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Non-invasive spectrophotometric sensing of carrot quality from harvest to consumption

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Abstract

The impact of different storage conditions and minimal processing on quality changes of freshly harvested carrots were recorded by means of non-invasive spectrophotometric techniques. Methods were adapted and evaluated with conventional chromatographic methods to test their feasibility for non-invasive monitoring of compounds determining the product quality. Sugar contents, which are a major component of carrot taste, were non-invasively monitored by means of diffuse reflectance readings (800–1700 nm) applying partial-least squares regression with a percentage standard error of cross validation (SECV) of 15.4, 4.6, and 2.3% for sucrose, glucose, and fructose, respectively. Using spectrophotometry in the visible wavelength range, non-invasive analyses of α- and β-carotenes, as important contributors to the nutritional value of carrots, were obtained with an SECV <1%. An inter-cultivar validation highlighted the need for re-calibration in sugar analysis, while carotenes were measured with an SEP <18% and a coefficient of determination in the validation of $R_{P^2} > 0.9$. Application of non-invasive product monitoring shows that storage at high temperature (16 °C) as well as a break in the cooling chain can cause decreases in carotene contents. Under these conditions, in comparison with cool storage (3 °C), reducing sugars contents remained stable or were slightly enhanced, while sucrose contents decreased. After minimal processing all nutrients decreased. A loss was inhibited when the oxygen partial pressure was reduced. Monitoring such quality changes with rapid spectrophotometric methods can provide a quality control tool in modern supply chain management.

Keywords: Carotene; Carrot quality; Non-invasive spectrophotometry; Product monitoring; Sugars; Supply chain; Validation

1. Introduction

The major consumer requirements for carrot consumption are taste and nutritional quality. Therefore, carrot quality should be assessed in terms of sensory attributes such as sugar content, an important component of taste, and the contents of secondary plant compounds (Herrmann, 1994). Carrots have particularly high contents of α- and β-carotene, which show high provitamin A activity in humans. Thus carrot quality assessment needs to take into account the chemical composition with respect to both sugars and carotenoids (Van den Berg et al., 2000).

Carrot quality in terms of such nutrients is determined by the genomic constitution, and, to a lesser extent, by seasonal impacts and production systems (Alasalvar et al., 2001; Künsch et al., 2003). After harvest, quality losses appear as a function of time, mechanical impacts, and storage conditions (Nilsson, 1987; Herppich et al., 1999). Furthermore, when transforming fresh carrots to ready-to-eat food, domestically or on an industrial scale, enzymatic and oxidative degradation is caused by minimally invasive processing operations such as peeling and slicing. An average shelf-life of 5–10 days is generally advised for industrially produced minimally processed fresh produce, while after preparation in the household, shorter periods of storage can be assumed due to the more unfavourable storage conditions.

Low temperature storage decreases respiratory activity and, thereby, positively affects keeping quality of fresh, perishable produce. However, the cool chain from harvest to consumption is often not maintained continuously for technical or handling reasons, and this has a negative influence on the product quality. Having more quantitative information available on the impact of fresh keeping conditions on quality-related attributes of

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perishable produce would provide the basis for developing strategies for maintaining product quality at each step of product handling, processing, and preservation. Hence, rapid, diagnostic methods should provide valuable tools in process management (Luyten, 2003).

Spectral-optical techniques such as diffuse reflectance and remittance spectrophotometry in particular, fulfil all the requirements for continuous monitoring of compounds that can be related to the taste and nutritional value of horticultural products. Non-invasive analysis of agriculturally based food products by means of visible (VIS) and near infrared spectrophotometry (NIRS) has been studied since the sixties.

According to the Lambert–Beer–Law, absorbance spectrophotometry in the visible wavelength range can be used as an accurate technique for non-invasive analysis of fruit pigment contents (Richardson et al., 2002; Zude, 2003b). Indices, addressing wavelengths where the pigment under question absorbs light while exciting the molecules' electrons, have been developed for this purpose and successfully applied in remote sensing (Richardson et al., 2002). Indices and chemometric calibrations are presently applied to analyze plant pigments such as chlorophyll (Peñuelas et al., 1995; Merzlyak et al., 1999; Zude-Sasse et al., 2002) and related fruit maturity (Zude and Herold, 2002; Zude, 2003b; Solovchenko et al., 2005).

NIRS in the wavelength range up to 1100 nm has been non-invasively applied to fruit and vegetables for analysis of their soluble solids contents (Chen and Nattuvetty, 1980; Birth and Hecht, 1987; Bellon et al., 1993; Kawano and Abe, 1995; Zude et al., 2006) using multivariate calibration and correction algorithms (Bro and Kiers, 2003; Peirs et al., 2005). Such NIRS-based methods have been commercially used since 2001 in sorting lines and handheld devices (Walsh et al., 2004; Miller and Zude, 2004). They are an innovative step forward in the use of horticultural non-invasive technologies for measuring internal product quality parameters.

Using the wavelength range up to 1700 nm, alcohols, sugars, protein, fatty acid contents as well as structural changes in the conformation of starch, water clusters and proteins can be addressed. Calibration of sugar and moisture contents as well as derived characterization of the fruit maturity stage particularly shows high potential for fresh products. Results obtained on cherries, citrus fruit, peeled and non-peeled bananas and apples provided $R^2 > 0.9$ with respect to specific sugar compounds (sucrose, glucose, fructose) with low standard errors of cross-validation $<2.7\,g\,kg^{-1}$ on a dry weight basis (Tarkosova and Copikova, 2000; Zude, 2003a).

One of the biggest problems in applications of non-invasive spectrophotometry is the variation in the scattering characteristics of the product tissue. Besides the effect of the absorbing compounds determining the absorption coefficient (μ_a), the physical properties of the product determining the scattering coefficient (μ_s) also affect the intensities of the spectra measured. Light scattering is influenced by the spatial densities and refractive index at the air/liquid boundaries, membranes, vacuoles, and organelles (Fukshansky et al., 1993; Cubeddu et al., 2002). Since theoretical models on the resulting photon migration in the tissue, μ_{total} (μ_a, μ_s), have only recently been developed for fruit and vegetable tissue (Cubeddu et al., 2002; Fraser et al., 2003), empirical, chemometric approaches are still needed to address this problem.

The aims of the present work therefore are: (i) evaluation of spectrophotometric techniques to measure sucrose, reducing sugars, and carotenes in carrots; (ii) the study of the effect of minimal processing and storage on these compounds.

2. Materials and methods

2.1. Sampling

Experiments were carried out on *Daucus carota* L. of two cultivars. For developing calibration models and evaluating the measurement uncertainties and robustness of calibration models, non-invasive and chromatographic analyses were carried out on fresh carrots of cultivars 'Dordogne' ($n = 61$) and 'Bolero' ($n = 73$) grown in southern Germany and transported within 2 days to the laboratory. While calibration models were built on 'Dordogne' carrots, the data set obtained from 'Bolero' carrots was used for evaluating the calibrations by means of an inter-cultivar validation. Additionally, fresh 'Dordogne' carrots ($n = 5$) were used to analyse different sections of the tissue, taking into account the xylem and periderm at the crown, mid-section, and tip.

Carrot quality changes in the supply chain were subsequently studied on 'Dordogne' carrots, which were grown in south-eastern France, harvested mechanically, and transported under cool conditions (0–2 °C) to the laboratory within 8 h. In the laboratory, a sub-sample of carrots ($n = 3$ with duplicate analysis) was analyzed immediately (no. 1), while other samples (total $n = 21$ with duplicate analysis) were kept in glass vessels under ambient light conditions and treated as follows (Fig. 1):

No. 2: intact carrots were continuously kept at 16 °C for 4 days.
No. 3: intact carrots were kept at 3 °C for a period of 24 h, and the cool chain subsequently broken for 48 h at 16 °C. Following this period, storage conditions of 3 °C were re-established for another 24 h.
No. 4: intact carrots were continuously kept at 3 °C for 4 days.

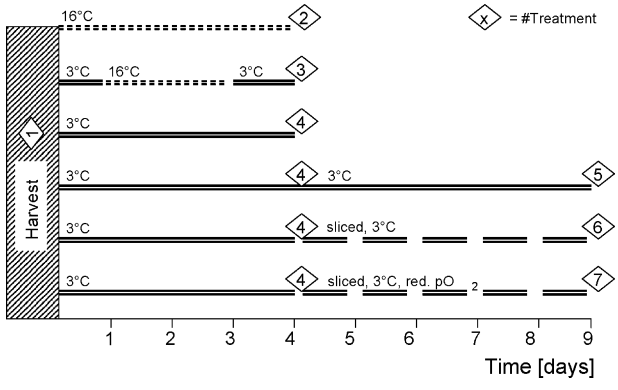

Fig. 1. Schematic view of postharvest treatments applied to freshly harvested carrots.