

## Virgin-Olive-Oil Color in Relation to Sample Thickness and the Measurement Method

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**Abstract** Color changes of virgin-olive-oil samples contained in cells with different thicknesses were analyzed. Ten different commercial virgin olive oils were measured at different sample thicknesses by two methods: conventional spectrophotometry (5.0, 10.0, and 50.0 mm path length cells), and spectroradiometry (cylindrical cells with 8.0, 11.2, 15.6, 19.6, 23.2, 27.2, 36.8 and 46.4 mm internal diameters) with samples placed on the floor of a commercial cabinet using a standard daylight source. The illumination in these two methods was different, resulting in notable color differences in the samples. Color variations of virgin olive oils depending on thickness do not follow the same trend for all samples. Neither the Bouguer-Lambert-Beer law nor the Kubelka-Munk theory provided successful color predictions in the whole range of thicknesses considered here. We can conclude that for precise and reproducible color measurements of virgin-olive-oil color, it is necessary to fix both the thickness of the sample and the illumination geometry. To achieve an easier communication between industries and/or consumers, we propose that virgin-olive-oil color be measured using a spectrophotometer with 5.0-mm path length cells, for three

reasons: conventional olive-oil laboratories have spectrophotometers more often than spectroradiometers; with virgin olive oils the cleaning of 5.0 mm cells is easier than for 1.0 mm cells and it does not consume a large amount of oil; spectrophotometric signals for 5.0-mm path length cells allow reliable measurements of even the darkest virgin-olive-oil samples.

**Keywords** Virgin olive oil · Color measurement · Color differences · Kubelka-Munk · Bouguer-Lambert-Beer

### Introduction

Color is usually the first property of virgin olive oils perceived by consumers, and this may have a strong influence in choices, although color does not significantly influence the remaining organoleptic properties of oils [1]. In this sense, professional tasters use different dyed glasses to conceal oil color, avoiding its influence on the evaluation of other oil properties [2]. Because color is a nearly independent property with direct influence on commercial consumption, it should be useful to specify color of virgin olive oils in a precise way, as a representative and distinctive property of highest quality oils. Accurate specification of virgin-olive-oil color is not an easy task [3, 4], and, as for any other liquid materials, color depends on sample thickness [5, 6]. In addition, for liquid samples, it is necessary to pay attention to the lighting geometry in the color measurement. By geometry, we mean not only the relative position between the source and the sample, but the entire trajectory of the light until arriving at the observer's eye. Thus, for a virgin-olive-oil sample, part of the incident light is reflected, part is transmitted, part is absorbed, and

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also part comes from the background and goes through the sample towards the observer's eye.

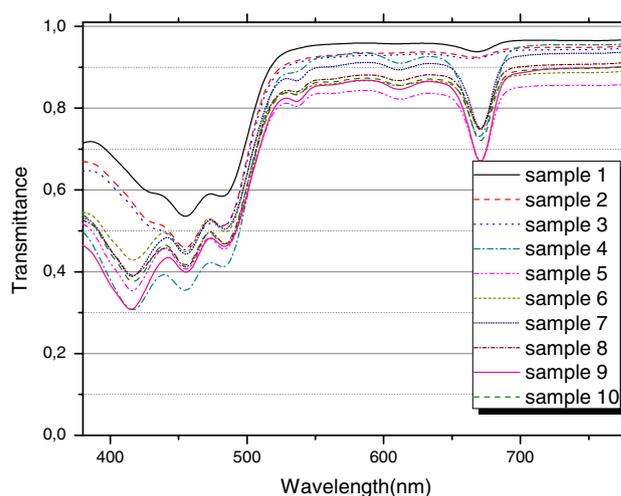
Traditionally, the most common method for color measurements of liquids is conventional spectrophotometry: the spectral transmittance of the sample placed in a cell is measured, and its color is computed assuming a standard illuminant and observer [7], as recommended by the International Commission on Illumination (CIE). The cells have a rectangular base and are available at different thicknesses, but no specific thickness has been recommended in the particular case of virgin-olive-oil samples. In previous works [8, 9] color measurements of oil have been made from transmittance measurements at low thickness values to achieve a measurable signal in the detector. These transmittance measurements have also been transformed to higher thickness values, assuming Bouguer-Lambert-Beer law, before final computation of the color coordinates. This procedure is reasonable because in usual practice, oil samples are thicker than those normally used in spectrophotometers (1–10 mm). Spectrophotometric measurements are fast and precise because these instruments have well-controlled geometry, but they measure the sample color only by transmission. Certainly, oil-color measurements by transmission can be useful for simple specification, but they do not correlate well with the color of the oil perceived by a consumer whose conditions of observation may be more or less diffuse lighting, oil in containers several cm thick, and samples against some background. These more realistic observation conditions are better simulated in color measurements with samples placed on the floor of a commercial light cabinet and a spectroradiometer placed at the position of the observer's eye [10].

The aim of this study was to determine how virgin-olive-oil color changes with sample thickness for spectrophotometric and spectroradiometric measurements. These two types of measurements involve constants belonging to the system (absorption coefficient in the spectrophotometric measurements, and absorption and scattering coefficients in the spectroradiometric ones), which allowed us to test the range of validity of the Bouguer-Lambert-Beer and Kubelka-Munk models [11] in order to predict the color of virgin-olive oils at different sample thicknesses.

## Materials and Methods

### Experimental Devices

We chose ten commercial Spanish extra-virgin olive oils, seeking colors as varied as possible to represent the extra-virgin olive oils that consumers can find in the marketplace. Figure 1 shows the spectral transmittance of these



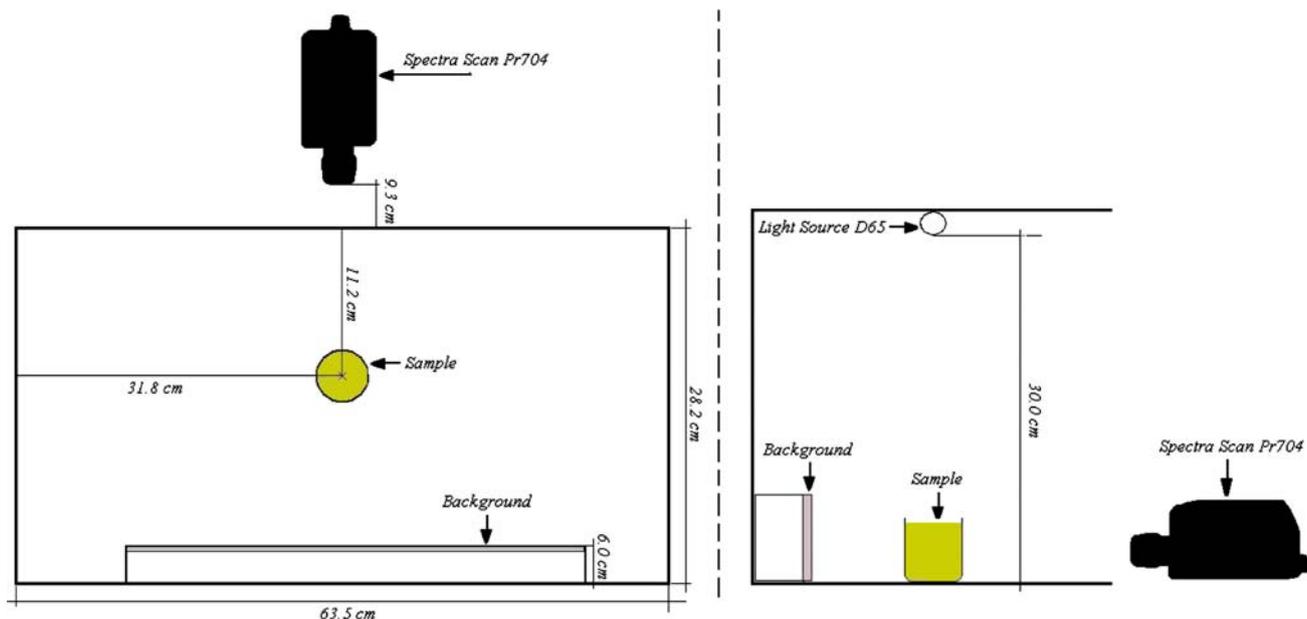
**Fig. 1** Spectral transmittances of the ten extra-virgin-olive oil samples measured in a 5.0-mm path length cell with a JASCO-V650 spectrophotometer

samples measured with a JASCO-V650 spectrophotometer (Jasco Europe S.R.L., Cremella, Italy) using a 5.0-mm path length cell. Their corresponding CIELAB coordinates are shown in Table 1, assuming the D65 illuminant and CIE 1964 Supplementary Standard Observer.

First, we measured the color of the ten extra-virgin olive oils trying to approximate to the conditions of a subject in a marketplace. Thus, the oils were placed in the center of the floor of a Verivide Portable cabinet (Konika Minolta, Nieuwegein, Netherlands) equipped with a daylight source simulating the D65 illuminant. Certainly, in the marketplace light sources other than the D65 can be used to illuminate oil samples [7], but D65 has long been the daylight source specifically recommended by the CIE for outdoor applications [12]. Because of the oil transparency,

**Table 1** CIELAB coordinates of the ten virgin-olive-oil samples at 5 mm, obtained from the spectrophotometric transmittance measurements shown in Fig. 1, assuming D65 illuminant and CIE 1964 Supplementary Standard Observer

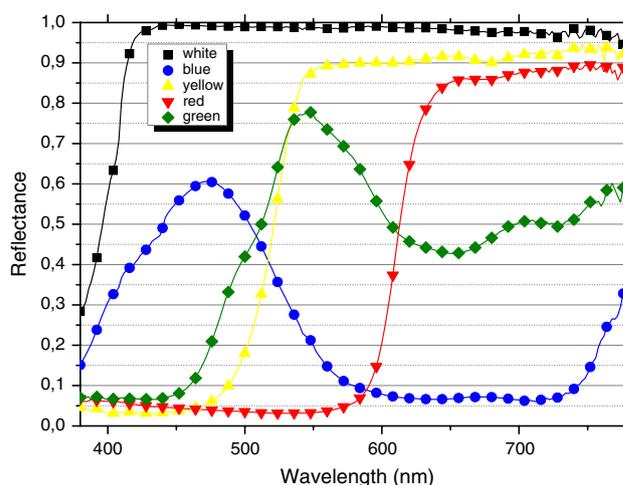
Oil samples	$L^*_{10}$	$a^*_{10}$	$b^*_{10}$
1	95.80	25.49	94.78
2	94.42	30.07	94.42
3	94.18	30.52	94.39
4	93.13	42.23	94.83
5	90.31	31.02	95.78
6	91.66	28.23	95.62
7	93.07	31.79	95.27
8	91.69	32.24	94.75
9	90.98	33.97	95.26
10	91.50	31.71	95.16



**Fig. 2** Outline of the geometry used in the spectroradiometric measurements: plan view (left) and cross section (right)

different fixed backgrounds were positioned behind the oil samples, and the spectral radiant power was measured at a position similar to the one occupied by the observer’s eye using a spectroradiometer SpectraScan PR704 (Photo-research Inc., Chatsworth, CA), which measures from 380 to 780 nm at 2 nm steps. Figure 2 shows the geometry used in our spectroradiometric measurements.

Six samples were employed as backgrounds in our experiment: white, blue, yellow, red and green samples from the NCS atlas [13], and a black plate, which unfortunately gave low signal (only noise is detected) in our measurements with and without oils, and therefore it could not be used in subsequent computations. The spectral reflectances and CIELAB coordinates of the five NCS backgrounds (D65 light source, CIE 1964 Supplementary Standard Observer) were measured as shown in Fig. 2, but using cells filled with transparent *n*-hexane at the same position as the oil samples, in order to compensate the effect of different refractive indexes (i.e. trying to compensate the effect of the internal glass liquid reflections considered in Saunderson’s correction [14]). The spectral reflectances of the five NCS backgrounds are given in Fig. 3 and the corresponding CIELAB coordinates are given in Table 2. Because computations of CIELAB coordinates always require a reference white, we employed a standard PTFE, provided by the manufacturer of our spectroradiometer, which was positioned in the cabinet at the place of the background and measured as shown in Fig. 2, again using cells with *n*-hexane at the position of the oil samples, to compensate for the internal glass–liquid reflections.



**Fig. 3** Spectral reflectances of the 5 NCS backgrounds employed

**Table 2** CIELAB coordinates of the NCS backgrounds used in our spectroradiometric measurements

Backgrounds	$L^*_{10}$	$a^*_{10}$	$b^*_{10}$
White	99.78	−0.16	0.23
Blue	54.82	28.38	−36.02
Yellow	83.43	8.53	96.17
Red	41.21	59.35	28.91
Green	78.92	−19.21	64.69

Secondly, we also measured the color of the ten extra-virgin-olive oil samples by transmission, using a JASCO-V650 spectrophotometer. The measurements were made

from 380 to 780 nm, with a 2 nm step. The reference beam of the spectrophotometer contained a cell with *n*-hexane. After the transmittance measurements were performed by the spectrophotometer, the D65 illuminant and CIE 1964 Supplementary Standard Observer were assumed to provide the CIELAB coordinates of the samples.

To study the color variations of virgin olive oils according to sample thickness, we used a set of cells with a thickness range as wide as possible. Specifically, in our spectroradiometric measurements, we used eight cylindrical cells made of Pyrex<sup>®</sup> glass, with internal diameters 8.00, 11.20, 15.60, 19.60, 23.20, 27.20, 36.80, and 46.40 mm ( $\pm 0.05$  mm). In the case of our spectrophotometric measurements, the instrument employed allowed only cells with three different thicknesses: 5.00, 10.00, and 50.00 mm ( $\pm 0.05$  mm).

In all cases (spectroradiometric and spectrophotometric measurements), we made three non-consecutive measurements, considering their average in further analyses. Between consecutive measurements the cells were carefully washed with *n*-hexane. In this way, we performed a total of 1,200 spectroradiometric measurements (10 virgin-olive-oil samples  $\times$  8 thicknesses  $\times$  5 backgrounds  $\times$  3 replications) and 90 spectrophotometric measurements (10 virgin-olive-oil samples  $\times$  3 thicknesses  $\times$  3 replications), plus some periodical measurements of the reference white provided with our spectroradiometer.

### Calculations

In the spectroradiometric measurements, we calculated the spectral reflectance,  $R_\lambda$ , and the spectral transmittance,  $\tau_\lambda$ , from the measurement of different spectral radiances, using Eqs. 1 and 2:

$$R_\lambda = \frac{r_{s\lambda}^i}{r_{0\lambda}} \quad (1)$$

$$\tau_\lambda = \frac{r_{s\lambda}^w}{r_\lambda^w} \quad (2)$$

where  $r_{s\lambda}^i$  is the spectral radiance of the oil sample with each of the *i* backgrounds,  $r_{0\lambda}$  is the spectral radiance of the PTFE reference white (corresponding to the D65 light source) positioned at the background and cells filled with *n*-hexane,  $r_{s\lambda}^w$  is the spectral radiance of the oil sample with the NCS white background, and  $r_\lambda^w$  is the spectral radiance of the NCS white background with cells filled with *n*-hexane.

In the case of our spectrophotometric measurements, we directly measured the spectral transmittance of the oil sample, and then CIELAB coordinates were computed assuming D65 illuminant and CIE 1964 Supplementary Standard Observer.

For color specifications, we used the CIELAB color space, currently recommended by the CIE [7], and color-difference computations were also made using CIELAB. Several CIELAB-based color-difference formulas, such as CIE94 [15] or CIEDE2000 [16], improved CIELAB predictions of visual-perceived color differences [17], but these advanced formulas are recommended for color differences lower than 5.0 CIELAB units, whereas the present work deals with far greater color differences.

We used the Bouguer-Lambert-Beer law [11] to analyze the color change with sample thickness taking into account the spectrophotometric and spectroradiometric measurements. We took as reference the spectral absorptivity multiplied by the concentration (constant for each oil sample in our case), which can be called absorption coefficient  $\beta_\lambda$ , and is defined by Bouguer-Lambert-Beer law (Eq. 3) as the ratio of the spectral absorbance (logarithm to the base 10 of the reciprocal of the internal spectral transmittance) measured at the lowest thickness and the value *x* of this thickness:

$$\beta_\lambda = -\frac{\log \tau_\lambda}{x} \quad (3)$$

From  $\beta_\lambda$  we again used Eq. 3 to compute the theoretical spectral absorbance that an oil sample would have for other thicknesses, and then the theoretical CIELAB coordinates corresponding to this oil sample at these thicknesses. These theoretical CIELAB coordinates were compared with the experimental CIELAB coordinates measured at these thicknesses.

The Kubelka-Munk equations enabled us to take into account the light absorption and the scattering effects in the samples [14]. We could not use here the classical black background because our black did not reflect enough light to be detected, as mentioned before. However we can obtain the value of parameter  $a_\lambda$  without black background measurements from Eq. 4:

$$a_\lambda = \frac{1}{2} \left[ R_\lambda + \frac{\frac{R_\lambda - R_{1\lambda} R_{g\lambda}}{1 - R_{g\lambda}(1 + R_{1\lambda} - R_\lambda)} - R_\lambda + R_{g\lambda}}{\frac{R_\lambda - R_{1\lambda} R_{g\lambda}}{1 - R_{g\lambda}(1 + R_{1\lambda} - R_\lambda)} R_{g\lambda}} \right] \quad (4)$$

where  $R_\lambda$  is the reflectance of the oil sample with any background (except the black),  $R_{g\lambda}$  is the reflectance of this background with *n*-hexane as sample, and  $R_{1\lambda}$  is the reflectance of the oil sample with white NCS background. Equation 4 comes from the next two equations provided by Kubelka-Munk theory [14] eliminating  $R_{0\lambda}$ , which is the reflectance of the sample with an ideal black background, not measurable in our case:

$$R_\lambda = \frac{R_{0\lambda}(1 - R_{g\lambda}) + R_{1\lambda} R_{g\lambda}(1 - R_{0\lambda})}{1 - R_{0\lambda} R_{g\lambda}} \quad (5)$$

$$a_\lambda = \frac{1}{2} \left[ R_\lambda + \frac{R_{0\lambda} - R_\lambda + R_{g\lambda}}{R_{0\lambda}R_{g\lambda}} \right] \quad (6)$$

From the measurement of oils with two different backgrounds (white background and any of the other four backgrounds) at the lowest thickness, and the reflectance of the background, we can compute  $a_\lambda$  (Eq. 4) and  $b_\lambda$  (Eq. 7), as well as  $S_\lambda$  (Eq. 8). Finally, the spectral reflectance of the sample with white background ( $R'_\lambda$ ) for any other thickness  $x$  is given by Eq. 9:

$$b_\lambda = \sqrt{a_\lambda^2 - 1} \quad (7)$$

$$S_\lambda = \frac{1}{b_\lambda x} \left[ \tanh^{-1} \left( \frac{a_\lambda - R_\lambda}{b_\lambda} \right) - \tanh^{-1} \left( \frac{a_\lambda - R_{g\lambda}}{b_\lambda} \right) \right] \quad (8)$$

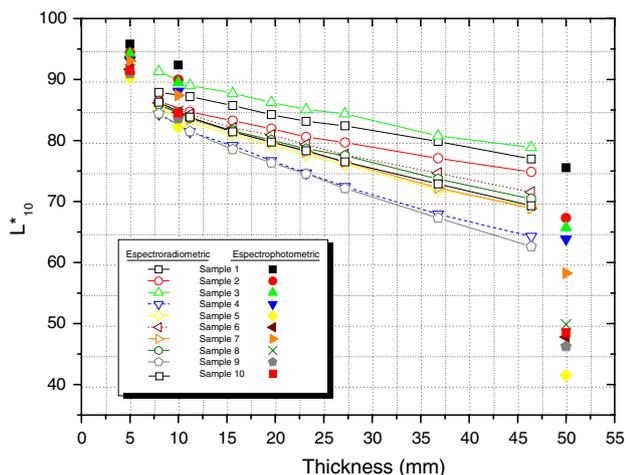
$$R'_\lambda = \frac{1 - R_{g\lambda}(a_\lambda - b_\lambda \operatorname{ctgh}(b_\lambda S_\lambda x))}{a_\lambda - R_{g\lambda} + b_\lambda \operatorname{ctgh}(b_\lambda S_\lambda x)} \quad (9)$$

In summary, by using the Kubelka-Munk theory, we found the theoretical spectral reflectance that an oil sample would have with different thicknesses for the white background. From these spectral reflectances the theoretical CIELAB coordinates were computed, and compared with the corresponding experimental measurements.

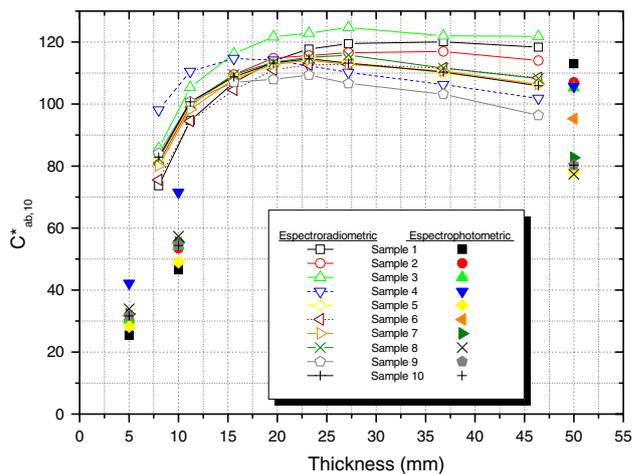
## Results and Discussion

### Color Dependence with Thickness

Figures 4, 5, and 6 show the  $L^*_{10}$  (lightness),  $C^*_{10,ab}$  (chroma), and  $h_{10,ab}$  (hue-angle) CIELAB coordinates, experimentally measured for the ten oil samples at each thickness. CIELAB lightness and hue-angle decreased with



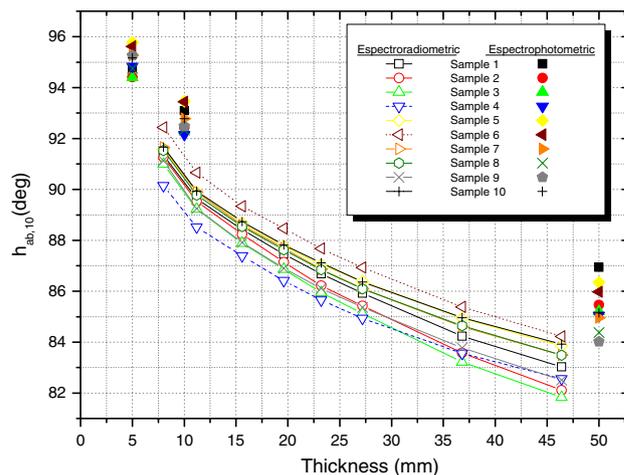
**Fig. 4** CIELAB lightness (D65, Supplementary Standard Observer CIE 1964) of the ten oil samples versus thickness, for spectrophotometric (symbols) and spectroradiometric (lines with symbols) experimental measurements



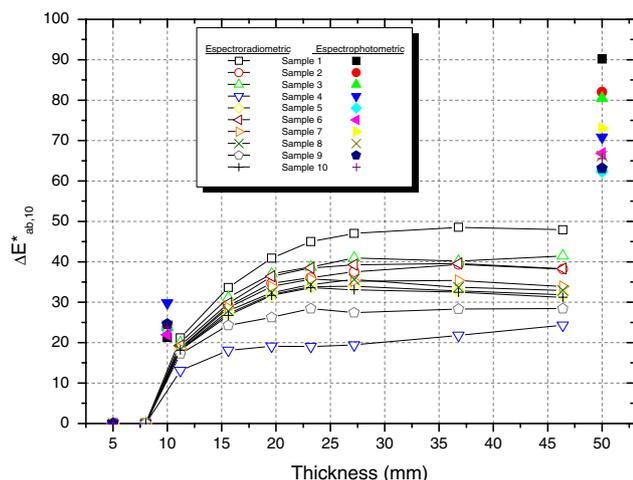
**Fig. 5** CIELAB chroma (D65, Supplementary Standard Observer CIE 1964) of the ten oil samples versus thickness, for spectrophotometric (symbols) and spectroradiometric (lines with symbols) experimental measurements

increasing sample thickness, while chroma increased up to about 19.6 mm thicknesses, and then reached a nearly constant value or even slightly decreased in some samples. It can also be noted in Figs. 4, 5 and 6 that when thickness increased the three color coordinates of the samples become more disperse; that is, for lesser sample thicknesses the color of the different oils was more similar than for greater thicknesses. Consequently, the discrimination between colors of extra-virgin olive oils should be better at greater thicknesses (e.g. few cm, as is usual in the commercial sector).

Figure 7 shows CIELAB color differences between experimental measurements at different sample thicknesses



**Fig. 6** CIELAB hue-angle (D65, Supplementary Standard Observer CIE 1964) of the ten oil samples versus thickness, for spectrophotometric (symbols) and spectroradiometric (lines with symbols) experimental measurements



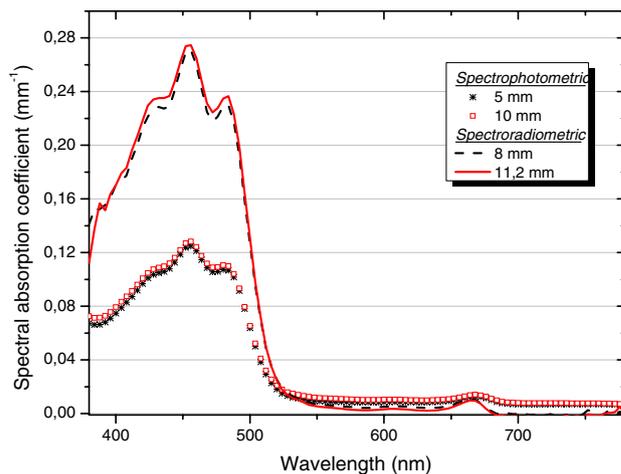
**Fig. 7** CIELAB color differences between the experimental measurements at the lowest thickness (5.0 and 8.0 mm for spectrophotometric and spectroradiometric measurements, respectively) and other greater thicknesses. Spectrophotometric measurements (*symbols*) and spectroradiometric measurements (*lines with symbols*)

and the smallest thickness (5.0 mm in spectrophotometric measurements and 8.0 mm in spectroradiometric measurements). In spectroradiometric measurements, color tends to stabilize at a certain thickness (about 15 mm in sample 4, or 25 mm in sample 1). This is an expected result because increasing thickness leads to reflectivity (i.e. the reflectance of the sample does not change when thickness increases). This saturation effect cannot be perceived in spectrophotometric measurements because of the small number of available thicknesses in our experiment. In addition, it is also important to note that spectrophotometric color differences between samples at 5.0 and 50.0 mm were very high—in fact, these color differences are not reliable because at 50 mm most virgin-olive-oil samples did not transmit light at some wavelengths.

#### Relationship between Spectrophotometric and Spectroradiometric Measurements

Comparing CIELAB color coordinates found with spectrophotometer and spectroradiometer (Figs. 4, 5, 6, 7) we see that results found by these two methods have no clear relationship. This result is not surprising, because these two kinds of measurements have been made using very different geometries: in the spectrophotometer the sample is illuminated by a collimated beam, while in the spectroradiometer the sample is illuminated by diffuse light coming from all directions.

We computed the spectral absorption coefficient (Eq. 3) for each of the two measurement methods at the two lowest thicknesses. Figure 8 shows the results for oil-sample #1

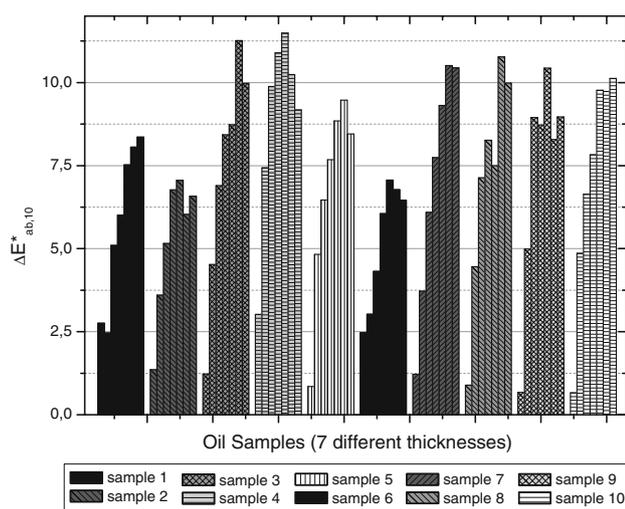


**Fig. 8** Spectral absorption coefficient  $\beta_{\lambda}$  of oil sample #1 measured at 5 and 10 mm with spectrophotometer (*symbols*), and 8 and 11.2 mm with spectroradiometer (*lines*)

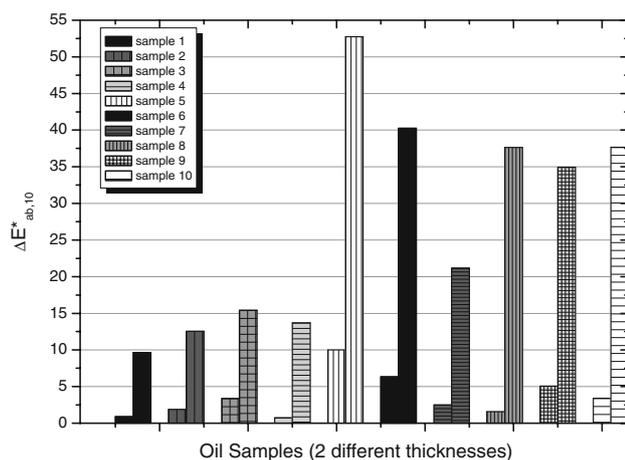
(similar results were found for the other samples). The curves corresponding to the thicknesses of 5.0 and 10.0 mm (spectrophotometric measurements) are very similar, but differ markedly from the curves corresponding to thicknesses 8.0 and 11.2 mm (spectroradiometric measurements), once again quite similar. As mentioned above, this difference is attributable to the very different lighting geometry employed in spectrophotometric and spectroradiometric measurements, as has also been reported in previous papers [18].

#### Relationship between Measurements at Different Thicknesses

We have computed the CIELAB color difference between each experimental measurement and the theoretical prediction made using the Bouguer-Lambert-Beer law. As described above, for this prediction we started from measurements at lowest thickness: 8.0 mm in the spectroradiometric and 5.0 mm in the spectrophotometric method. The results found are shown in Figs. 9 and 10, where each bar represents the color difference between the theoretical prediction and experimental measurement, and the bars are grouped considering samples with increasing thicknesses from left to right. Table 3 (from data plotted in Figs. 9 and 10) shows the average CIELAB color differences  $\Delta E^*_{ab}$  between Bouguer-Lambert-Beer law predictions and experimental measurements at each thickness, and their corresponding standard deviations (SD), both for spectroradiometric and spectrophotometric methods. Predictions of the Bouguer-Lambert-Beer law differ from the experimental measurements by more than 1.0 CIELAB unit in almost all cases. Assuming a large tolerance of 5.0 CIELAB units, the Bouguer-Lambert-Beer law should be



**Fig. 9** CIELAB color differences between spectroradiometric experimental measurements and theoretical predictions made by Bouguer-Lambert-Beer law. For each of the ten oil samples the *seven bars* are grouped in increasing thickness from *left to right*



**Fig. 10** CIELAB color differences between spectrophotometric experimental measurements and theoretical predictions made by Bouguer-Lambert-Beer law. For each of the ten oil samples the *two bars* are grouped in increasing thickness from *left to right*

applied only to thicknesses lower than two times the reference (lowest) thicknesses (i.e. 8.0 and 5.0 mm for spectroradiometric and spectrophotometric measurements, respectively). This result is not unexpected because, as indicated in the Bouguer-Lambert-Beer law, it can be assumed that beyond a given thickness color remains constant.

With respect to the Kubelka-Munk theory, which takes into account the spectral absorption and scattering of light, we have also tested its predictions for oil colors at different sample thicknesses. We can test the validity of this theory only in spectroradiometric measurements of oil samples because the Kubelka-Munk equations require the presence

of backgrounds. Figure 11 shows CIELAB color difference between the experimental measurements with a white background and the predictions made by Kubelka-Munk for the same white background, starting from the measurements made with the lowest thickness (8.0 mm) with white and green backgrounds. The bars are again grouped indicating samples with increasing thickness from left to right.

Table 4 shows the averages (and standard deviations SD) of the CIELAB color differences between Kubelka-Munk theoretical predictions using different backgrounds and thicknesses, and spectroradiometric experimental measurements at the same thicknesses, considering the ten oil samples analyzed. The color differences differed sharply, depending on the thickness we wish to predict and also the background used for the theoretical prediction. The best results pertained to the green and yellow backgrounds, and the worst to red and blue backgrounds. These results can be explained considering that olive oils have a high transmittance in the intermediate region of the visible spectrum, and the red and blue backgrounds do not reflect one of these two spectral regions (see Figs. 1, 3), in such a way that a considerable part of the spectrum of the oils is eliminated by these backgrounds.

Finally, comparing the average results found using the Bouguer-Lambert-Beer law (Table 3) with the ones found using the Kubelka-Munk theory (Table 4), we find that the Bouguer-Lambert-Beer law makes better color predictions at different sample thicknesses, except with the yellow background for five thicknesses.

## Conclusion

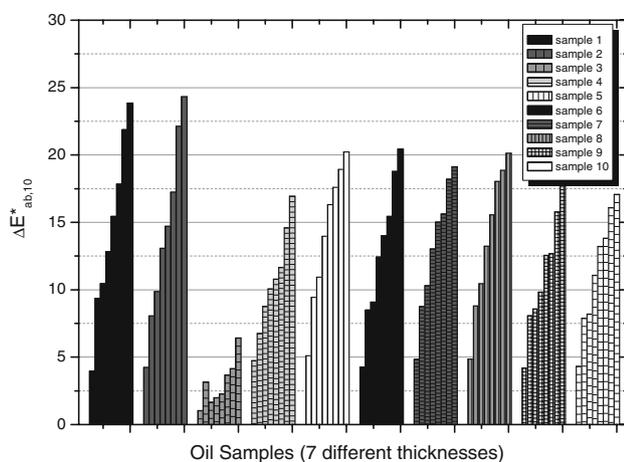
Current results show that extra-virgin-olive oil color not only strongly depends on sample thickness (Figs. 4, 5, 6), but also the lighting geometry strongly influences the measurement.

On the other hand, it would be useful to determine the color of a sample at different thicknesses starting from measurements made using a lesser thicknesses, because we could estimate oil color in bottles or transparent packaging. This dependence is studied by Bouguer-Lambert-Beer law and Kubelka-Munk theory, but unfortunately they do not provide reliable results when applied in our experimental conditions (see Figs. 9, 10, 11; Tables 3, 4). High average color differences between experimental and predicted results are also often accompanied by high values of standard deviations (SD). Perhaps large quantities of chlorophylls and carotenoids in virgin olive oils produce a non-linear relationship between spectral absorbance and thickness, as suggested by the Bouguer-Lambert-Beer law using high concentrated solutions [11]. In addition, the

**Table 3** CIELAB color differences  $\Delta E^*_{ab}$  and standard deviations (SD) between predicted (Bouguer-Lambert-Beer law) and experimental color measurements, for the ten oil-samples analyzed

Thickness (mm)	Spectroradiometric								Spectrophotometric		
	8	11.2	15.6	19.6	23.2	27.2	36.8	46.4	5	10	50
Average $\Delta E^*_{ab}$	0	1.51	4.39	6.66	7.84	8.77	9.12	8.85	0	3.58	27.57
SD	0	0.89	1.36	1.72	1.43	1.51	1.76	1.42	0	2.88	14.84

CIELAB color differences between predictions made by the Bouguer-Lambert-Beer law and experimental measurements (spectroradiometric and spectrophotometric), for each thickness considered. Average values and standard deviations (SD) for the ten oil samples are shown in the last two rows (thicknesses of 8.0 and 5.0 mm are the references to compute predictions for spectroradiometric and spectrophotometric measurements, respectively)

**Fig. 11** CIELAB color differences between spectroradiometric experimental measurements and theoretical predictions made by Kubelka-Munk theory using the green and white backgrounds. For each of the ten oil samples the *eight bars* are grouped in increasing thickness from *left to right*. The average results for other backgrounds are summarized in Table 4**Table 4** CIELAB color-differences  $\Delta E^*_{ab}$  and standard deviations (SD) between predicted (Kubelka-Munk theory) and experimental color measurements, for the ten oil samples analyzed

Background	Thickness (mm)	8	11.2	15.6	19.6	23.2	27.2	36.8	46.4
Green	Average $\Delta E^*_{ab}$	4.15	7.88	8.82	11.15	12.99	14.36	16.94	18.62
	SD	1.16	1.83	2.69	3.51	4.11	4.37	5.11	4.98
Yellow	Average $\Delta E^*_{ab}$	3.21	5.25	4.49	4.56	4.21	3.61	3.30	7.12
	SD	0.95	1.10	1.26	1.50	1.41	1.04	1.99	3.44
Red	Average $\Delta E^*_{ab}$	23.22	26.82	27.82	30.17	32.13	34.00	37.76	40.49
	SD	32.90	31.51	29.34	27.09	25.47	23.98	19.65	16.44
Blue	Average $\Delta E^*_{ab}$	16.75	22.59	26.80	31.88	35.62	38.74	44.55	48.39
	SD	24.09	22.67	20.15	17.88	16.33	15.33	12.53	11.24

CIELAB color differences between predictions of Kubelka-Munk theory and experimental spectroradiometric measurements, for each thickness considered and each background (in addition to the white one). CIELAB average values  $\Delta E^*_{ab}$  and standard deviations (SD) for the ten oil samples are shown

transparency of the oil samples under diffuse lighting in a color cabinet probably makes inappropriate the use of the two-flows Kubelka-Munk theory employed in the current paper.

In the current situation, in order to achieve uniformity of practice between different laboratories and/or industries, we propose the standardization of olive-oil color measurement (there are propositions for other foods liquids, as, for example, the method of the USDA orange juice color standards [19]), using a spectrophotometer and samples in cells with 5.0 mm path length. This proposal is a consequence of the unsuccessful results found with the Bouguer-Lambert-Beer law and Kubelka-Munk theory, and it is based mainly on the following practical reasons: (1) spectrophotometers (but not spectroradiometers) are available in most laboratories or oil-related industries; (2) while cells with 5.0 mm thickness require a small quantity of oil, the use of cells with less thickness (e.g. 1.0 mm) is cumbersome because they are not easy to clean when using most olive oils; (3) cells with 5.0 mm are appropriate for

spectrophotometric measurements of most virgin olive oils, including turbid and dark ones. In addition, the choice of a 5.0 mm thickness approximately follows previous findings for many other food liquids, which showed good agreement between transreflectance measurements made “at a depth of a few mm” and observed color [19].

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## References

- Alba J, Izquierdo JR, Gutiérrez F (1997) Aceite de oliva virgen. Análisis sensorial. Madrid. Agrícola Española, SA
- Standard COI/T.20/Doc. n°5 (1987) Glass for olive oil tasting
- Moyano MJ, Melgosa M, Alba J, Hita E, Heredia FJ (1999) Reliability of the bromthymol blue method for color in virgin olive oils. *J Am Oil Chem Soc* 76:687–692
- Melgosa M, Pérez MM, Hita E, Heredia FJ, Alba J, Moyano MJ (2000) Precision and accuracy in the color specification of virgin olive oils from the bromthymol blue method. *J Am Oil Chem Soc* 77:1093–1099
- Martínez JA, Melgosa M, Pérez MM, Hita E, Negueruela AI (2001) Note. Visual and instrumental color evaluation in red wines. *Food Sci Tech Int* 7:439–444
- Huertas R, Yebra A, Pérez MM, Melgosa M, Negueruela AI (2003) Color variability for a wine sample poured into a standard glass wine sampler. *Color Res Appl* 28:473–479
- CIE Publication 15:2004 (2004) Colorimetry (Technical Report), International Commission on Illumination (CIE), CIE Central Bureau, Vienna
- Moyano MJ (2002) Estudio del color de aceites de oliva vírgenes de Andalucía. PhD dissertation. Facultad de Farmacia (Universidad de Sevilla), Instituto de la Grasa (CSIC), Sevilla, Spain
- Melgosa M, Pérez MM, Hita E, Heredia FJ, Alba J, Moyano MJ (2001) Reproducibility of the bromthymol blue standards used for color specification of virgin olive oils. *J Am Oil Chem Soc* 78:265–270
- Sánchez-Marañón M, Delgado G, Delgado R, Pérez MM, Melgosa M (1995) Spectroradiometric and visual color measurements of disturbed and undisturbed soil samples. *Soil Sci* 160:291–303
- Berns RS (2000) Billmeyer and Saltzman's principles of color technology, 3rd edn. Wiley, pp 157–167
- Roa R, Huertas R, López-Álvarez MA, Gómez-Robledo L, Melgosa M (2008) A comparison between illuminants and light-source simulators. *Opt Pur Apl* 41:291–300
- Hard A, Sivik L, Tonnquist G (1996) NCS, natural color system—from concepts to research and applications. Part I. *Color Res Appl* 21:180–205; Part II. *Color Res Appl* 21:206–220
- Judd DB, Wyszecki G (1972) Color in business, science and industry. Wiley, pp 420–438
- CIE Publication 116-1995 (1995) Industrial colour-difference evaluation. CIE Central Bureau, Vienna
- CIE Publication 142-2001 (2001) Improvement to industrial colour-difference evaluation. CIE Central Bureau, Vienna
- Melgosa M (2000) Testing CIELAB-based color-difference formulas. *Color Res Appl* 25:49–55
- Lomas AM, Negueruela AI, Echavarri JF (1994) Determination of the color of Rioja red wine by trans-reflectance. *Opt Pur Apl* 27:70–77
- Hutchings JB (1999) Food color and appearance, 2nd edn. Aspen Publishers, pp 198–203