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Prediction ability of firmness decay models of nectarines based on the biological shift factor measured by time-resolved reflectance spectroscopy

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ABSTRACT

The maturity of nectarines at harvest can be assessed by measuring the absorption coefficient at 670 nm (μ_a) with the non-destructive technique of time-resolved reflectance spectroscopy (TRS). A kinetic model links μ_a, converted into the biological shift factor (BSF), to firmness decrease during ripening; in this way the firmness decay model includes the variations in maturity at harvest, thereby allowing prediction of shelf-life for individual fruit. In order to study how this methodology could be practically used at the time of harvest, when μ_a can be measured non-destructively on all fruit, while the destructive measurement of firmness can only be done on a small sample, various firmness decay models were developed using either data at harvest or within 1–2 d after harvest from previous experimental research with nectarines carried out over a 5-year period. These models were then tested for prediction and classification ability by comparing the predicted firmness and class of usability to the actual ones measured during ripening and their performance compared to that of models based on data during the whole shelf-life. Our results suggest that the methodology might be used as a management tool in the nectarine supply chain. Independently from the actual softening rate, the classification at harvest based on μ_a is able to segregate fruit of different quality and maturity according to their softening behaviour during shelf-life. Among the various models, those estimated using data at harvest and after 24 h of shelf-life had better performance than those based only on data at harvest. In the 2002 and 2005 seasons, this model showed a classification ability very close to that of models based on data during the whole shelf-life. However, its performance in the 2004 season was not so good, because it could not take into account the influence of cold storage periods prior to shelf-life. All the steps necessary to apply this methodology are detailed.

1. Introduction

Fruit maturity at harvest is of paramount importance for quality during subsequent marketing and consumption. Peaches and nectarines, if harvested ripe, have excellent eating quality but may be subjected to mechanical injury and decay during handling. On the other hand, if fruit are harvested too early, they lack flavour, and sometimes, ripening capacity (Crisosto et al., 2003a,b; Eccher Zerbini and Mari, 2005).

Previous research has found that maturity of nectarines at harvest can be assessed non-destructively by using time-resolved reflectance spectroscopy (TRS) to measure the absorption coefficient (μ_a) of the fruit flesh at 670 nm, near the chlorophyll peak (Cubeddu et al., 2001; Eccher Zerbini et al., 2006). TRS is a non-destructive technique based on the injection of a short pulse of monochromatic light in the fruit flesh and on the analysis of time distribution of re-emitted photons (Cubeddu et al., 2002). Using TRS, it is possible to differentiate between the absorption coefficient, related to chemical composition, and the reduced scattering coefficient, related to physical structure. The volume probed by a TRS measurement is a "banana shaped" region connecting the injection and collection points, and depth of light penetration in most fruit and vegetables is about 1–2 cm, depending on their optical properties (Cubeddu et al., 2001).

In nectarines the absorption coefficient at 670 nm (μ_a) decreases with fruit degreening and ripening according to a sigmoidal decay. By using an appropriate logistic model, the μ_a value of a fruit can be converted into its biological shift factor (BSF), which represents the time relative to the midpoint of the μ_a decay curve (Tijskens et al., 2006). In previous research with nectarines carried out over

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a 4-year period, it was found that the decay of fruit firmness after harvest and during ripening also follows a logistic curve, synchronized with the decrease of μ_a. In this way, the BSF derived from μ_a is linearly related to the BSF for firmness, which represents the time relative to the midpoint of the firmness decay curve. A kinetic model was developed relating firmness decay to BSF (Tijskens et al., 2007a). Thus, the variation in maturity of individual fruit, assessed by μ_a, could be incorporated into the model for fruit softening and so μ_a can be used as an index of the biological age or development stage of individual fruit: fruit with a μ_a value above 0.4 cm^{-1} do not ripen, probably because of insufficient availability of the enzymes responsible for softening; those suitable for transport purposes should have a μ_a value of at least 0.25 cm^{-1}; those having μ_a values ranging between 0.1 and 0.2 cm^{-1} will last only for a couple of days, while nectarines characterized by μ_a values below 0.1 cm^{-1} are already suitable for immediate consumption (Tijskens et al., 2007a).

The relationship between μ_a and firmness was not affected by fruit size/mass (Eccher Zerbini et al., 2006) nor by cold storage as Eccher Zerbini et al. (2006) reported that nectarines soften as much in 100 h at 0 °C as in 1 h at 20 °C. However Rizzolo et al. (2009) found that the softening kinetics decreases after cold storage periods longer than 10 d, probably because of an imbalance in cell wall metabolism (Lurie et al., 2003).

The TRS measurement coupled with the BSF theory was successfully applied in an export trial from Italy to The Netherlands, simulating on a small scale the fruit supply chain from the packing-house to the consumer (Eccher Zerbini et al., 2009). In this experiment the application of a TRS prototype in grading nectarines at harvest according to their μ_a value in classes of potential handling and/or softening behaviour under commercial transport conditions was studied.

The aim of the current research was to study how this methodology based on a non-destructive measurement technique (TRS) coupled with the BSF theory could be used in practice at the time of harvest, when μ_a can be measured non-destructively on all fruit, while the destructive measurement of firmness can only be done on a sample. For this research, we used the data of the previous experiments (Tijskens et al., 2007a; Eccher Zerbini et al., 2009) to develop various firmness decay models and to classify fruit into different classes based on their μ_a value measured at harvest. Every year, softening behaviour was predicted based on the data available at harvest or within 1–2 d after harvest. The predictive capacity of the different models was assessed by comparing the predicted firmness and class of usability to the actual ones measured during ripening.

2. Materials and methods

2.1. Fruit and experimental plan

In all the seasons (years 2002, 2004, 2005 and 2006) 'Spring Bright' nectarines (*Prunus persica* L. Batsch) were picked in Faenza (Italy) at the second commercial harvest (Table 1). The details of the experimental plan for each season have been described by Eccher Zerbini et al. (2006, 2009) and Tijskens et al. (2007a). In this work, data of season 2003 were not considered as the time employed for fruit handling before the first measurement was too long and almost overlapped that of the first sampling in shelf-life, so impairing the estimation of model parameters using only firmness data at harvest. For 2002 and 2005 seasons, all fruit were considered in this work, whereas for the 2004 season only fruit assigned for shelf-life at 20 °C after 6 d at 0 °C were selected. Nectarines kept at 0 °C for longer times were excluded, as it has been previously found that softening kinetics decrease after cold storage periods longer than 10 d (Rizzolo et al., 2009).

Table 1
Harvest date, time (h) at 20 °C elapsed from harvest for the first firmness measurement (Harvest time), days at 0 °C before shelf-life and times (h) of shelf-life for firmness measurement.

Season	Harvest date	Harvest time (h)	Days at 0 °C	Shelf-life times (h)
2002	18 July 2002	24	3	55, 79
2004	19 July 2004	36	6	42, 61, 87, 108, 136
2005	15 July 2005	12	3	36, 56, 84, 152, 158
2006	17 July 2006	18	8[a]	120[b], 144, 312

[a] 1 d at 0 °C + 7 d at 4–5 °C.
[b] Sensory assessment of softness.

In all the seasons, fruit were stored at 0 °C for 4 h immediately after harvest in order to remove field heat; afterwards, nectarines with defects and bruises were removed, and the resulting fruit were graded according to size (size *A* = 67–72.9 mm diameter, size *B* = 61–66.9 mm diameter, and size *C* = 56–60.9 mm diameter (only available in season 2006)), individually measured by TRS at 670 nm with a prototype built at Politecnico di Milano (Torricelli et al., 2008) and then ranked by decreasing μ_a value at 670 nm within each size. The firmness of fruit in a sample representing the whole range of μ_a, was measured at harvest by a penetrometer (Texture Analyzer TA.Xtplus, Stable Micro Systems, England, 8 mm diameter plunger, crosshead speed 3.33 mm s^{-1}): season 2002, 40 fruit (20 size A, 20 size B); seasons 2004 and 2005, 60 fruit (30 size A, 30 size B); and season 2006, 38 fruit (15 size A, 23 size B).

For seasons 2002, 2004 and 2005 the remaining fruit were held for shelf-life at 20 °C after a 3–6 d period at 0 °C, and firmness was measured during shelf-life according to the experimental plans summarized in Table 1 (more details can be found in Eccher Zerbini et al., 2006 and Tijskens et al., 2007a). In 2006, the remaining nectarines were segregated into the classes of predicted softening potential and usability as described below and transported from Faenza (Italy) to Wageningen (The Netherlands) by a refrigerated truck (4–5 °C, 2 d). Upon arrival, fruit were kept at 4–5 °C for a further 5 d and then at 20 °C for shelf-life. A sub-batch of 5 fruit per size and per μ_a class (70 fruit in total) was selected for softness assessment during shelf-life at 20 °C by sensory evaluation (finger feeling) according to the experimental plan summarized in Table 1. Each fruit was scored on a scale 1–7, from 1 = "very firm", to 7 corresponding to extreme softness (more details on sensory softness evaluation can be found in Eccher Zerbini et al., 2009).

2.2. Fruit categorization criteria

Nectarines from the 2006 season were categorized into six principal μ_a classes of predicted firmness potential for handling and eating according to the μ_a limits reported by Eccher Zerbini et al. (2009), corresponding to different uses and/or softening potentials: 'will never soften' (N), 'dangerously hard' (H), 'sufficiently firm to be transported without damage', hereafter called 'transportable' (T), 'ready to eat' ('ready to eat-firm' (RF) and 'ready to eat-soft' (RS)) and 'already soft at shipment', hereafter called 'overripe' (O). These classes were separated by intervals (Table 2) which were not considered for the export trial, and hence the fruit corresponding to the intervals between classes were discarded. In this study, fruit of seasons 2002, 2004 and 2005 were categorized according to the same criteria as 2006, also using fruit belonging to the intervals, which have been considered as additional classes.

2.3. Data processing

The μ_a values of individual fruit were converted into the TRS biological shift factor ($\Delta t^*_{\mu a}$) according to Eq. (1) (Tijskens et al.,