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Original article

Analysis of carotenoids in fruit of different apricot accessions reveals large variability and highlights apricot as a rich source of phytoene and phytofluene

K. Shemesh[1,2], M. Zohar[1], I. Bar-Ya'akov[1], K. Hatib[1], D. Holland[1] and T. Isaacson[1,a]

[1] Department of Fruit Tree Sciences, Agricultural Research Organization, Newe Ya'ar Research Center, P.O. Box 1021, Ramat Yishay 30095, Israel

[2] Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, Faculty of Agriculture, Food and Environmental Quality Sciences, The Hebrew University of Jerusalem, Rehovot 76100, Israel

Summary

Introduction – **Carotenoids are tetraterpene pigments which have a major impact on fruit color and nutritional value. Very little is known about the carotenoids' profile and the extent of its variation within different apricot (*Prunus armeniaca*) accessions.** *Materials and methods* – **We analyzed carotenoid content and composition, as well as color criteria, of fruit from 113 different apricot accessions from the Newe Ya'ar germplasm collection in Israel.** *Results and discussion* – **Apricot fruit contains a unique profile of carotenoids consisting mainly of β-carotene, phytoene and phytofluene, and small amounts of other intermediates of the biosynthesis pathway, including *cis*-lycopene. The different accessions show great variability in total carotenoid content (5–95 µg g^{-1} fresh weight) as well as in carotenoid composition. The percentage of β-carotene, phytoene and phytofluene varies between 2 to 67%, 6 to 59% and 12 to 44% respectively.** *Conclusion* – **Our findings highlight apricot as one of the richest natural sources of the colorless carotenoids phytoene and phytofluene, whose health benefits were recently noted. The distinctive carotenoid profile alongside the high diversity in fruit carotenoid composition and content among apricot varieties can assist future breeding programs and may help in understanding the factors contributing to color and nutritional traits of apricot fruit.**

Keywords
Israel, apricot, *Prunus armeniaca*, lycopene, carotene, fruit color

Résumé

L'analyse des caroténoïdes dans les fruits de différentes accessions d'abricot révèle une grande variabilité et souligne la richesse de l'abricot en phytoène et phytofluène.

Introduction – **Les caroténoïdes sont des pigments tétrastropènes qui ont un impact majeur sur la couleur des fruits et leur valeur nutritive. Cette étude vise à connaître le profil des caroténoïdes de l'abricot (*Prunus armeniaca*) et l'étendue de leur variation dans un large éventail d'accessions.** *Matériel et méthodes* – **Nous avons analysé la teneur et la composition en caroténoïdes, ainsi que les caractéristiques de couleur des fruits provenant de 113 accessions différentes d'abricot provenant de la collection de ressources génétiques de Newe Ya'ar en Israël.** *Résultats et discussion* – **Le fruit de l'abricotier possède un profil unique en caroténoïdes, constitué principalement de β-carotène, de phytoène et de phytofluène, et de petites quantités d'autres composés intermédiaires de la voie de biosynthèse, y compris du *cis*-lycopène. Les différentes accessions ont présenté une grande variabilité de la teneur totale en caroténoïdes (5 à 95 µg g^{-1} poids frais) ainsi que de la composition en caroténoïdes. Les pourcentages de β-carotène, de phytoène et de phytofluène ont varié de 2 à 67%, de 6 à 59% et de 12 à 44%, respectivement.** *Conclusion* – **Fort de ces résultats originaux l'abricot représente l'une des sources naturelles les plus riches en caroténoïdes incolores tels que le phytoène et le phytofluène, dont les bienfaits pour la santé ont été récemment notés. Le profil distinctif en caroténoïdes peut contribuer, à côté de la grande diversité de composition en caroténoïdes des fruits parmi les variétés d'abricot, à élaborer des programmes de sélection et à comprendre les facteurs contribuant à la couleur et aux traits nutritionnels de l'abricot.**

Mots-clés
Israël, abricot, *Prunus armeniaca*, lycopène, carotène, couleur du fruit, diversité des ressources génétiques

Significance of this study

What is already known on this subject?

- Carotenoids are natural plant pigments contributing to the color, taste and nutritional value of many fruits. Little is known about carotenoids in apricot.

What are the new findings?

- Analysis of 113 apricot accessions revealed a great variability in the carotenoid content and composition, highlighting apricot as a rich source of phytoene and phytofluene.

What is the expected impact on horticulture?

- This study could contribute to the identification of genetic factors controlling carotenoid accumulation in apricot, and in breeding varieties with desired carotenoid profiles.

[a] Corresponding author: tali@volcani.agri.gov.il.

Introduction

Carotenoids are 40 carbon isoprenoid molecules synthesized by all photosynthetic organisms. In addition to their functions as essential agents in the photosynthetic apparatus and as precursors of the plant hormones abscisic acid (ABA) and strigolactones (McQuinn *et al.*, 2015; Nambara and Marion-Poll, 2005), carotenoids accumulate in tissues of many fruits, providing their colors: yellow, orange and red. Carotenoid degradation products are important aroma volatiles contributing greatly to the unique flavor and aroma of many fruits (Auldridge *et al.*, 2006; Lewinsohn *et al.*, 2005). The carotenoid biosynthesis pathway is well conserved among plants and has been extensively studied in model plants such as tomato and *Arabidopsis* (Cazzonelli and Pogson, 2010; Moise *et al.*, 2013; Nisar *et al.*, 2015). The first carotenoid in the pathway is the colorless molecule phytoene, which is a product of the condensation of two geranylgeranyl diphosphate (GGPP) molecules. Four double bonds are introduced into the phytoene molecule to form phytofluene, ζ-carotene, neurosporene and lycopene respectively. The desaturation process is accompanied by isomerization reactions, assuring that the produced lycopene is in the all-*trans* configuration (Figure 1). The biosynthetic pathway splits into two branches after the synthesis of all-*trans* lycopene according to the type of cyclization it undergoes. β-Type cyclization at both ends of the molecule leads to the formation of β-carotene and to its oxygenated products, the β-xanthophylls. β-type cyclization of one side of the lycopene molecule and ε-type cyclization at

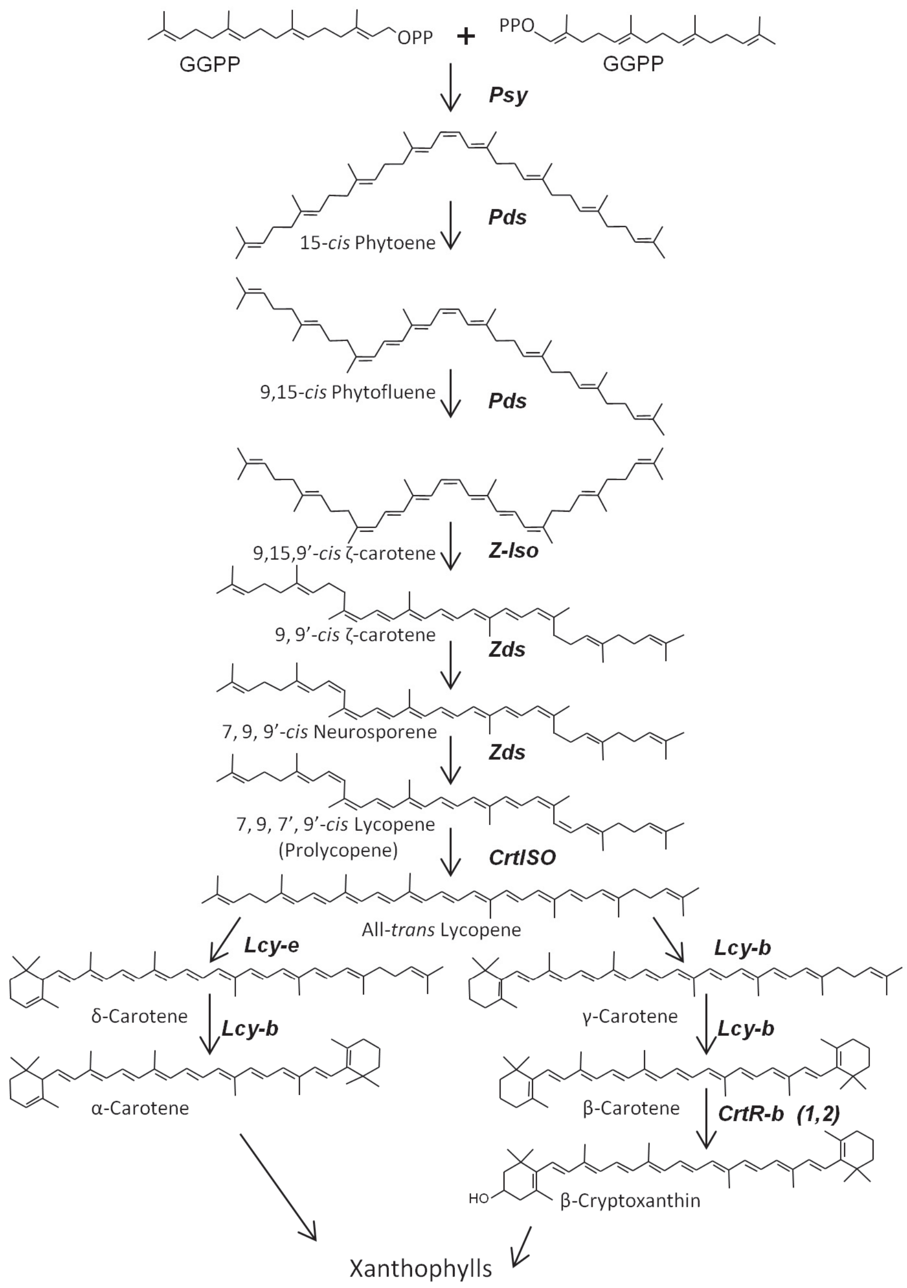


FIGURE 1. The carotenoid biosynthesis pathway in plants. GGPP, Geranylgeranyl diphosphate; *Psy*, Phytoene synthase; *Pds*, phytoene desaturase; *Zds*, ζ-carotene desaturase; *CrtISO*, carotene isomerase; *Ziso*, ζ-carotene isomerase; *Lcy-e*, lycopene ε-cyclase; *Lcy-b*, lycopene β-cyclase; *CrtR-b* (1,2), carotene β hydroxylase1 or 2.

the other side generate α-carotene, which is the precursor of α-xanthophylls such as lutein (Cazzonelli and Pogson, 2010; Moise *et al.*, 2013; Nisar *et al.*, 2015).

Apricot (*Prunus armeniaca* L.) is an important *Prunus* crop, along with peach, cherry and plum. Despite their short harvest season, apricots are highly appreciated and consumed fresh, dry or processed all over the world. The content and composition of carotenoids in apricots determine their color. Despite the vast knowledge on carotenoid biosynthesis in plants, not much is known about the carotenoid profile of apricot fruit. The first and most thorough carotenoid characterization was done by Curl (1960) on a single variety he obtained from the market. The main carotenoid in the fruit Curl analyzed was found to be β-carotene (60%), yet, substantial amounts of phytoene (10%), phytofluene (6%) and *cis*-isomers of lycopene (5%) were also detected. A later survey conducted on two varieties with contrasting fruit color (Marty *et al.*, 2005), and a selection of their progeny (Ruiz *et al.*, 2008), found β-carotene, phytoene and phytofluene to be the main carotenoid constituents in the fruit flesh (10–30%, 25–36% and 42–51%, respectively) (Ruiz *et al.*, 2008). However, another survey of a single apricot variety found a very different profile of carotenoids, including 98% β-carotene (Khachik *et al.*, 1989). Most other surveys examining the carotenoid profiles of apricot fruit concentrated on measuring a few specific carotenoids rather than trying to provide a complete profile. Some surveys concentrated on the pro-vitamin A type of carotenoids (γ-carotene, β-carotene and β-cryptoxanthin) (Ruiz *et al.*, 2005), while other surveys measured only major visible carotenoids (Katayama *et al.*, 1979; Campbell *et al.*, 2013; Radi *et al.*, 1997; Dragovic-Uzelac *et al.*, 2007; Drogoudi *et al.*, 2008). Thus knowledge on carotenoid content and composition of apricot fruit, and its variation among different accessions is lacking.

Carotenoids are essential in human and animal diets. Carotenoids containing at least one unsubstituted β-ionone end group, such as γ-carotene, β-carotene and β-cryptoxanthin, are precursors of vitamin A and some carotenoids are considered protective agents against different chronic diseases, such as cancer and cardiovascular disorders. Among the well-studied carotenoids in this respect are β-carotene and lycopene, as well as the xanthophylls lutein and zeaxanthin (Fraser and Bramley, 2004; Krinsky and Johnson, 2005; Fiedor and Burda, 2014). Phytoene and phytofluene have recently been highlighted as antioxidants that may contribute to our health too (Engelmann *et al.*, 2011; Meléndez-Martínez *et al.*, 2015). Phytoene was shown to possess antitumor activity in mice and in cell culture (Mathews-Roth, 1982; Nishino, 1998) as well as protective activity against sunburn (Mathews-Roth and Pathak, 1975). Phytofluene was suggested to act against cancer by inhibiting cell proliferation (Kotake-Nara *et al.*, 2001; Nara *et al.*, 2001) and by activating protective cellular pathways *in vitro* (Gijsbers *et al.*, 2013). Different *in vitro* studies suggest that the combination of phytoene and phytofluene have various effects: an inhibitory effect on cancer cells (Hirsch *et al.*, 2007), involvement in protecting LDL from oxidation (Shaish *et al.*, 2008) and free radical scavenging properties (Martínez *et al.*, 2014). Surveys presenting correlations between tomato products consumption and health benefits found that along with lycopene absorbance, high levels of phytoene and phytofluene were also observed in body fluids and tissues (Aust *et al.*, 2005; Melendez-Martinez *et al.*, 2013; Porrini *et al.*, 2005). Aust *et al.* (2005) showed that consumption of lycopene alone does not provide similar levels of protection against UV radiation, as did tomato products, leading the researchers to suggest that phytoene and phytofluene contribute to these differences. Another study supported this assumption by finding that the combination of phytoene, phytofluene and lycopene has a synergistic anti-cancer effect when applied to a prostate cancer cell-line (Linnewiel-Hermoni *et al.*, 2015). These findings suggest a beneficial role for phytoene and phytofluene, though further investigation into their biological function is required.

All-*trans*-lycopene, the red pigment coloring tomatoes, is well known, however, its accumulation in plant tissues in nature is rare (Schaub *et al.*, 2005) and usually correlates with selection during domestication. It was shown that down regulation of lycopene cyclase genes is responsible for lycopene accumulation in the cultivated red tomato (Ronen *et al.*, 1999, 2000). Other fruits that accumulate lycopene, such as pink guava, red watermelon and red grapefruit are likely also lycopene cyclase mutant lines that were selected by humans. In the majority of these fruits lycopene is usually found in the all-*trans* configuration. *Cis*-isomers of lycopene, mainly the tetra-*cis* lycopene (named prolycopene), were reported primarily in mutant lines such as the '*tangerine*' mutant of tomato (Zechmeister *et al.*, 1943), the '*yofi*' mutant of melon (Galpaz *et al.*, 2013), the '*Orangelo*' of watermelon (Tadmor *et al.*, 2005) and the '*Orange Queen*' of Chinese cabbage (Watanabe *et al.*, 2011). Research on lycopene and human health has shown the benefits of its consumption [reviewed

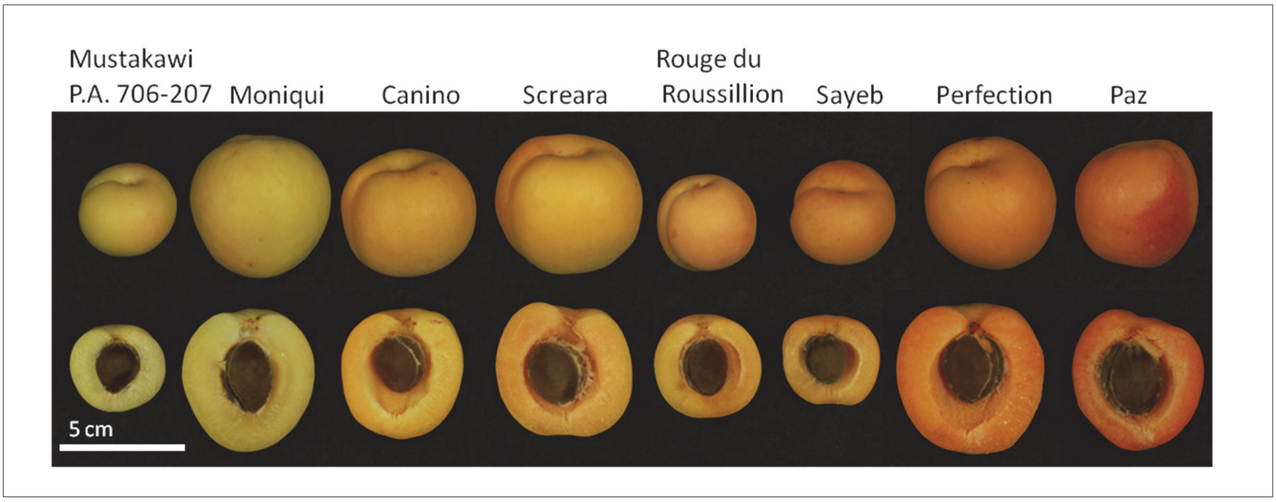


FIGURE 2. Pictures of ripe apricot fruit of selected accessions from the Newe Ya'ar germplasm collection.

in Cámara *et al*. (2013) and Friedman (2013)]. For example, lycopene was linked to prevention and protection against various cancers (Holzapfel *et al*., 2013; Okajima *et al*., 1998; Zu *et al*., 2014) and cardiovascular diseases (Müller *et al*., 2015). *Cis*-isomers of lycopene originating from the tomato mutant '*tangerine*' were shown to have higher bioavailability than lycopene in *trans* configuration from red tomatoes, leading the researchers to suggest that *cis* lycopene might have greater potential to exert its protective activity (Cooperstone *et al*., 2015).

Due to the lack of knowledge regarding the variation in carotenoid profile of apricot and since previous studies indicated that some apricot varieties accumulate unusual amounts of phytoene, phytofluene and *cis*-isomers of lycopene, our main objective was to characterize the carotenoid content and composition of apricot fruit and to examine their variation among accessions exhibiting wide range of fruit color. To achieve this goal we used the apricot germplasm collection at Newe-Ya'ar Research Center, Israel (Trainin *et al*., 2013), which includes a wide range of fruit color phenotypes, from very pale yellow to intense orange (Figure 2). The germplasm collection includes international accessions, local accessions, recently bred local cultivars, old local varieties and landraces (Holland *et al*., 2006), and a set of hybrids.

Materials and methods

Plant material

The apricot accessions and hybrids used in this study are all grown at the Newe Ya'ar Research Center, in the Jezreel Valley (32°42'N, 35°11'E), two trees of each accession. The germplasm collection can be divided into three groups according to the origin of the accessions: the first group consists of 65 "international" accessions (most of them originating from the USA and France, but some from other countries as well); a second group consisting of local accessions, which include 15 cultivars that were recently bred in Israel and 20 accessions which are old local varieties and landraces (Holland *et al*., 2006). The third group consists of a set of hybrids, progeny of the germplasm accessions. Fruits were harvested at their ripe stage (full size, full color, still firm) and were chosen randomly. Fruits from international and local accessions were picked from May 15th till July 6th, 2012. Fruits from hybrids were picked from May 6th till June 4th, 2013.

Color measurements

For each accession or hybrid 10 fruits were selected and their external color was determined at three different positions around the equatorial region of each fruit (blushed areas were avoided). The color parameters L* (Lightness), a* (red/green) and b* (blue/yellow) were measured by a Konica-Minolta chromameter (CR-400), and the hue angle (h°) was calculated [h° = arctangent (b*/a*)].

Carotenoid extraction

Three biological replicates, each replicate consisting of a single fruit, were used for each accession. Each fruit was peeled and diced. The pieces of flesh from each fruit were mixed and a sample of about 1–2 g was collected, weighed and frozen. Carotenoids were extracted from each sample by grinding the tissue in an acetone:dichloromethane mixture (1:1, v/v) by pestle and mortar, the solvent was collected and filtered and the grinding and collecting of the solvent was repeated until the solvent was colorless. Carotenoids were extracted by partitioning the solvent mixture against an equal volume of diethyl ether and 0.2 volume of 12% w/v NaCl/H_2O. The colored upper ether fraction was collected, dried under a stream of N_2 and then redissolved in 1 mL acetone. 100 µL of the sample in acetone were diluted ten folds in acetone and spared for spectroscopic quantification (see below). The rest of the sample was again dried under a stream of N_2 for concentration, and redissolved in acetone (150–500 µL) for further analysis by HPLC. Of each sample, a single injection of 50–100 µl (according to color intensity) was applied to the HPLC. All steps were carried out under dim light and, when possible, carotenoid samples were kept under anaerobic conditions, on ice or at -20 °C.

HPLC analysis of carotenoids and quantification

HPLC analysis was performed on a Waters HPLC system equipped with a Waters 600 pump, a Waters PDA detector 996 and a Waters 717 plus autosampler. A Spherisorb ODS2 C18 column (Waters, 5 µm, 4.6 × 250 mm) coupled with a guard cartridge system SecurityGuard™ (Phenomenex) was used. A gradient was applied at a constant flow of 1.6 mL min^{-1} with acetonitrile:water (9:1; A) and ethylacetate (B) as described (Isaacson *et al*., 2004). Spectra at a wave length range of 250–600 nm of eluting HPLC solvent were recorded and absorption peaks were recorded and analyzed by the Empower software (Waters). Linear limit of detection was estimated to be between 10–20 ng to 1.5–2 µg, depending on the carotenoid. Carotenoids were identified by their absorption spectra and retention time. β-Carotene standard was obtained from Sigma-Aldrich, phytoene standard was obtained from CaroteNature (Switzerland), *E. coli* cells transformed with plasmid pAC-Zeta (Cunningham *et al*., 1994) served as a source for ζ-carotene standard, as previously described (Isaacson *et al*., 2002). *cis*-lycopene isomers, including prolycopene and di-*cis* lycopene, as well as ζ-carotene isomers, phytofluene and phytoene were identified by comparison to the previously established carotenoid profile from the fruit of the tomato mutant '*tangerine*' (Zechmeister *et al*., 1943; Isaacson *et al*., 2002, 2004; Clough and Pattenden, 1979). All carotenoid peaks were integrated at their individual λ_{max} and were normalized to correct for their specific mass extinction coefficients (Britton *et al*., 2004) in relation to β-carotene (= 1), using xanthophylls (1), β-cryptoxanthin (1.086), γ-carotene (0.788), *cis*-lycopene isomers (0.965), ζ-carotene (1.014), phytofluene (1.920) and phytoene (2.074). Total carotenoid content was determined on an aliquot of the acetone extract as follows: first, quantification of total carotenoids with spectral absorption maximum at around 450 nm (xanthophylls, β-cryptoxanthin, β-carotene, γ-carotene, *cis*-lycopene isomers) was performed spectroscopically following Schiedt and Liaaen-Jensen (1995) by measuring absorbance at 450 nm, and using an averaged absorbance coefficient of 2,400. Then, quantities of ζ-carotene, phytofluene and phytoene were calculated according to their normalized peak areas in comparison with the normalized peak areas of the carotenoids with spectral absorption maximum at around 450 nm. The sum of total carotenoids (xanthophylls, β-cryptoxanthin, β-carotene, γ-carotene, *cis*-lycopene isomers, ζ-carotene, phytofluene and phytoene) is given as µg g^{-1} (FW).

Statistical analysis

Correlation coefficients were determined by the coefficient of Pearson. Statistical analyses were performed using Microsoft Excel (2007). Two-way Ward hierarchical cluster analysis was performed by JMP (version 12).

Results and discussion

Apricot cultivars exhibit a wide variability in terms of carotenoid content and composition

Carotenoids were extracted from ripe apricot fruits of three groups of accessions: international accessions (61), Israeli accessions (old local cultivars and recently bred cultivars; 25 accessions) and hybrids (27) (see Materials and methods), and their content and composition were determined (Figure 3, Table 1). Carotenoid content and composition of 18 selected accessions, representing variation, is depicted in Figure 4. In accordance with the great variability in fruit color (Figure 2), a wide variation in carotenoid content and composition was observed. Total carotenoid content varied from about 5 µg g^{-1} FW in the pale yellow ('white') fruit of some accessions, to more than 90 µg g^{-1} FW in the dark-orange fruits of other accessions (Figure 4, Table 1). The proportion of each individual carotenoid also showed great variation, with the main three carotenoids, β-carotene, phytoene and phytofluene, ranging between 2% to 67%, 6% to 59% and 12% to 45% of the total carotenoid content respectively (Figure 4, Table 1). It is important to note that great variation was also found within the different samples of each accession, illustrated by the often high values of standard deviation (Table 1). Similar variation was described in apricot fruit previously (Ruiz *et al.*, 2005). This could be due to the difficulty in determining fruit developmental stages ('ripe') based on parameters of external color and firmness. In this respect, it is also important to note that fruit samples of some accessions were collected in 2012 while samples for others were collected in 2013. However, our experience shows that the variation between different samples of fruit of a given accession seems to be greater than the variation found within an accession over different years of harvest (data not shown).

Apricot fruit contains a unique carotenoid composition typified by large amounts of the first products of the biosynthesis pathway: phytoene and phytofluene

In general, and as expected based on previous analysis described in the literature, β-carotene was found to be the most dominant carotenoid in the fruit (Curl, 1960; Marty *et al.*, 2005; Ruiz *et al.*, 2005, 2008; Khachik *et al.*, 1989; Katayama *et al.*, 1971; Campbell *et al.*, 2013; Radi *et al.*, 1997; Dragovic-Uzelac *et al.*, 2007; Drogoudi *et al.*, 2008); however, on average it constitutes only 33% of the total carotenoids (Table 1). Surprisingly, the other dominant carotenoids were mostly upstream intermediates of the carotenoid biosynthesis pathway, mainly the first products of the pathway, phytoene and phytofluene, constituting on average 26% and 23% of the total carotenoids, respectively. Other intermediates of the pathway, ζ-carotene, lycopene *cis*-isomers and γ-carotene, constitute together almost 10% of the total carotenoids on average (Table 1).

Phytoene is the first product in the carotenoid biosynthesis pathway; its spectral absorption maximum is at 286 nm, making it colorless to our eyes. Insertion of one double bond into the phytoene molecule results in the formation of phytofluene (Figure 1), another colorless carotenoid, whose spectral absorption maximum is at 350 nm. While β-carotene accumulation is quite common, phytoene and phytofluene are usually found in plant tissues in minute amounts. In the analyzed accessions, phytoene and phytofluene content varied from few µg g^{-1} FW, such as in 'Amal', to more than 60 µg g^{-1} FW in 'Avikaline' (Figure 4, Table 1). The few studies that measured phytoene and phytofluene content in apricot fruit reported levels in the range of 15–95 µg g^{-1} FW (Ruiz *et al.*, 2008; Biehler *et al.*, 2012; Müller, 1997). Our results confirm these observations in a wide number of different apricot accessions and demonstrate that the occurrence of both colorless carotenes in significant levels is a typical feature of apricot varieties. To our knowledge, no other plant

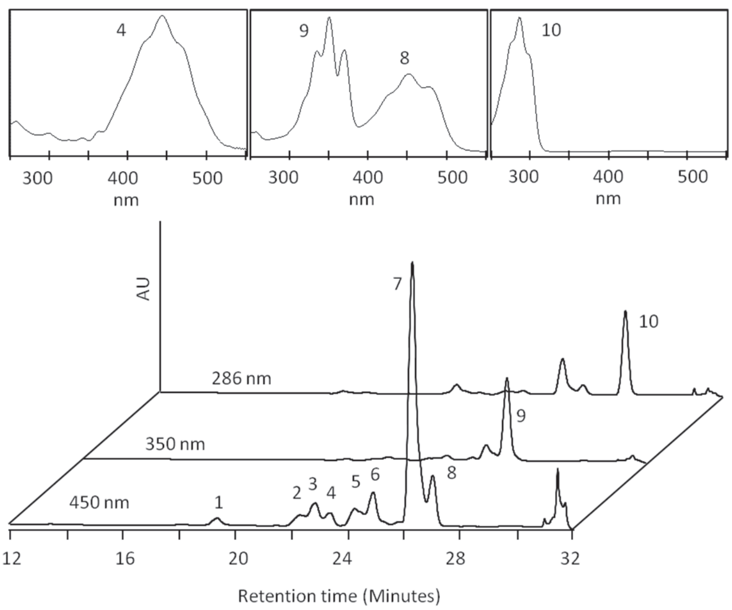


Figure 3. Analysis by HPLC of carotenoids in the apricot fruit of the 'Pazza' cultivar. Chromatograms are given at three different wave lengths: 286 nm, 350 nm, 450 nm. Peak 1, β-cryptoxanthin; peak 2, unidentified *cis*-isomer of lycopene; peak 3, di-*cis* lycopene; peak 4, prolycopene; peak 5, γ-carotene; peak 6, unidentified; peak 7, β-carotene isomer; peak 8, β-carotene isomer; peak 9, phytofluene; peak 10, phytoene. Absorption spectra of some peaks are presented in the inserts.

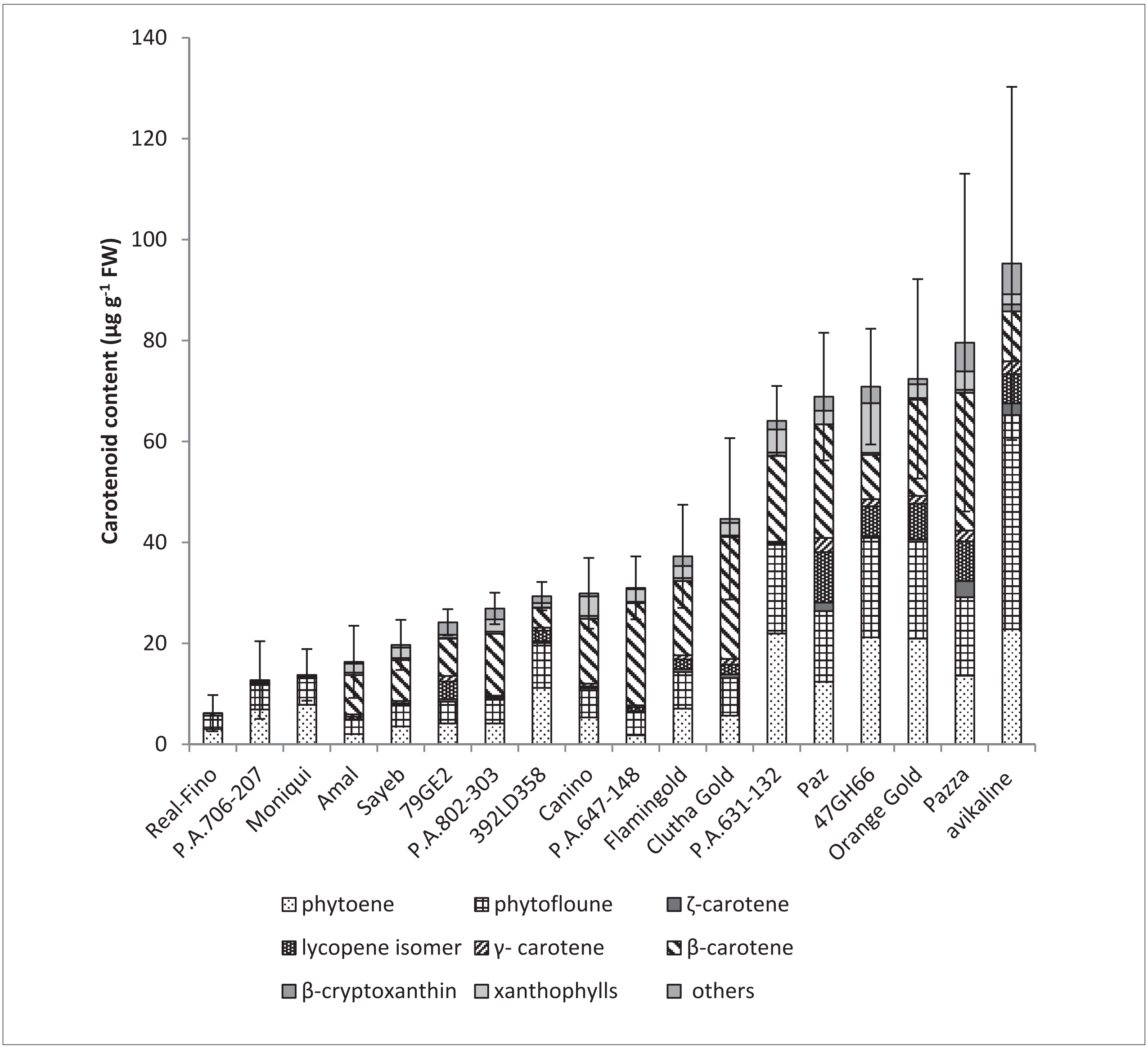


FIGURE 4. Carotenoid content (μg g-1 FW) in ripe fruits from selected apricot accessions. Means of three biological replicates are given.

tissue is as rich in phytoene and phytofluene as apricot fruit. Other fruits that were reported to contain high amounts of phytoene and phytofluene have substantially lower amounts in comparison to apricot. For instance, tomato, which is considered a relatively rich source of phytoene and phytofluene, was reported to contain between 0–18 μg g-1 FW (Biehler *et al*., 2012; Müller, 1997; Fraser *et al*., 1994). In carrot varying amounts of phytoene and phytofluene were reported (Biehler *et al*., 2012; Jourdan *et al*., 2015; Maass *et al*., 2009; Yahyaa *et al*., 2013) for different accessions, the highest (~210 μg g-1 dry weight; ~30 μg g-1 FW) reported for a hybrid (Jourdan *et al*., 2015).

Apricot accumulate *cis*-isomers of lycopene

We detected three *cis*-isomers of lycopene in apricot fruit. We identified them by comparison to the well-characterized lycopene isomers from the tomato mutant '*tangerine*' (Zechmeister *et al*., 1943; Isaacson *et al*., 2002, 2004; Clough and Pattenden, 1979). We identified these isomers as a possibly mono-*cis* isomer, a di-*cis* isomer, and the tetra-*cis* isomer prolycopene (peaks number 2, 3, 4 in Figure 3, respectively). The proportion of lycopene isomers of the total carotenoids varies from none up to 14.5%, which could translate to as much as 10 μg g-1 FW (Figure 4, Table 1). The combination of high levels of phytoene and phytofluene, with *cis*-lycopene, suggests a high nutritional value for apricot fruit as was suggested for tomato (Aust *et al*., 2005; Linnewiel-Hermoni *et al*., 2015).

The carotenoid profile of apricot, which contains primarily early intermediates of the carotenoid biosynthesis pathway, is unique when compared with the carotenoid profiles reported for fruits from other *Prunus* species, which are typically later products of the pathway. Peach, for instance, contains mainly xanthophylls such as violaxanthin (Katayama *et al*., 1971; Curl, 1959; Gross, 1979; Ma *et al*., 2014), plum contains mainly β-carotene and β-cryptoxanthin (Bobrich *et al*., 2014; Kaulmann *et al*., 2014), and Japanese apricot (*Prunus mume*) accumulates mainly β-carotene and lutein (Kita *et al*., 2007). The distinctive carotenoid profile of apricot suggests that during the divergence of apricot from other *Prunus* species they acquired genetic alterations that led to the different profile.

Table 1. Carotenoid composition (%) and total content (μg g^{-1} FW) in ripe fruits from different apricot accessions and hybrids. Means of 3 biological replicates are given (± SD). Accessions are divided into three groups according to their origin and ordered by their total carotenoid content. An averaged composition of all accessions is given in the last row.

Accession	β-Cryptoxanthin	Lycopene isomers	γ-Carotene	ζ-Carotene	β-Carotene	Phytofluene	Phytoene	Xanthophyll esters	Others	Total carotenoids content
International accessions										
Real Fino	0.1 ± 0.3	0 ± 0	0 ± 0	0.4 ± 0	7.4 ± 1.9	42.7 ± 4.1	49.4 ± 2.6	0 ± 0	0 ± 0	6.2 ± 3.6
MA.46	0.9 ± 0.2	2.9 ± 2	0.5 ± 0.4	3.4 ± 0.9	24.3 ± 6	32.4 ± 4.5	31 ± 5.1	3.1 ± 1.6	1.4 ± 0.6	8.1 ± 4.8
Rouge de Rivesaltes	0.4 ± 0.3	6.6 ± 3.1	1.1 ± 1.5	3.7 ± 0.7	18.7 ± 8	32.2 ± 4.8	33 ± 5.3	2.7 ± 1.1	1.6 ± 0.3	9.7 ± 1.9
Pelese di Giovanniello	0.4 ± 0.2	6 ± 1.1	1 ± 0.4	3.7 ± 1.4	23.8 ± 9.6	32.7 ± 5.7	30.1 ± 4.4	1.1 ± 1.1	1.2 ± 0.1	9.9 ± 2.7
A.1758	1.2 ± 0.4	2 ± 0.3	1.6 ± 0.6	1.8 ± 0.7	14.2 ± 13.5	29.4 ± 5.9	44.4 ± 16.3	1.9 ± 1.1	3.5 ± 10.1	11.3 ± 4.5
Moniqui	0.4 ± 0.2	0.1 ± 0.2	0.1 ± 0.1	1.1 ± 0.3	2.4 ± 0.6	38.3 ± 1	57.1 ± 0.3	0.2 ± 0.2	0.4 ± 0.3	13.8 ± 5.1
Tardif de Bordaneil	1.1 ± 1	7.2 ± 1.7	0.9 ± 0.8	5.4 ± 2.8	36.4 ± 9.2	22.2 ± 4	20.5 ± 2.9	4.2 ± 1.5	2.1 ± 0.1	13.8 ± 6.4
A.1740	3.3 ± 0.6	2.9 ± 1.7	3 ± 0.9	1.7 ± 0	35.1 ± 4.1	19.2 ± 6.1	19.3 ± 9.7	14.3 ± 9.6	1.1 ± 1	14.2 ± 0.4
A.S.1875	1.1 ± 0.8	7.9 ± 2.9	1.6 ± 0.8	4.2 ± 1.6	43.1 ± 5	20.7 ± 3.2	14.6 ± 3.2	5.4 ± 3.9	3.6 ± 1	15.1 ± 8.3
A.S.3445	0.3 ± 0.2	10.2 ± 4.4	0.8 ± 1.6	7.9 ± 3.6	7.6 ± 6.9	29.7 ± 6	36.7 ± 5.3	3.1 ± 2.6	3.8 ± 1	15.5 ± 10.2
Screara	1.8 ± 0.9	3.4 ± 0.7	1.9 ± 0.3	3.1 ± 1.1	55.3 ± 1.5	12.8 ± 1.7	9.1 ± 1.9	10.5 ± 0.4	2.2 ± 0.5	15.5 ± 4.3
Amal	2.9 ± 1.3	3.2 ± 2.1	2.8 ± 0.5	0.7 ± 0.7	47.7 ± 7	17.3 ± 2.3	12.4 ± 5.6	10.9 ± 3.2	2.1 ± 1.6	16.3 ± 7.1
Quardi	3.2 ± 1.3	1.2 ± 1.4	2.2 ± 1.3	1.1 ± 0.5	32.6 ± 8.5	24.2 ± 2.9	27 ± 8	7.8 ± 1.1	0.7 ± 0.7	17 ± 7.3
Sayeb	2 ± 0.6	0.9 ± 0.7	2.3 ± 0.9	1.5 ± 0.2	41.2 ± 0.9	21 ± 2.4	18 ± 2.2	10.6 ± 2.3	2.6 ± 1.4	19.7 ± 5
Poppy	0.9 ± 0.1	10.2 ± 2.6	2.6 ± 0.3	1.5 ± 0.4	33.2 ± 2.7	23.8 ± 3.3	23.2 ± 2.2	2.5 ± 0.5	2 ± 2.2	21 ± 8.6
55EE454	1.2 ± 0.2	8.3 ± 2	4.8 ± 0.6	2.5 ± 0.1	20.8 ± 2.3	24.7 ± 2.5	30 ± 2.9	4.4 ± 1	3.2 ± 2.7	21.6 ± 5.5
Stella	1.2 ± 1.7	1.6 ± 0.2	0.5 ± 0.1	1 ± 18.3	17.7 ± 1.9	26.2 ± 21.6	46.7 ± 1.7	2.4 ± 1.5	2.6 ± 1.5	22 ± 13.3
772-833	1.3 ± 0.8	4.7 ± 1.4	2.5 ± 0.8	1 ± 0.5	59 ± 4.3	16.3 ± 3.6	10.9 ± 2.1	2.5 ± 1	1.7 ± 0.5	22.1 ± 8.6
79 GE 2	0.6 ± 0.2	14.5 ± 1.7	4.5 ± 0.6	2.1 ± 0.1	30.6 ± 2.2	17.8 ± 3	17.1 ± 2.3	2.6 ± 1.4	10.1 ± 3.3	24.2 ± 2.6
774-835	0.2 ± 0.1	2.3 ± 0.8	1 ± 0.4	1.3 ± 0.4	5.6 ± 1.4	35.7 ± 4.1	52.4 ± 12.1	0.7 ± 0.4	0.9 ± 0.8	24.2 ± 6.5
58/5	2.4 ± 1	5.3 ± 3.4	4.1 ± 1.6	1.4 ± 0.4	56 ± 10.5	14.9 ± 5.7	11.6 ± 3.5	2.4 ± 1.2	1.8 ± 1.8	25.5 ± 5.9
47 EA 10	1 ± 0.4	5.7 ± 3.8	2.2 ± 0.5	2.4 ± 0.7	35.9 ± 6.3	23.8 ± 5.2	22 ± 5.4	5.2 ± 1.8	1.7 ± 1	26.4 ± 20.8
A.1570	1.1 ± 0.5	2.5 ± 1	3.2 ± 1.1	2.6 ± 0.8	49.5 ± 6	17.8 ± 0.4	13.9 ± 2.8	7.6 ± 0.8	1.9 ± 1	26.7 ± 8.5
Luizet	0.6 ± 0.1	6.1 ± 1	2 ± 0.6	2.8 ± 0.3	41 ± 3.5	21.3 ± 5.3	12.4 ± 9.3	10.7 ± 1.5	3.1 ± 0.9	28.7 ± 9.9
Rouge du Roussillion	0.5 ± 0.2	13 ± 3.3	0.9 ± 0.2	6.3 ± 0.5	23.3 ± 2.9	24.9 ± 1.7	26 ± 1	1.2 ± 1.1	4.0 ± 0.6	29 ± 11.9
48 G 1105	4.3 ± 3.5	10.1 ± 3.8	3.1 ± 1.4	1.9 ± 0.6	42.8 ± 19.7	15.9 ± 5.8	19.1 ± 7.8	1.6 ± 0.5	1.2 ± 1.8	29.2 ± 13.9
392 LD 358	0.3 ± 0	7.1 ± 0.9	2 ± 0.1	1.2 ± 0.3	13.3 ± 1.5	30.4 ± 1.5	38.1 ± 2.8	3 ± 0.7	4.6 ± 3.9	29.4 ± 2.8
Canino	1.9 ± 0.5	1.1 ± 1.4	1.8 ± 1.1	1.4 ± 0.5	43 ± 5.3	18 ± 2.7	17.8 ± 2.3	13 ± 0.4	1.9 ± 1.1	29.9 ± 7
MA.170	0.7 ± 0.3	8 ± 1.9	2.2 ± 0.9	4.5 ± 0.9	39.2 ± 6.3	15.7 ± 1.3	15.3 ± 4.5	9 ± 3.7	5.3 ± 1.3	31.3 ± 11.2
Selecta CNEEE 4	1.9 ± 0.7	1.4 ± 0	2.2 ± 0.8	2 ± 0.5	43.9 ± 4.5	18.2 ± 0.4	17.4 ± 1.6	11 ± 1.6	2 ± 0.7	31.6 ± 12.8
Spring Giant	1.5 ± 0.5	9 ± 4	3 ± 0.4	1.2 ± 0.2	28.6 ± 3.8	21.5 ± 1.8	22.9 ± 3.2	8.4 ± 2.2	3.9 ± 1.4	31.6 ± 10.7

Table 1. Continued.

Accession	β-Cryptoxanthin	Lycopene isomers	γ-Carotene	ζ-Carotene	β-Carotene	Phytofluene	Phytoene	Xanthophyll esters	Others	Total carotenoids content
International accessions										
A.1625	1 ± 0.1	2.2 ± 1.7	1.7 ± 0	0.6 ± 0.2	29.1 ± 8.6	25 ± 2.6	28.5 ± 10.2	7.5 ± 1	4.4 ± 4.7	32.8 ± 8.1
MA.283	0.2 ± 0.1	6.3 ± 1.5	1.2 ± 0.4	3.1 ± 0.5	25.1 ± 4.7	29.1 ± 2	31.8 ± 2	1.6 ± 0.7	1.7 ± 0.5	34.1 ± 14.6
Flamingold	1.6 ± 0.7	5.1 ± 3	2.2 ± 0.4	1.7 ± 1.1	39.4 ± 14	19.4 ± 3	19 ± 8.2	6.4 ± 2	5.1 ± 3.8	37.2 ± 10.2
5 EA 293	1.9 ± 1.9	9.5 ± 3.4	3.5 ± 0.3	2.5 ± 0.9	41.8 ± 12.4	22.7 ± 2.6	10.8 ± 8.7	3.8 ± 3.8	3.5 ± 2.6	37.7 ± 7
Precoce de Tyrinthe	0.1 ± 0.1	12.2 ± 2	2.6 ± 0.2	0.7 ± 0.1	24.8 ± 2.8	26.2 ± 2.9	27.6 ± 0.9	3.2 ± 0.5	2.6 ± 2.3	39.1 ± 1.6
Castle Bright	0.5 ± 0.3	3.7 ± 1	1.9 ± 0.7	0.9 ± 0.3	29.1 ± 2.2	29.5 ± 2.3	32.7 ± 3.2	0.8 ± 0.3	0.8 ± 2	39.1 ± 17.1
Dr. Mascle	1 ± 0.4	12.2 ± 2.2	3.4 ± 0.1	2.6 ± 0.4	36 ± 8.4	16.5 ± 1.6	14 ± 2.7	7.7 ± 1.1	6.6 ± 5.5	40 ± 10
Precoce de Portugal	0.6 ± 0.2	10.5 ± 2.2	2.6 ± 0.7	2.6 ± 0.5	22.1 ± 6.1	26.3 ± 1.4	30 ± 2.8	2.5 ± 1	2.8 ± 0.8	41 ± 7.8
Gabriel	0.9 ± 0.3	7.5 ± 0.4	2.9 ± 0.3	2.3 ± 0.7	50.3 ± 10.4	16.9 ± 3.9	12.3 ± 5.1	4 ± 2.2	2.8 ± 0.9	41 ± 17.8
Helena	1.6 ± 0.9	6.5 ± 1.1	3.1 ± 0.9	1.1 ± 0.4	54.6 ± 8.6	13.9 ± 2.2	12.1 ± 4.4	3.7 ± 0.3	3.6 ± 2.6	41.3 ± 17.1
384 LD 362	1.1 ± 0.7	3 ± 3.8	2 ± 0.6	1.9 ± 0.6	34.3 ± 2.1	22.5 ± 1.3	28.2 ± 0.4	1.5 ± 0.2	5.3 ± 3	42.5 ± 4.4
Barracca	2 ± 0.8	4.4 ± 1.9	2 ± 0.5	1.4 ± 0.2	50.2 ± 5	18.4 ± 1.4	14.8 ± 1.5	5.8 ± 1	1.1 ± 0.5	42.7 ± 9.6
Skaha	0.9 ± 0.6	3.1 ± 1.5	2.2 ± 0.4	1.1 ± 0.1	46.4 ± 5.2	22 ± 1.6	19.3 ± 4	2.4 ± 1.9	2.7 ± 0.7	44.6 ± 9.9
Clutha Gold	0.6 ± 0.1	4.3 ± 2	2.5 ± 0.1	1.6 ± 0.1	54.1 ± 2.3	16.7 ± 1.4	12.7 ± 1.8	5.6 ± 1.6	1.8 ± 0.5	44.7 ± 16
170 LH 182	1.3 ± 0.8	1.9 ± 0.7	1.7 ± 0.9	1.7 ± 0.4	52.2 ± 5.1	18.2 ± 0.3	15.4 ± 0.2	2.4 ± 0.9	5.1 ± 4.7	48.9 ± 8.2
Earliril	0.6 ± 0.1	6.9 ± 1.5	2.5 ± 0.6	1.9 ± 0	43.2 ± 1.5	20.1 ± 2.5	17.4 ± 1.1	5.8 ± 1.1	1.6 ± 0.4	51.3 ± 16.6
Precoce de Boulbon	2.5 ± 0.8	3.1 ± 0.3	2.3 ± 1.3	0.9 ± 0.1	47.4 ± 5.5	18 ± 1.4	15.1 ± 2.9	9.5 ± 2.2	1.1 ± 2	52.1 ± 9.7
Earlicot	0.8 ± 0.1	5.3 ± 0.8	1.8 ± 0.1	0.6 ± 0.1	36.6 ± 4.3	23.2 ± 1	26.2 ± 3.3	3.8 ± 0.9	1.7 ± 0.4	53.7 ± 17.8
Sundrop	0.9 ± 0.5	4.5 ± 1.7	2 ± 0.4	1.2 ± 0.4	35.8 ± 4.3	24.7 ± 0.9	25.7 ± 2.4	2.6 ± 1	2.7 ± 1.6	54.1 ± 18.6
Harogem	1.2 ± 1.1	2.7 ± 1.5	3.3 ± 0	1.1 ± 7.9	28.3 ± 5.7	13.9 ± 6.2	38.5 ± 5	8.7 ± 1.5	2.4 ± 1.5	55.6 ± 3.6
MAS955	0.8 ± 0.3	7.2 ± 2	3 ± 0.4	1.8 ± 0.4	26.4 ± 4.5	25.4 ± 1.5	30.4 ± 3.5	1.8 ± 0.3	3.2 ± 0.9	57.1 ± 21.3
Palsteyn	0.8 ± 0.4	5 ± 1.6	2.2 ± 0.3	0.8 ± 0.2	42.1 ± 2.8	21.6 ± 1.6	20.4 ± 1.4	4.9 ± 1.1	2.1 ± 0.8	58.5 ± 7
Rival	1 ± 0.8	4.9 ± 1.5	2.1 ± 0.4	0.6 ± 0.5	34.7 ± 4.4	24.6 ± 0.3	29.4 ± 1.4	2.5 ± 0.2	0.2 ± 0.4	59.4 ± 23.6
Royal Rosa	0.9 ± 0.4	8.7 ± 3	3.3 ± 0.3	2.3 ± 0.4	35 ± 7.6	21.2 ± 0.3	22.8 ± 2.3	3.8 ± 1	2 ± 2.2	60 ± 17.1
Perfection	1 ± 0.6	8.2 ± 1.7	2.1 ± 0.4	1.4 ± 0.1	40.4 ± 1.8	20.5 ± 2	19.7 ± 3.1	3.8 ± 0.7	2.9 ± 2.2	66.8 ± 15.1
47GH66	0.6 ± 0.1	8.3 ± 2.5	2 ± 0.4	0.5 ± 0.2	12.4 ± 0.4	27.8 ± 2.6	29.9 ± 2.3	13.9 ± 3.6	4.6 ± 3.8	70.9 ± 11.5
Castleton	0.8 ± 0.3	7.7 ± 2.8	2.6 ± 0.5	1.1 ± 0.3	23.5 ± 1.6	25.8 ± 1.1	29.5 ± 4.9	4.6 ± 1	4.4 ± 2.8	75.8 ± 29.7
Pazza	0.8 ± 0.1	9.9 ± 2.3	2.7 ± 0.2	4 ± 0.8	34.3 ± 5.6	19.5 ± 1.6	17.1 ± 0.6	4.6 ± 1.5	7.1 ± 2.1	79.6 ± 33.5
384 LD 373	0.7 ± 0.5	7.8 ± 1.6	2.8 ± 0.5	1.7 ± 0.1	19.1 ± 3.3	27.9 ± 1.1	38.4 ± 3.7	0.6 ± 0.2	1.2 ± 0.8	91.2 ± 35.1
Avikaline	1.5 ± 2.9	6.1 ± 1	2.7 ± 0	2.4 ± 7.2	10.4 ± 7	44.5 ± 8	23.9 ± 0.3	2.1 ± 3	6.4 ± 3	95.3 ± 35

TABLE 1. Continued.

Accession	β-Cryptoxanthin	Lycopene isomers	γ-Carotene	ζ-Carotene	β-Carotene	Phytofluene	Phytoene	Xanthophyll esters	Others	Total carotenoids content
Local accessions										
P.A.811-312	1.3 ± 0.5	3.4 ± 2.5	1.1 ± 0.7	2.3 ± 0.9	47.7 ± 5.9	18.8 ± 2.4	14 ± 0.4	9.6 ± 2.3	1.8 ± 0.4	9.7 ± 7.4
P.A.706-207	0.6 ± 0.2	0.5 ± 0.4	0.6 ± 0.6	1.3 ± 1	2.4 ± 1.8	38.1 ± 0.5	54.4 ± 3	2 ± 2.7	0.2 ± 0.5	12.7 ± 7.7
P.A.658-159	2.3 ± 1.4	0.3 ± 0.5	0.2 ± 0.5	0.2 ± 0.3	47.3 ± 11.9	27.8 ± 4.4	13.9 ± 12.2	7.2 ± 3.3	0.7 ± 1.6	16.9 ± 2.8
P.A.803-304	2.2 ± 0.2	0 ± 0	1.9 ± 0.7	0.1 ± 0.1	67.2 ± 9.1	12 ± 2.8	8.6 ± 3.8	6.2 ± 1.8	1.8 ± 1.4	17.1 ± 3.8
P.A.638-139	1.9 ± 0.1	3.8 ± 1.2	2.3 ± 0.6	1.8 ± 0.6	22.7 ± 4.8	28.3 ± 3.8	29.1 ± 7.5	6.9 ± 2.5	3.2 ± 5.5	18 ± 5.9
P.A.648-149	3.1 ± 0.3	0.4 ± 0.6	1.4 ± 0.4	1.4 ± 0.6	48.6 ± 8.6	15.1 ± 2	11.2 ± 4.4	12.8 ± 3.6	6 ± 1	18.8 ± 2.5
P.A.755-256	0.7 ± 0.1	3.5 ± 1.6	1.7 ± 0.6	0.9 ± 0.5	28.7 ± 7.2	25.2 ± 1.6	29.9 ± 6.9	5.7 ± 1	3.7 ± 4.3	20.2 ± 5.5
Eden	1.8 ± 0.8	4.2 ± 3.4	2.2 ± 1.2	1.5 ± 1.7	20.6 ± 4.4	25.9 ± 3.3	32.6 ± 10	7 ± 1.1	4.2 ± 2.1	20.2 ± 5
Nitzan	2.4 ± 0.3	2.5 ± 2.2	3.6 ± 1.4	1.4 ± 0.3	32.6 ± 4.2	22.1 ± 0.8	23.8 ± 2.5	10.7 ± 3.6	0.9 ± 1.4	23.8 ± 7.7
Behor Shotan	1.1 ± 0.4	0.3 ± 0.2	1.4 ± 0.3	0.6 ± 0.5	35.1 ± 4.3	25.2 ± 2.3	22 ± 5.9	10.6 ± 3.2	3.5 ± 8.6	24.8 ± 13.7
P.A.757-258	4.3 ± 2.3	1 ± 0.9	1.7 ± 0.9	0.4 ± 0.2	35.4 ± 3	23.1 ± 1.3	23.9 ± 1.6	6.4 ± 2.9	3.8 ± 0.5	25.7 ± 6.2
P.A.802-303	1.6 ± 0.5	1.5 ± 2.6	0.8 ± 1.4	0.7 ± 1.2	45.6 ± 10.1	17.5 ± 1.8	15.4 ± 6.7	9 ± 3.8	8 ± 8.6	26.9 ± 3.1
Shiler	1.6 ± 0.5	2.9 ± 2.4	2.6 ± 1	1.2 ± 0.4	37.4 ± 3.4	21.4 ± 3	17.2 ± 1.1	11.5 ± 2.5	4.2 ± 3.8	28.6 ± 11.1
P.A.647-148	0.9 ± 0.2	2.4 ± 2	1.3 ± 0.4	0.9 ± 0.3	65.3 ± 3.3	14.6 ± 1.4	5.8 ± 0.7	8 ± 2.1	0.8 ± 0.6	31 ± 6.2
P.A.754-255	0.8 ± 0.1	0.1 ± 0.3	0 ± 0	1.5 ± 0.2	2.4 ± 0.3	36.1 ± 1.5	59.1 ± 1.1	0 ± 0	0 ± 0	31.5 ± 17.7
Gal	1.4 ± 0.2	9.2 ± 2	6.3 ± 0.4	2.9 ± 0.6	17.4 ± 0.8	24 ± 2.3	30 ± 3.8	3.7 ± 3	5.1 ± 5.1	32.6 ± 6.2
P.A.705-206	1.2 ± 0.6	3.3 ± 1.1	2 ± 0.6	1 ± 1	34 ± 2.3	22.6 ± 2.8	26.2 ± 2	8.1 ± 1.1	1.5 ± 1.4	34.4 ± 5.7
P.A.650-151	0.9 ± 0.2	2.3 ± 1.9	1.2 ± 0.3	0.6 ± 0.4	44.7 ± 1	20.9 ± 2	20 ± 1.6	8.3 ± 1.7	1 ± 0.4	38.3 ± 4.5
P.A.660-161	1.8 ± 0.9	0.5 ± 0.4	1.5 ± 0.5	1.5 ± 1.2	46.9 ± 4.9	15.9 ± 1.6	14.4 ± 3.4	9.2 ± 1.5	8.3 ± 3.1	43.2 ± 13.2
311	0.5 ± 0.1	12.6 ± 0.4	2.8 ± 0.2	1.3 ± 0.4	21.7 ± 1.6	25.3 ± 1.5	28.5 ± 2.1	4.4 ± 1.1	2.7 ± 2.9	47.2 ± 12.1
Tarog	0.9 ± 0	8.2 ± 1.1	2.5 ± 0.2	1.1 ± 0.1	26.4 ± 2.4	21.8 ± 0.3	31.1 ± 1.4	3.9 ± 1.6	4.1 ± 0.4	48.5 ± 12.8
Daniel	0.8 ± 0.2	3.2 ± 1.5	3.4 ± 1.5	0.7 ± 0.2	29.5 ± 2.9	23.1 ± 1.5	32.8 ± 4	5.3 ± 3.2	1.2 ± 1.3	60.6 ± 9.1
P.A.631-132	1.1 ± 0.4	0 ± 0	0.4 ± 0.3	0.5 ± 0.2	26.5 ± 13.4	27.4 ± 2.4	34.3 ± 9.7	7.1 ± 0.8	2.7 ± 1.4	64.1 ± 6.9
PAZ	0 ± 0	14.5 ± 3.7	4.1 ± 0.6	2.5 ± 0.3	32.7 ± 5.4	20.3 ± 1.8	18 ± 2.4	3.9 ± 0.7	4 ± 4.3	68.9 ± 12.6
Orange Gold	0.5 ± 0.4	9.8 ± 2.1	2.1 ± 0.7	0.7 ± 0.2	26.3 ± 3.8	26.5 ± 6	28.9 ± 2.6	3.8 ± 0.9	1.5 ± 1.3	72.4 ± 19.8

TABLE 1. Continued .

Accession	β-Cryptoxanthin	Lycopene isomers	γ-Carotene	ζ-Carotene	β-Carotene	Phytofluene	Phytoene	Xanthophyll esters	Others	Total carotenoids content
Hybrids										
55/30	1 ± 0.6	3.6 ± 0.7	2.2 ± 0.3	2.1 ± 0.6	47 ± 5.3	21.7 ± 1.8	19.1 ± 3.1	3 ± 2.2	0.3 ± 0.3	5.8 ± 2
58/53	0.6 ± 0.2	2.1 ± 0.2	1 ± 0.3	1.2 ± 0.3	2.4 ± 0.8	35.2 ± 3.1	56 ± 3.3	0.9 ± 1	0.8 ± 0.5	17.9 ± 6.5
27/82	0.3 ± 0.2	0.4 ± 0.4	0.2 ± 0.1	0.7 ± 0.6	2 ± 1.8	31.9 ± 5	64 ± 3.7	0.5 ± 1	0.1 ± 0.1	18.5 ± 5.9
55/75	0.6 ± 0	4.1 ± 0.4	1.2 ± 0.1	2.1 ± 0.5	16.3 ± 2.6	31 ± 1.2	39.3 ± 2.7	4.2 ± 0.9	1.2 ± 0.2	20.4 ± 11
60/36	0.8 ± 0.7	1.2 ± 1	1.1 ± 0.4	0.4 ± 0.3	44.6 ± 9.4	21.7 ± 1.2	22.2 ± 2.7	3.8 ± 1.3	4.3 ± 3.5	23.1 ± 8.4
58/56	0.6 ± 0.1	8.5 ± 0.3	2.4 ± 0.6	2.8 ± 2.7	13.8 ± 1.2	25.5 ± 4.6	38.2 ± 6.8	3 ± 1.6	5.3 ± 9.8	23.3 ± 4.2
57/81	1.5 ± 0.9	1.3 ± 0.8	1.3 ± 0.2	1.7 ± 0.3	48.2 ± 13.3	18.8 ± 2.2	17.1 ± 4.9	5.9 ± 2.3	4.1 ± 2.4	24 ± 3
22/84	1.4 ± 0.1	1.2 ± 0.5	1.5 ± 0.3	0 ± 0	43.5 ± 12.1	20.1 ± 3.1	19.8 ± 7.2	7.7 ± 1	4.9 ± 2.3	25.3 ± 7.7
57/66	1.8 ± 0.2	1.4 ± 0.8	1.9 ± 0.5	1.3 ± 0.2	56 ± 6	16.5 ± 0.9	13.9 ± 5.3	2.4 ± 1	4.8 ± 1.2	25.5 ± 2.9
53/7	1.5 ± 0.6	4 ± 3.2	3.2 ± 1.5	0.9 ± 0.4	38.5 ± 8.1	21.4 ± 1.8	22.7 ± 7	5.6 ± 3	2.2 ± 1.9	28.8 ± 6.4
53/50	0.6 ± 0.8	5.2 ± 1	2.2 ± 0.4	1.1 ± 0.2	52.3 ± 9.9	16.7 ± 2.4	14.8 ± 3.8	2.8 ± 1.3	4.3 ± 3.6	29 ± 7.5
60/27	1.7 ± 0.4	9.2 ± 0.8	5.1 ± 1.7	1.2 ± 0.4	24 ± 2.2	19.1 ± 1	22.8 ± 2.2	4.1 ± 0.9	12.7 ± 1.1	29.1 ± 6.6
53/71	1.2 ± 0.4	5.7 ± 0.2	2 ± 0.3	0.8 ± 0.2	30.7 ± 0.7	22.3 ± 0.8	29.8 ± 0.9	3.4 ± 1.2	4 ± 0.6	29.4 ± 1.1
19/2	0.5 ± 0.1	4.1 ± 2	1.1 ± 0.6	0.4 ± 0.2	16.4 ± 4.7	32.5 ± 6.4	39.3 ± 0.8	3.2 ± 0.4	2.6 ± 0.6	29.9 ± 5.5
60/23	1.1 ± 0.6	12.1 ± 2.5	2.2 ± 1.1	2.7 ± 0.4	22.7 ± 2.6	20.3 ± 0.5	25.8 ± 1.4	2.8 ± 3.1	10.3 ± 1.8	31.8 ± 8.7
14/71	1.1 ± 0.4	10 ± 1.5	3 ± 0.8	1.7 ± 0.5	42.1 ± 6.3	17.6 ± 2.2	15.8 ± 3.5	5.3 ± 1	3.4 ± 1.2	33.5 ± 6.1
28/71	0.5 ± 0.1	9.4 ± 3.1	3.5 ± 0.9	1.1 ± 0.6	18 ± 2.7	25.7 ± 4.6	31.6 ± 2.9	5.7 ± 2.4	4.4 ± 3.5	35.2 ± 11.8
53/60	0.8 ± 0.9	5.7 ± 1.6	2.7 ± 0.4	1.1 ± 0.2	50.1 ± 3.5	14.1 ± 0.6	14.9 ± 1.2	7.4 ± 1	3.1 ± 2.8	36 ± 4.3
53/6	1.1 ± 0.5	7.6 ± 3.6	2.1 ± 1.5	1.7 ± 0.1	17.1 ± 3.7	25.1 ± 2.9	30.3 ± 9.9	9.5 ± 3	5.5 ± 6.4	36.1 ± 13.7
60/21	0.5 ± 0.1	4.4 ± 5	1.5 ± 1.3	0.2 ± 0.2	23.4 ± 7.4	30 ± 9.3	30.6 ± 8.1	5.7 ± 5.3	3.7 ± 2.3	36.9 ± 12.1
34/8	0.7 ± 0.3	5.2 ± 1	1.6 ± 0.1	0.7 ± 0.1	25.5 ± 12.6	24.3 ± 3.6	29.3 ± 7.6	11.2 ± 0.7	1.5 ± 0.3	40.3 ± 10.5
60/38	1.3 ± 0.6	4 ± 0.5	1.8 ± 0.5	0.9 ± 0.2	38.6 ± 8.5	18.8 ± 1.7	21.9 ± 4.7	5.5 ± 0.3	7.3 ± 2.4	41.1 ± 7.7
54/88	0.6 ± 0.3	4.1 ± 2.9	1.3 ± 0.6	0.7 ± 0.3	31.3 ± 10.7	23.6 ± 0.8	26.4 ± 5.3	8.8 ± 0.8	3 ± 1.2	41.4 ± 2.4
57/45	0.4 ± 0.3	7 ± 3.6	2 ± 1.3	0.6 ± 0.3	13.9 ± 7.1	29.5 ± 6.6	29.9 ± 2.8	7.9 ± 0.8	8.6 ± 1.5	41.5 ± 20.9
58/138	0.5 ± 0.4	2.1 ± 0.5	1.4 ± 0.3	0.4 ± 0.3	20 ± 1.1	27.8 ± 1.5	42.2 ± 1.4	3.1 ± 0.4	2.5 ± 1.6	49.5 ± 3.7
15/99	0.8 ± 0.4	6.8 ± 2.7	2.5 ± 0.4	0.6 ± 0.1	46.2 ± 4.6	18.7 ± 1.5	17 ± 2.6	3.3 ± 0.9	4.1 ± 1.3	54.8 ± 1.4
37/68	0.6 ± 0.2	3.4 ± 0.6	2.3 ± 1	0.7 ± 0.1	22.7 ± 2.6	29.6 ± 1.9	36.3 ± 1.7	3.6 ± 1.1	0.9 ± 0.8	62 ± 23.2
Average	**1.2 ± 0.8**	**5.1 ± 3.6**	**2.1 ± 1.1**	**1.6 ± 1.2**	**32.6 ± 14.7**	**23.4 ± 6.3**	**25.6 ± 11.7**	**5.3 ± 3.3**	**3.2 ± 2.3**	**34.8 ± 18.2**

Apricot fruit exhibit a wide range of fruit color

To test for possible correlations between apricot fruit color (appearance) and carotenoid content, we measured color parameters (L*, a*, b*, hue°) of ~10 ripe apricot fruits from each accession (Table 2). Fruit from different accessions exhibited a wide range of external color values. The a* parameter (axis of red-green) ranged from negative values of -5.1 in the pale apricots up to 22.4 in the dark orange ones. The b* parameter (axis of yellow-blue) ranged from 30.8 to 58.6. The L* (lightness) parameter ranged from 58.6 to 78.2. The h° angle parameter varied from 64.5 to 98.7 (Table 2). Fruits with the lowest a* values and highest L* and hue° values were the pale-yellow well known accessions 'Moniqui' and 'Real-Fino', the local accessions 'P.A.706-207' and 'P.A.754-255' and the hybrids 27/82 and 55/75. The accessions with the deep orange colored fruit, '384LD362', '384LD373', '58/5', 'MAS955', 'Paz' and the hybrid 57/45, had the highest a* values (Table 2). Previous studies examining the correlation between fruit color and carotenoid content in apricot fruit showed contrasting results. While some found strong correlations when comparing total carotenoid content of flesh or skin with the color indices of the respective tissue (Ruiz *et al.*, 2005, 2008), others found no correlations or weak correlations when comparing total carotenoid content of fruit tissue containing both flesh and skin, with color indices of either flesh or skin (Campbell *et al.*, 2013), or when comparing total carotenoid content of flesh with color indices of skin (Drogoudi *et al.*, 2008). In order to effectively resolve the possible correlation between apricot flesh carotenoid composition and fruit color indices we calculated the amount of visible carotenoids in the fruits, meaning only carotenoids with spectral absorption maximum greater than 400 nm (*i.e.*, excluding the abundant colorless carotenoids phytoene and phytoflouene). Visible carotenoid content varied from 0.5 μg g^{-1} FW in the pale fruit accessions, such as 'Moniqui' and 'Real Fino', up to 47 μg g^{-1} FW in the intense-orange accession

TABLE 2. Mean (±SD) values of total carotenoid content (μg g^{-1} FW) of ripe apricot fruit and external color indices from different apricot accessions and hybrids. Accessions are divided to 3 groups according to their origin and ordered by their total carotenoid content.

	Total carotenoids	L*	a*	b*	Hue angle h°
International accessions					
Real Fino	6.2 ± 3.6	78.2 ± 1.1	-3.7 ± 1	33.8 ± 1.8	96.3 ± 1.6
MA.46	8.1 ± 4.8	74.2 ± 0.7	4.2 ± 3.6	49.4 ± 3.2	85.2 ± 3.9
Rouge de Rivesaltes	9.7 ± 1.9	71 ± 1.7	8.5 ± 2.8	47 ± 2.1	79.8 ± 3.2
Pelese di Giovanniello	9.9 ± 2.7	71.2 ± 1.9	2 ± 2.7	46.4 ± 2.4	87.5 ± 3.3
A.1758	11.3 ± 4.5	69.2 ± 2.9	6.1 ± 1.8	48.2 ± 2.7	82.7 ± 2.3
Moniqui	13.8 ± 5.1	75.8 ± 2.4	-4 ± 2.1	39.7 ± 1.8	95.7 ± 3.1
Tardif de Bordaneil	13.8 ± 6.4	70 ± 1.5	9.8 ± 3.8	50.7 ± 2.6	79.2 ± 4
A.1740	14.2 ± 0.4	66.3 ± 2.4	10.3 ± 1.6	50 ± 2.2	78.4 ± 1.8
A.S.1875	15.1 ± 8.3	69 ± 1.4	3.9 ± 2.7	47.7 ± 1.6	85.3 ± 3.2
A.S.3445	15.5 ± 10.2	66.6 ± 2.5	11.2 ± 2.9	44.6 ± 2.1	76 ± 3.4
Screara	15.5 ± 4.3	68.5 ± 2.5	7.1 ± 1.2	50.2 ± 3.4	81.9 ± 1.3
Amal	16.3 ± 7.1	66.8 ± 2	15.9 ± 1.8	51.8 ± 3.2	73 ± 1.2
Quardi	17 ± 7.3	65.4 ± 3.1	10.2 ± 2.1	47.4 ± 3.5	77.9 ± 2.5
Sayeb	19.7 ± 5	68.1 ± 0.9	15.2 ± 1.5	51.4 ± 2.7	73.5 ± 1.5
Poppy	21 ± 8.6	66.4 ± 2	10.5 ± 2.2	43.3 ± 1.7	76.4 ± 2.7
772-833	22.1 ± 8.6	68.1 ± 1.8	0.7 ± 2.7	44.9 ± 2.5	89 ± 3.5
79 GE 2	24.2 ± 2.6	62 ± 2	13.5 ± 2.3	45 ± 1.7	73.2 ± 2.8
774-835	24.2 ± 6.5	69.8 ± 1.5	4.9 ± 0.8	43.6 ± 1.6	83.6 ± 1
58/5	25.5 ± 5.9	63.1 ± 1.2	20.8 ± 2.2	49.3 ± 1.4	67.1 ± 2
47 EA 10	26.4 ± 20.8	66.8 ± 1.8	5.6 ± 2.1	42 ± 1.1	82.4 ± 2.8
A.1570	26.7 ± 8.5	65 ± 4.7	12.8 ± 1.7	51.2 ± 3.8	75.9 ± 1.8
Luizet	28.7 ± 9.9	63.3 ± 0.9	19.2 ± 1.1	47.4 ± 1.7	68 ± 0.9
Rouge du Roussillion	29 ± 11.9	70.3 ± 2.8	8.8 ± 2.8	43.9 ± 2.3	78.7 ± 3.6
48 G 1105	29.2 ± 13.9	66.5 ± 1.4	8.5 ± 2.5	47 ± 1.9	79.9 ± 2.8
392 LD 358	29.4 ± 2.8	66.6 ± 1.9	9.9 ± 1.6	42.8 ± 1.8	77 ± 2.1
Canino	29.9 ± 7	71 ± 1.7	9.3 ± 3	54.6 ± 1.5	80.4 ± 2.9
MA.170	31.3 ± 11.2	70.5 ± 1.5	9.5 ± 3.3	50.5 ± 2	79.3 ± 3.7
Selecta CNEEE 4	31.6 ± 12.8	70.4 ± 1.9	11.3 ± 1.2	53.6 ± 1.8	78.1 ± 1.3
Spring Giant	31.6 ± 10.7	64.9 ± 2.4	14 ± 2.9	48.4 ± 2.2	74 ± 2.8
A.1625	32.8 ± 8.1	63 ± 2.6	10.5 ± 2	48.6 ± 3.5	77.9 ± 1.7
MA.283	34.1 ± 14.6	64.8 ± 1.4	13.1 ± 2.2	44.7 ± 1.8	73.7 ± 2.7
Flamingold	37.2 ± 10.2	63 ± 1.3	19.6 ± 1.2	48.1 ± 1.5	67.9 ± 1.2
5 EA 293	37.7 ± 7	67.6 ± 1.5	13.4 ± 2.4	47.6 ± 1.1	74.3 ± 2.5

Table 2. Continued.

	Total carotenoids	L*	a*	b*	Hue angle h°
Precoce de Tyrinthe	39.1 ± 1.6	66.6 ± 1.8	15.5 ± 2.2	46.7 ± 2	71.7 ± 2.7
Castle Bright	39.1 ± 17.1	64.7 ± 1.5	17.3 ± 2.1	47 ± 0.9	69.9 ± 2.2
Dr. Mascle	40 ± 10	66.1 ± 1.6	19.3 ± 1.8	52.3 ± 2.4	69.7 ± 2
Precoce de Portugal	41 ± 7.8	69.5 ± 1.3	14.7 ± 2.5	50 ± 1.3	73.6 ± 2.8
Gabriel	41 ± 17.8	63.6 ± 1.6	16.1 ± 3.5	48.8 ± 2.2	71.8 ± 3.9
Helena	41.3 ± 17.1	65.6 ± 0.6	17 ± 2	49.8 ± 1	71.1 ± 2.2
384 LD 362	42.5 ± 4.4	65.8 ± 1.6	20.1 ± 1.7	50.7 ± 1.3	68.5 ± 1.5
Barracca	42.7 ± 9.6	68.5 ± 1.2	12.9 ± 2.1	48.6 ± 2.2	75.2 ± 2.4
Skaha	44.6 ± 9.9	65.7 ± 1.1	14.3 ± 2.4	49.7 ± 1.7	74 ± 2.5
Clutha Gold	44.7 ± 16	63.1 ± 1.8	12.3 ± 1.9	49.6 ± 1.7	76.1 ± 2
Earliril	51.3 ± 16.6	62.8 ± 1.9	14.5 ± 2.1	46.2 ± 1.7	72.6 ± 2.4
Precoce de Boulbon	52.1 ± 9.7	66.7 ± 1.8	15.1 ± 1.4	54.3 ± 1.6	74.5 ± 1.3
Earlicot	53.7 ± 17.8	67.9 ± 1.2	13 ± 1.3	49.4 ± 1.2	75.2 ± 1.4
Sundrop	54.1 ± 18.6	65.8 ± 1.3	15.7 ± 2.8	51.8 ± 1.4	73.2 ± 2.8
MAS955	57.1 ± 21.3	61 ± 0.8	20.3 ± 2	47 ± 1	66.7 ± 1.9
Plasteyn	58.5 ± 7	61.1 ± 1.8	14.9 ± 2	43.7 ± 3.3	71.1 ± 2.7
Rival	59.4 ± 23.6	63.5 ± 1.3	15.5 ± 2.2	46.9 ± 1.3	71.7 ± 2.3
Royal Rosa	60 ± 17.1	65.8 ± 1.9	14.6 ± 4.1	51.3 ± 2.5	74.2 ± 4.3
Perfection	66.8 ± 15.1	62.6 ± 0.8	15.7 ± 2.4	47.5 ± 1.5	71.8 ± 2.6
Castleton	75.8 ± 29.7	63.3 ± 1.2	19.8 ± 1.5	45.3 ± 1.5	66.4 ± 1.7
Pazza	79.6 ± 33.5	66.4 ± 1.7	14.5 ± 2.1	50.4 ± 1.4	73.9 ± 2.1
384 LD 373	91.2 ± 35.1	62.5 ± 0.9	20.1 ± 2.3	48.3 ± 1.6	67.4 ± 2.2
Local accessions					
P.A.811-312	9.7 ± 7.4	69.4 ± 2.9	2.8 ± 2.4	49.4 ± 1.8	86.9 ± 2.8
P.A.706-207	12.7 ± 7.7	75.1 ± 1.6	-4.7 ± 1	34.4 ± 1.3	97.7 ± 1.4
P.A.658-159	16.9 ± 2.8	70.1 ± 2.2	10.8 ± 2.5	55.7 ± 1.1	79 ± 2.5
P.A.803-304	17.1 ± 3.8	58.9 ± 1.4	6.6 ± 1.4	44 ± 1.9	81.5 ± 2
P.A.638-139	18 ± 5.9	69.1 ± 1.6	6.7 ± 1.9	55.2 ± 2.9	83.1 ± 1.8
P.A 648-149	18.8 ± 2.5	66.9 ± 1.9	7.8 ± 2.2	49.6 ± 1.5	81.1 ± 2.6
P.A755-256	20.2 ± 5.5	68.4 ± 2.2	9.2 ± 1.6	47.7 ± 2	79.1 ± 1.9
Eden	20.2 ± 5	71.6 ± 1.5	7.5 ± 1.9	47.4 ± 2	81.1 ± 2.2
Nitzan	23.8 ± 7.7	69.3 ± 1	9.2 ± 1.9	47.2 ± 1.4	79 ± 2.2
Behor Shotan	24.8 ± 13.7	63.6 ± 2	10.7 ± 2.1	46.9 ± 1.9	77.2 ± 2.3
P.A.757-258	25.7 ± 6.2	63.9 ± 1.5	5.8 ± 2.8	48.2 ± 2.3	83.1 ± 3.3
P.A.802-303	26.9 ± 3.1	58.6 ± 1.2	3.6 ± 2.6	41.7 ± 1.3	85 ± 3.4
Shiler	28.6 ± 11.1	63.7 ± 2	11.6 ± 1	45.9 ± 1.4	75.8 ± 1.3
P.A 647-148	31 ± 6.2	72.3 ± 2.1	7 ± 3.2	54.9 ± 1.4	82.8 ± 3.2
P.A.754-255	31.5 ± 17.7	75.7 ± 2.1	-3.9 ± 1.3	30.8 ± 3.1	97.2 ± 1.9
Gal	32.6 ± 6.2	62.2 ± 1.8	11.3 ± 2	42.5 ± 1.8	75.2 ± 2.3
P.A 705-206	34.4 ± 5.7	70.4 ± 1.4	10.7 ± 1.6	57.8 ± 1	79.5 ± 1.4
P.A 650-151	38.3 ± 4.5	62.9 ± 2.1	5.8 ± 1.4	42 ± 2.5	82.2 ± 1.5
P.A.660-161	43.2 ± 13.2	68.5 ± 0.9	11.8 ± 2.4	54.6 ± 2.2	77.8 ± 2.2
311	47.2 ± 12.1	66.2 ± 2.1	13.4 ± 2.6	45.3 ± 1.8	73.5 ± 3
Tarog	48.5 ± 12.8	66.8 ± 1.1	16.8 ± 1.6	52.3 ± 2	72.2 ± 1.6
Daniel	60.6 ± 9.1	67.5 ± 1.5	12.4 ± 1.2	48.4 ± 1.1	75.6 ± 1.5
P.A.631-132	64.1 ± 6.9	63.9 ± 1.8	11.4 ± 1.8	53.1 ± 2	77.9 ± 1.8
Paz	68.9 ± 12.6	64.3 ± 1.2	22.4 ± 1.1	47 ± 2	64.5 ± 1.3
Orange Gold	72.4 ± 19.8	66.1 ± 1.2	18.6 ± 1.5	47.4 ± 2	68.6 ± 1.8
Hybrids					
55/30	5.8 ± 2	73.2 ± 0.9	3.1 ± 2.4	50.2 ± 1.5	86.5 ± 2.7
58/53	17.9 ± 6.5	72.4 ± 2	5.4 ± 2.7	47.3 ± 1.2	83.5 ± 3.3
27/82	18.5 ± 5.9	78.4 ± 1.8	-5.1 ± 1.4	33.2 ± 2.6	98.7 ± 2
55/75	20.4 ± 11	65.8 ± 1.6	-2.4 ± 4.5	38 ± 2.9	93.9 ± 7

Table 2. Continued.

	Total carotenoids	L*	a*	b*	Hue angle h◦
60/36	23.1 ± 8.4	71.6 ± 1.6	10.7 ± 3.8	58.6 ± 2.9	79.8 ± 3.4
58/56	23.3 ± 4.2	69.7 ± 1.7	8.6 ± 1.6	42.2 ± 2.6	78.4 ± 2.1
57/81	24 ± 3	61.8 ± 2	19.2 ± 1.6	49.6 ± 1.8	68.8 ± 1.3
22/84	25.3 ± 7.7	58.6 ± 2.4	7.7 ± 3.2	44.5 ± 2.8	80.2 ± 4
57/66	25.5 ± 2.9	65 ± 1.2	18.2 ± 2	53.1 ± 1.1	71.1 ± 1.7
53/7	28.8 ± 6.4	69.2 ± 1	12.1 ± 1.3	52 ± 1.4	76.9 ± 1.1
53/50	29 ± 7.5	64.4 ± 1.2	14 ± 3	50.9 ± 1.2	74.6 ± 3.1
60/27	29.1 ± 6.6	66.7 ± 2.4	12.3 ± 2.7	44.5 ± 0.8	74.6 ± 3.2
53/71	29.4 ± 1.1	63.3 ± 1.3	11.3 ± 2	48.8 ± 2	77 ± 1.9
60/23	31.8 ± 8.7	68.4 ± 1.4	10.8 ± 1.8	45.1 ± 0.6	76.5 ± 2.2
14/71	33.5 ± 6.1	64.6 ± 2.1	10.3 ± 2.1	41.9 ± 2.5	76.2 ± 2.6
28/71	35.2 ± 11.8	64.1 ± 1.5	15 ± 1.8	46.1 ± 1.7	72 ± 1.8
53/60	36 ± 4.3	65.3 ± 1.4	14.5 ± 1.6	48.4 ± 0.5	73.3 ± 1.6
53/6	36.1 ± 13.7	63.2 ± 0.7	7.4 ± 1.5	44.2 ± 1.2	80.5 ± 1.7
34/8	40.3 ± 10.5	67.4 ± 2.5	13.8 ± 2	50.6 ± 2.7	74.7 ± 2.5
60/38	41.1 ± 7.7	69.1 ± 1.4	6.8 ± 3.9	48.3 ± 2.5	82.3 ± 4
54/88	41.4 ± 2.4	66.2 ± 1.1	10 ± 2.1	48.1 ± 1.7	78.3 ± 2.2
57/45	41.5 ± 20.9	64.1 ± 2.4	20.2 ± 1.6	51 ± 1.2	68.4 ± 1.8
58/138	49.5 ± 3.7	64.4 ± 0.4	12.7 ± 1.4	51.2 ± 1	76.1 ± 1.6
15/99	54.8 ± 1.4	65 ± 1.7	10 ± 3.2	45.3 ± 2.6	77.7 ± 3.2
37/68	62 ± 23.2	67.9 ± 2.1	13.6 ± 1.7	49.8 ± 1.9	74.7 ± 1.8

'Pazza'. According to these results neither total carotenoid content nor total visible carotenoid content of the fruit flesh correlated well with the fruit (skin) color parameters, showing best 'r' values of 0.62 and 0.66 respectively when correlated with a* values or a*/b* values (Table 3). *Trans*-lycopene is known as a red colorant; however its *cis* isomers, which are the ones found in apricots, have a lower spectral absorbance range, and more of an orange hue. We wanted to find out whether the presence of the lycopene isomers in the fruit tissue correlates with its external color. Again we found no significant correlation between the lycopene content and a* (r = 0.59) or a*/b* (r = 0.60) (Table 3). Interestingly, γ-carotene which is a carotenoid with a color that is redder than β-carotene, showed a relatively higher correlation to a* (r = 0.66) and to a*/b* (r = 0.67) (Table 3) despite its small fraction (on average 2.1%) of the total carotenoids in apricot (Table 1). The results indicate that the fruit external color is not generally a good predictor of carotenoid content in the flesh of the apricot fruit. It is possible that the lack of correlation is due to the different tissues compared: total carotenoids were extracted from the flesh tissue of the fruit, while color indices were measured on the external skin of the fruit.

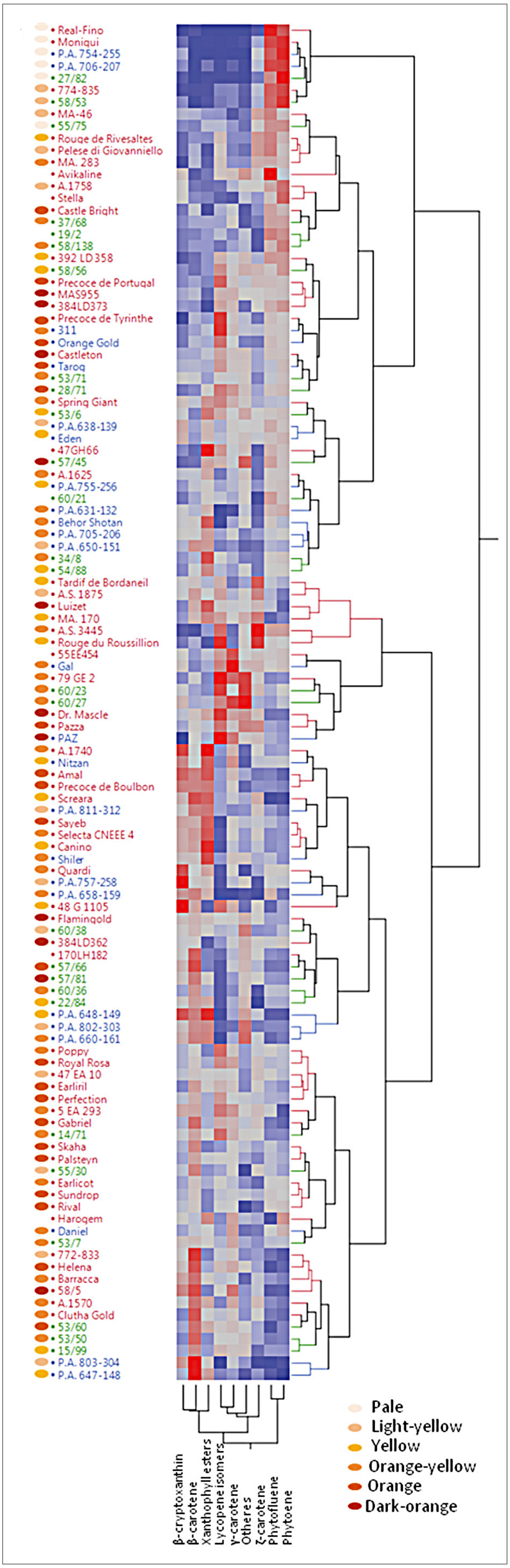
Hierarchical clustering and Heat-Map analysis

A multivariate cluster analysis of carotenoid composition of fruit samples from the different apricot accessions suggests hierarchies of both accessions and carotenoids (Figure 5). The apricot accessions are divided to two major clusters. Roughly, one cluster of accessions show relatively low proportion of phytoene and phytofluene and relatively high β-carotene, and the second cluster show high proportion of phytoene and phytofluene and low β-carotene (Figure 5; right). In general, within these two major clusters there are subgroups, each sharing somewhat similar carotenoid composition. None of the accessions of each subgroup seems to share a common origin. In addition, the accessions of each subgroup, but one, do not seem to have similar fruit color. The exception is a cluster of seven accessions at the top of the heat-map ('Moniqui', 'Real-Fino', '774-835', 'P.A.754-255', 'P.A.706-207', 58/53 and 27/82). The total carotenoid content of fruit of these seven accessions is not very high, ranging between 6.2 μg g^{-1} FW in 'Real-Fino' to 31.5 μg g^{-1} FW in 'P.A.754-255' (Table 1). However, more than 88% of the total carotenoid in fruit of these accessions is composed of phytoene and phytofluene, leaving less than 12% to colored carotenoid such as of β-carotene (Table 1). Accordingly, the fruit color of these seven accessions is pale, with a* values of -5.1 to 5.4 (Table 2). This might indicate a correlation between the unique carotenoid composition and the fruit color of the accessions in this group. In this respect, the clustering of the individual carotenoids shows that phytoene is paired with phytofluene (Figure 5; bottom). Phytofluene is an asymmetric carotenoid, the intermediate of phytoene desaturation to ζ-carotene (Figure 1). The pairing of these consecutive intermediates: phytoene with phytofluene, as well as the high correlation between their amounts (r = 0.86; Table 3) show that they tend to accumulate together and suggest that the early steps might represent a bottleneck in the carotenoid biosynthesis pathway in apricot. Hence, it is possible that the reason for the pale color in these accessions is a blockage in the first step of the carotenoid biosynthesis pathway; phytoene desaturation (Figure 1), which could lead to accumulation of phytoene and phytofluene and to limited production and accumulation of colored carotenoids.

Similarly, γ-carotene is an asymmetric intermediate of lycopene cyclization to β-carotene (Figure 1). The coupling of γ-carotene and lycopene together (Figure 5; bottom), and the high correlation between their amounts (r = 0.82; Table 3) might indicate that lycopene isomerization and cyclization represent an additional bottleneck in the biosynthesis pathway in apricot.

TABLE 3. Correlation coefficients between carotenoid contents (in µg g^{-1} FW) and color values of apricot fruit. Correlation coefficients were determined by the coefficient of Pearson. β-Crypto, β-Cryptoxanthin; Phytofl, Phytofluene; Xantho esters, Xanthophyll esters; Total, Total carotenoid content; Total colored, Total colored carotenoid content calculated as the total of all carotenoids with spectral absorption maximum >400 nm in the sample (total carotenoid content excluding phytoene and phytofluene).

	β-Crypto	Lycopene isomers	γ-Carotene	ζ-Carotene	β-Carotene	Phytofl	Phytoene	Xantho esters	Others	Total	Total colored	L*	a*	b*	Hue angle H°
Lycopene isomers	0.17														
γ-Carotene	0.44	0.82													
ζ-Carotene	0.24	0.68	0.60												
β-Carotene	0.51	0.45	0.60	0.36											
Phytofluene	0.39	0.64	0.68	0.49	0.36										
Phytoene	0.21	0.53	0.59	0.31	0.24	0.86									
Xantho esters	0.38	0.28	0.37	0.11	0.44	0.33	0.28								
Others	0.37	0.58	0.58	0.57	0.35	0.55	0.35	0.38							
Total	0.48	0.74	0.83	0.55	0.70	0.88	0.81	0.51	0.60						
Total colored	0.54	0.68	0.78	0.54	0.94	0.55	0.40	0.57	0.58	0.85					
L*	-0.32	-0.33	-0.45	-0.14	-0.48	-0.31	-0.18	-0.32	-0.37	-0.43	-0.51				
a*	0.32	0.57	0.66	0.35	0.57	0.49	0.34	0.42	0.46	0.62	0.66	-0.60			
b*	0.34	0.00	0.14	0.05	0.37	0.02	-0.09	0.32	0.13	0.16	0.33	-0.13	0.52		
Hue angle: H°	-0.30	-0.59	-0.67	-0.36	-0.55	-0.49	-0.32	-0.40	-0.47	-0.61	-0.66	0.65	-0.99	-0.47	
a*/b*	0.29	0.60	0.67	0.36	0.55	0.49	0.33	0.40	0.47	0.61	0.66	-0.65	0.99	0.45	-1.00



Conclusion

Our survey demonstrates that the distinctive carotenoid profile of apricot fruit, which includes high levels of phytoene and phytofluene as well as small amounts of lycopene in *cis* isomers is common to a wide range of accessions. However, the different accessions exhibit great variation in both total carotenoid content and ratios between the individual carotenoids (composition). We did not find correlations between specific compositions, total carotenoid content and fruit external color except for one exception; accessions with very high percentage of phytoene and phytofluene and very low percentage of β-carotene in their fruits are all characterized by pale color and relatively low carotenoid content (Figure 5; Tables 1 and 2).

Our results suggest that apricot has a nutritional advantage over other β-carotene accumulating fruits, since it can serve as a rich natural source of phytoene and phytofluene. It is interesting to note that despite the high portion of phytoene and phytofluene in the pale fruit of the accessions with pale fruit described above, the actual amounts of accumulated phytoene, phytofluene and *cis*-lycopene in their fruit is relatively low (up to 30 µg g^{-1} FW in 'P.A.754-255') and therefore they do not seem to have a nutritional advantage over accessions with fruit of more intense color (Tables 1 and 2). For instance, the accessions '384LD373' and 'Avikaline', which contain levels higher than 6 µg g^{-1} FW, 25 µg g^{-1} FW, and 23 µg g^{-1} FW of phytoene, phytofluene and *cis*-lycopene respectively, represent accessions with high potential of nutritional value.

The data obtained may pave the way to understand the genetic factors regulating carotenoid accumulation in apricot, and may be used for breeding more nutritious apricot cultivars.

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FIGURE 5. Hierarchical clustering of apricot accessions based on fruit carotenoid composition. Clustering was calculated by two-way Ward cluster analysis (JMP; version 12) and is presented as a heatmap. Standardization of carotenoid composition is done by subtracting the mean and dividing by standard deviation for each carotenoid compound. Red, grey and blue colors represent high, average and low values respectively. Apricot accessions are listed in red, blue and green according to their international, local or hybrid origin respectively. Fruit color, according to average a* values, is indicated next to the accessions' names. Pale, light yellow, yellow, orange-yellow, orange and dark-orange fruit color correspond to a* values <0, 0–<7, 7–10, >10–14, >14–19 and >19 respectively.

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