Agronomy Research **20**(X), xxx–ccc, 2022
https://doi.org/10.15159/AR.22.027

Non-destructive identification of defects and classification of Hass avocado fruits with the use of a hyperspectral image

D.A. Metlenkin[1,*], Y.T. Platov[1], R.A. Platova[1], E.V. Zhirkova[1] and O.T. Teneva[2]

[1]Plekhanov Russian University of Economics, Faculty of Trade Economics and Commodity Science, Department of Commodity Science, Stremyanny lane 36, RU115054 Moscow, Russia
[2]University of Plovdiv 'Paisii Hilendarski', Faculty of chemistry, Department of Chemical Technology, 24 Tsar Assen Str., BL4000 Plovdiv, Bulgaria
[*]Correspondence: Metlenkin.DA@rea.ru

Received: January 15th, 2022; Accepted: April 19th, 2022; Published: May 2nd, 2022

Abstract. Sensory analysis and instrumental analytical methods are used in determining the maturity and quality monitoring of avocado fruits, which are labor-intensive and do not allow the determination of fruit quality in real time. The use of hyperspectral imaging (HSI) methods in the range of 400–1,000 nm and of the multivariate analysis was demonstrated for a non-destructive grading of Hass avocado fruits into quality classes according to the number of hidden defects. Using the sensory analysis, avocado fruits were separated into quality classes according to the number of defects after being stored for 10 days. Development of a classification model included several steps: image recording and analysis using the ANOVA and PCA method, image segmentation (selection of ROI), pre-processing (SNV-correction, centering), selection of a multivariate classification method (PLS-DA, SIMCA) and a spectral range, model verification. The analysis of hyperspectral images of avocado fruits has detected spectral regions with the maximal variance responsible for the change of the content of pigments and moisture within the avocado fruit exocarp. Comparison of PLS-DA and SIMCA models on the basis of best accuracy and test-validation results was carried out. Comparison of models showed SIMCA model as the most efficient model for fruit classification into quality classes depending on the number of hidden defects. The implementation of the developed approach as a digital avocado fruit sorting system at different stages of the product life cycle is proposed.

Key words: HSI, sensory analysis, chlorophyll, multivariate analysis, PCA, PLS-DA, SIMCA.

INTRODUCTION

Fresh avocado fruits from the evergreen tropical plant (*Persea americana Mill.*) are persistently in high demand by consumers due to their high nutritional qualities and the ability to be consumed fresh (Ferreira da Vinha et al., 2013; Hurtado-Fernandez, 2018). Post-harvest losses in the supply chain of fresh avocado fruits are between 25% and 50% of the total yield and affect economic indicators of suppliers and sales organizations

(Bustos & Moors, 2018). In this connection, the control of avocado fruit quality is one of the most important challenges in improving the economic distribution efficiency.

The development and ripening stages of avocado fruits are important in determining the minimum quality requirements that allow continuing the ripening process and achieving the consumer maturity (UNECE, 2019). The quality control of avocado fruits including maturity testing is done both by a sensory analysis (ISO 6658:2005 2017), for example by determining a skin (exocarp) color and by instrumental methods: fruit hardness measurement with the use of a penetrometer (Ochoa-Ascencio et al., 2009), measurement of moisture, MS%, and dry matter, DM%, determining lipid content in pulp (mesocarp) (Donetti & Terry, 2014).

In addition to the labor intensity and the destructive character one of the defects of said instrumental methods is the increased risk of marketing substandard fruits and the increased losses in the distribution chain because of the fruit quality heterogeneity in a large batch. In recent years attempts are made to use a non-destructive technology for fruit quality control, in particular imaging methods such as: spectral analysis methods (Raman imaging, multi- and hyperspectral imaging, fluorescent visualization and laser light backscatter imaging), nuclear magnetic methods (magnetic resonance imaging and soft X-ray imaging) and other methods including thermal, infra-red thermography and microwave imaging (Hussain, 2018; Avotins et al., 2020; Starý et al., 2020).

The HSI method (Lohumi et al., 2015; Abdulridha et al., 2019) is considered as the advanced non-destructive instrumental method of fruit and vegetable control. As opposed to the other spectroscopy methods, the HSI technology permits: first, scanning the whole sample and thereby considering the heterogeneity of samples and segmenting the image into the regions of interest (ROIs); second, hyperspectral images also generate a set of information both in VIS- and in NIR-ranges while presenting both spatial and spectral information of the objects (Elmasry et al., 2012; Manley, 2014). Most HSI-cameras are intended for recording the information in VIS-/NIR-spectral ranges. The HSI and the multivariate analysis allow monitoring and controlling the product quality within the PAT concept (Process Analytical Technology - PAT) (Rodionova & Pomerantsev, 2006). For analyzing hyperspectral images multivariate analysis methods: classification and quantification are used (Granato et al., 2018; Ferraz et al., 2019).

Due to the integration of the principal functions of imaging and spectroscopy the HSI method is used both for monitoring the ripeness (Pinto et al., 2019) and for forecasting the values of physical and chemical properties of avocado fruits (Pu et al., 2015; Vega Díaz et al., 2021). The HSI for avocado quality control was used for assessing the dry matter content as shown in (Vega Díaz et al., 2021). With the use of the HSI in the range of 400–1,000 nm and a support vector machine regression the authors achieved a significant accuracy (R^2 = 0.9) in the prediction of dry matter content of Hass avocado fruits. The classification of avocado fruits according to the ripening stage is possible with the use of the HSI in the range of 300–900 nm and of different ripeness indices (Pinto et al., 2019).

The principal cause of the decline of avocado fruit quality indices is superficial and hidden defects that appear and are manifested at different stages of the product life cycle. The problem in identifying superficial and hidden defects of Hass avocado fruits is related to the peculiarities of exocarp color, which is characterized by a darker shade by contrast with other avocado varieties and depends on a quantitative ratio of pigments at different ripeness stages. So, there is a need in the development of a procedure of identification of hidden avocado fruit defects with the use of a real-time HSI-technology.

The identification of defects is one of the complicated tasks of the control of fruit quality indices because of the diversity of defect types (Bhargava & Bansal, 2021). The review (Bhargava & Bansal, 2021) provides the studies on the identification of defects of fruits and vegetables: apples, pears, bananas, potatoes, cucumbers etc. The article (Patel et al., 2019) presents the study involving the identification of superficial defects of mango with the use of spectroscopy methods and the HSI-technology.

The studies show that a hyperspectral image of an apple and mango skin (Elmasry et al., 2009; Rivera et al., 2014) can be used not only for predicting the ripening stage but also for determining internal damages and hidden defects. The fruits characterized by a leathery dark skin like avocado are not used for developing non-destructive quality monitoring technologies (Magwaza & Tesfay, 2015; Arendse et al., 2018). Therefore, the development of a non-destructive method of monitoring the quality and detecting hidden defects of Hass avocado fruits with the use of a sensory analysis of the condition of exo- and mesocarp is topical and is intended to decrease the loss at all stages of the product life cycle.

It is evident that the identification of defects in individual fruits in a large batch with the use of the HSI-technology would allow grading them in real-time into groups of uniform quality and hence to decrease the amount of waste.

The goal of the study consists in the development of a non-destructive method of identifying (detecting) defects of avocado fruits and their classification according to the number of defects into quality classes with the use of the HSI methods and the multivariate analysis.

MATERIALS AND METHODS

Objects of the study were taken from the commercial batch avocado fruits, in which defects were determined by organoleptic method. The objects of the study involved the samples of premium Hass avocado fruits (n = 10) (country of origin: Tanzania; yield of 2021) which were selected from one batch and used for developing a chemometric classification model into quality classes according to the number of defects.

The avocado fruits were stored for 10 days (the storage life established by the supplier is 14 days) in a refrigerator at t = 4 °C. The samples of avocado fruits were distributed after the storage among quality classes by the number of defects in accordance with the provisions of the standard (UNECE, 2019).

The sensory analysis of avocado fruit exocarp was performed before the storage, after 10 days of storage at t = 4 °C exo- and mesocarp of the samples were investigated. Hass avocado fruits had specific external characters: oval shape, leathery and bosselated exocarp. The fruits were closely sized, healthy, clean, at the stage of consumer maturity, not overrippen, without significant mechanical damages, without excessive external humidity, with a carefully cut off fruit stem. In two samples of Hass avocado fruits (No 4 and 5) minor superficial defects were detected as wrinkles and corking on the skin, respectively.

According to the sensory analysis the avocado fruits were separated into three classes (Table 1) in accordance with (UNECE, 2019): critical defects – 'crit'; slight superficial defects – 'slight'; healthy fruits, no defects - good quality 'good'). According to the standard (UNECE, 2019), avocados are classified into three classes: 'Extra' Class, Class I, Class II, which classes are generally distinguished by a number of minor superficial defects. So, for Class I the area of mesocarp defects shall not exceed 4 cm^2 and for Class II – 6 cm^2. So, following the sensory analysis, the avocado fruits having intolerable defects were placed into an individual category Crit.

Modelling of avocado fruit grading into quality classes according to the number of defects with the use of the HSI-technology includes several steps: image recording and analysis using the ANOVA and PCA method, image segmentation (selection of ROI), pre-processing (SNV-correction, centering), selection of a multivariate classification method and a spectral range, model verification.

Hyperspectral images were obtained with the hyperspectral camera Specim IQ (Spectral Imaging Ltd, Finland) in the range of 400–1,000 nm (204 bands). For obtaining the images the image illuminated region with a halogen lamp QL 500BW Falcon Eyes. The illumination angle was 30° to achieve an even illumination of the samples. The hyperspectral camera was placed in the top part of the illuminated region with the lamp at a distance of 30 cm from the samples. The following hyperspectral images were obtained: 2 images of each side of all ten fruits (with the half turn). A similar building of a hyperspectral image database is provided in the study (Wedding et al., 2011). The obtained hyperspectral images were imported to a PC for a subsequent processing.

During the analysis of hyperspectral images and the development of models of avocado fruit classification into quality classes according to the number of defects the following multivariate methods have been used: variance analysis (ANOVA) and principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA), soft independent modelling of class analogies (SIMCA), in Albedo 4.0.23 (MFTI, Russia) (Strakhov et al., 2013) and Prediktera Breeze ver. 2021.1.0 (Prediktera AB, Sweden) software applications. Data obtained by ANOVA and PCA was used as pseudocolors to build an RGB-image for estimating the fruit condition and confirming wavelengths that are significantly responsible for the total variance of hyperspectral images. The PLS-DA is a generic chemometric method for multivariate discrimination and classification of data (Zontov et al., 2020) based on the use of PLS2 regression for the correlation between the **X** predictor matrix / the **Y** response matrix and dummy variables. SIMCA in its turn is also a method for data classification based on the analysis of samples from each class by PCA.

The classification modeling included the segmentation of hyperspectral images with the use of ROI selection (the whole fruit, ellipses), preprocessing of spectral data: Standard Normal Variate (SNV-correction) and centering. Centering is the subtraction of the mean value from each variable to analyze the variance about the mean. The SNV-correction is a transformation that separates light scattering effects from spectral data by centering and scaling individual spectra. During the chemometric modelling the SNV-correction (Barnes et al., 1989) was used to reduce the effects of multicollinearity and background shift in a hyperspectral image.

The model verification was performed using the accuracy index (%) and during the test-validation using the test-validation accuracy index, %. During test-validation of classification models 30% of HSI data (different ROI's of 3 avocado fruits) was used as a test set of samples.

RESULTS AND DISCUSSION

Sensory analysis

The results of the sensory analysis of avocado fruit condition before and after storage are presented in Table 1.

Table 1. Condition of avocado fruit exocarp before and after storage

Sample number	Description of avocado fruit condition from the sensory evaluation	
	Before storage	After storage / quality class
1	No defects	Anthracnose / crit
2	No defects	Anthracnose / crit
3	No defects	Damages resulting from a low temperature / slight
4	Skin defect (wrinkles)	Skin defect (wrinkles) / slight
5	Skin defect (corking)	Skin defect (corking) / slight
6	No defects	No defects / good
7	No defects	Skin defect (wrinkles) / slight
8	No defects	No defects / good
9	No defects	Skin defect (wrinkles) / slight
10	No defects	No defects / good

The sensory analysis of the condition of exo- and mesocarp performed after the storage of avocado fruit has detected the following:

- Avocado fruit sample No. 5 (Fig. 1, a) was characterized by an exocarp corking however no changes in the mesocarp consistency were detected. The defect is related to tolerable ones, for it does not lead to critical changes of the fruit pulp;
- Avocado fruit sample No. 3 (Fig. 1, b) was characterized by a local mesocarp darkening and softening. The detected defect was supposedly due to the exposure of the fruit to a low temperature but was tolerable, as the area of the damaged pulp did not exceed 6 cm2. Specific signs of chilling do not appear at once but 12–48 hours later, so this defect can be related to hidden ones;
- Samples No. 4, 7 and 9 (Fig. 1, c) were characterized by a skin defect as wrinkles. The study of the mesocarp has detected a minor pulp softening but the change was not of a progressive pattern, what allows relating it to tolerable defects;
- Two avocado fruit samples (No. 1 and 2) developed critical defects (Fig. 1, d) within the storage period. Rounded brownish black depressed spots were recorded on the surface of the avocado fruits and the pulp under the affected skin area became dark and softened. Said signs correspond to the fungal disease - the anthracnose crown rot (ACR) induced by *Colletotrichum gloeosporioides* (Lu et al., 2017). Microorganisms and fungi present in air and on the fruit surface can penetrate into fruit tissues via various microdamages of the exocarp when the fruits are harvested, packed and transported. As the fungal disease is quickly transmitted to healthy fruits, it is important to detect these critical defects at an early stage to remove the damaged fruits from the bulk of the batch;
- Avocado fruit samples No. 6, 8 and 10 were characterized by the absence of defects of exo- and mesocarp. The development of tolerable and critical defects of the fruits was not recorded. The sensory analysis of the avocado fruits allowed observing the enhancement of the ripening stage characterized by the skin browning and the decreased mesocarp density.

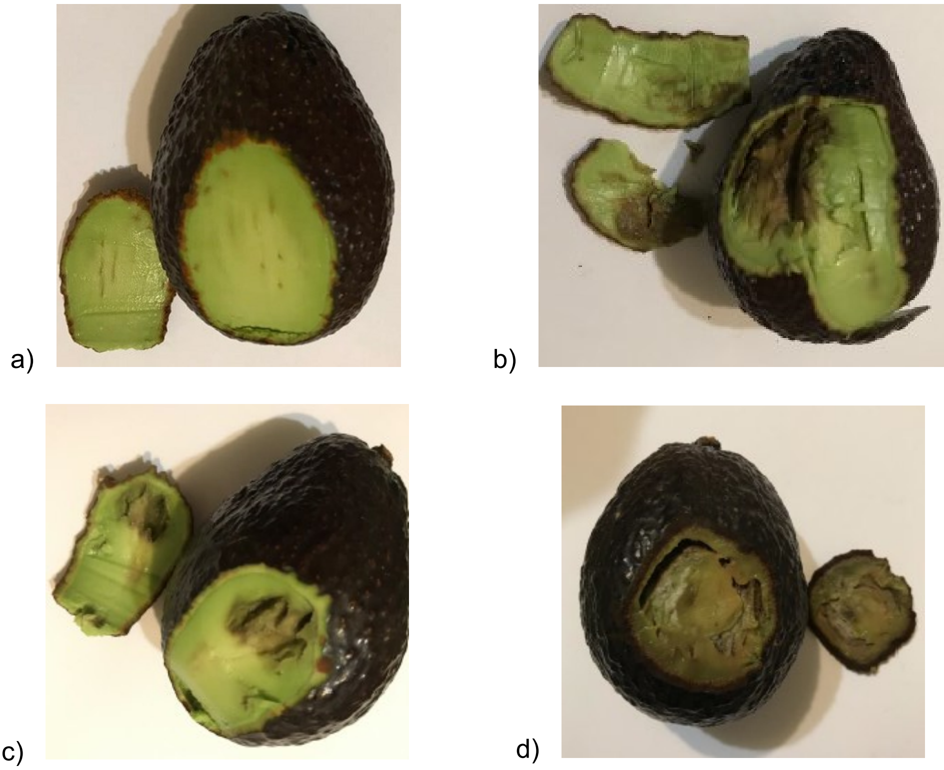

Figure 1. Mesocarp of avocado fruit samples with different superficial skin defects: a) No. 5 with corking – without mesocarp changes; b) No. 3 with the defects resulting from the low temperature exposure – local browning and change in mesocarp density; c) No. 4 with wrinkles – insignificant loss of mesocarp density; d) No. 2 with the signs of a disease (anthracnose) – significant darkening and loss of the pulp density.

During the storage of avocado fruits in the presence of oxygen a number of natural oxidative processes are promoted followed among other by the activation of enzymes. The modification of avocado mesocarp density is related to the transformation of protopectin to pectin, it is enhanced as the maturation progresses and is accompanied by the disintegration of the pulp plant tissue and the increased moisture (Obenland et al., 2012). At the same time a significant reduction of the fruit pulp density relative to the exocarp results in the formation of voids under the skin and in a more active exposure of avocado fruit pulp to oxygen, what accelerates the oxidation. According to the performed studies (Lyu, 2019) in overripe avocado fruits the oxidation leads to critical defects (significant darkening of the pulp, deterioration of consumer properties). A late detection of avocado fruit hidden defects that are rapidly developed during the after-ripening can result in the decrease of quality indices of the whole batch of avocado fruits and in the increase of storage losses. The specification of the classes established by the standard (UNECE, 2019) was used to generate a reliable and accurate classification model, which will allow determining fruits with hidden and intolerable defects quickly and taking a decision on the optimal shelf life and period of sale of avocado fruits.

An average response of the spectral signatures of avocado fruits of the three classes (see Sensory analysis) is shown in Fig. 2. Spectral signatures was selected after assigning category for each avocado fruit using whole fruit ROI from four hyperspectral images.

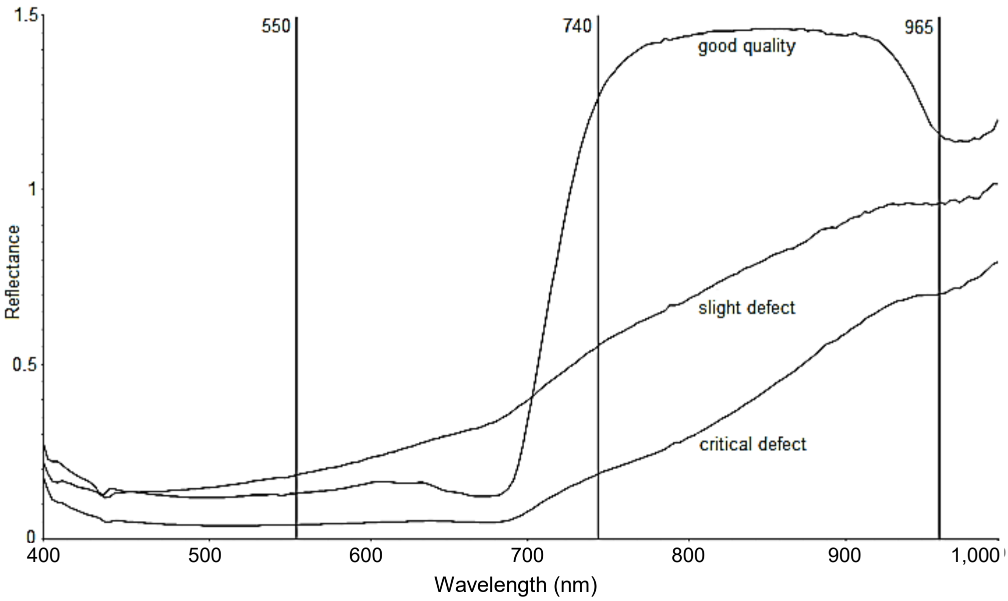

Figure 2. Average response of the spectral signatures of avocado fruits classified into 3 classes: Good, Slight and Crit.

So for increasing the efficiency of grading of a large batch of avocado fruits the use of the HSI-technology is proposed to detect superficial and hidden (internal) defects.

Hyperspectral image analysis by the ANOVA method. According to the variance estimation of hyperspectral image data, spectral wavelengths with the maximal variance at 550, 740 and 965 nm were selected. Principal distinctions in spectral signatures of avocado fruits were analyzed within spectral wavelengths with the maximal variance at 550, 740 and 965 nm:

- The reflection band at 550 nm corresponds to chlorophyll reflection (Matsuda et al., 2012). During the sensory analysis of avocado fruits having anthracnose signs a significant darkening of the exocarp was recorded. It is related to the degradation of chlorophyll *a* to pheophytin *a* (Milenković et al., 2012) which is enhanced during the bacteriological damage of fruits and is accompanied among others with the mesocarp darkening. The comparison of absorption spectral signatures showed the shift of the chlorophyll *a* absorption band from 666 nm to 672 nm for avocado fruit samples with anthracnose signs.
- The red-edge spectral region including the wavelength range from 690 to 750 nm (Croft & Chen, 2017) correlates with the physiological condition of plants. According to (Curran et al., 1990) the red-edge region is susceptible to the changes in chlorophyll content and the maximal slope in the red-edge region is indicative of the fruit ripeness stage. The study (Lyu, 2019) also notes that the reflection in the red-edge region is reduced progressively as the avocado fruits are ripening and notably

over-ripening. As shown in Fig. 1 the red-edge spectral region is closely related to the number of defects in avocado fruits: the maximal slope for the samples with the mold damage of exocarp and the minimal slope for the fruits without defects. For fruits with defects from the slight and crit quality classes the NIR-spectrum in the range of 700–970 nm has lower reflection values than for undamaged fruits from the 'good' class.

- The spectral region of 900 to 965 nm is corresponding to the first overtone of the OH stretch frequency (Ollinger, 2011; Joe & Gopal, 2017). Avocado fruit ripening is accompanied by the reduction of water mass fraction with the increase of lipid and dry matter mass fraction, pit darkening and the development on the fruits of the exocarp color characteristic of the variety (Clark et al., 2003). Possibly, the differences in the reflection intensity at 965 nm are due to chlorophyll modification processes and a subsequent change in refractive properties of cells manifested in the near-infrared range (Croft & Chen, 2017).

The wavelengths with the maximal variance were assigned to pseudocolors and were used to build an RGB-image (Fig. 3, a): 550 nm - green, 740 nm - red, 965 nm - blue. According to the RGB- image (Fig. 3, a) avocado fruits are graded into quality classes by the number of defects: fruits of slight and crit quality classes have a blue pseudocolor (965 nm), the anthracnose fruits have a higher blue color over the whole surface; fruits of the good quality class have a green pseudocolor (550 nm), what is connected with the absence of chlorophyll degradation processes. A RGB-image with the use of pseudocolors allows estimating the fruit condition and confirming wavelengths that are significantly responsible for the total variance of a hyperspectral image selected by the ANOVA variance analysis.

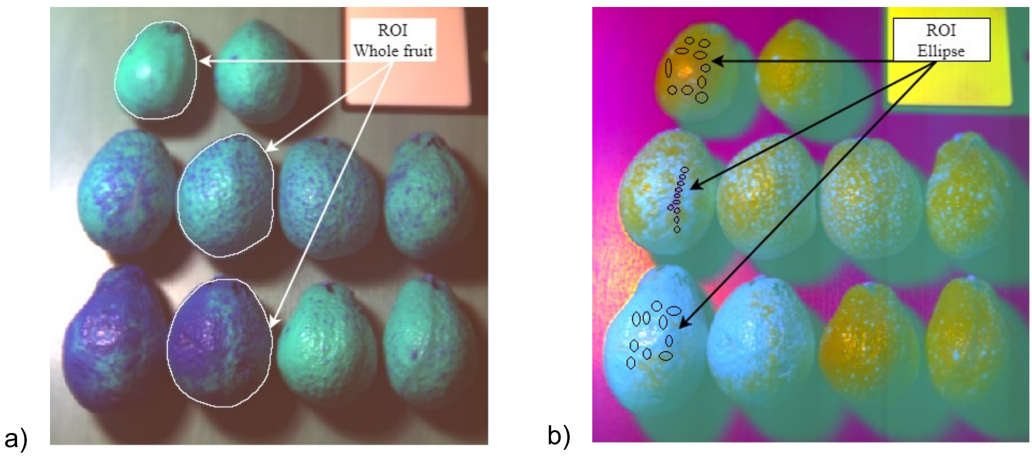

Figure 3. RGB-image of avocado fruits with the use as colors of a) spectrum wavelengths; b) principal components. The figure a) shows the segmentation of a hyperspectral image by selecting a whole fruit as ROI, the figure b) – ROI are ellipses.

The analysis of a hyperspectral image of avocado fruit samples was performed by the principal component analysis method. Following the analysis four principal components (PC) were determined: the first, the second, the third and the fourth PC in a combination account for 99.9% of the total variance (81.6%, 15.5%, 1.8% and 0.9%, respectively).

Test coefficients showing the correlation of reflection coefficients at the wavelengths for 1–4 PCs are provided in Fig. 4. The data were used to interpret the PCs.

The first PC accounting for 81.6% of the total variance is related to all reflection coefficients of the spectrum wavelengths, is presented with the sign (+) over the whole spectral range and possibly is responsible for the total variance and correlation between the pixels (including the pixels of avocado samples) of the hyperspectral image (Fig. 4).

For the 2nd PC according to the sign (+/–) and the wavelength test coefficients the spectrum is divided into two ranges: the sign (+) is related to test coefficients of the spectrum wavelengths corresponding to the VIS-range, the sign (–) is related to the NIR-range (Fig. 4). By analogy with the test coefficients according the 1st PC, the 2nd PC is related to all reflection coefficients of the spectrum wavelengths but separates the range of values by the sign (+/–).

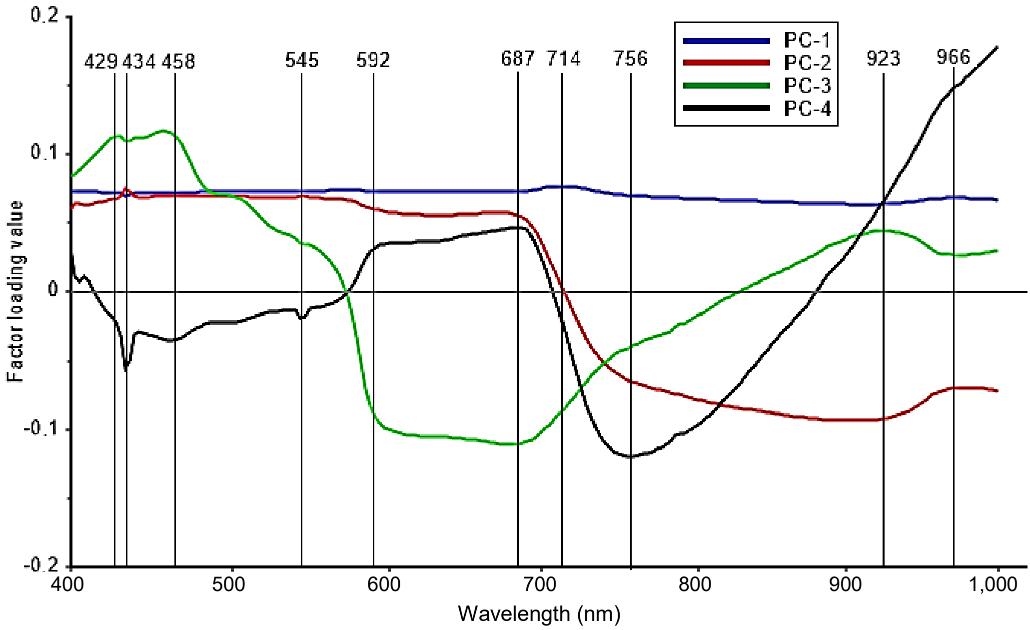

Figure 4. Line loadings plot of PCA.

For the 3rd PC crests of bands were detected that are attributed to carotenoid pigments (429, 434 and 458 nm) (Hooijschuur et al., 2015) and to the 1st overtone of OH (923 nm) with the sign (+), to chlorophyll *a* (687 nm) and chlorophyll *b* (592 nm and 603 nm) (Croft & Chen, 2017) with the sign (–). The test coefficients at 592 and 687 nm are related to a decrease of chlorophyll content in avocado fruits. The reduction of chlorophyll concentration during storage increases the content of carotenoid pigments in the exocarp of avocado fruits. The increase of lutein (a yellow pigment related to the class of carotenoid pigments) content in the skin and pulp of an avocado fruit during ripening is supported by the studies (Ashton et al., 2006). So, the interpretation of the 3rd PC is connected with the change of reflection in the band range of chlorophyll and lutein during storage within the exocarp of avocado fruits without hidden defects, the ripening stage of the fruits being not critical.

For the 4th PC crests of bands were detected that are attributed to anthocyans (545 nm) (Merzlyak et al., 2003), carotenoids (434 and 458 nm), the red-edge crest (756 nm) with the sign (–) against the 1st overtone of OH (923 and 966 nm), chlorophyll *a* (687 nm) and chlorophyll *b* (592 nm) with the sign (+). As shown in the study (Ashton et al., 2006) anthocyan content in avocado fruit exocarp is increased as Hass avocado fruits are over-ripening. At the same time the reflection band at 545 nm with the sign (–) corresponding to the reflection of anthocyans acts as an indicator of the critical ripening state of avocado fruits and as an indirect indicator of the fruit bacterial damage (Ashton et al., 2006). Such avocado fruits have to be quickly sorted and removed from the bulk of the batch to reduce storage losses. It its turn the maximal value of the test coefficients for the 4th PC with the sign (–) at 750 nm corresponds to the red-edge spectral region, what correlates to the physiological condition of the plants. In view of the foregoing, it is determined that the 4th PC is responsible for the fruit degradation process considering the test coefficient extrema with the sign (–) at 545 and 750 nm.

According to the interpretation of the PCs and their contribution to the total variance three PCs were selected which were assigned to pseudocolors (1st PC – red, 3rd PC - green, 4th PC – blue) and the following RGB-image (Fig. 3, b) was developed. According to the figure (Fig. 3, b) the 4th PC detects defective avocado fruits which are presented by a blue pseudocolor.

The RGB-images (Fig. 3) with the use of pseudocolors were used for the HSI segmentation and the development of a classification model. Based on the obtained RGB-images different regions of interest (ROI's) of avocado fruit surface were selected: whole fruit, ellipses as circles about a place of defect.

During the selection of ROIs, the shape and the intensity of spectral signatures of avocado fruits from three quality classes (Fig. 3) were considered. The ROI selection was carried out manually by the segmentation of a whole avocado fruit and by the selection of 10 spectral signatures as ellipses from each fruit. During the selection of ellipse ROIs a hyperspectral image was magnified to define exactly the boundaries of a healthy skin surface of avocado fruits and a defect one. Once being segmented each ROI was assigned to classification variables – quality classes according to the number of defects. Each ROI both of a whole fruit and of an ellipse represents an average response of the spectral signature of an avocado fruit from one of the three quality classes.

The classification of avocado fruits into quality classes according to the number of defects by multivariate analysis methods was performed with the use of different multivariate classification methods (Torres & Amigo, 2020), regions of interest and spectral ranges (Jia et al., 2020). For increasing the accuracy of the final models the calibration was performed with the selection of regions of interest - ellipses ($n = 10$) on avocado fruits from different quality classes. The advantage of the selection of such regions of interest is in that for each class determined according to the number of defects it is possible to select more variables, to increase respectively the prediction reproducibility and adequacy. The SNV (Standard Normal Variate) -correction and centering were used as a pre-processing of hyperspectral image data. At the pre-modelling stage data smoothing by Savitzky-Golay method was also used but the obtained results in the model accuracy were not satisfactory (not shown in the Table).

Whole fruits ($n = 5$) over the total area were selected as the regions of interest for the prediction, what is required for a correct quality monitoring after the development of a model. Modelling results are presented in Table 2.

Table 2. Multivariate models of Hass avocado classification according to the defects

Method	Region of interest (ROI)	Average spectrum		
		Spectral range, nm	Training Accuracy, %	Test-validation Accuracy, %
PLS-DA	Whole fruit	400–1,000	0	0
	Whole fruit	500–990	100.0	40.0
	Ellipse	400–1,000	100.0	60.0
	Ellipse	500–990	100.0	80.0
SIMCA	Whole fruit	400–1,000	36.4	20.0
	Whole fruit	500–990	36.4	20.0
	Ellipse	400–1,000	93.3	80.0
	Ellipse	500–990	**100.0**	**100.0**

The grading of avocado fruits into quality classes is supported by the sensory analysis including the sensory analysis of a mesocarp condition after hyperspectral images are recorded. For developing a classification model three classes were used according to the sensory analysis of quality classes: 1) Crit - fruits with the marked skin anthracnose (critical defects); Slight - fruits with damages resulting from a low temperature, an excessive external moisture, skin corking and skin wrinkles (minor superficial defects); Good - fruits without defects.

When modelling, a low accuracy of the models with the use of whole fruits as the ROIs was recorded, it is related to data sets that are not sufficient for classification: with the use of whole fruit ROIs the number of variables for calibration was 10, while with the use of ellipse ROIs the number was 100 (10 ellipses from 10 fruits). Among others a low accuracy of the models with the use of whole fruit ROIs is determined by the incorporation in the ROIs of spectral signatures of shadows and reflections caused by a high illumination of the samples with a halogen lamp. The increased accuracy of classification models depending on the selection of a spectral range is also recorded: excluding the region of 400–500 nm (weak signal with a low reflection intensity or the absence of a signal), excluding the region of 990–1,000 nm (significant noises). So, the number of predicting variables and the selection of a spectral range has a direct effect on the accuracy of classification models.

According to the results of modelling and test-validation the SIMCA model with the use of ellipses as the ROI's in the range of 500–990 nm was selected as the most representative one. During modelling critical distances (Dcrit) between the classes were selected. The SIMCA Cooman's model diagram within the model coordinates Good (X-axis) and Crit (Y-axis) is presented in Fig. 5. A higher accuracy and efficiency of the SIMCA model as compared to the PLS-DA model is related to the structure of the used data (Pomerantsev & Rodionova, 2018): the class Good is used as a target one and the classes Crit and Slight can be considered as one class including defects of various degree. With this data structure one class is implied to be located in the middle and the remained classes occupy the periphery (Pomerantsev & Rodionova, 2018). According to (Oliveri & Downey, 2012; Pomerantsev & Rodionova, 2014) SIMCA is a classifier of one class, so in the case of classification of avocado fruits according to the number of defects it is a more efficient algorithm as opposed to PLS-DA.

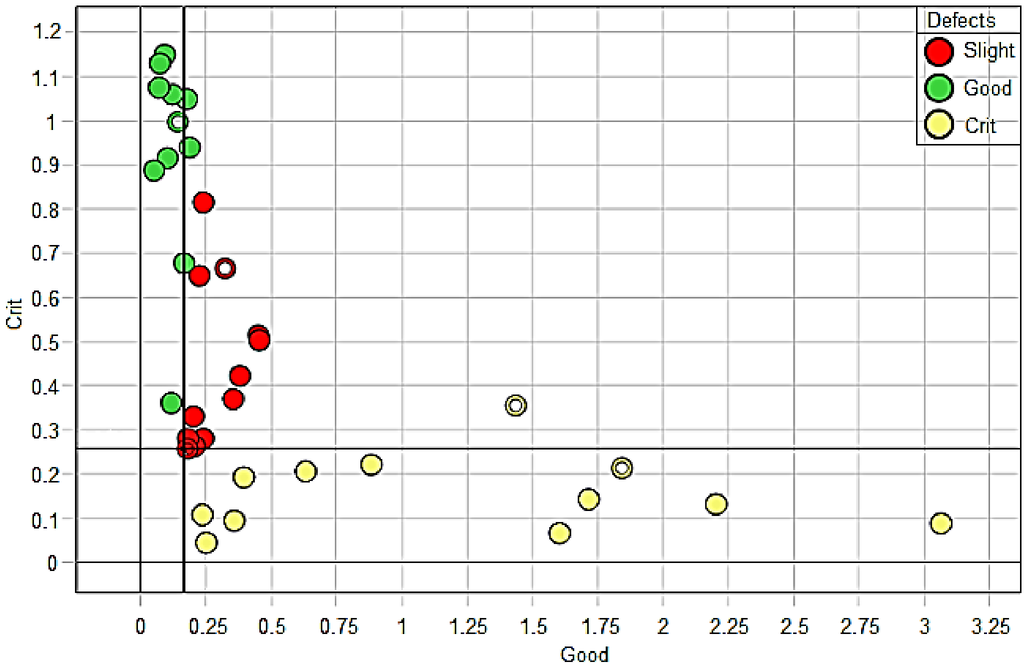

Figure 5. Coomans plot of SIMCA model.

Upon the completion of the records of hyperspectral images a SIMCA multivariate model was built to classify avocado fruits into quality classes according to the number of defects. The quality and accuracy of the obtained model are supported by the test-validation with the accuracy of 100% (Table 2).

However, the developed SIMCA model is not suitable for sorting other avocado varieties, due to differences in exocarp color characteristics of other avocado varieties such as Fuerte or Pinkerton. Comparing the results with similar approaches, it should be noted that deep learning algorithms are structurally different from traditional machine learning or multivariate methods and have dramatically more parameters (Hu et al., 2021). Thus, implementing deep learning algorithms to build an effective classification model of avocado fruits might be a challenging task both for a developer and an operator. Proposed approach provides diagnostic tools, intuitive modelling and rapid predictions (Vikström, 2021) that can be applied *on-line* with performance comparable to modern deep learning algorithms.

CONCLUSIONS

The potential of using a hyperspectral image in a visual-near infrared range and the multivariate analysis has been shown for the non-destructive identification of hidden defects of avocado fruits. The analysis of a hyperspectral image of avocado fruits by ANOVA and PCA algorithms has detected spectral regions responsible for the presence within avocado fruits of pigments and moisture and correlating to physiological condition of the fruits and the number of hidden defects. RGB-image based on data obtained by ANOVA and PCA as pseudocolors was used for estimating the fruit condition and selection of different ROI's of avocado fruit surface. For grading avocado fruits into quality classes (the number of hidden defects) different regions of interest of hyperspectral images and multivariate analysis method - PLS-DA, SIMCA were used. The SIMCA method allowed building a classification model of avocado fruits with the accuracy of 100%. The use of the proposed approach permits grading avocado fruits into quality classes without using destructive methods. The current study could form the basis for future R&D projects and implementation of digital avocado fruit sorting systems in retail quality control laboratories.

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