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Characterisation of Position-Dependant Ripening Dynamics of Nectarines Using Near-Infrared Spectroscopy and ASCA

Jokin Ezenarro[1] | Daniel Schorn-García[1] | Anna Palou[2] | Montserrat Mestres[1] | Laura Aceña[1] | Maribel Abadias[3] | Ingrid Aguiló-Aguayo[3] | Olga Busto[1] | Ricard Boqué[1]

[1]Department of Analytical Chemistry and Organic Chemistry, Universitat Rovira i Virgili, Chemometrics and Sensorics for Analytical Solutions (CHEMOSENS) Group, Tarragona, Spain | [2]Fundació Miquel Agustí, Campus Baix Llobregat, Castelldefels, Spain | [3]IRTA, Postharvest Programme, Parc Agrobiotech Lleida, Edifici Fruitcentre, Lleida, Spain

Correspondence: Ricard Boqué (ricard.boque@urv.cat)

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ABSTRACT

Nectarines, a popular pit fruit closely related to peaches, are renowned for their nutritional value and associated health benefits. However, challenges arise in maintaining optimal organoleptic properties during harvest and handling, eventually leading to production waste and heterogeneous quality in the fruit that arrives to the consumer. This study investigates the impact of nectarine position on trees during the whole ripening process using non-destructive near-infrared (NIR) spectroscopy. Nectarines exposed to more sunlight mature faster and this influences sugar content and acidity, emphasising the significance of considering height, prominence and orientation in ripening dynamics of the fruit. Different data unfolding strategies were compared, using ANOVA-Simultaneous Component Analysis (ASCA) to reveal the significance of in-tree position factors at different ripening stages, and observing high significance at harvest. This underscores the necessity for growers and handlers to consider these factors for reducing waste. NIR spectroscopy, with adequate data analysis, is a valuable tool for the holistic analysis of fruit ripening, providing crucial insights for maintaining optimal fruit organoleptic properties from harvest to consumer.

1 | Introduction

Nectarines are a type of pit fruit that belong to the *Prunus* genus and are closely related to peaches. They are a popular and nutritious fruit, widely grown and consumed worldwide. Nectarines are a rich source of vitamins, minerals, fibre and antioxidants and have been associated with various health benefits, such as improved cardiovascular health and reduced risk of age-related diseases [1]. Nevertheless, consumers not only look for these specific attributes but also demand optimal organoleptic properties that make the fruit appealing for consumption. Achieving this requires careful harvesting and handling of the product. This poses a challenge to farmers who, in their efforts to reduce costs and prevent losses caused by natural elements such as hailstorms or insect infestations, tend to harvest the fruit before reaching the optimal state of ripeness, relying on postharvest ripening during storage. This approach often leads to an imbalanced fruit composition in terms of sugar content, acidity and even flavour quality [2]. This may lead to a lower demand for the product, exacerbating the economic challenges faced by the sector, forcing to leave the fruits unpicked due to the lack of profitability in the harvest, as shown by the downward trend in Spanish production during the last decades [3].

Like in any other fruit, the quality and shelf life of nectarines are greatly influenced by their ripening process, which can be

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affected by various internal and external factors, such as soil, training system (tree structure and organisation through wires and pruning), temperature, humidity and storage conditions. However, one of the keys is to harvest them at the right ripeness point [4]. To ensure that consumers have access to high-quality, fresh nectarines, it is essential to understand and control the ripening process. Adequate control of the ripening process can improve fruit quality, increase shelf life and reduce food waste. In addition, understanding the factors that affect nectarine ripening can help growers optimise growing and harvesting practises to produce high-quality fruits that meet consumer demands [5].

However, although variability in nectarine ripening is a major concern for growers and handlers (as a large variability in terms of size may mean that a significant part of the harvested fruit does not meet market requirements), this variability is not usually assessed as a function of the position of the fruit on the tree. In fact, when physicochemical and organoleptic analyses are performed to assess nectarine ripeness in terms of sugar concentration, acidity or the ratio between the two, the within-tree variability can easily exceed 10% of these values [6]. This makes it difficult to obtain a uniform quality product that meets consumer requirements, even more considering that these analyses are only performed on a limited number of fruits due to the destructive nature of traditional analytical methods [7].

In the present work, the variability in nectarine ripening is studied using near-infrared (NIR) spectroscopy, which is a fast, green and nondestructive analysis technique. As most organic molecules absorb light in the NIR region, the use of this technique offers a holistic analysis of biologic samples (such as nectarines in this case), revealing every noticeable change in the composition of the fruits that will affect the NIR spectrum [8]. Because NIR spectroscopy is a multivariate data source, chemometric tools are needed to obtain as much information as possible from the data. ANOVA-Simultaneous Component Analysis (ASCA) was used to evaluate the significance of the experimental factors considered and quantify their effect on the overall ripening process of nectarines and on each of the ripening stages. ASCA has been widely used to determine and quantify the sources of variability in NIR spectroscopy, for the analytical technique itself [9], or even to assess agronomical factors that affect fruit ripening, as in this case [10].

The combination of these techniques (NIR and ASCA) and different data unfolding strategies has led to a comprehensive study of the changes that occur in nectarines on the tree during the overall ripening process and at each stage of ripening, in an easy, rapid and cost-effective way. In addition, quantifying the impact of the different positional factors over time could allow a selective harvest, following a strategy of precision agriculture and, ultimately, offering a product of homogeneous quality.

2 | Material and Methods

2.1 | Samples

Nectarines (*Prunus persica* var. *nucipersica*) of the '*Luciana*' variety were selected as they are widely available commercially, and they are representative of the production in the area [3]. The nectarines were collected from an orchard located in Artesa de Lleida (41°32′20.2″N 0°42′43.7″ E; Catalonia, Spain), with an altitude of 205.15 m, 60 km away from the Mediterranean Sea. The climate is characterised by high solar irradiation throughout the year, with hot, dry summers and severe, wet winters. Twelve trees, randomly located in the field, were specifically reserved for this study, meaning that nectarines were not collected by the owners. Instead, only the necessary fruits were sampled at each ripening stage. This approach ensured that the number of fruits remained nearly constant, safeguarding the trees' vegetative cycle from any alteration due to a decrease in fruit quantity. Nevertheless, the trees studied were subjected to the same management as the rest of the trees in the orchard, such as pruning and thinning.

2.2 | Experimental Design

Exposure to sunlight is one of the most important factors affecting the fruit ripening process and has been widely studied. Nectarines that are exposed to direct sunlight tend to ripen faster and have a higher sugar content than those that are shaded by leaves or other fruits [11]. However, fruit position does not affect their ripening process and quality just based on the received sunlight, but also because they may have different nutrient distribution and other complex biological dynamics that are position-dependant [12]. To study the effect of position, three spatial factors were established as primary in this study for individual nectarines, based on experience and literature (Figure 1a): the height of the nectarine on the tree (medium or high; nectarines in a low position were lost due to a period of severe frost during flowering), orientation in the tree (northwest, less solar radiation, or southeast, more solar radiation), and position on the branch (closer to or farther from the trunk). Four biological replicates were collected, that is, four nectarines, randomly sampled from the studied trees and fulfilling the conditions mentioned above. Since time is the most important factor in the growth and development of nectarines, the same sampling was repeated once a week for 11 weeks since the nectarine pit hardened (3rd week of May 2022). The number of trees reserved exclusively for this study was sufficient so that the sampling did not affect the ripening dynamics of the nectarines, having sampled around 20% of the production of each tree at the end of the experiment.

Additional factors affecting the spectroscopic measurement of nectarines (Figure 1b) were also studied. After collection, two replicates of the measurement were performed on each side of the nectarines (dark side and light side), first on the skin and then, after peeling, on the flesh. Thus, a total of eight spectra were recorded on each nectarine. Each week, 32 nectarines that met the experimental design were collected, peeled and preprocessed for further analysis (which destroyed the samples).

2.3 | NIR Spectroscopy

A benchtop spectrophotometer, the Antaris II FT-NIR Analyser (Thermo Fisher Scientific, Waltham, MA USA), was used. It covers the entire NIR range (from 1000 to 2500) with an average spectral resolution of 1 nm. The spectra were recorded in diffuse

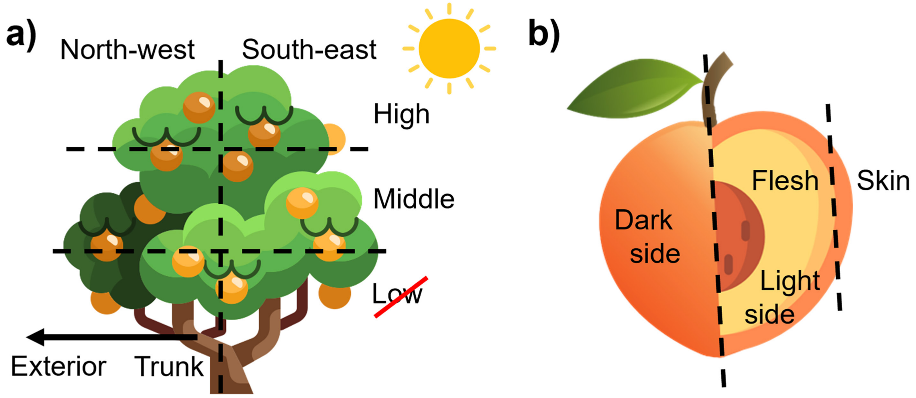

FIGURE 1 | Factors considered in the experimental design. (a) Factors affecting the individual nectarines. (b) Factors affecting the spectra obtained for each nectarine.

reflectance mode, avoiding any sample preparation. The final spectrum was obtained by averaging 25 scans. These conditions were previously selected using commercial nectarines to have a good signal-to-noise ratio in a reasonable measurement time. The blank reference was measured once per sample, as in this instrument, it is measured automatically (with a robotic flap) and minimises spectral shift over the analytical session. Spectra were preprocessed using standard normal variate (SNV), as it minimises scattering effects present in the data, which may be caused by changing the light path or composition [13, 14]. Spectra were finally mean centred (MC).

2.4 | Reference Analyses

In order to control nectarine ripening, classical measurements were carried out. Fruits were weighed one at a time, and, after the spectral measurements, firmness was measured on two sides of each fruit (the dark side and the light side, opposite the first) using a penetrometer (Fruit Pressure Tester, mod. FT-327, Italy) equipped with an 8 mm probe. The results were expressed in kilograms. After squeezing the fruits, in the juice, pH was measured with a pH metre (7+series, XS Instruments, Italy), total acidity was determined by a NaOH (0.1 M) titration until pH 8.2 was reached, and results were expressed as malic acid equivalent grammes per litre of juice. The concentration of Total Soluble Solids (TSS) in juice was determined using a digital refractometer (HI 96801, Hanna Instruments, United States) and expressed as °Brix. Due to the small volume of juice obtained in the first stages of nectarine ripening, pH was determined from the 3rd week on (after pit hardening) and acidity from the 7th week on. Firmness values were outside the range of the equipment (> 13 kg) until the 5th week.

2.5 | ASCA

ASCA is a statistical technique used to analyse complex datasets in which multiple factors may influence the observed data. This technique is particularly useful in experimental designs where multiple factors operate simultaneously, and the goal is to identify the relative contribution of each factor to the variation observed in the data.

ASCA combines analysis of variance (ANOVA) and SCA to identify significant sources of variation in the data. The method involves performing an ANOVA on every variable in the dataset, using the experimental factors as predictors. The resulting residuals are then analysed using SCA to identify the underlying patterns of variation in the data. Therefore, ASCA decomposes the original data matrix (**X**), which usually is MC, based on the DoE matrix (Figure S1) as described in Equation (1):

$$\begin{aligned} X = {} & X_{\text{Week}} + X_{\text{Orientation}} + X_{\text{Height}} + X_{\text{Prominence}} + X_{\text{Face}} \\ & + X_{\text{Week}\times\text{Orientation}} + \ldots \mathbf{X}_{\mathbf{Week\times Height}} + \mathbf{X}_{\mathbf{Week\times Prominence}} \\ & + \mathbf{X}_{\mathbf{Week\times Face}} + \mathbf{X}_{\mathbf{Orientation\times Height}} + \mathbf{X}_{\mathbf{Orientation\times Prominence}} \\ & + \ldots \mathbf{X}_{\mathbf{Orientation\times Face}} + \mathbf{X}_{\mathbf{Height\times Prominence}} + \mathbf{X}_{\mathbf{Height\times Face}} \\ & + \mathbf{X}_{\mathbf{Prominence\times Face}} + \mathbf{E} \end{aligned} \tag{1}$$

where $\mathbf{X}$ is the original data matrix, $\mathbf{X}_{\mathbf{Factor}}$ is the matrix representing the effect of a Factor in the original data, $\mathbf{X}_{\mathbf{Factor\times Factor'}}$ is the matrix representing the effect of the interaction of Factor and Factor' in the original data, and **E** is the residual matrix [15].

ASCA offers a number of advantages over traditional methods for analysing complex datasets. First, it allows to identify significant sources of variation in the data independently, even in cases where the effects of individual factors are not strong. Second, it can identify interactions between factors, which may not be apparent with other methods. Finally, it allows visualising the results of the analysis in a way that is easy to interpret.

3 | Results and Discussion

In order to determine whether the fruit collection process is optimal or if it can be improved, it is important to determine which factors significantly affect the ripening process and evaluate their impact. This is essential, since what consumer's value in nectarines is a consistent size and a consistently high sugar concentration [16]. Irregularities in these characteristics can arise from different variability sources. On the one hand, the climate or type of soil explains the variations between fields, and on the other, the irrigation or training systems (agricultural techniques used in the cultivation of trees to influence their growth and development) affect the distribution of solar radiation and explain intrafield variations [17]. In the present article, in-tree variability sources are studied, not only in the global ripening process but in every stage of the process, as a factor that is not significant at the beginning could determine the ripening of the fruit in the final stage of the process.

As in all ASCA models performed, the replication factor had a significantly null effect, and the models were recalculated by averaging the replicates, so they are not shown and will not be considered further in this study.

3.1 | Evolution of Physicochemical Parameters

The samples collected for this work, apart from being measured by NIR spectroscopy, were also studied using the classical approach for nectarine ripeness assessment. The evolution of the physicochemical quality parameters over the ripening process is shown in Figure 2.

First, it is observed that the weight of nectarines did not increase until the 6th week, after which a noticeable increase in size was observed (Figure 2a). The observed growth in weight over time followed a sigmoidal curve, as reported by many authors [18]. Understanding the weight fluctuations of nectarines and peaches is crucial, given their correlation to TSS, as sugars constitute up to 60% of the dry matter in these fruits [19]. Both evolution curves (weight and TSS) show analogous patterns, characterised by a consistent increase in value, as well as a simultaneous increase in variability in the later growth stages. This variability may be due to the experimental design carried out, since it maximised the variability in light exposure of samples, and there is a link between the photosynthetic activity of the plant and the accumulation of sugars [20]. In addition, it is worth pointing out that TSS has been linked with the 'degree of liking' of fruits, with TSSs over 10 ~ 11 °Brix providing a degree of liking up to 70% of consumers, so it is important for the fruit to reach that level of ripening before being collected [16].

On the other hand, the pH of nectarines (Figure 2c) also reveals an upward sigmoidal curve, introducing an additional layer of variability from the 7th week onward. It is noteworthy, however, that due to their small size before the 7th week, total acidity measurements were deferred until that point, showing only a marginal increase in later ripening stages (Figure 2e). Finally, the firmness of nectarines illustrates a perceptible downward trend, reaching a point at week 11 where quality standards for consumer acceptance were not met.

3.2 | Factor Assessment in the Nectarine Ripening Process

In order to assess the factors that most affect the ripening process of nectarines, that is, to quantify and study which of the factors considered in the experimental design are more important to properly describe the ripening of this fruit, ASCA was applied in the sample-wise unfolded matrix. The original tensor was (32 samples × 2 sides) × 1557 spectral variables × 11 weeks (this is, 64 × 1557 × 11), which was unfolded to a 704 × 1557 matrix. This matrix contained all measured spectra for the samples, one in each row, with the different sampling days below each other. The corresponding DoE matrix (see Figure S1) contained a column for 'Week' (from 1 to 11), 'Orientation' (SE or NW), 'Height' (middle-height or top of the tree), 'Prominence' (near the trunk or exterior) and 'Face' (dark or light).

The first thing that stands out from the ASCA results (from both models, using raw and scatter-corrected data) is that the 'Week' effect, that is, the ripening process over time, explains a very high part of the variance in the spectra, as expected [10]. Even if

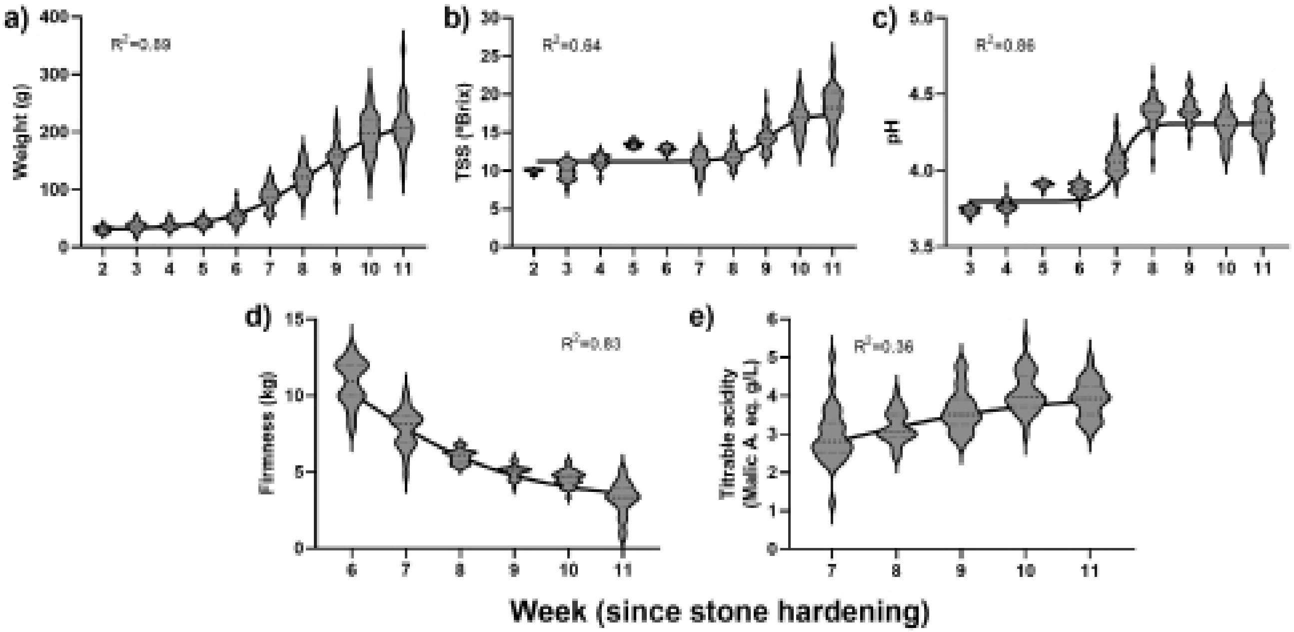

FIGURE 2 | Evolution of the physicochemical parameters of the nectarines over the weeks. Dotted lines represent the first quartile, the median and the third quartile, from bottom to top. The determination coefficient in each plot corresponds to the sigmoid curve fitted to each of the parameters. (a) Weight. (b) TSS. (c) pH. (d) Firmness. (e) Titrable acidity.

other factors have a great significance, their effect on the spectra is minimal compared to the one of the 'Week'. This means that the significance of these factors in the ripening process of nectarines cannot be properly studied from these results. Similar results were obtained using spectra of peeled nectarines (Table S1), which can be explained by the fact that NIR radiation, even if it is partially affected by the skin and its properties, is able to penetrate enough to collect information of the physicochemical properties of the flesh using both measurement approaches: raw and peeled [21]. This was confirmed by comparing the spectra of a raw nectarine, only the peel and only the flesh, and observing that the spectrum of the raw nectarine is a combination of the latter, but mainly affected by the flesh. Score evolution for raw (unpeeled) and peeled nectarines with and without SNV is shown in Figure 3.

The approach using peeled nectarines was not studied further as it was found to provide similar information, but it is a method that requires sample preparation and is destructive. Furthermore, in the latter stages of ripening, the fruit flesh loses its integrity and can generate problems (and errors) when measuring spectra in a diffuse reflectance configuration.

When comparing the ASCA results from raw and scatter-corrected spectra (see Table 1), they indicate that the scatter effects present in the spectra may not be solely attributable to the experimental conditions. Rather, they may be related to the physicochemical properties of the samples and contain information about them. As nectarines ripen, the mesocarp (the internal part of the fruit) softens, causing the fruit to lose its structural integrity and become more aqueous. Consequently, the light path and scattering effects change with the ripening of the fruit, which significantly affect the spectra. This is also observed in the evolution of firmness (Figure 2d), which depicted a great evolution in the latter stages of nectarine ripening. When the scattering effects are minimised using SNV, the submodel of the ASCA explaining the 'Week' factor is no more based on the scattering to explain the ripening process. This causes the dispersion of the samples to grow in the last 3 weeks (see Figure 3b,d), not because of the factors considered in the experimental design but because the heterogeneity from the biological origin grows. This dispersion increase is related to the one that can be seen in weight and TSS (see Figure 2a,b).

However, as in this case, the observed scattering effects do contain information about the physicochemical properties of the sample, and the approach using only MC is more interesting. The varying penetration of NIR radiation into fruit flesh has been extensively studied, since the objective of the spectroscopic models is to obtain information from the fruit flesh or fruit mesocarp. Lammertyn et al. stated that depending on the ripeness of the apples, NIR radiation can penetrate from 2 to 4 mm (at the unripe and ripe stages, respectively) [14]. In fact, it has been described that thin-peel fruits are easily penetrated by NIR light, but it should be noted that the contribution of the skin contributes to the collected spectra [21]. Thus, the 'Face' factor presents a weak but significant effect on the spectra that could be related to the heterogeneity of the peel (as can be seen by the colour); however, internectarine variability shows to be more important than intranectarine variability.

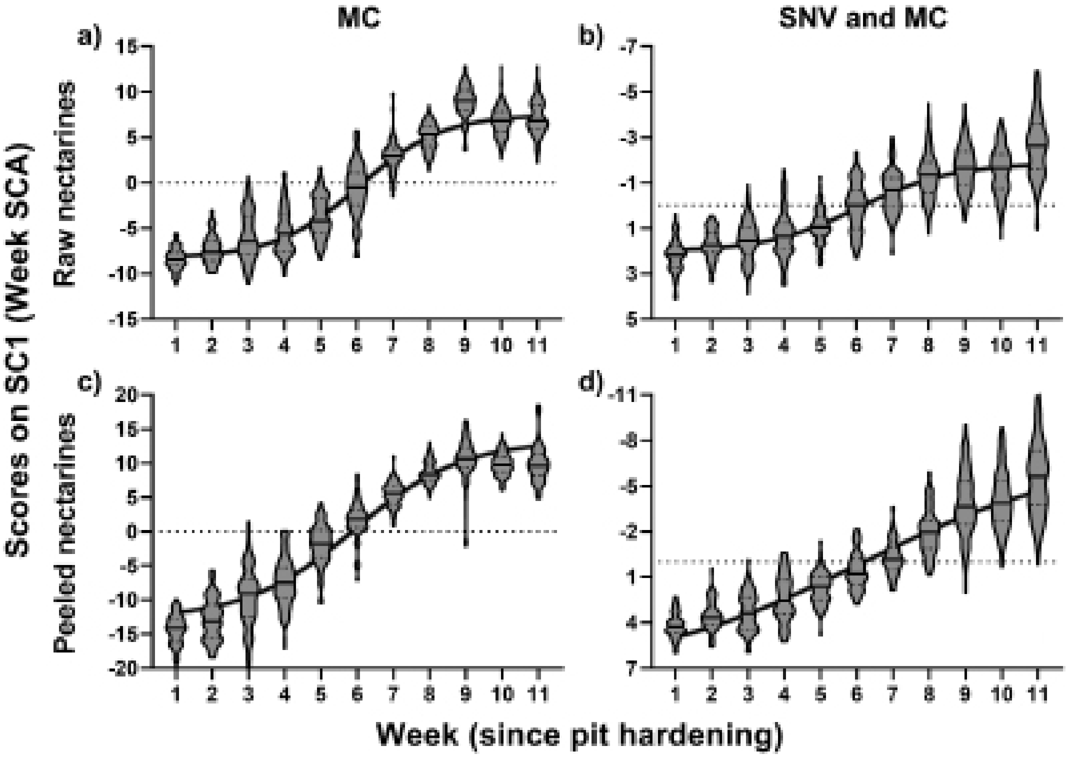

FIGURE 3 | Scores of the first component of the SCA of the week factor in each sampling day, with a sigmoid curve fitted. Continuous horizontal lines within a day represent the median, and discontinuous horizontal lines represent quartiles. Spectra from different measurement approaches were used: raw nectarines (a and b) and peeled nectarines (c and d). In addition, different preprocessing was applied: mean centring (a and c) and SNV and MC (b and d).

TABLE 1 | Results of the ASCA applied to the sample-wise unfolded spectral matrix (MC only and using SNV and MC) considering the main factors from the DoE and their two-way interactions.

	MC		SNV and MC	
Factor	**Effect (%)**	***p* value**	**Effect (%)**	***p* value**
Week	82.56	0.001*	64.13	0.001*
Orientation	0.01	0.303	0.08	0.038*
Height	0.10	0.002*	0.45	0.001*
Prominence	0.18	0.001*	0.47	0.001*
Side	0.04	0.048*	0.74	0.001*
Week × orientation	0.39	0.001*	0.56	0.004*
Week × height	0.26	0.003*	0.96	0.001*
Week × prominence	0.27	0.011*	0.75	0.001*
Week × side	0.20	0.067	0.53	0.007*
Orientation × height	0.00	0.629	0.05	0.126
Orientation × prominence	0.02	0.268	0.01	0.714
Orientation × side	0.01	0.312	0.01	0.786
Height × prominence	0.00	0.792	0.02	0.302
Height × side	0.00	0.836	0.01	0.616
Prominence × side	0.00	0.607	0.01	0.642
Residuals	15.95		31.21	

*Statistically significant effects (*p* value < 0.05).

From Table 1, it can also be deduced that although the positional factors have a great significance, their effect on the spectra is minimal compared to that of the 'Week'. Although it can be stated that the observed trends are not due to random variations, the implication of these factors in the ripening process cannot be adequately studied from these results. To assess this, the variance corresponding to the small factors in the spectral data set must be enhanced, since these factors are masked by the 'Week' factor, which mainly governs the ripening process [22]. Furthermore, considering that most of the interactions between the positional factors and the 'Week' factor have a significant effect, it can be said that each of the positional factors has a different effect on the ripening process depending on the maturity stage. To study the individual effects of the positional factors in each week, the variance caused by the 'Week' effect must be removed from the spectral data set.

3.3 | Assessment of Position Factors Applying a Week-Wise Unfolding

One way to remove the effect of the 'Week' factor in the data set is to do a week-wise unfolding of the matrix, that is, join the spectra corresponding to samples with the same DoE but from different weeks, one after the other. Therefore, the original (64 × 1557 × 11) tensor was unfolded as a (64 × 17,127) matrix (Figure S2).

Despite the spectra assigned to the same row are not from the same individual fruit (due to the use of destructive analyses, as mentioned above), the replication factor was determined not to be significant, so that the joint spectra can be assumed to be equivalent to the spectra that would be obtained from the same sample.

As the results in Table 2 show, now, the main part of the variance present in the data set is related to the positional effects and can be adequately explained. From this ASCA model, it can also be deduced that the most important positional factors are 'Height' and 'Prominence', followed by 'Orientation' and their binary interactions. This indeed confirms that these are factors that should be considered in order to study the ripening process of the nectarines and could be used as criteria for differentiated fruit harvesting, which is a key step in precision agriculture. In addition, the accumulation of different metabolites in peaches and nectarines has been linked to the position of the fruit in the tree, specifically related to the amount of sunlight received by the nearby leaves [20]. The amount of local sunlight received by nectarines at the considered tree positions is variable, as shown by the ASCA results, but also, specific positions (i.e., interactions between positional factors) receive different amounts of sunlight, which is reflected in the spectral profiles.

Since the spectra of different sampling times have been included as additional variables, the loadings of the SCA models should be examined. All these SCA models only have one component, due to the positional factors having a binary experimental design, so the loadings of the first components have been studied (Figure S3). For the sake of interpretability, only the loadings of the significant factors are shown in Figure 4 and, in addition, the loadings of the spectral variables corresponding to the same week have been averaged, as they have shown to have the same magnitude. This means that, from Figure S3, loading values from the same week have been averaged for each factor to build Figure 4, also showing their standard deviation. From Figure 4a, it can be concluded that whilst 'Height' and 'Prominence' are significant in the whole ripening process, their effect on the spectra, and consequently on the fruit, is greater in the middle of the process. This aligns with the fastest ripening period characterised by swift physicochemical changes, which still occur noticeably during the week of collection (9 weeks after pit hardening). It should be noted that a desynchronization of this process between different parts of the canopy has been reported, as the maturity curve that follows the different parts is the same, but with a gradual phase difference from top to bottom. However, as shown by Forlani et al., maturity gradients tend to be less obvious in the latter stages [23]. From Figure 4b, it can be inferred that the interaction between 'Height' and 'Prominence' as well as the interaction of 'Prominence' with 'Orientation' follow a similar trend to the main effects discussed above. More importantly, the interaction between 'Orientation' and 'Height' shows a larger and persistent effect towards the end of the ripening process (from week 9 onward). This suggests that at the time collection, there may still be differences in fruit caused by these positional effects.

Although this approach allows for the calculation of the individual effects of the positional factors in each stage of the ripening process, only the factors that remain significant throughout the whole process can be studied and interpreted. However, there may be other factors that only have a significant effect on part of the ripening process or do not have a particularly large effect on the process but are more important at one stage than at another. These effects cannot be studied using the week-wise spectra unfolding approach, and more importantly, they cannot be properly quantified. Another approach needs to be used to quantify and therefore deepen the study of individual effects each week.

TABLE 2 | Results of the ASCA applied to the week-wise unfolded spectral matrix (mean centred) considering all the main factors from the DoE except 'Week' and their two-way interactions.

	MC	
Factor	**Effect (%)**	***p* value**
Orientation	8.63	0.080
Height	13.01	0.008*
Prominence	19.22	0.001*
Side	5.24	0.381
Orientation × height	7.69	0.003*
Orientation × prominence	15.20	0.003*
Orientation × side	3.21	0.147
Height × prominence	12.55	0.001*
Height × side	1.74	0.739
Prominence × side	2.06	0.553
Residuals	11.44	

*Statistically significant effects (p value < 0.05).

3.4 | Assessment of Positional Factors Applying a Week-Wise Stratification

The strategy that enables the study of individual effects is stratification, where an ASCA model is calculated for the spectra of each sampling point to examine the evolution of the effects of each of the aforementioned factors over the weeks. Therefore, the original (64 × 1557 × 11) tensor was divided into 11 matrices of dimensions (64 × 1557). The effects of the considered factors have been plotted against the sampling week in Figure 5a, and the effects of the combinations of these factors in Figure 5b. This, analogous to Figure 4, provides information on the significance of the factors at each point. But instead of having information only about the factors that are significant throughout the whole ripening process, the factors that are significant at specific stages can also be studied. This means that some results are not significant (Table S2), and just the significant ones are discussed below. First, the height factor (and its combination with the prominence factor) plays a major role when the ripening rate starts to rise. This means that as nectarines start to change, those located at the top of the tree (and closest to the rip of the branches) ripen faster than those in the middle (and closer to the log), due to different sunlight exposure. Then, when the ripening rate reaches its maximum, the effect of height diminishes,

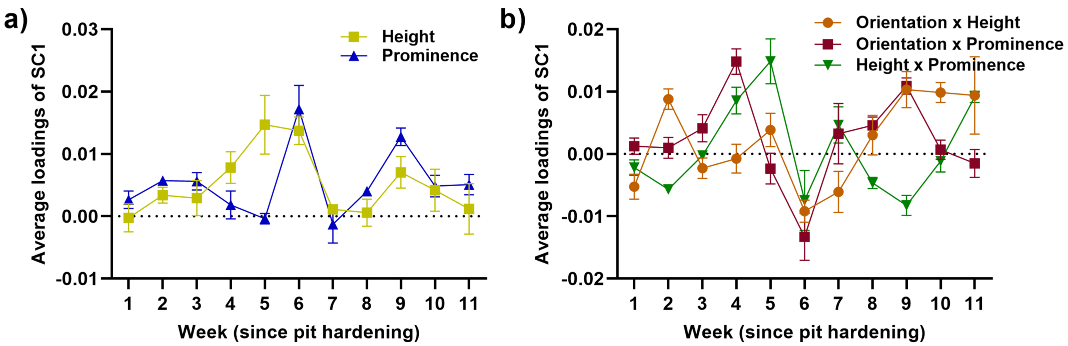

FIGURE 4 | Loadings of the SC1 of the SCA submodels for the different factors (each data point represents the average value of the spectral variables of each week), where only significant factors (p value < 0.05) are shown. (a) Main factors. (b) Two-way interactions between main factors.

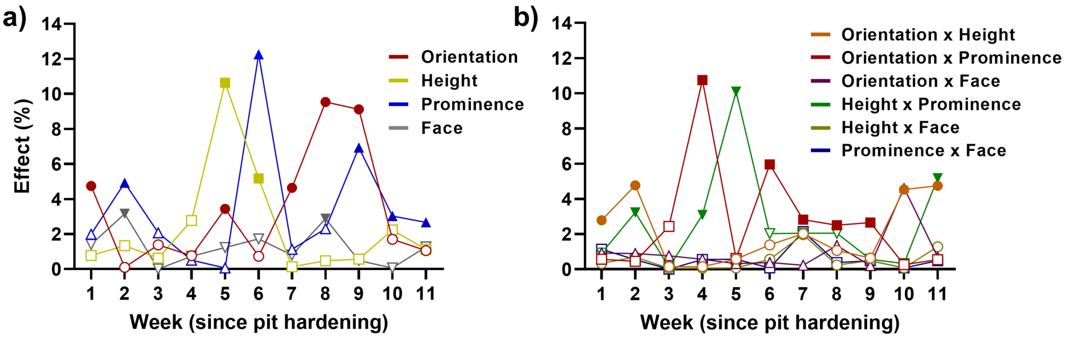

FIGURE 5 | Evolution of factors affecting the spectra of raw nectarines during the different sampling days, where significant factors (p value < 0.05) are represented as filled points. (a) Main factors. (b) Two-way interactions between main factors.

resulting in less difference between top and middle nectarines. Meanwhile, the prominence effect on the branch rises again because the fruits are affected by less shadows and receive more sunlight. At last, there is the effect of the orientation and its combination with the effect of prominence. The prominence effect rises when the ripening process begins and then gradually decays, whilst the orientation effect increases towards the end of the ripening process. This means that the effect of orientation is noticeable throughout the entire ripening process and is also related to the prominence at the beginning. Later, as the prominence effect disappears, the pure orientation factor gains importance until the last 2 weeks. Consequently, nectarines on the southeast side of the tree ripen faster than those on the northwest side due to their greater exposure to sunlight. Same can be concluded from the spectra of peeled nectarines (Figure S4).

It can be said that the initial and final stages of the ripening process do not show important differences due to the factors related to the position in the tree and, therefore, to the sunlight exposure. However, these factors play a major role during ripening, so they will determine which nectarines will ripen faster or slower. On the other hand, during the final stage of the ripening process (day of collection, week 9 after pit hardening, and thereafter), the 'Orientation' and 'Prominence' effects, as well as some interaction between effects, become significantly high. Thus, on the collection day, nectarines on the sunniest side (southeast side) show significantly higher maturity compared to those on the less sunny side (northwest side), suggesting the possibility of adjustments in the collection process based on this disparity. In fact, from these results, it becomes evident that fruit quality can be easily improved, which would benefit the farmer. Specifically, carrying out two harvests where the most mature side of the tree is harvested before the other one (in weeks 9 and 10, respectively) would allow a more uniform high-quality product to be obtained. Furthermore, this approach offers more advantages from the management point of view, requiring fewer workers (over a longer period) and using less storage space at the same time.

Conclusions

Using NIR spectroscopy and ASCA, this work has shown that nectarines exposed to direct sunlight ripen faster than those shaded by leaves or other fruits, as expected. In other words, nectarines located at the top of the tree, on the sunny side and with a higher prominence tended to ripen faster than those in shadier positions.

The results suggest that the position of nectarines on the tree has a significant impact on their ripening process and on their quality, especially significant at the time of harvest, so growers and postharvest handlers should take this into account when handling and storing nectarines. By understanding and quantifying the factors that affect nectarine ripening, production waste can be minimised, and the quality and shelf life of this popular fruit can be improved, thereby ensuring that consumers have access to fresh, high-quality nectarines.

The ripening process of nectarines is a complex and multifactorial phenomenon that is influenced by various internal (biological and physiological) and external factors. Because of this, more research is needed to fully understand the mechanisms behind the impact of nectarine position on the tree on their ripening process and quality. However, NIR spectroscopy and ASCA have proven to be a powerful combination to study this process and its sources of variability. In addition, using different data unfolding strategies has shown that looking at the problem from different perspectives allows more conclusions to be drawn from the same data. This valuable approach could be used for further studies considering the influence of other factors, such as variety, climate or geographical position and storage and transport conditions, on the ripening process of nectarines.

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Conflicts of Interest

The authors declare no conflicts of interests.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.