

Quality of carrots as affected by pre- and postharvest factors and processing

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Abstract

The aim of this review is to provide an update on factors contributing to quality of carrots, with special focus on the role of pre- and postharvest factors and processing. The genetic factor shows the highest impact on quality variables in carrots, causing a 7–11-fold difference between varieties in content of terpenes, β -carotene, magnesium, iron and phenolics as well as a 1–4-fold difference in falcarindiol, bitter taste and sweet taste. Climate-related factors may cause a difference of up to 20-fold for terpenes, 82% for total sugars and 30–40% for β -carotene, sweet taste and bitter taste. Organic farming in comparison with conventional farming has shown 70% higher levels for magnesium and 10% for iron. Low nitrogen fertilisation level may cause up to 100% increase in terpene content, minor increase in dry matter (+4 to +6%) and magnesium (+8%) and reduction in β -carotene content (–8 to –11%). Retail storage at room temperature causes the highest reduction in β -carotene (–70%) and ascorbic acid (–70%). Heat processing by boiling reduces shear force (–300 to –1000%) and crispiness (–67%) as well as content of phenolics (–150%), terpenes (–85%) and total carotenes (–20%) and increases the risk of furan accumulation. Sensory and chemical quality parameters of carrots are determined mainly by genetic and climate-related factors and to a minor extent by cultivation method. Retail temperature and storage atmosphere as well as heating procedure in processing have the highest impact in quality reduction.

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Keywords: carrot; *Daucus carota*; quality; preharvest; postharvest; heat processing

INTRODUCTION

The study of carrot quality in the 1950s was focused on sensory quality, with main emphasis on the bitter taste.^{1,2} At the beginning of the 1980s the so-called hash flavour associated with the strong burning flavour of turpentine was given high priority in the study of carrot varieties.³ During this period, attention was also given to β -carotene as a health constituent with effect against human cancer, as reviewed by Peto *et al.*⁴ Lately, the study of health effects of polyacetylenes such as falcarinol and falcarindiol has attracted most attention concerning health aspects of carrots.^{5,6}

Carrot is very sensitive with respect to influences by biotic and abiotic stress on quality characteristics. During the entire production chain, from seed to consumption, carrots are exposed to abiotic and biotic factors that affect the quality in different directions. The genetic factor gives the initial code for the level of important chemical compounds involved in sensory and health-related aspects of carrots.^{7–13} Furthermore, climatic factors such as temperature and precipitation,^{7,14,15} farming system (organic versus conventional),^{15–17} fertilisation status, uptake of constituents present in soil^{18–20} as well as postharvest handling^{21,22} and processing factors such as heat treatment^{23,24} affect the sensory quality of carrots.

The aim of this review is to provide an update of the last three decades on factors contributing to quality of carrots, with

special focus on the role of pre- and postharvest factors and processing on the enhancement of and detracting from quality characteristics of carrots. The review deals with important aspects

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of quality control and makes it possible to compare results from the literature on the different factors affecting quality. This is done by examples from the literature on reported differences in quality characteristics (significance level $P \leq 0.05$). To allow comparison of results from descriptive sensory analyses using different scales from a to b , the score results from diverse studies are converted to a uniform scale with gradation from c ($= 1$, low intensity) to d ($= 9$, high intensity). The transformation is done by the function

$$y = d[(x - a) / (b - a)] + c[(b - x) / (b - a)]$$

where x is the given score value measured within the scale interval a to b .

Calculations of percentage difference, increase or decrease are presented to facilitate comparisons. Differences between highest and lowest values are calculated as percentage of lowest value. In cases where an increase is described, this is indicated by plus (+) and the percentage is calculated from the lowest value. Similarly, reduction is indicated by minus (−) and the percentage is calculated from the highest value.

Most of the studies included in this review deal with orange-coloured varieties, but different-coloured varieties are mentioned where actual studies are published. Where no other information is given, the presented studies are from orange-coloured carrot varieties.

QUALITY-AFFECTING FACTORS

Quality properties of carrots are investigated by the aspects 'food safety', 'nutritional value', 'health value', 'sensory quality' and 'shelf life'.

The factors affecting these quality aspects are divided into groups according to occurrence preharvest, postharvest or during processing. The first preharvest steps are mainly quality-building measures during growth and development of the plants in the field. Of these, the choice of variety is the most important factor for potential quality. After harvest of the carrots the critical operations are handling, storage and sometimes processing. During the production chain the possibility to trace irregularities in handling that compromise quality can be difficult. This demands a need for detailed control and documentation of the production chain. There has been evidence that certain labelled products, e.g. 'sweet snack carrots' or 'organic carrots', were believed to possess superior quality compared with bulk products. However, such a quality difference is difficult to guarantee. The initial quality at harvest can be changed during handling, storage or processing. The impact of different factors on the defined quality aspects is summarised by grouping actual studies in Tables 1–3. These factors are described in the preharvest, postharvest and processing sections below.

PREHARVEST FACTORS INFLUENCING QUALITY

During growth and development of carrots, quality can be affected from sowing to harvest by (1) general preharvest factors such as genetic variation and climatic conditions (light, temperature, precipitation) as well as (2) farming system-related factors that deal with organic or conventional cultivation systems, fertilisation and pest control (Table 1). In the following subsections the preharvest factor contributions to differences in content of chemical compounds or sensory quality are discussed.

General preharvest factors

Variety

The genetic background seems to be the most important factor under human control in modifying the nutritional and health aspects as well as sensory aspects of carrots. A large number of quality characteristics, especially aroma components such as terpenes, sugars,^{7,9,25} nutrients and possible health-related compounds such as carotenes and falcarinol, seem to be genetically determined.^{9,51,52}

The aroma components terpinolene and caryophyllene showed particularly high variation within the open-pollinated orange variety 'Imperator', with 630 and 502% differences respectively.⁷ For an inbred orange line ('B10138'), differences were 23% for terpinolene and 50% for caryophyllene between varieties with lowest and highest contents.⁷ Particularly high variation was detected between varieties for terpinolene, with 650% difference between the extremes 'Imperator' (0.8 mg kg⁻¹ fresh weight (FW)) and 'Nantes' (6.0 mg kg⁻¹ FW).¹¹ Similarly, caryophyllene varied by 730% between 'Oregon' (1.2 mg kg⁻¹ FW) and 'Nantes' (10 mg kg⁻¹ FW).¹¹ High variation in terpene content between cultivars was also confirmed by Simon and Peterson⁷ for α -phellandrene, limonene and terpinolene.

Sugar content differed between varieties from 45 to 72 mg g⁻¹ FW (60%)⁷ and from 26 to 62 mg g⁻¹ FW (138%) in a study by Bajaj *et al.*⁹ (for 'Nantes' and a yellow carrot cultivar respectively). Of the sugars, sucrose content exhibited the highest variation between orange varieties, showing a 300% difference between highest and lowest levels when comparing five inbred lines.⁷ Sensory score for sweet taste varied between varieties from 4.4 to 6.1 (39%) when transformed to the 1–9-point scale.⁷ Similar differences in sensory scores varied between genotypes from 3.8 to 6.8 for sweet taste (79%), from 2.7 to 4.6 for bitter taste (70%), from 5.3 to 6.3 for carrot flavour (19%) and from 6.6 to 7.6 for hardness (15%).¹³ Bardseth *et al.*²⁵ found variation in sensory scores between the carrot cultivars 'Merida', 'Fontana', 'Newburg' and 'Nandrin' for sweet taste (from 5.2 to 5.5, 6%), bitter taste (from 2.4 to 2.9, 21%), juiciness and crispiness (both varied from 5.0 to 5.9, 18%).

Sensory scores differed by 55% for bitter taste, 54% for sweet taste and 11% for carrot flavour between the orange varieties 'Nottingham', 'Tornado', 'Bolero' and 'Nairobi'.¹² When different-coloured varieties were included, there were 119 and 209% differences between the varieties with lowest and highest sensory scores for sweet taste and bitter taste respectively.¹²

Nutritional value as measured by mineral content also differed between 23 varieties of different colours by 370% for manganese (1.1–5.2 $\mu\text{g g}^{-1}$ FW), 294% for iron (12.3–48.5 $\mu\text{g g}^{-1}$ FW) and 108% for potassium (1990–4140 $\mu\text{g g}^{-1}$ FW).⁹ Content of β -carotene varied by 900% when a yellow carrot (0.85 $\mu\text{g g}^{-1}$ FW) was compared with an orange type (Nr 10-75A, 85 $\mu\text{g g}^{-1}$ FW).⁹ Alasalvar *et al.*⁸ found 120–130% higher α - and β -carotene levels in purple carrots compared with orange varieties, only trace amounts in yellow types and no carotene in white varieties. Similar results were reported by Metzger *et al.*¹⁰

Content of health-related phenolics differed more than 10-fold (1127%) between varieties of different colours as determined for 5'-caffeoylquinic acid, which varied from 44 $\mu\text{g g}^{-1}$ FW (yellow and white varieties) and 85 $\mu\text{g g}^{-1}$ FW (orange variety) to 540 $\mu\text{g g}^{-1}$ FW (purple variety).⁸ Falcarinol content differed up to 430% between white and purple varieties (from 0.3 to 1.6 $\mu\text{g g}^{-1}$ dry weight (DW)), while an orange-coloured sample was intermediate in level (0.6 $\mu\text{g g}^{-1}$ DW).¹⁰

Table 1. Preharvest factors affecting quality aspects of carrots^a

Preharvest factor	Food safety	Nutritional value	Health value	Sensory quality	Shelf life
Variety (% diff. is between varieties with lowest and highest values)		Iron: 294% ⁹ Potassium: 108% ⁹ Manganese: 370% ⁹ Total sugars: 60% ⁷ , 138% ⁹ Sucrose: 300% ¹²	Falcarinol: 430%# ¹⁰ α -Carotene: 120%# ⁸ β -Carotene: 130% ⁹ , 900%# ⁸ 5'-Caffeoylquinic acid: 1127% ⁸	Terpenes: 23% ⁷ , 730% ¹¹ Total sugars: 60% ⁷ , 138% ⁹ Sucrose: 300% ⁷ Sweet taste: 6% ²⁵ , 39% ⁷ , 79% ¹³ , 119%# ¹² Bitter taste: 70% ¹³ , 209%# ¹² Carrot flavour: 11% ¹² , 19% ¹³ Dry matter: 13% ¹² , 27%# ⁹ , 60%# ¹²	Total sugars (storage energy for cells): 60% ⁷ , 138% ⁹ Dry matter: 13% ¹² , 27%# ⁹ , 60%# ¹²
Soil conditions (% diff. is between lowest and highest levels)	pH red. 5.5 to 6.5 Cd: -46% ²⁰ Risk of accumulation of heavy metals in soil ^{19,26,27} Diff. in radioactive compounds in soil ²⁸	Minerals present in soil in different amounts Mo, Se, Zn ²⁹		Peat soil vs sand or loam Sweet taste: +7% ³⁰ Bitter taste: -9% ³⁰ Earthy flavour: -13% ³⁰ Terpene flavour: -13% ³⁰	
Climatic conditions (year, location, light, temperature) (% diff. is between lowest and highest levels)	Wind directions Atmospheric deposition of heavy metals ¹⁸ Soil Cd diff. locations 67–300% ³¹	Location, year Total sugars: 82% ⁷ Sucrose: 15% ³² , 422% ⁷ Fructose: 15% ³² Temp. (9 vs 21 °C) Fructose: +49% ³³ Glucose: +28% ³³ Bitter taste: -30% ³³ Sucrose: -33% ³³	Diff. years β -Carotene: 24% ³² Polyphenol (5-CQA): 28% ¹⁵ Reduced plant density α -Carotene: +13% ³⁴ Temp. (9 vs 21 °C) β -Carotene: -40% ³³ Drought stress Increase in 6-methoxymellein ³⁵	Diff. locations Caryophyllene: 1982% ⁷ Terpinolene: 85% ⁷ Sucrose: 422% ⁷ Diff. years Sucrose: 15% ³² Fructose: 15% ³² Titratable acidity: 29% ³² Citric acid: 67% ³² Diff. location and year Total sugars: 82% ⁷ Temp. (9 vs 21 °C) Bitter taste: -30% ³³ Sweet taste: +35% ³³ Fructose: +49% ³³ Glucose: +28% ³³ Sucrose: -33% ³³ Dry climate Increased turpentine flavour and reduced sweet taste ^{35,36}	Temp. (9 vs 21 °C) Dry matter: +5 to +26% ³³ Location Total sugars: 82% ⁷
Organic versus conventional (+, organic highest; -, conventional highest)	Nitrite: -46% ³⁷	Phosphorus: +12% ¹⁷ Iron: +10% ¹⁷ Magnesium: +70 ¹⁷ Ascorbic acid: -3% ¹⁷	β -Carotene: NS ³⁸ Polyacetylenes: NS ³⁹ Polyphenol (5-CQA): NS ¹⁵ Flavonoids: NS ³⁹		
Fertiliser source	Animal manure Increased risk of microbial contamination (e.g. <i>E. coli</i> O157:H7) ⁴⁰ Mineral fertiliser Risk of Cd contamination from phosphate rock fertilisers ²⁰				

Table 1. *Continued*

Preharvest factor	Food safety	Nutritional value	Health value	Sensory quality	Shelf life
Nitrogen level (high versus low) (% diff. low vs high N)	Nitrate: -20% ⁴¹	Glucose: -20% ⁴² Fructose: -57% ⁴² Sucrose: -2.5% ⁴¹ , +14% ⁴² Total sugars: NS to -3% ⁴¹ -43 Calcium: NS to -8% ^{41,43} Potassium: NS ⁴³ Magnesium: +8% ⁴¹	β -Carotene: -8% ⁴³ , -12% ⁴¹	Terpenes: +22% ⁴² ; +100% ⁴² Total sugars: -3% ⁴² Glucose: -20% ⁴² Fructose: -57% ⁴² Sucrose: +14% ⁴² Citric acid: -63% ⁴² Malic acid: +48% ⁴² Bitter flavour: +16% ³² Green flavour: +12% ³²	Total sugars: NS to -3.25% ⁴¹ -43 Dry matter: +1 to +6% ⁴³
Pest attack (+, increase by pest attack; -, decrease by insect attack)		<i>Trioza apicalis</i> Sugars: -33% ⁴⁴ , -40% ⁴⁵	<i>Trioza apicalis</i> Antioxidant capacity: +64% ⁴⁴ Falcarindiol: +300% ⁴⁴	<i>Trioza apicalis</i> Bitter taste: +50% ⁴⁴ 6-Methoxymellein: +3000% ⁴⁴ Falcarindiol: +300% ⁴⁴ Total terpenes: +90% ⁴⁴ Terpene flavour: +43% ⁴⁴ Sweet taste: -70% ⁴⁴	
Pest control method	Pesticide use Risk of residues in carrots ⁴⁶⁻⁴⁹		Insect nets Reduction in falcarinol ⁵⁰		

^a Differences are shown between highest and lowest values of compared samples (calculated as percentage of lowest value). In cases where an increase is described, this is indicated by plus (+) and the percentage is calculated from the lowest value. Similarly, reduction is indicated by minus (-) and the percentage is calculated from the highest value. Each of the given difference examples is made between samples within the same publication. In cases where no other information is given, the examples are from orange carrot varieties. Different-coloured varieties are marked with a hash (#). NS = variable not affected significantly by the given factor ($P > 0.05$). References are given in the reference list.

The variety also affects dry matter (DM) content. The percentage differences in DM between lowest and highest contents in a study of varieties by Kreuzmann *et al.*¹² were 13% for orange-coloured varieties (from 10.5% DM for 'Soprano' to 11.8% DM for 'Bolero') and 60% for mixed colours (from 9.1% DM for 'White Satin' to 14.6% DM for 'Purple Haze'). Carrots of mixed colours in a study by Bajaj *et al.*⁹ showed 27% difference in DM between the cultivars with highest and lowest levels (from 8.8% DM for 'Sel. 5a' to 11.2% DM for 'Kurna').

High-yielding carrot varieties are often chosen for industrial processing. However, in general, these varieties may have less appealing sensory characteristics. This is exemplified in a comparison study that revealed higher content of descriptors having negative impact on the perceived quality (such as bitter taste, soil flavour, terpene flavour, green odour, astringency or toughness) for the traditional industry variety 'Fontana' in comparison with the fresh market variety 'Natalja', which showed more positively associated sensory variables such as sweet taste, sourness, juiciness and crispness.^{30,53} To a certain extent, bitter taste and toughness can be minimised by processing,⁵⁴ so these high-yielding varieties can to some extent be used in processed products.

Soil conditions

Carrots and other plants not only accumulate nutrients from fertiliser added to soil, they also accumulate trace elements and heavy metals released from soil particles.^{19,26} Toxic compounds such as mercury and other heavy metals^{19,26} and radioactive compounds (radionuclides)²⁸ may accumulate when present in soil and thereby affect the safety aspect of carrots. Cadmium is one such compound that easily accumulates in carrots from contaminated soil.²⁷ Higher cadmium accumulation levels were detected in carrots than in radish by Zheng *et al.*²⁷ Levels of cadmium in European carrots vary from 0.024 mg kg⁻¹ DM in Finland to 0.040 mg kg⁻¹ DM in the Netherlands (67%) as compared with 0.028 mg kg⁻¹ DM in the USA.³¹ Cadmium levels in carrots grown in different areas of Sweden varied from 0.12 mg kg⁻¹ DM in Gotland County to 0.48 mg kg⁻¹ DM in Malmöhus County (300%).³¹ Accumulation of cadmium may be caused by atmospheric deposition of heavy metals,¹⁸ polluted soils or rock material as a natural constituent of soil. The element can also be added by conventional mineral fertilisers (bound to phosphorus), sludge¹⁹ from animal production as well as compost²⁶ or phosphate rock fertilisers,²⁰ which may be used in both organic and conventional farming.

The pH level influences the availability of trace elements essential for carrot growth, but also other trace elements such as nickel and zinc as well as selenium that are not necessary for growth and development of the plant.⁵⁵ Lowering the pH decreases the uptake of selenium and increases the accumulation of other trace elements such as copper, nickel and zinc. In a Swedish study, 76–85% of the variation in cadmium content in carrots could be explained by pH, organic matter content and cadmium and zinc content in soil at harvest.³¹ Cadmium accumulation was found to be up to 46% higher at pH 5.5 compared with pH 6.5.²⁰ Thus adjustment of pH to 6.5 is preferable to ensure both safety and health aspects.

The soil composition (soil class) may to some extent affect sensory quality of carrots. In comparison with loam and sand soils, which not differed in sensory characteristics, growing of carrots in peat soil yielded 7% higher score for sweet taste (4.6 vs 4.3) and 4% higher for juiciness (5.3 vs 5.1) when means were compared.³⁰

The score for bitter taste was 9% lower in peat soil (4.0) compared with loam and sand soils (mean 4.4). Similar reductions for peat soil were found for earthy flavour (–13%) and terpene flavour (–13%) in comparison with sand and loam soils.³⁰ The effect of peat on sweet taste can be explained in part by the lower soil temperature measured in peat soil, which may increase sugar content as seen in other studies.^{33,56,57}

Climatic conditions and irrigation

The effect of year and location on the quality aspect pertains to annual or local variations in climatic conditions such as precipitation and temperature, but also variations in pest attack. With the exception of water supply, which can be increased by irrigation, these factors are outside the control of the farmer.

When comparing different locations (Florida and Texas, F1 hybrids), typical 50–100% differences were found in single terpenes, while total sugars differed by only 10% (42–46 mg g⁻¹ FW).⁷ However, climatic variation indicated by location and year can be much higher. An inbred line grown at four locations over two years showed a dramatic difference between locations and years in content of caryophyllene (1982%) as well as for terpinolene (85%), sucrose (422%) and total sugars (82%).⁷ Differences between years (28%) were found for content of 5-O-caffeoylquinic acid, which accounts for 80% of the total phenol content in carrots.¹⁵ Differences between years were also seen in a study by Paoletti *et al.*³² on the content of sugars (3% for glucose and 15% for fructose and sucrose content), β -carotene (24%) and acids (fumaric acid 25%, citric acid 67%, titratable acidity 29%).

Water availability is very important to the growth and healthiness of carrots. Precipitation and irrigation influence the availability and uptake of nutrients from soil in the same manner. Stress from high or low water content in soil can reduce growth and yield and induce the production of undesirable compounds in carrots.^{58,59} Drought stress is known to increase ethylene production and 6-methoxymellein in carrots^{35,60} as well as acetaldehyde and ethanol in other plants.⁵⁸

Besides precipitation, temperature and light conditions are the most important climatic factors. A warm, humid climate seems to affect the sensory quality by creating stronger turpentine-flavoured and less sweet-tasting carrots than a cooler, dry climate.^{33,36} It has been shown that low cultivation temperature (9 vs 21 °C) affects the sensory aspect by increasing sweet taste (+35%) and content of fructose (+49%) and glucose (+28%) and reducing bitter taste (–30%) and content of sucrose (–33%) and β -carotene (–40%) (mean of four cultivation periods in phytotron).³³ DM content varied for different cultivation periods by +5 to +26% when cultivation at 21 °C was compared with that at 9 °C.³³

The α -carotene content in carrots was found to be higher (+13%) with a low plant density (18 mg kg⁻¹ FW for 400 000 plants ha⁻¹) than with a high plant density (16 mg kg⁻¹ FW for 700 000 plants ha⁻¹).³⁴ This can be explained by an increase in UV radiation to the plants and the fact that carotenoids act as photoprotection compounds in the photosynthetic function.⁶¹ This indicates that growing seasons with a high intensity of UV light may cause an increase in carotene content of carrots.

Also, wind stress has been shown to increase the DM in carrots, while at the same time decreasing the concentration of phosphorus, magnesium, sodium and calcium.⁶²

Effect of preharvest factors related to farming system (conventional or organic)

Comparison of organic and conventional systems

The farming system consists of certain quality-affecting factors in which fertilisation and pest treatment methods are the main differences between organic and conventional systems. In this part of the review, studies that compare conventional and organic farming systems will be presented. This is done by a general organic *versus* conventional comparison, and thereafter in subsections that focus on specific factors that can be varied within the systems (fertilisation, pest treatment method).

Owing to consumer willingness to pay extra for organic products, the possible differences between organic and conventional products in regard to the aspects of nutritional and health-promoting value are important.^{63–66} Studies that attempt to demonstrate differences between organic and conventional foods can be divided into three groups: (1) studies that measure the 'nutritional composition' of foods that are organically *versus* conventionally produced; (2) studies that consider the 'health-promoting effects' of organically *versus* conventionally produced foods (including measurement of secondary metabolites and other substances that may be of interest with regard to health promotion); (3) animal feeding and human intervention studies that include the measurement of 'health status'.

Studies assigned to the first group show small and inconsistent differences between organic and conventional farming systems.^{67,68} However, in most of these studies, only macronutrients, vitamins and minerals were analysed and secondary metabolites were not determined. The levels of secondary plant compounds might be enhanced in organic products because of a diminished input of nitrogen.^{41,50,69} In the reviews by Worthington¹⁷ and Rembalkowska⁷⁰ it is concluded that a variety of different organic crops have a higher content of phenolics (+119%) and vitamin C (+29%) as well as magnesium (+29%) and iron (+21%). Studies allocated to the second group make the assumption that differences in the concentration of vitamins and secondary metabolites translate into a perceived health benefit, although for many compounds there are no available data in this area to justify this assumption. The third group of investigations has been associated with difficulties in the choice of health markers, as the term 'health' has a very broad definition, and the data available from such studies are generally sparse and often limited by a lack of replication in the farming systems.⁷¹

There are in general very few studies that have compared the content of secondary plant metabolites from different cropping systems under comparable field conditions. A recent meta-analysis⁷² reviewed original papers published on organic *versus* conventional cultivation. The content of secondary metabolites in fruits and vegetables was 12% higher in organic products compared with conventional products.⁷² However, of the studied components, only the carotenes are relevant for carrots, and they were not affected by the cultivation system.

Organic vegetables have in some studies shown a higher content of nutrients and secondary compounds compared with conventionally grown products.^{17,73} In the review by Worthington,¹⁷ statistical methods were used to identify significant differences and trends in published studies comparing nutrient contents of organic and conventional crops. The results show 10% more iron, 12% more phosphorus, 70% more magnesium and 3% less ascorbic acid in organic compared with conventional carrots. Carotenes (lutein, α -carotene, β -carotene) seem to decrease⁵⁰

or remain unaffected by organic farming compared with conventional cultivation.³⁸ Similarly, there were no differences between conventional and organic farming systems in content of the polyacetylenes falcarinol, falcarindiol and falcarindiol-3-acetate³⁹ and the common phenolic acid 5-O-caffeoylquinic acid.¹⁵

Only a limited number of studies make direct comparisons of the bioavailability of individual nutrients from the same food products produced by organic and conventional systems.⁷⁴ In a human intervention study, no differences between the two systems were found on the bioavailability of carotenoids, antioxidant effect and antigenotoxic or immunological effects in healthy subjects after carrot consumption.⁷⁵ Similarly, in a rat study, no effects on the bioavailability of major and trace minerals were detected. The rats were fed, among other foods, dried carrots grown from two consecutive years in farming systems with high or low fertilisation, with and without pesticides.⁷⁶

Besides the health aspects, sensory quality is often cited as being an important aspect motivating consumers to purchase organic foods.^{64,65} Despite this, there are few studies that compare the sensory quality of organically and conventionally grown carrots under comparable conditions. Haglund *et al.*⁷⁷ found higher bitter taste (+19%) in organic carrots (2.5) in comparison with conventional carrots (2.1, mean of two years and three varieties). In one of the two years, organic carrots also had a 6% lower score for sweet taste (6.2) compared with conventional carrots (6.6) and a more pronounced aftertaste.

Fertilisation

Among the factors that explain the difference between organic and conventional farming, fertilisation regime seems to have the highest impact.

The use of animal manure fertilisation introduces a possible risk of microbial contamination in organic as well as conventional farming systems. Contamination by organisms such as *Escherichia coli* O157:H7 and *Listeria monocytogenes* is a potential risk with animal manure fertilisation, as exemplified by lettuce plants in organic farming systems.^{78,79}

Microbial contamination has been studied in carrots on the market.⁸⁰ Carrots can be exposed to preharvest contamination with e.g. *E. coli* (O157:H7) by manure or irrigation water.⁴⁰ Also, this pathogen can be present in manure that has been exposed to a composting procedure, and the pathogen can survive for several months in soil.⁴⁰ High temperatures during composting and duration of the composting period are important factors in control of the pathogen. In any case, manure as well as irrigation water should be free of potential pathogens before use. This is important, since carrots are often eaten with the peel intact in raw conditions. For processed carrots, e.g. dried carrot slices, citric acid has been used in combination with moderate heat treatment to eliminate *Salmonella*.⁸¹

Nitrate accumulation in vegetables has been the cause of some concern, especially for vegetables used as raw material for baby food. Nevertheless, nitrate accumulation in carrots seems to be less of a safety problem, as carrots fertilised with nitrogen levels up to 150 kg N ha⁻¹ had nitrate levels below the threshold value for baby food (250 mg NO₃ kg⁻¹ FW).^{82,83} Increasing the nitrogen fertilisation from 60 to 240 kg N ha⁻¹ increased the nitrate content in carrots from 54 to 65 mg NO₃ kg⁻¹ FW (+20%).⁴¹ However, undesirable accumulation of nitrate in carrots seems to occur only in rare situations with high amounts of available nitrogen prior to harvest.⁶⁹ In general, levels of fertilisers, the

source and timing of fertilisation, conditions for mineralisation, water supply, species and variety are important factors that influence nitrate accumulation in vegetables.^{69,84} Organic carrots showed 46% reduction in nitrite in comparison with conventional carrots when results from ten conventional and ten organic farms were compared.³⁷ A general tendency of lower nitrate level in organically grown vegetables compared with conventional crops can be due to restricted nitrogen supply.⁸⁵

Farming systems with low nitrogen input showed increased bitter flavour (+16%) and green flavour (+12%) in comparison with conventional and different organic systems with higher levels of nitrogen.³² Reduced nitrogen fertilisation may affect nutrient and health aspects of fresh carrots in a positive^{17,70,85–87} or negative^{41,43,88} manner. Sørensen⁴¹ reported that β -carotene content was reduced by 12% with a reduction in nitrogen fertilisation from 240 to 60 kg N ha⁻¹. This could be in accordance with the finding that the biosynthesis of carotene is a nitrogen-demanding process.⁸⁹ A similar retarding effect on carotene production in carrots is also seen with a shortage of other elements such as molybdenum, selenium and zinc in fertilisation studies of carrots.²⁹

In an experiment where organic carrots were given different levels of green manure fertilisation corresponding to 0, 80 and 154 kg N ha⁻¹, DM increased by 2–6% with decreasing nitrogen levels, depending on year and climatic conditions.⁴³ There were no differences in content of sugars, calcium, magnesium or potassium in these studies. However, decreasing the level of nitrogen from 240 to 60 kg N ha⁻¹ reduced the content of β -carotene by 8 and 11% and increased the content of ascorbic acid by 9 and 14% in carrots in two different years respectively.⁴³

In general, limitation on the use of nitrogen fertilisers in organic farming systems compared with conventional systems seems to be the reason for higher content of nutrients, sugars and essential amino acids^{17,70,85–87} and phenolic compounds and falcariinol^{41,50,69,90} in organically grown carrots. A reduction in nitrogen from 240 to 60 kg N ha⁻¹ on a sandy loam soil increased the content of manganese by 3%, magnesium by 8%, calcium by 9% and sucrose by 3%.⁴¹ The higher concentration of these constituents can partly be explained by an increase in DM content occurring at reduced nitrogen fertilisation levels.^{41,43} Typically, the DM increase for carrot roots was 1% by reducing the nitrogen fertilisation from 120 to 60 kg N ha⁻¹, 3% by reducing it from 240 to 120 kg N ha⁻¹,⁴¹ and 2–6%, depending on the year, by reducing it from 200 to 25 kg N ha⁻¹.⁴³ It appears that the nitrogen effect (time, amount and availability) of the farming system affects the DM content and thereby indirectly affects the concentration of compounds.^{91,92}

In a pot experiment reported by Schaller and Schnitzler,⁴² a decrease in nitrogen supply (from 2.4 to 0.3 g N per pot) increased terpinolene (+22%), β -caryophyllene (+54%), α -phellandrene and β -pinene (both +100%), sucrose (+14%) and malic acid (+48%). On the other hand, the same reduction in nitrogen supply decreased nitrate (–458%), glucose (–20%), fructose (–57%) and sucrose (–63%). Thus farming with reduced levels of nitrogen can increase carrot aroma and decrease sugar content and sweet taste.

Among other macronutrients, potassium seems to have no influence on quality characteristics such as sugar content or carotene⁹³ or sensory quality.³⁰ On the other hand, increasing potassium nutrition may affect the shelf life of carrots positively by decreasing postharvest moisture loss.⁹⁴

Pest attack

In addition to yield losses, attacks by plant pathogens and insect pests can influence the safety of carrots by stimulating the production of secondary compounds either by the plant (phytoalexins) or by fungi (mycotoxins). Phytoalexins may be either healthy or unhealthy to humans, and not all compounds have been studied with respect to safety. Mycotoxins are either more or less toxic to humans.⁹⁵

Even though some mycotoxin-producing fungi are able to grow on carrot tissue in the laboratory,^{96,97} there are no reports on mycotoxins in carrots on the market. The studies of effects of farming system on mycotoxin-producing plant pathogens show contradictory results and do not clearly favour organic or conventional farming.^{98,99}

The most studied carrot phytoalexins are dihydroisocoumarins (mainly 6-methoxymellein), which are induced after exposure to ethylene, UV radiation, mechanical injury or temperature stress under pre- and postharvest conditions.^{21,22} These compounds are known to have antibiotic properties and are also produced by carrots after being infected by several plant-pathogenic fungi, e.g. *Botrytis cinerea*, *Ceratocystis fimbriata*, *Ceratocystis ulmi*, *Helminthosporium carbonum*, *Fusarium oxysporum* and *Fusarium lycopersici*.^{22,100,101}

Attack from insect pests may stimulate the production of certain secondary compounds in carrots as a protection mechanism. Long-term stress from insect attack by *Trioza apicalis* had an enhancing effect on antioxidant capacity (+175%), content of tocopherol (+208%), bitter compounds such as falcariindiol (+300%) and 6-methoxymellein (+3495%) as well as terpenes (+90%). These changes resulted in increased sensory scores for bitter taste (+98%), chemical flavour (+171%), terpene flavour (+116%) and toughness (+121%).⁴⁴ Attack of *T. apicalis* decreased total sugar (–26%), fructose (–27%), glucose (–50%) and sensory variables sweet taste (–195%), colour hue (–45%), crispiness (–35%) and juiciness (–43%).⁴⁴ However, these dramatic results were obtained in an extreme situation with 86% reduction in yield. The observation of increased bitter taste that sometimes occurs in organic cultivation systems⁷⁷ may partly be explained by an increase in psyllid attack and production of bitter compounds such as 6-methoxymellein and falcariindiol.⁴⁴

Pest control method

In addition to fertilisation regime, the main differences between organic and conventional farming systems are the pest control methods used. Pesticide residues have become a special concern not only as a threat to humans but also in terms of consumer anxiety. In a German study of pesticide residues in carrots, 93% of conventionally grown carrots were contaminated as opposed to 32% of organically grown carrots during the period 2002–2006.⁴⁶ According to the follow-up 2011 report, pesticide residues (clomazon and pendimethalin) were found in only 7.1% of investigated organic carrot samples.¹⁰² The negative pesticide effect is an important factor favouring organic over conventional carrots.⁴⁶ In contrast to conventional pesticide treatment, organic systems mainly use insect nets to protect against insect pests, crop rotation to protect against fungal diseases, and mechanical and thermal treatment to protect against weeds. Insect nets can influence sensory or health-related quality aspects by increasing temperature and humidity and reducing light intensity during carrot growth. In a study by Rashed⁵⁰ the content of falcariinol was reduced by insect nets compared with conventional crop protection by pesticide use.

POSTHARVEST FACTORS INFLUENCING QUALITY ASPECTS

The quality of carrots at harvest is not an end-point quality but could be affected by certain factors occurring in the period between harvest and consumption (Table 2). After harvest, carrots are normally kept for a period in cold storage before being transported to grocery stores. Following a certain period on the shelf (chilled or at room temperature), carrots are stored by consumers in the refrigerator before consumption. Temperature, atmosphere and humidity during storage and distribution are important factors that affect nutritional and health aspects as well as shelf life. In the following subsections the postharvest factor contributions to differences in content of chemical compounds and sensory quality are discussed.

Mechanical stress

During the harvesting process, carrots are exposed to stress. Mechanical stress from traditional machine harvesting (ASA-LIFT, Dianalund, Denmark) did not cause changes in sensory aspect by harvesting with shock absorbers.¹⁰³ However, exposure of newly harvested carrots to strong mechanical stress ('shipping tester' EMB 049, Nofima, Ås, Norway) had clear negative effects on sensory quality, expressed by 34% reduction in sweet taste (from 5.03 to 3.75), 45% increase in ethanol flavour (from 1.24 to 2.27) and 27% increase in sickeningly sweet taste (from 1.40 to 1.91).¹⁰³ These results matched the occurrence of ethanol (not detected, ND, vs 226 mg kg⁻¹), a small reduction in sucrose content (-4%) as well as a 14-fold increase in the bitter compound 6-methoxymellein (+1395%).¹⁰³

Temperature

Exposure to high postharvest temperatures affects the shelf life aspects as well as nutritional, health and sensory aspects of fresh and minimally processed carrots. Increased respiration and aging processes of carrots are related to effects of postharvest factors such as mechanical stress, low humidity and unfavourable atmosphere in packaging.^{35,105,107} In long-term cold storage at 0 °C the respiration rate is minimal¹¹⁶ and pathogen growth is restricted.¹¹⁷ High retail temperature (20 vs 2 °C) increased the negatively associated characteristics bitter taste (+13%), aftertaste (+11%), sickeningly sweet taste (+48%), terpene flavour (+15%) and earthy flavour (+22%) as well as causing a reduction in acidic taste (-20%) of carrots.¹⁰⁵ The storage of carrots seems to have inconsistent effects on the content of β -carotene, depending on temperature levels. At low temperature (4 °C), β -carotene increased by 8–23% after 4 weeks of storage compared with the level at harvest.¹⁰⁶ In a study by Negi and Roy,¹⁰⁴ 8 days of storage at different temperatures reduced the β -carotene content by 46% (7.5–8.5 °C), 51% (17–21 °C) and 70% (22–37.5 °C) compared with initial levels.¹⁰⁴ Similarly, ascorbic acid was reduced by 38% after 8 days of storage at 7.5–8.5 °C and by 70% at 22–37.5 °C.¹⁰⁴ Total sugars decreased by 4% after 10 days of storage at 20 °C compared with 2 °C.¹⁰⁵

Humidity

Because the peel of carrots is very thin and highly water-permeable, low air humidity reduces shelf life by increasing shrivelling of carrots.^{109,110} Storage of carrots at 98–100% relative humidity combined with low temperature is required to preserve their content of health-related compounds, sensory

quality and shelf life.^{118,119} This is mainly achieved by bulk storage in boxes with a perforated plastic lining to obtain humidity saturation. To maintain the necessary humidity during the distribution chain, carrots are generally packed in ventilated polyethylene bags.¹²⁰

Storage of unpacked carrots compared with carrots packed in ventilated PE bags showed reduction in β -carotene (-42 and -45%) and ascorbic acid (-44 and -114% for ambient and cool storage respectively).¹⁰⁴ In a study by Soria *et al.*,¹⁰⁸ dehydration of carrots caused a reduction in β -carotene (-35%), fructose (-67 to -81%) and glucose (-54 to -85%) and an increase in sucrose (+50 to +53%). However, these results are influenced by the variety factor. The results indicate that unpacked carrots or carrots packed in paper bags or other materials that do not provide high humidity are exposed to rapid losses of nutrients during marketing.

Atmospheric gases and ethylene

Storage in controlled or modified atmosphere positively increases the shelf life of many plant products¹²¹ by slowing down respiration. Respiration rate is influenced by gas concentration and temperature, and the rate has been modelled for shredded carrots.¹¹⁶ Nevertheless, storage of carrots at low O₂ status in modified atmosphere (7 vs 21% O₂) in different package types seems to affect the sensory aspect in a negative manner by increasing the anaerobic respiration and ethanol content (ND to 576 mg ethanol kg⁻¹ FW).¹⁰⁵ The anaerobic respiration clearly increased the sensory scores for sickeningly sweet taste (from 1.98 to 3.33, +68%) and ethanol flavour (from 1.35 to 3.10, +130%) of the carrots after 10 days of low O₂ concentration.¹⁰⁵ Increasing the temperature from 2 to 20 °C magnified the effect of low O₂ level and increased the sickeningly sweet taste by 49% and the ethanol flavour by 102%. The negative effects of low-O₂ atmosphere are confirmed by other studies.^{114,115} Thus modified or controlled atmosphere should be avoided or used with discretion for fresh or minimally processed carrots, and the O₂ permeability of packages should be sufficient to avoid negative impact on the sensory aspect.¹⁰⁵

Ethylene stimulates the production of the bitter compound 6-methoxymellein in carrots and thus affects the sensory aspect negatively.^{35,111,112} 6-Methoxymellein is normally present at minor levels in carrots stored in air, but upon storage in ethylene-enriched air (1 μ L L⁻¹) the level increased to 5, 7 and 13 mg kg⁻¹ FW after 1, 2 and 3 weeks respectively.¹¹¹ The level after 3 weeks of storage corresponded to a 20-fold increase (+2580%) compared with the level in carrots stored in air (0.5 mg kg⁻¹ FW). The sensory score for bitter taste increased by 30% under storage in ethylene-enriched air (1 μ L L⁻¹) compared with storage in ethylene-free air (5.1 vs 4.2) after 2 weeks.¹¹¹ The ethylene treatment also caused a reduction in total sugars (-30%) and an increase in terpene flavour (+17%) and aftertaste (+7%).¹¹¹ Storage of carrots with apples and other ethylene-producing fruits and vegetables induces a bitter taste in carrots.^{112,113} This should be avoided during transport, at retail stores and in consumers' refrigerators.

PROCESSING FACTORS INFLUENCING QUALITY ASPECTS

Processing of carrots positively affects the preservation of the product, prolongs shelf life and provides ready-to-use products for the consumer. However, processing also affects several quality aspects (Table 3). Therefore processing treatments

Table 2. Postharvest factors affecting quality aspects of carrots^a

Postharvest factor	Food safety	Nutritional value	Health value	Sensory quality	Shelf life
Physical stress (handling, mechanical exposure)			Virgous physical exposure 6-Methoxymellein: +1395% ^{22,103}	Virgous physical exposure by transport simulator: Sweet taste: -34% ¹⁰³ Ethanol flavour: +45% ¹⁰³ Sickeningly sweet taste: +27% ¹⁰³	
Temperature		At harvest vs 8 days at high temp. (22–37.5 °C) Ascorbic acid: -70% ¹⁰⁴ β -Carotene: -70% ¹⁰⁴ At harvest vs 8 days at 8 °C Ascorbic acid: -38% ¹⁰⁴ β -Carotene: -46% ¹⁰⁴ 20 vs 2 °C Total sugars: -4% ¹⁰⁵	At harvest vs 2 weeks at 4 °C β -Carotene: +8 to +23% ¹⁰⁶ At harvest vs 8 days at 8 °C β -Carotene: -46% ¹⁰⁴ At harvest vs 8 days at high temp. (22–37.5 °C) Ascorbic acid: -70% ¹⁰⁴ β -Carotene: -70% ¹⁰⁴	20 vs 2 °C Bitter taste: +13% ¹⁰⁵ Aftertaste: +11% ¹⁰⁵ Sickeningly sweet taste: +48% ¹⁰⁵ Terpene flavour: +15% ¹⁰⁵ Acidic taste: -20% ¹⁰⁵	20 vs 2 °C Total sugars: -4% ¹⁰⁵ Temp. effects on respiration and aging ^{35,105,107}
Humidity (package) (low versus high)		Dehydration β -Carotene: -35% ¹⁰⁸ Fructose: -67 to -81% ¹⁰⁸ Glucose: -54 to -85% ¹⁰⁸ Netlon vs PVC packed β -Carotene: -45% ¹⁰⁴ Ascorbic acid: -30% ¹⁰⁴	Dehydration β -Carotene: -35% ¹⁰⁸ Netlon vs PVC packed β -Carotene: -45% ¹⁰⁴ Ascorbic acid: -30% ¹⁰⁴		Effects on shrivelling ^{109,110}
Ethylene and O₂ (gas composition in storage environment)	Ethylene in air (1 μL L⁻¹) vs air storage, 3 weeks 6-Methoxymellein: +2580% ¹¹¹ , confirmed by others ^{21,22}			Ethylene in air (1 μL L⁻¹) vs air storage, 3 weeks Total sugars: -30% Terpene flavour: +17% Ethylene in air (1 μL L⁻¹) vs air storage, 2 weeks Bitter taste: +31% ¹¹¹ , confirmed by others ^{112,113} Low O₂ Sickeningly sweet taste: +68% ¹⁰⁵ Ethanol flavour: +130% ¹⁰⁵ , confirmed by others ^{114,115}	

^a Differences are shown between highest and lowest values of compared samples (calculated as percentage of lowest value). In cases where an increase is described, this is indicated by plus (+) and the percentage is calculated from the lowest value. Similarly, reduction is indicated by minus (-) and the percentage is calculated from the highest value. Each comparison is made between samples within the same study. References are given in the reference list.

Table 3. Processing factors affecting quality aspects of carrots^a

Processing factor	Food safety	Nutritional value	Health value	Sensory quality	Shelf life
Washing and peeling	Steaming prior to storage Microbial contamination: –92% ¹²² Washing without reuse of water Microbial contamination: –73% ^{103,105}		Peeling Falcarindiol: –50% ⁵⁴	Machine washing vs hand washing Bitter taste: +8% ¹⁰⁵ Aftertaste: +4% ¹⁰⁵ Terpene flavour: +7% ¹⁰⁵ Earthy flavour: +12% ¹⁰⁵ Peeling Falcarindiol: –50% ⁵⁴	Increased respiration and microbial contamination ¹²³
Temperature treatment	Heat sterilisation Furan: increase to 20–50 µg kg ⁻¹ ¹²⁴ Air drying at 133 °C till 4% water content Furan: +1000% ¹²⁵	Boiling Total carotenoids: –7 to –20% ²³	Boiling Total carotenoids: –7 to –20% ²³ Polyphenols: NS to –150% ²⁴ Freezing after boiling β-Carotene: –10% ¹⁰⁶	Crispiness: –46 to –67% ¹²⁶ Shear force (N): –1000 to –3000% ^{23,127} Ascorbic acid: –50 to –100% ¹²⁸ Glucose: –39% ¹²⁹ Fructose: –39% ¹²⁹ Sucrose: –38% ¹²⁹ Terpenes: –65 to –85% ²³ confirmed by others ^{130,131} Freezing Sweet taste: –55% ¹⁰⁶ Carrot-like odour and taste: –45 to –50% ¹⁰⁶	
Additives			Oil additive Increased carotene bioavailability ¹³¹		

^a Differences are shown between highest and lowest values of compared samples (calculated as percentage of lowest value). In cases where an increase is described, this is indicated by plus (+) and the percentage is calculated from the lowest value. Similarly, reduction is indicated by minus (–) and the percentage is calculated from the highest value. Each comparison is made between samples within the same study. The examples shown are from orange carrot varieties. References are given in the reference list.

should be as careful or mild as possible in order to preserve nutritional and health aspects and safety. In the following subsections the processing factor contributions to differences in content of chemical compounds and sensory quality are discussed.

Washing and peeling of raw material

Washing is the first step in the processing of carrots. Traditional machine washing of carrots has been shown to increase the risk of infection by plant pathogens. In comparison with hand washing, washing by machine increased sensory scores for bitter taste (+8%), aftertaste (+4%) and terpene flavour (+7%) as well as earthy flavour (+12%).¹⁰⁵ The dropping of roots on assembly lines causes stress, and the higher the drop, the higher the stress.¹⁰⁵ The type of machinery and the use of shock absorbers may reduce the stress level during washing and grading.

Quantitative analysis of the intermediate products in industrial carrot processing revealed that removing the peel as well as green parts successfully decreased the concentration of bitter-tasting falcariindiol in carrot puree by 50%.⁵⁴ Nevertheless, peeling after washing of carrots may increase respiration rates and microbial contamination as well as affecting pH level¹²³ and thereby influence safety and shelf life aspects. Micrographs of the peeled surfaces confirmed that abrasion peeling inflicted the greatest damage.¹²³ Washing and peeling should be done as close to processing as possible to avoid development of off-flavours by the carrots.

Afek *et al.*¹²² showed that carrot decay caused by pathogens can be reduced by 92% (from 65 to 5% damage) by steaming carrots for 3 s prior to storage. A reduction in pathogen infection and thereby a prolongation of shelf life are also seen by washing without reuse of water (73% pathogen reduction).^{103,105}

The use of additives in the water used for washing of organic products is regulated and very limited compared with that of conventional production. There are no regulations about the reuse of water on organically grown carrots.¹³² New possibilities such as the use of ozone instead of citric acid could be an alternative for reducing water consumption in the washing of organic vegetables.¹³²

Temperature treatment (boiling or freezing)

One of the most common processing steps for preservation is heat treatment. Boiling highly affects the sensory aspects by reducing crispiness and making the texture softer¹²⁶ and reducing shear force (N) (−1000 to −3000%).^{23,127} Boiling for 5 min reduced the sensory score for crispiness by 44–67% (from 8.4 for fresh carrots to between 2.8 and 4.7 for boiled carrots, depending on the cultivar).¹²⁶ A 10–30-fold reduction in shear pressure was measured after cooking of fresh or frozen raw material of carrots.^{23,127} Further, heat treatment affects the safety aspect by reducing the risk of microbial contamination. Pre-cut heat treatment (100 °C, 45 s) decreased the microbial activity and also reduced the respiratory activity of shredded carrots and extended the shelf life more than chlorinated water treatment (200 µg mL^{−1} active chlorine, 1 min, 5 °C).¹³³ In addition to traditional heat treatment (boiling), high-pressure homogenisation processing is a promising technology to achieve pathogen decontamination. This method is commonly used in the processing of juice.¹³⁴

The digestibility and bioavailability of different nutrients in carrots may vary with the mode and degree of preparation and

processing. As an example, absorption of carotenoids from raw vegetables can be fairly low (18% from mixed vegetables), while heating can give up to a 6-fold increase in uptake.^{135,136}

Despite its positive effects on the safety aspect and carotene bioavailability, thermal treatment during cooking may have a negative impact on nutritional and health aspects through formation and degradation of health-related compounds. Depending on the cultivar, carotenoid levels were reduced by 11–20% for fresh cooked carrots and 7–20% for frozen cooked carrots.²³ At the same time, aroma compounds (terpenes) were reduced by 70–85% for fresh cooked carrots and 65–80% for frozen cooked carrots. Boiling for 7 min decreased the contents of glucose, fructose and sucrose by 39, 39 and 38% respectively.¹²⁹ Boiling can also reduce the ascorbic acid content by 50–100%.¹²⁸

Frozen storage of cooked carrots reduced total carotenes by 10% after 4 weeks of storage at −18 °C and by 6% after 8 weeks of storage at −25 °C.¹⁰⁶ Immediately after freezing of fresh carrots a 45% decrease in sensory score for sweet taste (6.6 vs 3.6), a 37% decrease in carrot-like odour (6.4 vs 3.9) and a 44% decrease in carrot-like taste (6.8 vs 3.8) were observed.¹⁰⁶ After 1 year of frozen storage of blanched carrots (at −18 to −28 °C), higher scores for grassy flavour and firm texture were observed in comparison with fresh blanched carrots.

The carcinogenic compound furan may be formed during heat treatment of carrots via thermal oxidation of carotenoids and sugars, particularly during sterilisation of sealed containers.¹³⁷ This contaminant is very reactive and increases the risk of cancer by binding to DNA and forming the highly carcinogenic metabolite *cis*-2-butene-1,4-dial.^{138–140} Furan may accumulate by heat treatment of canned carrot products to levels between 20 and 50 µg kg^{−1}.¹²⁴ In canned vegetables, furan is trapped in the product during the heat sterilisation process.¹⁴¹ The accumulation of furan can be reduced by alternative sterilisation techniques such as ohmic heating, which allows very rapid temperature increase followed by rapid cooling in the complete volume.¹⁴² This limits heat-generating reactions. Smashing and cooking operations may also increase the level of other neoformed compounds such as carboxymethyllysine and furosine, which have been used as markers for product age and heat exposure.¹⁴³ Front face fluorescence can be used as a tool to monitor the effect of heat processing on neoformed contaminants in carrot products.¹⁴³

Furan may also increase during air drying of carrot slices at temperatures from 93 to 133 °C.¹²⁵ Furan formation started at <40% water content and thereafter increased exponentially with drying temperature. By 133 °C, carrot slices at 5% moisture content contained 275 µg kg^{−1} furan, which was 10 times higher than that found in fresh carrot slices.¹²⁵

Additives

More than 300 additives are registered for conventional products while only 47 are available for organic products (EC Regulation No. 1333/2008). Addition of other food products during processing of food to create mixed products is debatable. Reduction in selected additives could be of importance for persons who show allergic reactions to specific additives. However, addition of oils can improve the quality of carrot products, since the occurrence of dietary lipids is believed to be important for carotenoid bioavailability in humans.^{131,135} Adding 10% of olive oil to boiled carrots increased the uptake of carotenes in by 80%. This improvement could be utilised in the development of processed carrot products with specific health profiles.

DISCUSSION AND CONCLUSION

The genetic factor, which can be controlled by the farmer through selection of variety, clearly has the highest impact on most of the quality variables. When extreme varieties are compared, 7–11-fold differences can be found in phenolics (1127%), β -carotene (900%) and terpenes (730%) as well as 1–4-fold differences in falcariindiol (430%), magnesium (370%), iron (294%), bitter taste (209%) and sweet taste (160%) and up to 60% difference in DM (Fig. 1A).

Climate factors may affect terpene content 20-fold between extremes (1982%). Considerable variation can also be seen for total sugars (82%), β -carotene (40%), phenolics (28%), sweet taste (35%), bitter taste (30%) and DM (29%) when comparing carrots grown in different climates, locations or years (Fig. 1B). Thus the quality that is laid down by a particular variety or cultivation practice can to large extent be changed in unexpected directions by climate factors.

Choice of organic compared with conventional farming may to some extent change the quality of carrots by increasing the content of minerals such as magnesium (+70%) and iron (+10%) as well as decreasing nitrite content (–46%) and slightly decreasing ascorbic acid content (–3%) (Fig. 1C). Low nitrogen fertilisation of carrots, which is part of the organic cultivation concept, may increase the content of terpenes (+100%), magnesium (+8%) and DM (+6%) as well as reduce the content of nitrate (–20%) and β -carotene (–12%) (Fig. 1D).

Another factor related to organic cultivation is the ban on pesticides, which reduces the risk of pesticide residues but increases the risk of damage by pest attack. In addition to yield loss and product damage, insect pests may reduce sensory quality by

raising the content of the bitter compounds falcariindiol (+300%) and 6-methoxymellein (+3495%) as well as increasing bitter taste (+98%) and reducing sweet taste (–195%) and sugar content (–26%) (not shown in figure).

Quality obtained at harvest may be degraded by elevated temperatures during storage and retail (Fig. 1E). High versus low retail temperature (room temperature versus cold storage) reduces shelf life but also affects nutritional and health aspects of carrots by decreasing the content of β -carotene (–70%), total sugars (–4%) and ascorbic acid (–70%). At the same time, high retail temperature represents a potential risk for reduction in sensory quality by increasing bitter taste (+13%) and sickeningly sweet taste (+48%). Postharvest mechanical stress due to low O₂ level or ethylene exposure may additionally reduce sensory quality by generating sickeningly sweet taste or bitter taste respectively (not shown in figure).

Heat processing by boiling affects texture by reducing shear force, crispiness and DM. At the same time, boiling affects nutritional and health aspects by degrading phenolics (–150%), ascorbic acid (–100%), terpenes (–85%), total carotenes (–20%) and sucrose (–38%) (Fig. 1F). Heat treatment of sealed containers also affects the safety aspect by increasing the content of the unwanted compound furan up to 10-fold. This can be minimised by the use of ohmic heating in the sterilisation process of closed containers. Bioavailability of carotenes in the body may increase up to 6-fold by boiling and by 80% with oil addition.

From the perspective of safety the most important factors are the control of human pathogens (e.g. *E. coli*) in fertilisers and irrigation

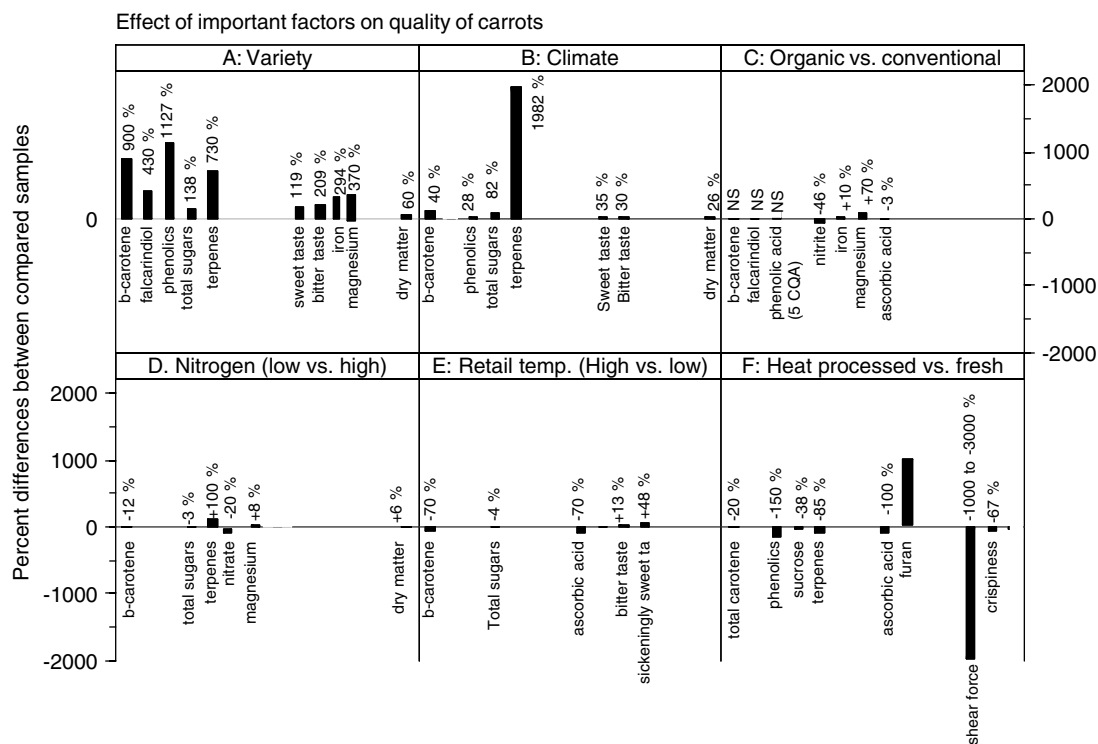


Figure 1. Illustration of reported maximum variation between high and low levels of important response variables describing quality of carrots. Examples are given for variation between extremes within varieties (A)^{7–13} and climate-related factors (B)^{7,14,15,33} as well as organic versus conventional farming system (C),^{15–17,38,39} low versus high nitrogen fertilisation (D),^{38,41–43} high versus low retail temperature (E)^{104,105} and heat-processed versus fresh (F).^{23,24,124,125,127–129} Comparisons are made between samples within the same study. In cases where an increase is described, this is indicated by positive bar (+) and the percentage is calculated from the lowest value. Similarly, reduction is indicated by negative bar (–) and the percentage is calculated from the highest value. NS = not significantly affected by the tested factors.

water and the control of pesticide residues in products. Also, the accumulation of radioactive compounds as well as cadmium and other heavy metals from soil represents a preharvest hazard in some areas. To some extent, heavy metal accumulation can be controlled by adjusting the pH level in soil. To ensure consumer trust, these safety factors are of high importance.

Owing to the strong genetic effect on several important quality parameters, there is potential to plan and ensure a certain quality at harvest. However, these genetically determined characteristics may be influenced in unpredictable directions by climate-related factors. The cultivation method seems to have a minor influence on quality in comparison with genetic and climate-related factors. During storage the initial quality may be influenced by further changes. A low retail temperature and absence of ethylene and sufficient O₂ concentration in the atmosphere and packaging are important to avoid quality reduction. For heat-processed carrot products the heating method should be adjusted to avoid formation of the carcinogenic compound furan.

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