REVISTA BRASILEIRA DE
FRUTICULTURA
Published by the Brazilian Society of Fruit Crops
ISSN 0100-2945

Harvest And Postharvest - Original Article - Edited by: Ricardo Antonio Ayub

VIS-NIR portable espectrometer for non-destructive assessment of maturity and quality of 'Gala' apples

Jádina Cristina Vaz Moraes Bellotto[1], William Coser[1], Cassandro Vidal Talamini do Amarante[1], Cristiano André Steffens[1], Luiz Carlos Argenta[2], Sérgio Tonetto de Freitas[3].

[1] Centro de Ciências Agrárias e Veterinárias, Universidade do Estado de Santa Catarina. Lages-SC, Brazil.
[2] Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina Estação Experimental de Caçador, Caçador-SC.
[3] Embrapa trópico semi árido de Petrolina, Petrolina-PE, Brasil.
*Corresponding author: *jadnamoraes@hotmail.com*

Abstract: Visible and near infrared (VIS-NIR) spectroscopy is a non-destructive, fast, practical and reliable technique to determine maturity and quality attributes in apple fruit. However, the effects of cultivar and growing conditions on the predictive performance of the equipment must be determined before its commercial application in the apple industry. This study was carried out to evaluate the efficiency of a VIS-NIR portable spectrometer for fast and non-destructive determination of quality attributes in apples of the 'Gala' group ('Maxi Gala', 'Royal Gala', 'Imperial Gala' and 'Galaxy') harvested in three commercial orchards (corresponding to the production sites: Vacaria, Fraiburgo and São Joaquim) in Southern Brazil. At the commercial harvest and after three months of cold storage (1.5 ± 0.3 ºC and relative humidity of 92 ± 2%), fruit were assessed in terms of spectral data in the wavelength range between 310 and 1100 nm with a VIS-NIR portable spectrometer. After collecting the spectral data, fruit were submitted to physicochemical analysis of dry matter (DM), soluble solids content (SSC), flesh firmness and texture. The calibration models were developed using three sets of spectral and physicochemical data: (1) without separating by cultivar and orchard; (2): separating by cultivar, regardless of orchard; (3): separating by cultivar and by orchard. The calibration models were obtained by the partial least squares (PLS) regression technique. The accuracy of the calibration models for each dataset was evaluated in the validation step considering the values of the relative root mean square error of cross-validation (RMSECVr ≤ 10%). Models developed for each cultivar in each orchard (location) were more accurate and efficient to assess DM, SSC and flesh firmness, compared to the models developed for each cultivar, regardless of orchard, or without separating by cultivar and by orchard. Therefore, VIS-NIR spectrometer is a promising tool for the rapid and non-destructive analysis of quality attributes in 'Gala' apples. However, the equipment must be calibrated for each cultivar ('Maxi Gala', 'Royal Gala', 'Imperial Gala'

Rev. Bras. Frutic., v.45, e-660 DOI: *https://dx.doi.org/10.1590/0100-29452023660*
Received 16 Jun, 2022 ● Accepted 25 Jan, 2023 ● Published May/Jun, 2023. Jaboticabal - SP - Brazil.

All the contents of this journal, except where otherwise noted, is licensed under a *Creative Commons Attribution 4.0 International (CC BY 4.0).*

and 'Galaxy') and growing condition (orchard) in order to obtain more precise analyses of DM, SSC and flesh firmness in the fruit.

Index terms: Apple quality; maturity; multivariate calibration; non-destructive analysis; ripening; spectroscopy.

Espectrômetro VIS-NIR portátil para análise não destrutiva da maturação e qualidade de maçãs 'Gala'

Resumo: A espectroscopia, na região do visível e do infravermelho próximo (VIS-NIR) é uma técnica não destrutiva, rápida, prática e precisa para determinar atributos de maturação e qualidade de maçãs. Contudo, o estudo sobre os efeitos de cultivares e do ambiente de cultivo no desempenho preditivo do equipamento é fundamental para a introdução desta tecnologia na cadeia produtiva de maçãs. O objetivo deste trabalho foi avaliar a eficiência de um espectrômetro VIS-NIR portátil para a determinação rápida e não destrutiva de atributos de qualidade de maçãs do grupo 'Gala' ('Maxi Gala', 'Royal Gala', 'Imperial Gala' e 'Galaxy') colhidas em três pomares comerciais (localizados nos municípios de Vacaria, Fraiburgo e São Joaquim) no Sul do Brasil. Na colheita comercial e após três meses de armazenamento refrigerado (1,5 °C ±0,3 ºC e umidade relativa do ar de 92% ± 2%), os frutos foram utilizados para a coleta de dados espectrais em comprimentos de onda entre 310 e 1.100 nm, com o auxílio de um espectrômetro VIS-NIR portátil. Após a coleta dos dados espectrais, os frutos foram submetidos às análises físico-químicas de massa seca (MS), sólidos solúveis (SS), firmeza de polpa e textura. Os modelos de calibração foram desenvolvidos utilizando três conjuntos de dados espectrais e de atributos físico-químicos: (1) sem separação de cultivar e pomar; (2) por cultivar, independentemente do pomar; (3) por cultivar e por pomar. Os modelos de calibração foram obtidos através da técnica de regressão por mínimo quadrado parcial (MQP). A precisão dos modelos de calibração obtidos para cada conjunto de dados foi avaliada na etapa de validação, considerando os valores relativos da raiz do erro quadrático médio de validação cruzada (REQMVCr ≤ 10%). Os modelos desenvolvidos, para cada cultivar e pomar resultaram em maior precisão e eficiência na determinação dos valores de MS, SS e firmeza de polpa, comparados com modelos obtidos com dados por cultivar, independentemente do pomar, e sem separação da cultivar e pomar. O espectrômetro VIS-NIR é uma ferramenta promissora para a análise rápida e não destrutiva de atributos de qualidade em maçãs 'Gala'. No entanto, o espectrômetro deve ser calibrado para cada cultivar ('Maxi Gala', 'Royal Gala', 'Imperial Gala' e 'Galaxy') e para cada pomar de produção, para uma determinação mais precisa de MS, SS e firmeza de polpa dos frutos.

Termos de indexação: Qualidade da maçã; maturação, calibração multivariada; análise não destrutiva; amadurecimento; espectroscopia.

Introduction

Apple is the main fruit consumed in Brazil, especially of the 'Gala' group, which represents about 56% of apple cultivars produced nationally. Apple production occurs mainly in Southern Brazil, which is an important socioeconomic activity in this region (ABPM, 2019).

Due to the large volume of apples annually produced in Brazil, part of the production needs to be stored to prolong fruit supply to the market, stabilizing prices and minimizing losses. This requires the assessment of fruit maturity and quality in the orchard and at harvest to achieve better sensory quality and long-term storage of the fruit. Fruit maturity and quality can be assessed in terms of flesh firmness, dry matter (DM) and soluble solids content (SSC) (GIRARDI et al., 2015; MAGRIN et al., 2017; VIEIRA et al., 2018). However, these analyses require the transportation of fruit samples from the orchard to the laboratory. These conventional methods do not allow real-time analysis of fruit quality and decision-making at harvest, which is critical to the success of the apple production chain (PAZ et al., 2009). In addition, samples are usually constituted of small number of fruits (10 to 20 fruits) due to the time consuming of such analysis. In recent years, non-destructive methods have been developed to assess fruit quality attributes (DENNY; BUTTRISS, 2005; PAZ et al., 2009; JHA;RUCHI, 2010; HENDGES et al., 2011).

The spectroscopy in the visible and near infrared (VIS-NIR) regions is an alternative for the rapid, accurate and non-destructive analysis of quality attributes in apple fruit, such as DM, SSC, flesh firmness, titratable acidity (TA), skin color and starch index (GIOVANELLI et al., 2014; BUCCHERI et al., 2019; TEH et al., 2020). The VIS-NIR spectrometer is user friendly, reliable and fast to predict simultaneously different quality attributes in the fruit (SAEYS et al., 2019; SANTANA, 2020).

The performance of VIS-NIR spectrometer can be affected by environmental conditions, cultivars and orchard management system, which influence the physicochemical attributes of the fruit (ARGENTA et al., 2022), therefore reducing the accuracy of the equipment calibration models (PEIRS et al., 2003; NICOLAI et al., 2007). VIS-NIR spectroscopy has a great potential to assess fruit quality attributes, but cultivar and cultivation conditions must be considered for the development of prediction models for apples.

This study was carried out to evaluate the efficiency of a VIS-NIR portable spectrometer for fast and non-destructive determination of quality attributes in apples of the 'Gala' group.

Materials and Methods

This study was carried out in 2020/2021 with fruit of 'Gala' group. Fruit of 'Galaxy', 'Imperial Gala', 'Maxi Gala' and 'Royal Gala' were harvested at the commercial maturity in orchards located in Vacaria (RS), Fraiburgo (SC) and São Joaquim (SC), at altitudes of 971 m, 1,048 m, and 1,353 m, respectively. A total of 4,400 apples were assessed. Fruit were segregated into 22 lots (representing 'Gala' cultivars and orchards), each lot with 200 fruits. On each lot, 150 fruit were assessed at harvest, and 50 fruit were assessed after three months of cold storage (1.5 ± 0.3 ºC and relative humidity of 92% ± 2%). Fruit were also analyzed after cold storage to increase the range of each physicochemical attribute to improve the performance of the calibration models. For analysis performed at harvest and after cold storage, fruit were individually identified, numbered and marked with a circle at the equator, in the middle region between the red and the green/yellow parts of the fruit. On the same spot marked with the circle, fruit were submitted to nondestructive spectra acquisition with the VIS-NIR spectrometer, and destructively assessment for dry matter (DM), soluble solids content (SSC), flesh firmness and texture.

VIS-NIR spectral data were collected under laboratory conditions (at 22 ± 2ºC), using a portable VIS-NIR spectrometer (F-750 Produce Quality Meter, Felix Instruments, Camas, WA, USA) with a wavelength range of 310-1100 nm (resolution of 3 nm).

DM was measured in the same tissue used to collect the VIS-NIR spectra. The flesh (without skin) was sampled with a borer (2.0 centimeters diameter) to a depth of 2.5 cm. Sample fresh weight was quickly recorded, which was then dried at 65 °C for 7 d to determine the DM (%) (AOAC, 2016).

SSC (°Brix) was measured with a digital handheld refractometer (PR-201α, Atago, Tokyo, Japan), using 1 mL of juice sampled from the fruit.

Flesh firmness (N) was assessed after removal of the fruit skin, with an electronic penetrometer (Güss Manufacturing Ltd, Cape Town, South Africa) equipped with a 11 mm diameter probe.

Texture (N) was analyzed with a TAXT-Plus® electronic texturometer (Stable Micro Systems Ltd, Vienna Court, UK). The measurements represent the strength required to penetrate (1.0 mm/s) the skin and flesh tissues up to a depth of 30 mm, using a 2 mm diameter probe (model P/2).

Spectral data were processed with the software Unscrambler X (version 10.4, 64-bits, CAMO, Oslo, Norway). Two pre-processing methods were tested for each predictive model, Savitzky-Golay derivative (1st and 2nd order derivatives) filter and standard normal variation (SNV). After pre-processing, spectral data and physicochemical attributes were used for the development of multivariate calibration models. The calibration models were obtained by the partial least square (PLS) regression, a method that does not require any exploratory analysis, nor the prediction of interfering samples, considering that they are present to build the model (BRERETON, 1990). Outliers were identified by analyzing the calibration residue values, with residues having a high numerical value being excluded from the modeling process. The software automatically set limiting values for exclusion of anomalous samples. The calibration models were developed using three sets of spectral and physicochemical data: (1) without separating by cultivar and orchard; (2): separating by cultivar, regardless of orchard; (3): separating by cultivar and by orchard. The accuracy of the multivariate calibration models for each dataset was evaluated in the validation step considering the values of root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr). The model is considered acceptable for practical use when RMSECVr ≤ 10% (MARQUES et al., 2016; KAUR et al., 2017; MARQUES; FREITAS, 2020).

Results and Discussion

The samples had a high variability (range of values) in terms DM, SSC, flesh firmness and texture of the fruit, possibly reflecting differences in terms of maturity/ripening and differences among clones of 'Gala' and orchards (Table 1). SSC varied between 7.6 and 16.6 ° Brix, with mean value of 12.3 °Brix. DM and texture also exhibit a high variability, with values between 8.7-22.1% and 6.0-19.3 N, respectively. Flesh firmness varied between 26.8 and 99.8 N, with a mean value of 69.4 N. This variability for the attributes is desirable, improving the robustness and predictive performance of the models to analyze fruit at different maturity/ripening stages (SOUSA et al., 2011; MARQUES et al., 2016).

Two methods of pre-processing spectral data were tested for each predictive model, Savitzky-Golay derivative filter and standard normal variation (SNV). The predictive performance resulting from each spectral pre-processing method was evaluated by statistical criteria, choosing the method with lowest values of RMSECV and RMSEC. Pre-processing spectral data by SNV improved the predictive performance of calibration models, providing lower values of RMSECV and RMSEC than the Savitzky-Golay derivative filter (data not shown).

Table 1. Range of values, mean, number of samples (N), standard deviation (SD) and coefficient of variation (CV) for the entire dataset of quality attributes of 'Gala' apples.

Attributes	Range	Mean	N	SD	CV (%)
Soluble solids content (º Brix)	7.6-16.6	12.29	4.387	1.18	9.6
Dry matter (%)	8.7-22.1	14.06	4.374	1.44	10.2
Flesh firmness (N)	26.8-99.8	69.38	4.063	15.08	21.7
Texture (N)	6.04-19.3	12.00	4.084	2.26	18.8

[1]Remaining sample number. [2] Standard Deviation. [3]Coefficient of Variation.

The absorbance spectra recorded and adjusted in a spectral range between 620 and 980 nm (pre-processed by SNV, for calibration and prediction) had maximum peak at the wavelength of 751 nm, characteristic of the water (O-H bound) absorption band (data not shown). This is expected, since apple fruit consists mainly of water, as reported by Magwaza et al. (2012). Starch and sugars also exhibit absorption bands (fourth and third sober tons) at the wavelength of 750 nm, related to the C-H bounds (SUBEDI et al., 2007; MARQUES; FREITAS, 2020). In general, fruit organic compounds (starch, sugars and organic acids) have bands with high absorption close to the band of water in the spectrum (GOLIC et al., 2003; DELWICHE et al., 2008), making difficult to visualize the absorption spectra of these compounds.

The development of calibration models without separating cultivars and orchards (using the entire dataset) was unsatisfactory for texture and flesh firmness, with high values of RMSEC and RMSECV. For texture, RMSEC and RMSECV had a value of 2.17, with a high RMSECVr (18.08%). Flesh firmness showed high values for RMSEC (14.62) and RMSECV (14.68), therefore with a high RMSECVr (21.16%) (Table 2).

The unsatisfactory predictive value of flesh firmness, considering calibration models developed with the entire dataset (without separating cultivars and orchards), is not in accordance with results reported by other authors, showing a good predictive value for this attribute. Giovanelli et al. (2014) reported RMSECVr of 4.1% for flesh firmness prediction in 'Golden Delicious' apples, with NIR spectral data collected in the range between 380-1690 nm. Quing et al. (2007) reported RMSECVr of 8% for flesh firmness prediction in 'Fuji' apples, with NIR spectral data collected in the range between 700-1100 nm. Flesh firmness is an attribute difficult to estimate by nondestructive methods. NIR spectrometers have not been used widely to predict this attribute, as the prediction accuracy is usually unsatisfactory or inconsistent when compared to traditional methods (MCGLONE et al., 2002; PAZ et al., 2008; GIOVANELLI et al., 2014). However, the instrument can be useful to segregate apple fruit with different levels of flesh firmness (low, medium and high) (PAZ et al., 2009).

SSC had the highest predictive capacity, with calibration model developed without separating cultivars and orchards providing low values for RMSEC and RMSECV (0.93 and 0.94, respectively), as well as low RMSECVr (7.65%) (Table 2). This predictive performance for SSC was slightly lower than those reported in apple fruit by Giovanelli et al. (2014) and Nturambirwe et al. (2019), also using NIR spectrometers. Giovanelli et al. (2014) reported RMSECVr of 3.2% in 'Golden Delicious', while Nturambirwe et al. (2019) reported RMSECVr values of 4.19%, 5.05% and 2.94% for 'Golden Delicious', 'Granny Smith' and 'Royal Gala' apples, respectively. The VIS-NIR portable spectrometer was valuable to predict SSC in the present study, corroborating with previous studies using this non-destructive method to evaluate SSC in apples (NICOLAI et al., 2007).

DM had a slightly lower predictive performance (for model developed without sepa-

Table 2. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture, considering the entire dataset, without separating cultivars and orchards.

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	7.6-16.6 (12.3)	4.387	7	62	0.35	0.93	0.94	7.65
DM (%)	8.6-22.1 (14.1)	4.374	7	89	0.33	1.14	1.15	8.17
Flesh firmness (N)	2.8- 99.8 (69.4)	4.063	7	32	0.12	14.62	14.68	21.16
Texture (N)	6.0-19.3 (12.0)	4.084	4	64	0.08	2.17	2.17	18.08

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

rating cultivars and orchards) than SSC, with RMSECVr of 8.17% (Table 2). However, models with better predictive performance for DM have been reported in apples and other fruit species. With NIR spectral data collected in the range between 650-950 nm to determine DM, Kaur et al. (2017) reported RMSECVr values of 4.3% for apple, 3.4% for kiwifruit, and 6.0% for plum, peach and nectarine. Marques and Freitas (2020) reported RMSECVr of 4.3% for DM prediction in umbu (*Spondias tuberosa* Arruda) with NIR spectral data collected in the range between 750-1065 nm.

Figure 1 shows plots of reference values *versus* values predicted by the multivariate calibration models, pre-processed by SNV and using the partial least squares (PLS) regression technique, for attributes of SSC, DM, flesh firmness and texture, considering the entire dataset (without separating cultivars and orchards). The dispersion of the calibration (blue circles) and validation (red circle) sets were not substantially different, and samples are randomly distributed around the bisector line, evidencing the existence of anomalous samples.

The calibration models developed for each cultivar ('Imperial Gala', 'Royal Gala', 'Galaxy' and 'Maxi Gala') with dataset of all production orchards had RMSECVr > 10% for flesh firmness and texture (Tables 3, 4, 5 e 6). The RMSECVr values for flesh firmness of 'Galaxy', 'Maxi Gala', 'Royal Gala' and 'Imperial Gala' were 21.10%, 12.73%, 19.78% and 19.88%, respectively. For texture, the RMSECVr values for 'Galaxy', 'Maxi Gala', 'Royal Gala' and 'Imperial Gala' were 25.43%, 13.26%, 25.89% and 22.44%, respectively.

The calibration models developed for SSC and DM for each clone of 'Gala', considering all production orchards, had RMSECVr < 10% (Tables 3, 4, 5 and 6). For SSC, the RMSECVr values of 'Galaxy', 'Maxi Gala', 'Royal Gala' and 'Imperial Gala' were 7.68%, 6.35%, 6.27% and 6.67%, respectively. For DM, the RMSECVr values for 'Galaxy', 'Maxi Gala', 'Royal Gala' and 'Imperial Gala' were 8.85%, 8.17%, 7.66% and 7.37%, respective-

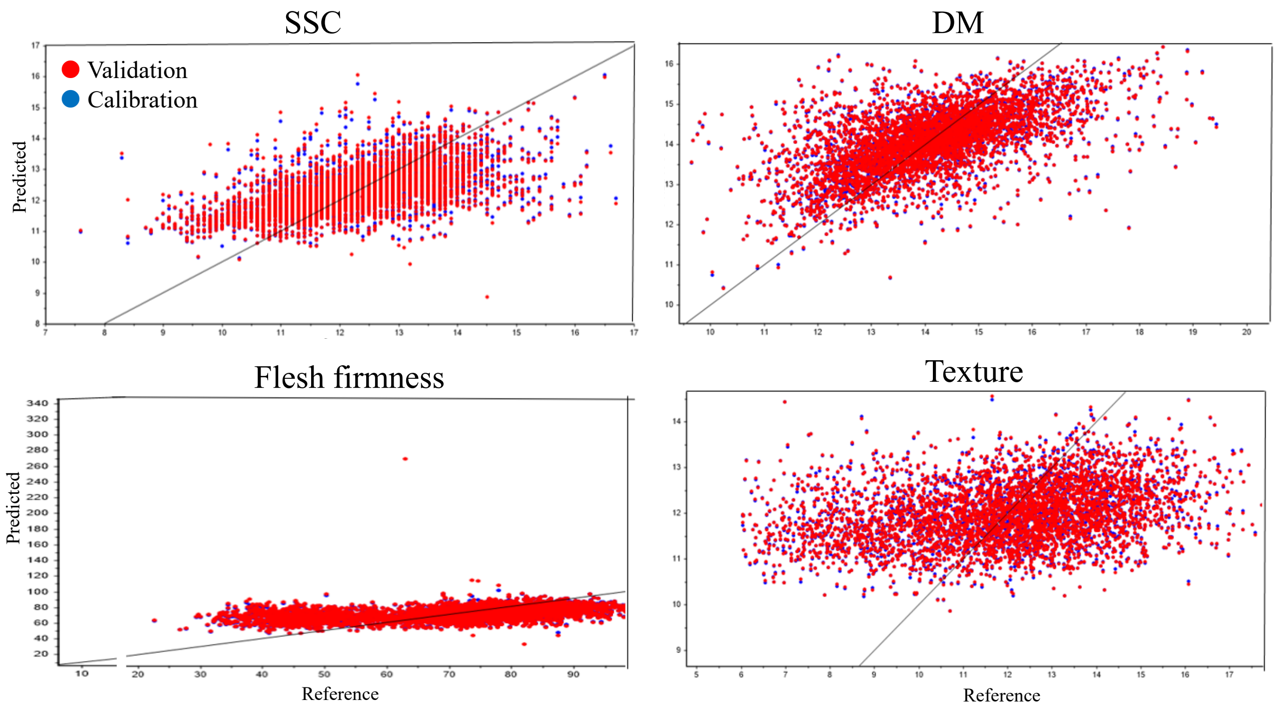

Figure 1. Plots of reference values versus values predicted by the multivariate calibration models using the partial least squares (PLS) regression technique, in the calibration (blue circles) and validation (red circles) steps, in apples of the 'Gala' group. The continuous black line represents the bisector.

Table 3. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Galaxy' apple fruit, considering the data of all orchards (locations).

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	7.6-16.2 (12.1)	1.396	7	46	0.52	0.92	0.93	7.68
DM (%)	8.6-26.1 (13.8)	1.396	7	38	0.32	1.21	1.22	8.85
Flesh firmness (N)	29.4- 99.6 (69.2)	1.369	6	47	0.09	13.45	14.59	21.10
Texture (N)	6.3-19.3 (12.2)	1.400	7	35	0.15	3.05	3.10	25.43

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 4. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Maxi Gala' apple fruit, considering the data of all orchards (locations).

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	9.8-16.1 (12.4)	400	6	20	0.38	0.76	0.79	6.35
DM (%)	11.2-20.9 (15.0)	400	7	16	0.42	1.03	1.08	8.17
Flesh firmness (N)	34.6- 99.9 (75.4)	380	7	13	0.66	9.21	9.60	12.73
Texture (N)	6.6-18.3 (12.9)	400	6	10	0.40	1.67	1.71	13.26

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 5. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Royal Gala' apple fruit, considering the data of all orchards (locations).

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	9.5-16.1 (12.6)	600	7	12	0.34	0.77	0.79	6.27
DM (%)	9.7-22.1 (14.36)	600	7	17	0.47	1.07	1.12	7.66
Flesh firmness (N)	27.7- 98.7 (66.2)	593	7	16	0.33	12.84	13.10	19.78
Texture (N)	6.1-18.0 (11.3)	562	4	10	0.14	2.85	2.92	25.89

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 6. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Imperial Gala' apple fruit, considering the data of all orchards (locations).

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	9.0-16.7 (12.3)	1.990	7	90	0.40	0.81	0.82	6.67
DM (%)	9.0-19.7 (14.0)	1.990	7	57	0.27	1.02	1.03	7.37
Flesh firmness (N)	26.8- 99.8 (69.3)	1.990	7	36	0.17	13.67	13.78	19.88
Texture (N)	6.1-17.5 (11.8)	1.990	4	42	0.09	2.64	2.66	22.44

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

ly. Values of RMSECVr for SSC and DM were uniform among cultivars, showing accuracy provided by the models for this variables prediction in all cultivars of 'Gala'.

Data analysis performed by cultivar and by orchard (location) greatly improved the performance of multivariate calibration models. The calibration models developed for

SSC, DM and flesh firmness had RMSECVr ≤ 10% (Tables 7, 8, 9 and 10). Although the calibration models developed for texture had a lower prediction power than those developed for SSC, DM and flesh firmness, the RMSECVr values were close to 10% (between 10.87% and 12.55%) (Tables 7, 8, 9 and 10).

Table 7. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Maxi Gala' apple fruit harvested in Vacaria-RS.

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	9.8-13.7 (11.9)	200	6	0	0.48	0.49	0.53	4.45
DM (%)	11.2-19.0 (15.1)	200	7	10	0.78	0.58	0.66	4.38
Flesh firmness (N)	64.2- 99.6 (88.7)	191	6	7	0.33	5.57	6.13	6.91
Texture (N)	6.9-18.3 (13.9)	200	3	10	0.06	1.51	1.59	11.45

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 8. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Imperial Gala' apple fruit, harvested in Fraiburgo-SC.

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	10.6-14.9 (12.5)	190	7	7	0.65	0.46	0.51	4.07
DM (%)	11.0-18.7 (14.8)	190	7	7	0.45	0.78	0.88	5.96
Flesh firmness (N)	40.2- 95.5 (76.6)	200	2	0	0.25	6.05	7.06	9.22
Texture (N)	8.2-17.5 (12.8)	200	1	7	0.18	1.41	1.61	12.55

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 9. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Royal Gala' apple fruit, harvested in São Joaquim-SC.

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSECV	RMSECVr (%)[2]
SSC (°Brix)	10.5-15.1 (12.86)	200	7	7	0.49	0.51	0.57	4.43
DM (%)	11.6-17.4 (14.2)	200	7	0	0.66	0.55	0.64	4.52
Flesh firmness (N)	53.5- 82.2 (68.1)	200	2	0	0.21	4.55	5.21	7.65
Texture (N)	8.0-14.1 (11.6)	200	1	7	0.14	1.07	1.34	11.53

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

Table 10. Range of values (and mean), total number of samples (N), number of factors or latent variables (LV), number of outliers, determination coefficient (R-square), root mean square error of calibration (RMSEC), root mean squared error of cross-validation (RMSECV) and relative root mean square error of cross-validation (RMSECVr) for soluble solids content (SSC), dry matter (DM), flesh firmness and texture of 'Galaxy' apple fruit, harvested in Vacaria-RS.

Attribute	Range (Mean value)	N	LV	Outliers[1]	R-Square	RMSEC	RMSEC	RMSECVr (%)[2]
SSC (°Brix)	9.4-14.1 (11.63)	200	5	7	0.51	0.49	0.53	4.56
DM (%)	10.81-19.70 (14.71)	200	4	7	0.37	1.07	1.48	10.06
Flesh firmness (N)	47.62- 96.60 (80.82)	193	7	0	0.24	6.03	6.52	8.07
Texture (N)	9.01-16.72 (12.79)	200	1	4	0.23	1.20	1.39	10.87

[1] Less than 5% of total samples analyzed; [2] RMSECVr (%) = [RMSECV / (attribute mean value)] x 100.

The multivariate calibration models developed by cultivar and by orchard had high determination coefficients (R-square) for DM and SSC (between 0.37 and 0.78), and low RMSECVr values for DM, SSC and flesh firmness (between 4.07% and 10.06%) (Tables 7, 8, 9 and 10). The best result was achieved for SSC prediction (calibration models with R-square > 0.37, RMSEC < 0.51, RMSECV < 0.57, and RMSECVr < 4.56). The models also provided a good prediction of fresh firmness, with RMSECVr values of 6.1% for 'Maxi Gala' in Vacaria (RS), 7.65% for 'Royal Gala' in São Joaquim (SC), 9.22% for 'Imperial Gala' in Fraiburgo (SC), and 8.07% for 'Galaxy' in Vacaria (RS). In addition, good model prediction was achieved for DM analysis (R-square > 0.48, RMSEC < 1.07, RMSECV < 1.48, and RMSECVr < 10.06).

The results show an improvement of prediction models for SSC, DM and flesh firmness when data were analyzed by cultivar and by orchard (location). This reflects the combined effects of cultivar and edaphoclimatic characteristics (orchard production sites) on physicochemical attributes of apple fruit (ARGENTA et al., 2022). The apple producing regions in Southern Brazil have a climatic heterogeneity that influences both the productivity and quality of apples (AMARANTE et al., 2010; FIORAVANÇO et al., 2010), which impacts the robustness of the models to estimate maturity/quality attributes in the fruit. Therefore, in order to ensure analytical accuracy, the VIS-NIR spectrometer should be calibrated for each genotype/cultivar and orchard/location to determine quality attributes in apples (TEH et al., 2020). Besides, the study should be repeated along 3-4 growing seasons to reduce the effect of environmental variability that influences the predictive performance of the VIS-NIR spectrometer, thus generating more reliable and robust models.

Conclusions

The VIS-NIR portable spectrometer had a good performance to evaluate SSC and DM, but not texture, in apples of the 'Gala' group ('Maxi Gala', 'Royal Gala', 'Imperial Gala' and 'Galaxy');

Calibration models developed for each 'Gala' cultivar and growing condition (orchard) provided better predictive performance than models developed for each cultivar in different production sites, or for all cultivars and all production sites;

The portable VIS-NIR spectrometer is a suitable equipment to assess nondestructively quality attributes of 'Gala' apples produced in Southern Brazil.

References

ABPM - Associação Brasileira de Produtores de Maçã. **Anuário brasileiro de maçã**. Santa Cruz do Sul: Editora Gazeta, 2019. 33 p. Disponível em: *https://www.abpm.org.br/anuarios-da-maca*. Acesso em: 15 jun. 2022.

AMARANTE, C.V.T. do; STEFFENS, C.A.; ERNANI, P.R. Identificação pré-colheita do risco de ocorrência de "bitter pit" em maçãs "Gala" por meio de infiltração com magnésio e análise dos teores de cálcio e nitrogênio nos frutos. **Revista Brasileira de Fruticultura**, Jaboticabal, n.1, v.32, p.27-34, 2010.

AOAC - Association of Official Analytical Chemistry. **Official methods of analysis of the Association of Official Analytical Chemistry**. 16th ed. Arlington, 2016. 1141 p.

ARGENTA, L.C.; AMARANTE, C.V.T. do ; FREITAS, S.T. de.; BRANCHER, T.L.; NESI, C.N.; MATTHEIS, J. P.Fruit quality of 'Gala' and 'Fuji' apples cultivated under different environmental conditions. **Scientia Horticulturae**, Nova York, v.303, p.1-4, 2022.

BRERETON, R.G. Chemometrics: applications of mathematics and statistics to laboratory systems. **Journal of Chemometrics**, London, n.4, v.6, p.228, 1990.

BUCCHERI, M. GRASSI, M.; LOVATI, F.; PETRICCIONE, M. REGA, P; SCALZO, R.L.; CATTANEO, T.M.P. Near infrared spectroscopy in the supply chain monitoring of Annurca apple. **Journal of Near Infrared Spectroscopy**, Milano, n.1, v.27, p.86-92, 2019.

DELWICHE, S.R.; MEKWATANAKARN, W.; WANG, C.Y. Soluble solids and simple sugars measurement in intact mango using near infrared spectroscopy. **HortTechnology**, Beltsville, n.3, v.18, p.325-544, 2008.

DENNY, A.; BUTTRISS, J. **Plant foods and health**: focus on plant bioactives. London: EuroFIR and British Nutrition Foundation, 2005. p.64.

FIORAVANÇO, J.C.; GIRARDI, C.L.; CZERMAINSKI, A.B.C.; SILVA, G. A. da; NACHTIGALL, G.R.; OLIVEIRA, P.R.D. de. **Cultura da macieira no Rio Grande do Sul: análise situacional e descrição varietal**. Bento Gonçalves: EMBRAPA Uva e Vinho. 2010. 60 p. (Documento 71).

GIOVANELLI, G.; SINELLI, N.; BEGHI, R.; GUIDETTI, R.; CASIRAGHI, E. NIR spectroscopy for the optimization of postharvest apple management. **Postharvest Biology and Technology,** Amsterdam, v.87, p.13-20, 2014.

GIRARDI, C.L.; PEGORARO, C.; CRIZEL, G.; STORCH, T. ZANUS, M.C. **Conservação da qualidade**: pós-colheita de maçã. Bento Gonçalves: EMBRAPA Uva e Vinho, 2015. 11 p. (Circular Técnico, 114).

GOLIC, M.; WALSH, K.; LAWSON, P. Short-wavelength near-infrared spectra of sucrose, glucose, and fructose with respect to sugar concentration and temperature. **Applied Spectroscopy**, Rockhampton, n.2, v.57, p.139-45, 2003.

HENDGES, M.V.; STEFFENS, C.A.; ANTONIOLLI, L.R.; AMARANTE, C.V.T. do.; BRACKMANN, A. Qualidade de maçãs 'Royal Gala' submetidas ao dano mecânico por impacto e aplicação de 1-metilciclopropeno em dois sistemas comerciais de armazenamento. **Revista Brasileira de Fruticultura**, Jaboticabal, n.1, v.33, p.32-9, 2011.

JHA, S.N.; RUCHI, G. Non-destructive prediction of quality of intact apple using near infrared spectroscopy. **Journal of Food Science and Technology,** Mysore, n.2, v.47, p.207-13, 2010.

KAUR, H.; KÜNNEMEYER, R.; MACGLONE, A. Comparison of hand-held near infrared spectrophotometers for fruit dry matter assessment. **Journal of Near Infrared Spectroscopy**, Hamilton, n.4, v.25, p.267-77, 2017.

MAGRIN, F.P.; ARGENTA, L.C.; AMARANTE, C.V.T. do; MIQUELOTO, A.; HAWERROTH, M.C.; MACEDO, C.K.B. de.; DENARDI, F.; KVITSCHAL, M.V. Índices de maturação para o ponto ideal de colheita de maçãs 'SCS425 Luiza'. **Agropecuária Catarinense**, Florianópolis, n.3, v.30, p.55-60, 2017.

MAGWAZA, L.S.; UMEZURUIKE, L.O.; NIEUWOUDT, H.; CRONJE, P.J. R.; SAEYS, W.; NICOLAÏ, B. NIR spectroscopy applications for internal and external quality analysis of citrus fruit – A review. **Food Bioprocess Technology**, New York, n.2, v.5, p.425-44, 2012.

MARQUES, E.J.N.; FREITAS, S.T. de; PIMENTEL, F.; PASQUINI, C. Rapid and nondestructive determination of quality parameters in the 'Tommy Atkins' mango using a novel handheld near infrared spectrometer. **Food Chemistry**, London, v.197, p.1207-14, 2016.

MARQUES, E.J.N.; FREITAS, S.T. Performance of new low-cost handheld nir spectrometers for nondestructive analysis of umbu (spondiastuberosa arruda) quality. **Food Chemistry**, London, v.323, p. 5-8, 2020.

MCGLONE, V.A.; JORDAN, R. B.; MARTINSEN, P.J. Vis/NIR estimation at harvest of pre- and post-storage quality indices for 'Royal Gala' apple. **Postharvest Biology and Technology**, Amsterdam, n.2, v.25, p.135–44, 2002.

NICOLAI, B.A.; BEULLENS, K.; BOBELYN, E.; PEIRS, A.; SAEYS, W.; THERON, K.I.; LAMMERTYN, J. Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. **Postharvest Biology and Technology**, Amsterdam, n.2, v.46, p.99-118, 2007.

NTURAMBIRWE, J.F.I; NIEUWOUDT, H.H.; PEROLDA, W.J.; OPARA, U.L. Non-destructive measurement of internal quality of apple fruit by a contactless NIR spectrometer with genetic algorithm model optimization. **Scientific African**, Kumasi, v.3, p.3-10, 2019.

PAZ, P.; SÁNCHEZ, M. T.; MARÍN, D. P.; GUERRERO, J. E.; VARO, A. G. Nondestructive Determination of Total Soluble Solid Content and Firmness in Plums Using Near-Infrared Reflectance Spectroscopy. **Journal of Agricultural and Food Chemistry**, Cordoba, v.56, p.2565-70, 2008.

PAZ, P.; SÁNCHEZ, M.T.; MARÍN, D.P.; GUERRERO, J.E.; VARO, A.G. Evaluating NIR instruments for quantitative and qualitative assessment of intact apple quality. **Journal of the Science of Food and Agriculture**. London, n.3, v.89, p.781-90, 2009.

PEIRS, A.; TIRRY, J.; VERLIDEN, B.; DARIUS, P.; NICOLAÏ, B. M. Effect of biological variability on the robustness of NIR models for soluble solids content of apples. **Postharvest Biology and Technology**, Amsterdam n.2, v.28, p.269-80, 2003.

QUING, Z.; JI, B.; ZUDE, M. Wavelength selection for predicting physicochemical properties of apple fruit based on near-infrared spectroscopy. **Journal of Food Quality**, London, n.4, v.30, p.511-26, 2007.

SAEYS, M.; TRONGA, N.N. do.; BEERSA, R.V.; NICOLAÏ, B.M. Multivariate calibration of spectroscopic sensors for postharvest quality evaluation: a review. **Postharvest Biology and Technology**, Amsterdam, n.110981 v.158, p.1-19, 2019.

SANTANA, F.B.; SOUZA, A.M. de; ALMEIDA, M.R.; BREITKREITZ, M.C.; FILGUEIRAS, P.R.; SENA, M.M.; POPPI, R.J. Experimento didático de quimiometria para classificação de óleos vegetais comestíveis por espectroscopia no infravermelho médio combinado com análise discriminante por mínimos quadrados parciais: um tutorial, parte V. **Química Nova**, São Paulo, n.3, v.43, p.371-81, 2020.

SOUSA, L.C.; GOMIDE, J.L.; MILAGRES, F.R.; ALMEIDA, D.P. de. Desenvolvimento de modelos de calibração NIRs para minimização das análises de madeiras de *eucalyptus spp.* **Ciência Florestal,** Santa Maria, n.3, v.21, p.591-9, 2011.

SUBEDI, P.P.; WALSH, K.B.; OWENS, G. Prediction of mango eating quality at harvest using short-wave near infrared spectrometry. **Postharvest Biology and Technology**, Amsterdam, n.3, v.43, p.326-34, 2007.

TEH, L.S.; COGGINS, J.L.; KOSTICK, S.A.; EVANS, K.M. Location, year, and tree age impact NIR-based postharvest prediction of dry matter concentration for 58 apple accessions. **Postharvest Biology and Technology**, Amsterdam, n.111125, v.166, p.1-8, 2020.

VIEIRA, M.J.; ARGENTA, L.C.; MATTHEIS, J.P.; AMARANTE, C.V.T. do; steffens, c. a. Relationship between dry matter content at harvest and maturity index and post-harvest quality of Fuji apples. **Revista Brasileira de Fruticultura**, Jaboticabal, n.2, v.40, p.1-7, 2018.