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Hyperspectral signatures and reflectance models related to the ripening index in four grape varieties

Héctor Flores-Breceda[1], Alejandro Isabel Luna-Maldonado[1*], María del Carmen Ojeda-Zacarías[1], Humberto Rodríguez-Fuentes[1], Juan Antonio Vidales-Contreras[1], Juan Arredondo-Valdez[1], Beatriz Adriana Rodríguez-Romero[1], Marina Burgaya-Ribell[2]

[1]Universidad Autónoma de Nuevo León, Facultad de Agronomía, Departamento de Ingeniería Agrícola y de los Alimentos, Francisco Villa S/N, Ex-Hacienda El Canadá, General Escobedo, Nuevo León, 66050, México.
[2]Universitat Autònoma de Barcelona, Facultat de Veterinària.Edifici V, Travessera dels Turons,08193 Cerdanyola del Vallès, Barcelona, España

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ABSTRACT

The preference for the consumption of red wine in Mexico is increasing because its components derived from the grape are attributed to health benefits. The quality of wine depends mostly on the vineyard conditions. The objective of this study was able to differentiate the physicochemical composition in the harvest stage of four varieties of red grapes that are used in the production of wine to relate their maturation with those of their hyperspectral signatures. Various parameters including pH, total soluble solids, color, weight, and morphology were determined from the bunches of grapes. Concerning the maturity index, it was observed that the grapes with the highest degree of maturity were Shiraz and Merlot at harvest time. The pH of grape juice is a measure of active acidity; the texture is considered a quick and inexpensive technique. The hyperspectral signatures reflectances versus color, total soluble solids, morphology, weight, texture, and pH for each grape variety was best fitted with Gaussian curves of order 8 to Cabernet sauvignon and Merlot, 7 to Malbec, and 5 to Shiraz with R^2 above 0.99.

* Corresponding author

E-mail: alejandro.lunaml@uanl.edu.mx (A. I. Luna-Maldonado)

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1 Introduction

The practice of viticulture developed in the Middle East in 8000 BC through the cultivation of wild grapes (Gur et al. 2021), later the grape variety *Vitis vinifera* was found, which originated in Europe and till now more than ten thousand white and red grapes varieties were recognized throughout the world (Lumbreras 2003). The development of grapevine plants starts from the shoots (a portion of stems) and after the fourth year, the crop starts giving a constant annual production of grapes, which can ensure their use for industrialization in winemaking (Gattullo et al. 2020). The importance of grapes production has been given slowly in the world and it is currently known that countries such as Italy, France, the United States, Germany, and China, are some of the largest grapes producers and consumers (Fernandez and Meraz Ruiz 2022).

One of the considerations to evaluate the quality of the wine is influenced by intrinsic and extrinsic elements, where the intrinsic factors such as flavor, color, acidity, and level of alcohol are contemplated while the extrinsic factors such as brand, price, year of production, country of origin, grape variety, labeling, tradition, awards, and recommendation are important (Ruso et al. 2021). Concerning the price of wine, these factors influenced the globalization of wine because it allows more wines to circulate throughout the world, increasing the competition for this product, and causing competition between the old wine producers and the countries considered new producers (Moscovici et al. 2022). As per the sale registered in 2007, the most consumed wine in Mexico is red wine, its consumption reached 61.4%, this was followed by white wine with 27% (Andrade et al. 2011). The wine has complex components which are associated with the grapes varieties and are released during the fermentation process (Sun et al. 2020). Further, the vine has antioxidant properties which coupled with the resveratrol, naturally improves blood circulation (Shaito et al. 2020) and reduces low-density lipoprotein (LDL) cholesterol (Merchant Martí 2017).

In general, grapes skin, pulp, and seed are used in vine making, and among these polyphenolic compounds are mainly found in the skin on the epidermal cells and seed (Hornedo-Ortega et al. 2020). Wine also has various phenolic compounds including cinnamic acids, tyrosine, phenolic acid derivatives, stilbenes, and flavonoids which are responsible for the antioxidant properties of the wine (Zeb 2020).

Traditional criteria to determine the ripening index in grape varieties are skin color, softening, titratable acidity, the concentration of soluble solids, and the availability of volatile compounds (Shahab et al. 2020). A physical property considered relevant in the food industry for evaluating the external quality of grapes is color (Peppi et al. 2006; Pisciotta et al. 2020). Zouid et al. (2010) studied the evolution of the mechanical properties of Cabernet Franc grapes, during their maturation, belonging to three vineyards from different regions. The rheological tests (compression and puncture) on the grapes were made to analyze changes in their maturity versus their ability to extract anthocyanins from the skin. They concluded that grapes with higher skin breaking forces produce extracts with a higher total content of anthocyanins. Further, according to Wang et al. (2020) aroma, firmness, and berry shape are three important quality traits that are perceived for table grape berries. On the other matter, throughout the development of the berry, the transverse and longitudinal diameters gradually increase, tending to certain regularity at the end of its maturation (Zhang et al. 2021).

Recently, an emerging technique that integrates conventional imaging and spectroscopy is hyperspectral imaging (HSI) to obtain a spatial image and wavelengths of objects (Grajeda et al. 2015). HSI is a non-destructive technique, in the case of fruits, it has taken greater use because fruits are not damaged during analysis and can carry out a greater amount of analysis in less time or during its maturation in real-time (Scalisi and O'Connell 2021). The use of hyperspectral images in agriculture is serving to detect problems of fruit and leaf damage in real-time (Grajeda et al. 2018). A hyperspectral image is composed of a series of sub-images, which represent the intensity distribution in each spectral band (Jia et al. 2020; Lavadiya et al. 2022).

When some fruit is exposed to light, the reflected radiation can be measured and recorded with a reflectance spectrum, which is related to the chemical composition of the fruit (Baiano et al. 2012). For the management of the information of its components, multivariate analysis, and machine learning have proven to be very efficient methodologies for the prediction of the oenological parameters of the grape berries (Melo-Pinto et al. 2022). The objective of this work is to predict the ripening index of the main grape varieties used for red wine production in Mexico using hyperspectral signatures.

2 Materials and methods

2.1 Grape sampling

The vineyard of the Agricultural Production Research Center of the UANL (Figure 1) is divided into four plots of approximately one hectare and had an arrangement per plot of 37 columns and 60 rows of vine plants, in which different varieties were grown of grapes.

The samples of red grape varieties were collected from the Cabernet Sauvignon, Shiraz, Melot, and Malbec vineyards. For sample collection, 10 plants from each of the red grape varieties were selected and from each plant, a bunch of 2.5 kg per plant was

Figure 1 Distribution of grape varieties in the plots of the CIPA-UANL vineyard

taken for analysis. From each selected bunch, six grapes were selected from the different positions of the bunch (upper, intermediate, and lower part) and used to carry out the physicochemical analyzes (morphology, weight, color, pH, texture, °Brix), as well as the acquisition and processing of hyperspectral images that were taken of the entire grape bunch.

2.2 Hyperspectral imaging system

To obtain the hyperspectral images, a system composed of a Pike F-210B camera and a V10E spectrograph that takes images with a resolution of 1392 X 1040 pixels, with a spectral range of 400 to 1000 nm with intervals of 2.8 nm and a 30 µm slot, integrated into a support structure with LED lighting and a conveyor belt with a variable frequency drive motor was used.

2.3 Software used for Hyperspectral image analysis

For the acquisition and analysis of the images, programs were developed on the Matlab R2020 platform and for image processing, the HyperTools V3 software (Graphical user interface for the analysis of hyperspectral images) was used. In addition, Matlab R2020 was used to do the curve fitting of the hyperspectral signatures.

2.4 Color measurement

For the measurement of the color parameters of the grapes (L*, a*, b*, C*, H*) the SPEC portable equipment was used. The color is measured directly on the skin of the grape.

2.5 Total soluble solids measurement

Benelli et al. (2020) measured soluble solids in grapes in their different stages of maturation using the manual refractometer in the field. Total soluble solids were measured in grape juice concentrate using a manual refractometer (Atago model, Tokyo, Japan), which has a measurement range of 0 to 33 ° Brix. The juice of the grape was extracted and poured into the prism of the refractometer, it was closed with the daylight plate and the total soluble solids in ° Brix were read after light.

2.6 Morphology, weight, and texture

One of the widely applied techniques in the food industry is the evaluation of mechanical and physical characteristics by texture analysis (Zulkifli et al. 2020). The thickness and hardness of the grape skin are indices that reflect the extraction potential of anthocyanins and the dehydration kinetics (Corona et al. 2020). Grape firmness was measured by puncture measured in Newtons and measured with a TAxT2i Texture Analyzer (Stable MicroSystems, Surrey, UK). The morphology of the grape was obtained using a vernier and the weight was measured with the help of a pomegranate scale.

2.7 pH measurement

A digital potentiometer (HANNA; HI99163, Woonsoket RI, USA) was used to measure the pH. For this, the skin and pulp of the grape were ground with the help of a porcelain crucible, filtered, and obtained juice was used for the estimation of pH.

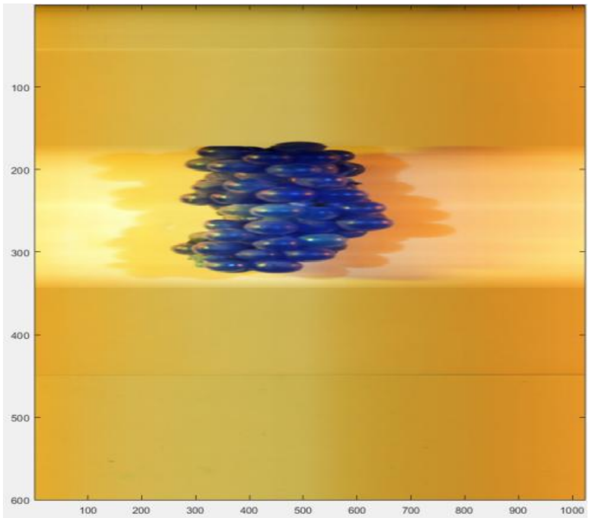

Figure 2 Composite image of grapes bunches

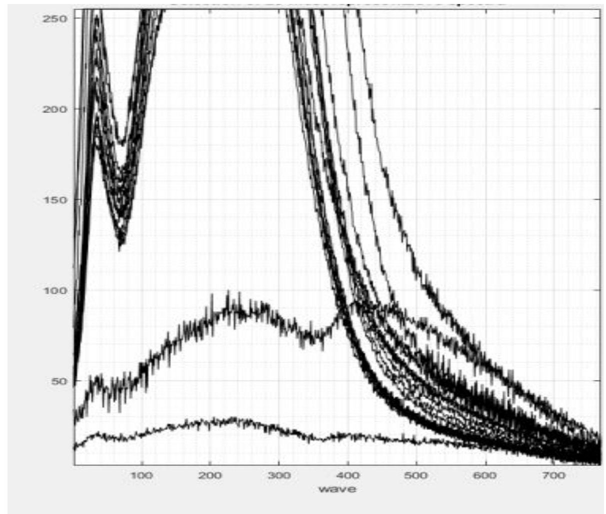

Figure 3 Selection of the 20 most representative spectra of grapes bunches

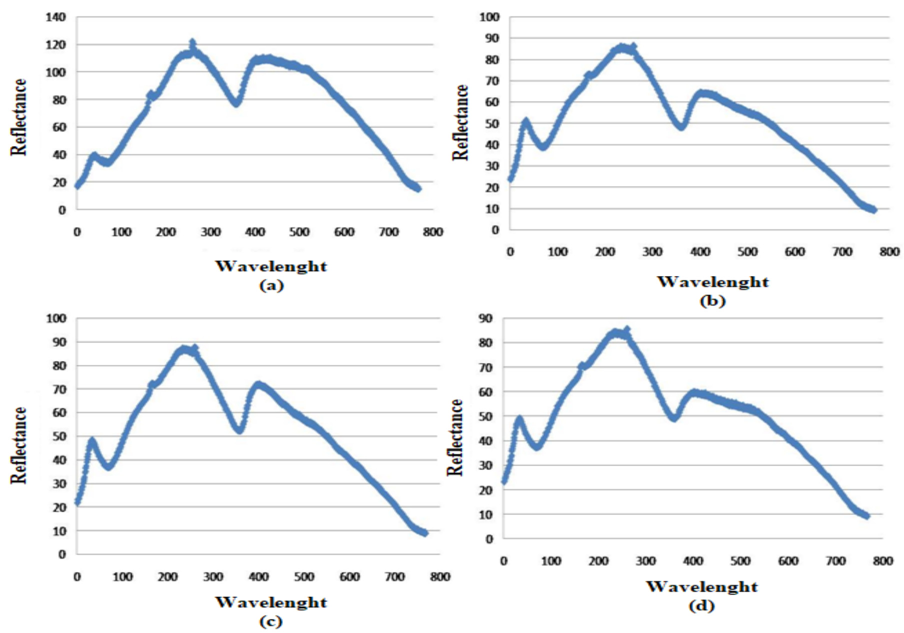

Figure 4 Hyperspectral signatures of the selected grape varieties (a) Cabernet Sauvignon, (b) Malbec, (c) Merlot, (d) Shiraz

3 Results and discussion

3.1 Hyperspectral imaging system

The images of the selected four varieties were acquired with a program developed in Matlab (Figure 2) and subsequently post-processed with HyperTools V3 (Figures 3 and 4). For this, the grapes bunches were placed on a conveyor belt at 30 cm away from the hyperspectral camera and the images were taken (Figure 2). From obtaining the possible spectral signatures, the most representative curves of the grapes bunch were selected by the program (Figure 3), and by averaging the representative curves, the hyperspectral signatures of the four grape varieties were obtained (Figure 4).

The hyperspectral signatures refer to the specific radiation profile emitted by the grapes varieties (Table 1). From these signatures, the area under the curve was calculated to ensure that a reliable result has been obtained and to avoid behaviors of the same curves. Among the studied species, the highest area under the curve was reported for cabernet sauvignon while the lowest value was reported for the Shiraz.

Table 1 Area under the curve of the hyperspectral signature

Grape Variety	Area under curve
Cabernet sauvignon	57,784.91
Malbec	39,195.16
Merlot	40,574.22
Shiraz	38,772.03

The adjustment of each of the hyperspectral signatures of the grape varieties was carried out, and the following models were developed for all four varieties:

3.1.1 Cabernet Sauvignon

$$\text{Reflectance}(X)= 57.92^{-(((X-271.8)/66.95))^{8}} + 271.8^{-(((X-397.8)/41.89))^{7}} + 0.5231^{-(((X-472.9)/3.112))^{6}} + 20.49^{-(((X-33.83)/30.25))^{5}} + 15.5^{-(((X-322.8)/28.1))^{4}} + 88.59^{-(((X-461.4)/113.5))^{3}} + 76.3^{-(((X-190)/124.2))^{2}} + 57.44^{-(((X-615.4)/126.6))} \quad (1)$$

The general fit model was Gaussian of order 8 with an error sum of squares of 1631, R squared of 0.9977, adjusted R squared of 0.9976 and root mean square error (RMSE) of 1.481.

3.1.2 Malbec

$$\text{Reflectance}(X)= 816^{-(((X-191.3)/91.59))^{7}} + 899.1^{-(((X-192.3)/95.64))^{6}} + 34.49^{-(((X-30.22)/30.52))^{5}} + 6.521^{-(((X-319.9)/31.65))^{4}} + 12.49^{-(((X-397.5)/28.97))^{3}} + 15.42^{-(((X-431.1)/63.14))^{2}} + 50.39^{-(((X-512.6)/196.2))} \quad (2)$$

The general fit model was Gaussian of order 7 with an error sum of squares of 591.7, R^2 was 0.998, adjusted R^2 was 0.9979 and RMSE was 0.89.

3.1.3 Merlot

$$\text{Reflectance}(X)= 2.608^{-(((X-259.4)/7.771))^{8}} + 6.721^{-(((X-233.2)/25.53))^{7}} + 18.39^{-(((X-326.8)/35.41))^{6}} + 20.41^{-(((X-140)/97.91))^{5}} + 19.20^{-(((X-360.8)/21.4))^{4}} + 80.03^{-(((X-301.2)/203.7))^{3}} + 32.58^{-(((X-577.1)/160.7))^{2}} + 26.41^{-(((X-31.29)/25.53))} \quad (3)$$

The general fit model was Gaussian of order 8 with an error sum of squares of 405.8, R^2 was 0.9988, adjusted R^2 was 0.9987 and RMSE was 0.7385.

3.1.4 Shiraz

$$\text{Reflectance}(X)= 5.997^{-(((X-242.6)/30.87))^{5}} + 73.03^{-(((X-220)/181.4))^{4}} + 15.99^{-(((X-348.3)/36.48))^{3}} + 22.58^{-(((X-31.45)/22.42))^{2}} + 47.99^{-(((X-520)/196.9))} \quad (4)$$

The general fit model was Gaussian of order 5 with an error sum of squares of 659.2, R squared of 0.9976, adjusted R squared of 0.9975, and RMSE of 0.9357.

3.2 Grape skin color parameters

The data obtained from the color analysis on the skin of freshly harvested four grapes varieties and the results based on the CIE L*a*b* and L*C*H* color spaces are presented in Table 2. Except for Malbec, rest three grape varieties have similar values. Suca Colana et al. (2019) established a relationship between the RGB and L*a*b models of grape skin color and this was based on the increased concentration of soluble solids and a regression with the total acidity parameter.

3.3 Total soluble solids

The total soluble solids, which is a measure of the potential alcohol content of a wine before it is manufactured was represented in Table 3. The highest °Bx (21.10) was reported for the Merlot while the lowest value was reported for the Cabernet Sauvignon (18.23). According to Perrot et al. (2015) established that the optimum measure of sugar content for the grape harvest is between 21 to 23 °Bx, from our results obtained, only the Merlot variety was at its optimum harvest point.

Table 3 Total soluble solids values of four grape varieties

Grape varieties	(°Brix)
Cabernet Sauvignon	18.23
Malbec	19.67
Merlot	21.10
Shiraz	20.62

3.4 Morphology, weight, and texture

The morphological parameters and weight of the grape are important factors in its commercial value, as well as an index of its

Table 2 Color parameters of four grape varieties

Grapes varieties	Grapes color				
	a	b	C	L	H
Cabernet Sauvignon	2.17	-1.13	2.63	31.26	331.57
Malbec	1.67	-1.37	2.23	31.87	324.12
Merlot	2.97	-1.30	3.33	29.17	338.95
Shiraz	2.52	0.48	3.02	29.33	319.07

quality (Table 4). Among the tested four grapes varieties, the Malbec variety had the highest grapes diameter and weight, rest three varieties have almost similar values. While in the case of puncture value, the highest value was reported for the Merlot, and this value was followed by Cabernet Sauvignon, Shiraz, and Malbec. The texture expressed as grape firmness is an attribute related to its quality and is a desirable characteristic for good storage (Table 5). Xu et al. (2022) suggested that grapes juice pH and fruit firmness are directly related to grape quality and price and these two could be effectively predicted using hyperspectral images.

Table 4 Morphology and weight of the four grape varieties

Grapes varieties	Grapes diameters		Weight (g)
	Axis X (mm)	Axis Y (mm)	
Cabernet Sauvignon	11.35	11.13	0.92
Malbec	14.42	14.80	1.97
Merlot	12.40	12.50	1.25
Shiraz	13.47	13.40	1.46

Table 5 Puncture values for the four grape varieties

Grape varieties	Puncture (N)
Cabernet Sauvignon	4.08
Malbec	2.56
Merlot	4.54
Shiraz	2.62

3.5 Grape juice pH

The pH value is an important factor in the wine quality because it can influence the various factors of the wine, such as the level of oxidation, color, and flavor, among others (Table 6). Fernandes et al. (2015) establish that the average pH value of grape juice must be close to 3.6, therefore, the results of the current study are in agreement with the findings of Fernandes et al. (2015), and all four grapes varieties had values similar to the standard value. From these results, it can be concluded that selected grapes varieties are suitable for the optimum production of red wine.

Table 6 pH values of the four grape varieties

Grape varieties	pH
Cabernet Sauvignon	3.45
Malbec	3.43
Merlot	3.60
Shiraz	3.78

3.6 Ripening index

The ripening index provides important information to determine the right time to harvest the grapes.

This index was calculated as the product of pH squared multiplied by the total soluble solids expressed in ° Brix (Table 7). All four varieties had ripening indexes in the range from 200 to 300 which was similar to the standard value proposed by Adsule (2014).

Table 7 Ripening index of the fourth grape varieties

Grape varieties	Ripening index
Cabernet Sauvignon	216.97
Malbec	230.70
Merlot	273.51
Shiraz	293.80

Conclusions

Results of the study suggested that the pH values of all four grape varieties are optimal at their harvest and suitable for the production of more oxidized wine with less color. The indexes of maturation and the soluble solids for the Merlot and Shiraz varieties are observed to have a direct relationship with their degree of maturity because in the field they were the varieties that were harvested first. The texture is a low-cost and fast application analytical technique that can be favorably applied to wine production, for grape monitoring. The fit models of the spectral signatures were of the Gaussian type of order 8, 7, 5 and their R^2 was greater than 0.99, which indicates that there is a fit of the curve to a known equation that can be related to the results obtained from the measurements of four grape varieties.

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