation to carotenoids had been preventing losses. Recent papers showing that mechanical and enzymatic disruption of the food matrix and thermal processing increase bioavailability (Stahl and Sies, 1992; Gärtner *et al.*, 1997; Rock *et al.*, 1998; Castenmiller *et al.*, 1999; van het Hof *et al.*, 2000) have shifted attention to this important topic.

In nature carotenoids are protected by the cellular structure, the destruction of which renders the carotenoids vulnerable to degradation as discussed above. On the other hand, this natural protection lowers bioavailability. Processing denatures proteins and breaks down the cell walls, making the release of carotenoids from the food matrix during digestion easier.

It is thus recommended that strategies to increase the dietary intake of carotenoids include enhancement of bioavailability. Cooking/processing conditions should be optimized so that appreciable losses of carotenoids are prevented while the bioavailability is increased.

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This paper has been submitted to the Internet Forum of FoodAfrica (http://foodafrica.nri.org). The content of the paper is the responsibility of the author(s). The organisers of FoodAfrica have made this paper available with minimal editing for the purposes of discussion within the Forum (31 March 2003- 11 April 2003). The paper will be subject to peer review and editing prior to a final version appearing in the Proceedings of FoodAfrica. Assuming that the paper is accepted for the Proceedings, the web address for this version of the paper may be different to that made available in the Proceedings