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ORIGINAL ARTICLE

Influence of Turbidity Grade on Color and Appearance of Virgin Olive Oil

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Abstract The appearance of most of the commercialized olive oils involves both their color and turbidity depending on the different technologies used for their elaboration. This research has been carried out to study the filtration impact on the colorimetric changes of virgin olive oils. Naturally turbid olive oils were blended at different proportions (100, 80, 60, 40, 20 and 0%) with their corresponding filtered replicates to obtain a scale of six levels of turbidity and simulating different turbidity grades. Tristimulus colorimetry, particularly the CIELAB uniform color, was used to follow color changes. As turbidity of the oil increased in the blend, yellowish oils, darker, and less saturated were obtained. Univariate correlations between the colorimetric parameters and turbid content were achieved with second degree polynomial equations, being chroma (C^*_{ab}) and hue (h_{ab}) the best correlated parameters. The color differences (ΔE^*_{ab}) calculated between turbid oils (100%) and the consecutively decreasing turbid oils blends ranged from 3.18 to 18.72 CIELAB units, revealing differences in color visually perceptible to the human eye.

Keywords Color · Filtration · Turbidity · Virgin olive oil

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Introduction

Visual attributes play an important role in food acceptance because visual appreciation is the first sensory impression of quality that consumers normally experience [1, 2]. Although olive oil color is not included in the International Olive Oil Council (IOOC) and in the European Communities standards [3, 4], many studies reveal that texture and color are determinant criteria for choosing specific olive oil brands by consumers from different countries, ranking ahead of price, taste and odor [5–7].

Extra virgin olive oil (EVOIL) is a natural product obtained by simple pressing of olive fruit (*Olea europea*) and the only one that can be consumed without refining. The European legislation states that EVOIL must be exclusively obtained through mechanical and physical processes, such as pressing, washing, decantation, centrifugation and filtration that do not modify its characteristics (EU regulations 2568/91).

From a commercial perspective, apart from the olive oil standard market which prefers the commercially filtered olive oil, there is also an increasing interest in cloudy (veiled) extra-virgin olive oil since it is considered less processed by some consumers [8, 9]. In this sense, a large increase in the demand for freshly produced virgin olive oil can be attributed not only to its potential health benefits but also to its particular organoleptic properties [10].

The oil extracted from the olive paste is naturally turbid and opalescent and contains microdroplets of vegetation water and solid particles from the olive fruit. According to the industrial practice, it is stored in tanks prior to final filtration and bottling. Storing allows the vegetation water and sediments to settle down by gradual decantation. In this way, the freshly pressed oil is slightly clarified. In artisan production methods, the oil is transferred to bottles just before storing, so it usually becomes turbid. But also different filtration processes have become widespread in the olive oil industry (traditional by a filter-press or innovative by cross-flow filtration using membranes) in order to remove damaging substances, shortening storage times and making the oil brilliant [11–14].

Microscopic examination has shown that virgin olive oil has the characteristics of a water-in-oil emulsion due to its vegetation water content [9]. This physicochemical state may explain the stability of the cloudy form, so that "veiled" oil can retain its turbidity for several weeks or even months before full deposition of the residue. Moreover, if filtration and bottling take place in haste, the oil may become cloudy again in the bottle. In this sense, the appearance of most commercialized olive oils involves both their color and turbidity.

Although a lot of research has been carried out with the goal of assessing color changes on olive oils determined by different factors (olive variety, cultivar conditions, maturation index, or production zone, humidity, temperature, light, oxygen exposure, container type, and material, etc. [5, 15–24] few studies have shown the influence of the turbidity or cloudiness on it. In a turbid medium, suspended particles divert light from its regular course producing scattering [25, 26]. The overall appearance of a turbid medium depends not only on the light absorbed in the visible region but also on the scattering of light because it strongly influences their color [27, 28] and consequently the consumer's perception of quality.

Therefore, the aim of this work was to assess how different grades of filtration affect the color characteristics of virgin olive oil. To accomplish the stated objective, naturally turbid oils with very different turbidity grades were used to obtain a scale of turbidity, which included the whole range of turbidity of the olive oil. Tristimulus colorimetry, particularly the CIELAB uniform color space, was used to follow color changes. The CIELAB system has been accepted worldwide in most industries. Its application to virgin olive oil samples provides better results than those obtained by visual methods [29].

Materials and Methods

Experimental Methodology

Twenty five samples of natural turbid olive oil with very different turbidity grades (ranging from 24.60 to 215 NTU) were considered to produce collections of olive oil turbidity scales. Samples were supplied by Almazara Experimental (Instituto de la Grasa, CSIC, Spain). First, 100 ml of each oil sample was filtered in the laboratory using a normal filter paper (9 cm, density: 62 g/m^2, porosity: normal, FilterLab). The handling of the samples was performed in the dark. Then, each original oil (turbid) was blended at different proportions (100, 80, 60, 40, 20 and 0%) with its corresponding filtered replicate obtaining a scale of six levels of turbidity (Table 1). The new oil samples resulting from the blends were placed in glass vials and closed with screw caps. Finally, 25 turbidity scales with a total of 150 oil samples differing in their filtration grade were obtained.

Instrumental

Nephelometric Turbidimeter

The nephelometric measurements were carried out with a Hach Turbidimeter Model 2100P (Loveland, CO, USA), which includes a tungsten-filament lamp, a 90° detector to monitor scattered light and a transmitted light detector. The instrument's microprocessor calculates the ratio of the signals from 90° and transmitted light detectors and compares the intensity of light scattered with those of a standard suspension. This micro-processor corrects for interference from color and/or light absorbing materials and compensates for fluctuations in lamp intensity. The optical design also minimizes stray light, increasing measurement accuracy.

Color Measurement

The instrumentation used in our study comprised a custom-made optoelectronic device for measuring the oil's absorption spectra (Fig. 1) with a PC-controlled interface. The optical probe consisted of a cylindrical jig containing the glass vial with the sample. Vial diameter was 23 mm. A white LED was used as the light source, spanning the 450–630 nm spectral range. The LED spectrum is showed in Fig. 2. A miniaturized optical fiber spectrometer was used as the detector, having a 350–1150 nm sensitive range with a spectral resolution of 3.3 nm. Standard multimode optical fiber strands, with a 200 μm core diameter, were used for connecting the source and the detector to the glass vial containing the sample. The optical fiber ended with GRIN μ-lenses for beam collimation. Illumination and

Table 1 Turbidity scales

Turbidity scales	Proportion turbid/filter oil
1	100% filtered oil
2	80% turbid oil + 20% filtered oil
3	60% turbid oil + 40% filtered oil
4	40% turbid oil + 60% filtered oil
5	20% turbid oil + 80% filtered oil
6	100% turbid oil

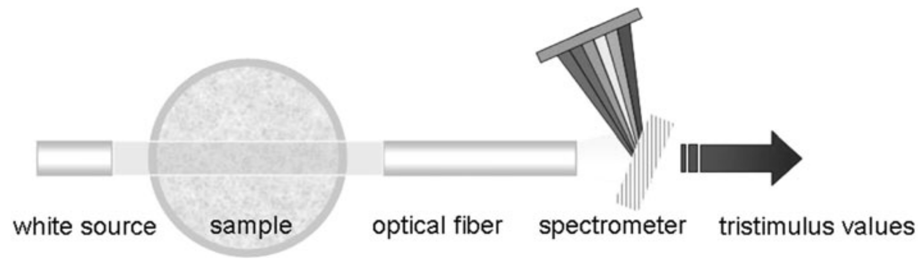

Fig. 1 Miniaturized optical fiber spectrometer used for measuring the absorption and transmission spectra of olive oils

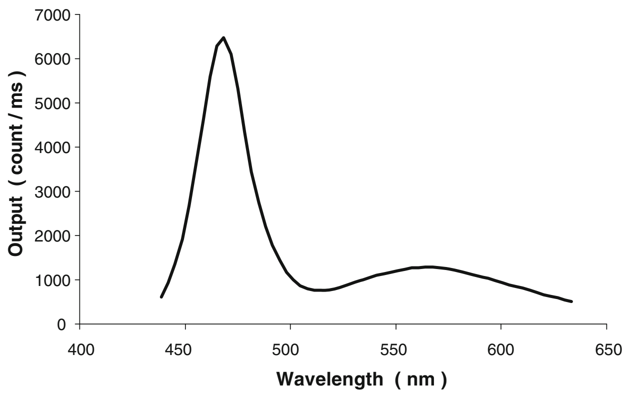

Fig. 2 Spectral power distribution of the LED used

detection fibers were aligned at 180° in order to measure the transmitted spectra. The LED intensity was electronically controlled to give adequate signal-to-noise ratios, providing a scanning system that was synchronized to the spectrometer receiver without bulky and complicated mechanical scanning arrangements [27, 28].

The samples were carefully homogenized prior to the spectrophotometric analysis to avoid sedimentation of turbidity and air bubbles. All the instrumental measurements were carried out in dim ambient illumination to avoid possible interferences from other external sources. In addition to this, the glass vial was placed inside a dark plastic material inside the cylindrical jig to avoid environmental light entry (radiation contamination). To calculate the transmittance spectrum, the wavelength λ radiation flux measured through distilled water was used as a reference. Distilled water is considered not to have any absorption or scattering properties. This way, the transmittance spectrum is described as:

$$T\forall\lambda_{429-681} = \mathrm{I}\ (0)\forall\lambda_{429-681\ \mathrm{sample}}/\mathrm{I}(0)\forall\lambda_{429-681\ \mathrm{distilledwater}}$$

The transmitted spectrum (429–679 nm) was recorded ($\Delta\lambda = 2$ nm). The Illuminant D65 and 10° standard observer (corresponding to the CIE 1964 (x_{10}, y_{10}) color matching functions) were considered in the calculation. The color parameters (L^*, a^*, b^*, ΔC^*_{ab} and h_{ab}) corresponding to the CIELAB uniform color space [30] were determined by using the original software CromaLab® [31], following the recommendations of the Commission Internationale de L'Eclariage [30].

Color differences, which are very important to evaluate relationships between visual and numerical analyses, are calculated as the Euclidean distance between two points in the three-dimensional space defined by L^*, a^* and b^*:

$$\Delta E_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$$

The lightness, chroma and hue differences (ΔL^*, ΔC^*_{ab} and Δh_{ab}) between the different turbidity levels were also calculated to assess the trend of the color changes.

Statistical Analysis

ANOVA and linear regression analysis of the data were performed using the Statistica® v 8.0 software [32].

Results and Discussion

Spectrophotometric Study

Figure 3 shows typical absorption and transmission spectra of an olive oil (sample no. 1) registered as a function of the six turbidity grades (100, 80, 60, 40, 20 and 0% of turbid oil in the blend). Regardless of turbidity level, all the olive oils showed similar VIS absorption spectra profiles characterized by a broad absorption band in the blue area, between 430 and 525 nm, corresponding to the yellow color transmission region. As it has been widely described, in this zone, three maxima were clearly defined: two of them over 433 and 457 nm, which could be assigned to chlorophylls and carotenoids in general, and the third over 480 nm, corresponding only to the carotenoid fraction, usually expressed as lutein, the dominant pigment in this fraction. At 677 nm a less intense maximum, corresponding to the red color absorption zone (green color transmission area) was found, which could be assigned to chlorophyll and mainly to pheophytin, its major component [5, 19].

Although VIS spectra pattern was similar in the oils studied, it was clearly noted an important influence of the turbidity phenomenon on the absorption or transmission

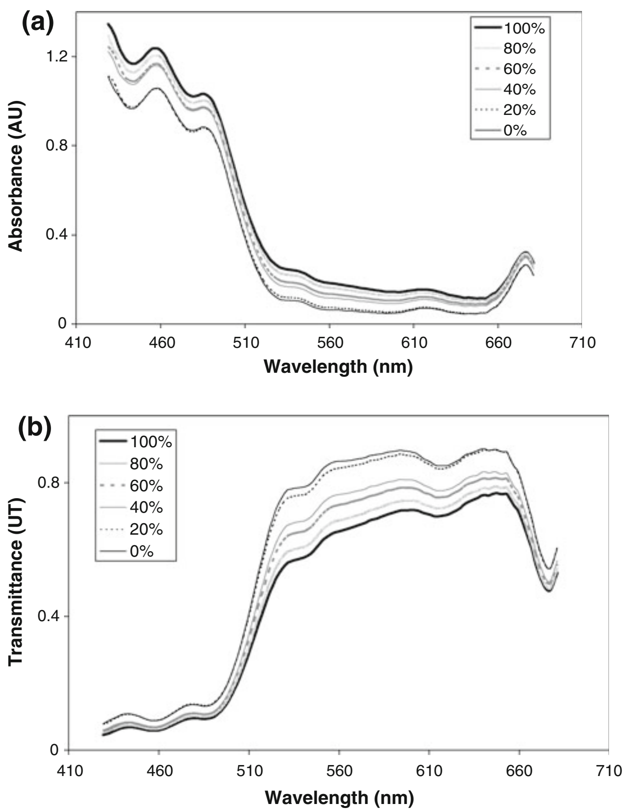

Fig. 3 Absorbance and transmittance spectra of an olive oil (sample 1) as a function of the percentage of turbid oil in the blend

intensities. The values in increasing order of turbidity (NTU) and the global transmittance values ($\Sigma T_{429–679}$, AU) for each olive oil sample as a function of the six turbidity grades are shown in Table 2. As can be observed, in all scales elaborated, the higher percentage of turbid oil in the blend (100%) the lower the values of total transmittance. This fact can be explained by the larger the percentage of turbid oil, the larger the fraction of light that was multiply scattered backwards by the droplets and therefore less light was transmitted through the emulsions [33]. However, in some cases, a particular increase in the percentage of the turbid oil in the blend did not always correspond to the same decrease in the transmitted light (*T*). This fact can be explained because the naturally turbid oils used in this study were originally very different according to the grade and kind of turbidity, which depend of the droplet characteristics (size and concentration). Consequently, the light scattering did not always occur to the same extent among the different samples considered.

Calculation of the simple regression coefficients between turbidity values and total transmittance for each turbidity scale confirmed that the relationship was significantly high (*r* values ranged from −0.92 to −0.99 units) independent of the lesser or greater turbidity range that the scales presented. The turbidity range of the scales elaborated varied from

Table 2 Turbidity units (NTU) and global transmittance ($T{:}\sum T_{429–682}$) of the olive oils blends analyzed ($n = 150$)

Oil samples		% Turbid oil					
		0%	20%	40%	60%	80%	100%
1	NTU	13.70	15.90	19.70	24.40	29.20	35.20
	T	67.74	62.85	59.26	54.40	49.56	44.58
2	NTU	40.00	42.50	45.90	48.80	57.65	66.50
	T	39.54	38.97	34.29	29.80	31.47	32.07
3	NTU	58.00	59.10	60.75	62.40	65.70	74.70
	T	23.35	21.91	21.64	21.38	19.64	17.60
4	NTU	19.00	22.90	30.90	31.60	38.40	39.90
	T	50.68	47.40	44.89	42.48	38.98	35.64
5	NTU	50.80	50.90	52.90	57.20	59.80	64.20
	T	33.14	32.31	32.04	31.77	27.74	27.42
6	NTU	18.30	19.60	40.20	53.80	140.00	215.00
	T	34.01	32.22	27.74	22.22	10.32	6.32
7	NTU	14.70	20.40	29.40	30.10	46.20	54.50
	T	56.31	49.01	48.08	45.53	39.48	33.43
8	NTU	10.60	11.50	15.50	16.40	21.00	24.60
	T	75.80	73.33	69.22	67.60	62.03	58.64
9	NTU	15.10	18.50	21.20	25.30	37.30	47.20
	T	65.78	60.64	60.45	50.00	50.03	43.92
10	NTU	11.50	15.60	17.70	21.40	26.40	28.10
	T	59.77	58.16	54.05	53.05	53.86	54.67
11	NTU	9.58	11.90	15.00	18.90	26.60	27.90
	T	75.15	74.14	67.18	65.13	61.74	59.29
12	NTU	26.90	28.10	38.80	45.30	80.90	99.70
	T	55.43	58.21	48.65	43.34	36.83	23.86
13	NTU	9.32	13.20	18.60	19.60	25.10	36.50
	T	72.36	68.66	59.38	55.96	52.75	50.26
14	NTU	16.60	23.50	38.00	38.90	51.20	55.90
	T	89.67	82.93	59.51	55.65	43.71	36.47
15	NTU	9.22	12.10	17.00	21.50	22.30	33.20
	T	78.75	70.65	67.04	63.42	55.89	53.94
16	NTU	32.80	36.70	40.10	49.30	58.00	65.30
	T	50.79	41.76	39.45	37.15	35.43	29.76
17	NTU	14.60	28.40	34.90	41.10	51.50	64.70
	T	80.65	58.26	53.14	52.21	39.94	35.85
18	NTU	23.60	28.90	46.50	50.20	63.20	74.80
	T	56.98	53.72	42.32	40.27	32.76	31.48
19	NTU	8.58	11.60	16.20	20.80	27.00	28.90
	T	86.21	86.49	78.75	71.02	68.01	66.79
20	NTU	49.90	54.40	56.85	59.30	67.90	74.90
	T	86.21	86.49	78.75	71.02	68.01	66.79
21	NTU	32.30	36.60	46.50	47.30	65.20	79.20
	T	63.60	57.80	52.90	47.29	43.82	41.35
22	NTU	52.10	55.10	63.90	72.10	85.70	93.70
	T	29.92	24.43	22.78	21.06	17.42	15.11
23	NTU	65.80	71.60	75.80	82.30	89.60	132.00
	T	30.61	28.02	22.76	22.91	16.65	14.74

Table 2 continued

Oil samples		% Turbid oil					
		0%	20%	40%	60%	80%	100%
24	NTU	38.60	50.00	51.40	55.70	58.90	62.90
	T	42.97	37.34	37.25	34.56	29.33	29.05
25	NTU	9.61	15.10	19.80	24.40	37.40	39.00
	T	80.22	73.91	59.01	59.88	54.77	45.45

values below 30 NTU (low turbidity scales) to values over 60 NTU (high turbidity scales) due to the fact that the original turbid oils presented very different turbidity grades (ranging from 24.60 to 215 NTU).

It is also worth noting that global transmission did not always decrease proportionally to the percentage of turbid oil containied in the blend. As a representative example (Fig. 3), it can be observed that the decrease was almost insignificant between the consecutive proportions 100–80% and 20–0% of turbid oil in the blend, while was considerable between samples having a difference of up to 40% of turbid oil. Analogously, when all the olive oil scales were considered individually, the majority of the samples showed similar spectral behavior. This fact suggests that the color differences between turbid olive oil and its corresponding filtered oil will be more or less notable according to the effectiveness and magnitude of the filtration process applied as well as the nature of the turbidity that the oil presents.

Colorimetric Study and Color Modification

With the objective of evaluating the effect of turbidity on the color of olive oils, a color analysis was performed in the CIELAB space. The color characteristics of the analyzed oils are summarized in Table 3, where the basic descriptive statistics for these variables are included in considering the different turbidity levels studied. The results showed that the turbidity provokes important changes both on qualitative and quantitative psychophysical components of the color (L^*, C^*_{ab}, h_{ab}). Figure 4 depicts the lightness (L^*) values (a) and the location of the whole set of samples within the (a*b*) diagram (b). For a better visualization of the turbidity effect on the color of a specific olive oil sample, the colorimetric parameters of oil sample no. 1 are also individually represented as a function of the six turbidity grades (Fig. 4c, d).

It can be observed that the lightness (L^*) of the filtered oils decreased as the percentage of turbid oil in the blend increased. Across the different oils scales studied, the lightness values fell between 7 and 52%, although most of the samples had values closed to the global mean (around 18%). An increase in the scattering power in the blend due to the increasing turbidity should be responsible for the observed decrease in the L^* values because as the amount of reflected light increases, the less light is transmitted through the sample. Consequently, they appeared to be darker.

Table 3 Statistical descriptive CIELAB color values of the oils studied by %turbid oil in the blend ($n = 25$)

CIELAB parameters	Turbid oil (%)	Mean	Interval	SD
L^*	0	84.15	61.00–95.78	10.62
	20	81.65	59.42–95.64	10.80
	40	78.36	59.00–90.69	9.40
	60	76.39	57.84–89.53	10.35
	80	72.73	43.72–87.76	12.11
	100	69.49	34.70–87.14	13.11
a^*	0	−26.73	−41.11–(−16.18)	5.95
	20	−25.17	−40.53–(−16.55)	5.92
	40	−23.41	−37.35–(−13.30)	6.47
	60	−22.17	−34.27–(−12.64)	5.90
	80	−20.24	−27.70–(−10.06)	5.68
	100	−18.68	−26.48–(−6.24)	5.79
b^*	0	63.52	47.77–81.99	8.09
	20	62.27	46.53–80.68	8.07
	40	62.74	51.01–77.21	6.64
	60	60.54	45.11–72.03	7.31
	80	58.79	44.90–67.30	6.94
	100	57.68	44.20–66.76	7.27
C^*_{ab}	0	68.15	54.77–91.72	9.07
	20	66.72	53.81–90.29	8.80
	40	66.33	53.30–85.77	8.21
	60	64.52	53.01–79.77	7.60
	80	62.43	52.03–72.78	7.02
	100	60.91	49.01–71.44	7.13
h_{ab}	0	113.29	106.77–119.48	3.84
	20	112.03	105.47–118.50	3.78
	40	110.36	103.70–115.81	3.94
	60	109.92	103.44–115.44	3.96
	80	108.75	100.91–114.37	4.25
	100	107.03	97.32–112.48	4.55

According to their location in the (a*b*) colorimetric diagram, turbidity seems to produce a slight displacement of the chroma (C^*_{ab}) and the hue angle (h_{ab}) of the oils. As turbid oil increase in the blend, the color of the samples became more achromatic (a^* and b^* tended toward zero), darker (L^* decrease) and with a lower color intensity (close to the coordinates axis). The qualitative component color, the hue angle (h_{ab}), tends to diminish with increasing turbidity (the global mean value is between 113.29° and 107.64°) from a greener toward a yellowish tone, which is to be expected because a^* decreased more strongly than

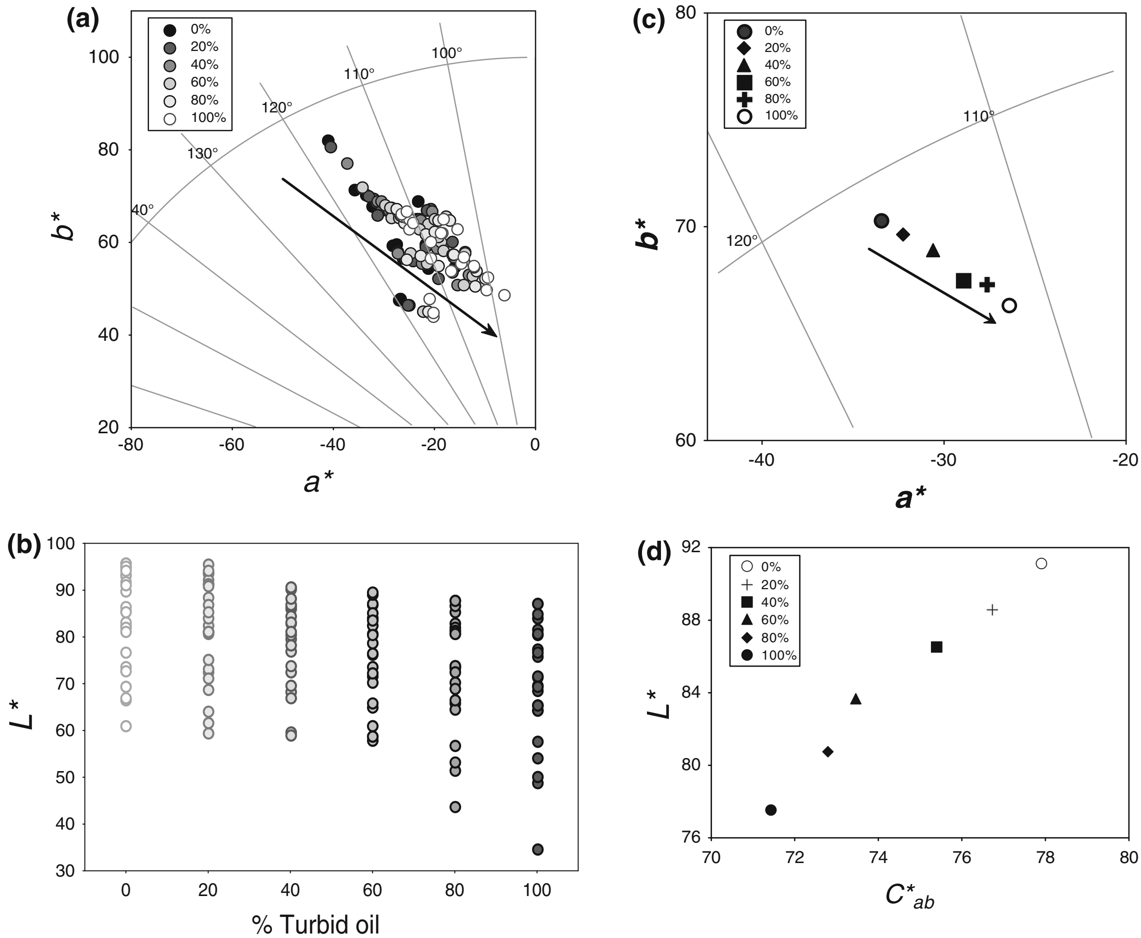

Fig. 4 Location of the samples within (**a**) the (a*b*) diagram and (**b**) lightness values (L^*) of the whole set of samples as well as the same colorimetric parameters corresponding to oil sample 1 (**c** and **d**)

b^*, so the intensity of the green color was minimized and the contribution of the yellow color was more apparent. The most likely reason for the increase in the "yellowish" of the turbid oils is that certain wavelengths are more selectively removed (scattered) from the light beam so the hue of an emulsion could change, even in the absence of a dye [34–36].

Concerning the chroma (C^*_{ab}) of the samples, the values decreased between 2% and 22% across the different oils scales studied. Again, as for the lightness, the chroma decreases observed in most of the samples were similar among them and to the mean values which were closer to 11%. When the whole set of samples was considered together, it was seen that the mean chroma value fell from 68.15 to 60.91 CIELAB units. The evolution of olive oil chroma observed could be explained because when a beam of white light is incident upon an emulsion, the intensity and the color of the light which is transmitted depends on the degree of scattering and absorption by the emulsion, which in turn depends on the droplet characteristics (size and concentration) and chromophore characteristics (absorption spectra and concentration) [37]. As scattering effects are more important, the reflectance increases, and the emulsion appears darker in color [2].

In conclusion, deep green oils, being more transparent and saturated were those having the highest percentage of filtered oil, while yellowish oils, darker and less saturated were those having the highest percentage of turbid oil. From a sensory perspective, these findings mean that for the same pigment content, the global appearance of an olive oil (in terms of luminosity, chromaticity and color intensity) changes notably as a consequence of the level of turbidity, which depends not only on the technical characteristics of the filter used (composition, porosity, diameter, etc.) but also on the operating parameters considered (pressure, flux, temperature, etc.).

After calculating the color characteristics, univariate correlations between the colorimetric parameters (L^*, C^*_{ab}, h_{ab}) and the turbid content (NTU) were explored in order to find out the significance of these changes. The best relationships obtained for each turbidity scale was achieved with second degree polynomial equations. Calculation of the simple regression coefficients (R^2) revealed that all the relationships were very strong (ranging from 0.91 to 0.99, $p < 0.05$), proving the relevance of this optical phenomenon on the global appearance of olive oil in terms of its color. Specifically, chroma (C^*_{ab}) and hue (h_{ab}) were the best correlated parameters since more than 70% of cases showed simple regression coefficients (R^2) higher than 0.97. A schematic representation of the lightness (L^*), chroma (C^*_{ab}) and hue (h_{ab}) evolution as a function of the turbidity content (NTU) are shown in Fig. 5 (corresponding to oil sample no. 1, the best correlation obtained), where the inverse relationship between all colorimetric parameters and increasing turbidity content can be observed. Therefore, as can be noted above, it was confirmed that higher turbidity grade results in a tendency toward darker and less vividly colored olive oils.

Considering the results obtained, which showed a clear tendency between the proportion of turbid/filtered oil in the blend and the color, an ANOVA test for repeated measurements ($\alpha = 0.05$) was applied to color parameters (L^*, C^*_{ab}, h_{ab}) between filtered oils (0%) and increasing consecutive proportions of turbid oil in the blends to test whether significant differences exist (Table 4). Taking into account the results of the test, significant differences ($p < 0.05$) were found in all color parameters between the group of filtered oils (0%) and their corresponding blends containing 60% (except to chroma), 80 or 100% of turbid oil. However significant differences between lower consecutive dilutions (0–20 and 0–40%) were not found for all colorimetric parameters. This has important consequences on perceived quality because when the turbidity decreased below a certain level the product appearance changed remarkable, allowing us to distinguish it regarding its color.

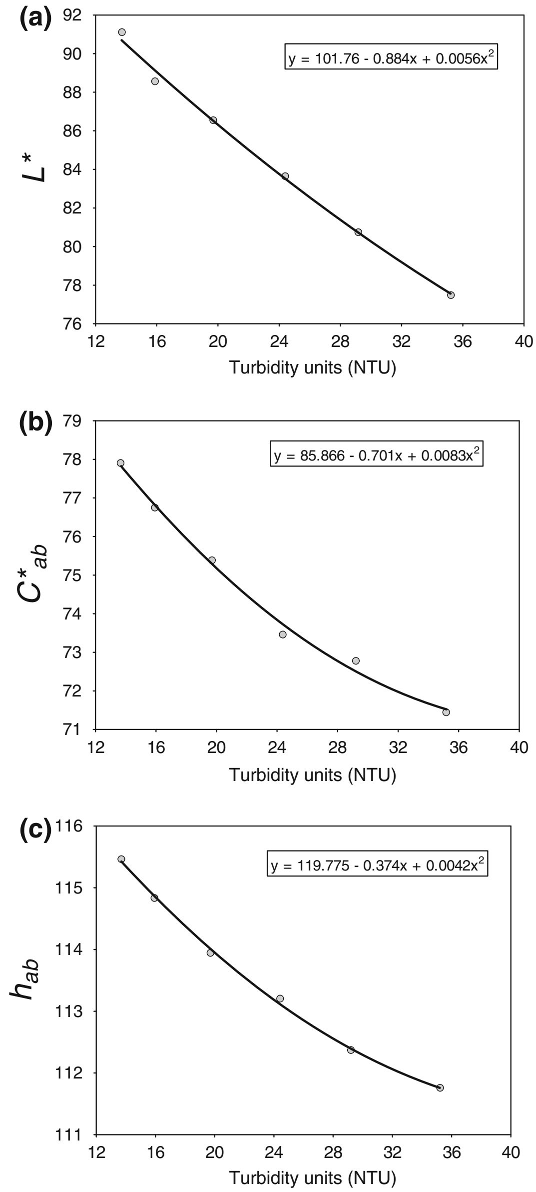

Fig. 5 CIELAB parameters evolution (L^*, C^*_{ab} and h_{ab}) as a function of turbidity content for six turbidity scale (corresponding to olive oil no. 1)

Table 4 Results of the ANOVA test for repeated measurements ($\alpha = 0.05$) between filtered oils (0%) and consecutively increasing proportions of turbid oil in the blends

	0–20%	0–40%	0–60%	0–80%	0–100%
L^*	0.41	0.05	*0.01*	*0.001*	*0.0001*
C^*_{ab}	0.57	0.48	0.13	*0.017*	*0.0030*
h_{ab}	0.24	*0.01*	*0.003*	*0.0001*	*0.0001*

p values in italics denote significant differences

CIELAB Color Differences

With the objective of evaluating the colorimetric implications attributable to turbidity phenomenon, the color differences (ΔE^*_{ab}) between filtered oils (0%) and the consecutive increasing turbid oils blends (20, 40, 60, 80 and 100%) were calculated for each olive oil sample. Table 5 shows the descriptive statistical values obtained. The lowest color differences were found between the lower consecutive dilutions (0–20%), taking values within the interval 0.74–6.63 CIELAB units, although most of the samples exhibited values lower than 3 CIELAB units. These colorimetric changes corresponded to the mean value of 3.18 CIELAB units for this pair of blends. As was expected, when the percentage of turbid oil in the blend was increased, the changes in color differences were more noticeable, especially between filtered oils and the higher turbidity pairs (over 60% of turbid oil in the blend). The

Table 5 Descriptive statistical values of color differences (ΔE^*_{ab}) and lightness, chroma and hue differences (ΔL^*, ΔC^*_{ab}, Δh_{ab}) between increasing turbid blends ($n = 25$)

CIELAB parameters	%Turbid oil (%)	Mean	Interval	SD
ΔE^*_{ab}	0–20	3.18	0.74–6.63	1.74
	0–40	7.36	1.64–15.99	3.59
	0–60	9.94	3.08–17.19	3.65
	0–80	14.95	5.63–41.85	7.86
	0–100	18.72	6.51–54.90	10.38
ΔL^*	0–20	+2.63	0.12–5.95	1.59
	0–40	+5.86	1.16–13.84	2.89
	0–60	+8.01	2.22–14.50	3.11
	0–80	+12.20	4.28–29.11	6.01
	0–100	+15.29	5.16–38.13	7.93
ΔC^*_{ab}	0–20	+1.49	0.11–4.90	1.08
	0–40	+3.09	0.23–8.01	2.05
	0–60	+3.68	0.39–11.95	2.4
	0–80	+5.85	1.04–29.92	5.79
	0–100	+7.41	1.30–39.34	7.38
Δh_{ab}	0–20	+0.96	0.06–2.80	0.68
	0–40	+2.94	0.91–9.58	2.02
	0–60	+3.47	1.02–10.80	2.15
	0–80	+4.73	1.62–13.10	2.51
	0–100	+5.79	1.93–15.31	3.01

greatest difference were found between filtered oils and the corresponding totally turbid one since their color difference values fell within the broad range 6.51–54.90 ($\Delta E^*_{ab} =$ 18.72 CIELAB units, as a mean value).

Considering that values of ΔE^*_{ab} greater than 3 CIELAB units indicate differences in color perceptible to the human eye [38], it is concluded that for most of the turbidity scales elaborated, a noticeable influence of scattering on the color of olive oils exists. Nevertheless, from an industrial point of view, it has been considered that the ranges of color differences 1.1–2.8 and 2.8–5.6 CIELAB units correspond with rigorous and normal color tolerances, respectively, whereas color differences over 5.6 CIELAB units ought to be easily distinguished [39, 40]. According to this view, the changes in olive oil color could become more appreciable to consumers ($\Delta E^*_{ab} > 5.6$) after the turbidity grade is increased to over 60% with respect to filtered oil.

In order to understand the trend of the color changes, the lightness, chroma and hue differences (ΔL^*, ΔC^*_{ab} and Δh_{ab}) between the different turbidity levels were also calculated (Table 5). The results showed that between 0 and 20% turbid oils (with only an increase of 20% in turbid oil content), for most of the samples the color differences were due to both quantitative and qualitative changes at a similar magnitude, which was reflected in the mean values for such colorimetric parameters ($\Delta L = +2.63$, $\Delta C^*_{ab} = +1.49$ and $\Delta h_{ab} = +0.96$). However, when higher turbid blends (80% and 100% pairs) were compared with respect to totally filtered oils, the changes in lightness (ΔL^*) resulted in the main contribution to the calculated color differences. Specifically when color differences were calculated between turbid oils and the corresponding totally filtered ones, it could be proved that turbidity reduced the mean values of lightness, chroma and hue to 15.29, 7.41 and 5.79 CIELAB units, respectively.

Table 6 Predictions of CIELAB color changes (%ΔE, %ΔL, %ΔC and %ΔH) of each oil sample as a function of the percentage of turbid oil in the blend

Oil samples	R^2 coefficients			
	%ΔE	%ΔL	%ΔC	%ΔH
1	0.99	0.99	0.99	0.98
2	0.99	0.99	0.99	0.98
3	0.99	0.99	0.99	0.98
4	0.98	0.99	0.97	0.90
5	0.92	0.93	0.92	0.92
6	0.98	0.98	0.98	0.97
7	0.99	0.97	0.99	0.97
8	0.98	0.99	0.97	0.95
9	0.99	0.98	0.99	0.99
10	0.97	0.98	0.99	0.99
11	0.97	0.98	0.99	0.99
12	0.98	0.98	0.95	0.97
13	0.97	0.98	0.97	0.94
14	0.98	0.97	0.99	0.98
15	0.95	0.98	0.95	0.97
16	0.97	0.98	0.97	0.99
17	0.97	0.95	0.99	0.99
18	0.98	0.97	0.99	0.99
19	0.99	0.99	0.99	0.99
20	0.99	0.99	0.99	0.97
21	0.98	0.99	0.92	0.99
22	0.99	0.99	0.99	0.95
23	0.95	0.95	0.94	0.93
24	0.97	0.97	0.97	0.99
25	0.95	0.92	0.99	0.97

In view to the clear influence of turbidity on olive oil color, it would be interesting to find mathematical equations that allow us to predict changes in color of the olive oils according to the percentage of turbid oil in the blend. Bearing in mind the high variability of turbidity ranges of olive oils scales elaborated, the relative color change between the different pairs of blends (0–20%, 0–40%, 0–60%, 0–80% and 0–100%) were calculated respecting to

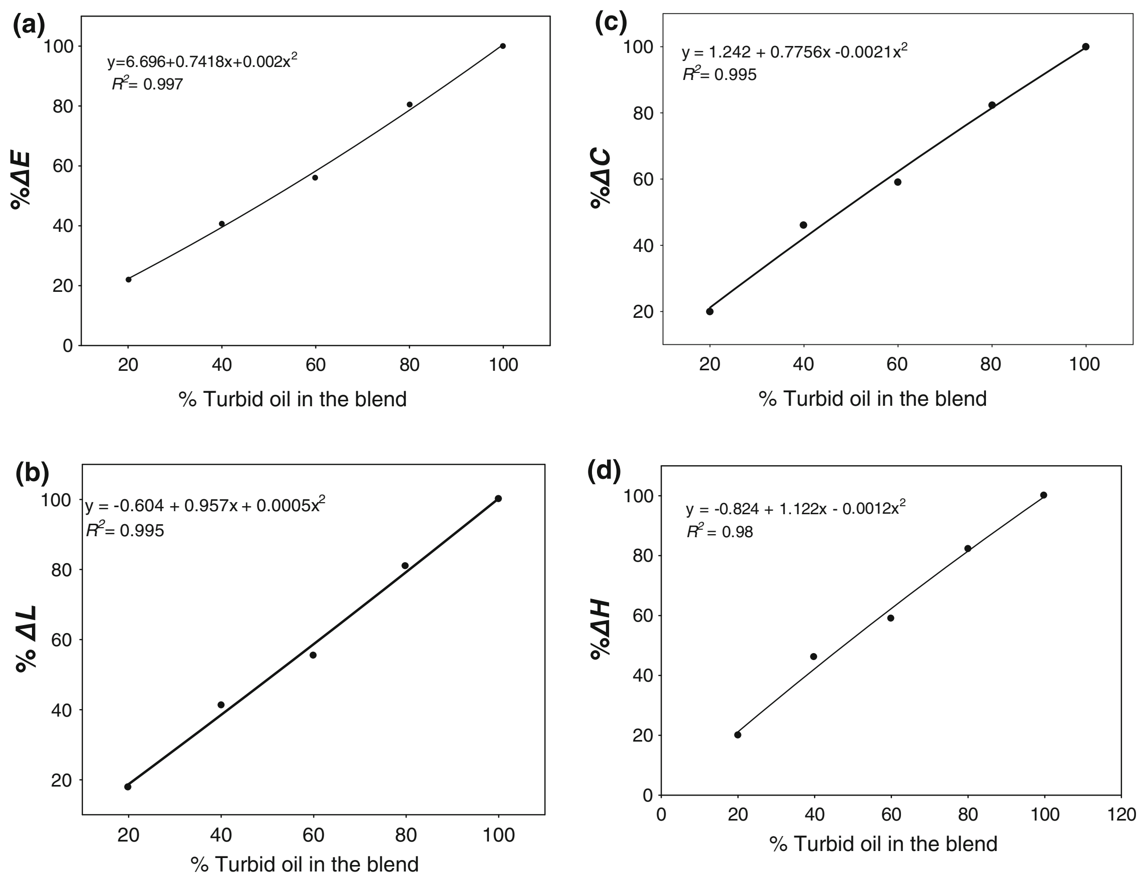

Fig. 6 Predictions of CIELAB color changes (%Δ*E*, %Δ*L*, %Δ*C* and %Δ*H*) of the mean values of whole set of olive oil as a function of percentage of turbid oil in the blend

the total color change (between 0 and 100%) in order to provide a rational basis on which to compare color modifications across all olive oil samples. Such parameters were defined as:

$$\%\Delta E = \left(\Delta E^*_{abn}/\Delta E^*_{abN}\right) \times 100$$
$$\%\Delta L = \left(\Delta L^*_n/\Delta L^*_N\right) \times 100$$
$$\%\Delta C = \left(\Delta C^*_{abn}/\Delta C^*_{abN}\right) \times 100$$
$$\%\Delta H = \left(\Delta h_{abn}/\Delta h_{abN}\right) \times 100$$

where n is the color change between the different pair of blend (0–20%, 0–40%, 0–60%, 0–80% and 0–100%) and N the total color change (between 0 and 100%).

To predict the oil color changes from the percentage of turbid oil in the blend, simple regression techniques were applied to the colorimetric changes (%Δ*E*, %Δ*L*, %Δ*C* and %Δ*H*) given by the scales of turbidity. The results show that the second degree polynomial equations gave the best adjustment model for all of them. Calculation of the simple regression coefficients (R^2) revealed that all the relationships were significant ($p < 0.05$), ranging from 0.90 to 0.99 values (Table 6).

The prediction of color difference changes (%Δ*E*) showed correlation coefficients values (R^2) higher than 0.97 for more than 80% of the olive oils considered, confirming that a strong relationship between the two variables exists. These results are very advantageous for quality control purposes in the industry, since it is then possible to obtain simple mathematical models which allow a preliminary estimation of color changes in olive oils as a function of their turbidity grades.

The graphic representation of these models which were calculated using the mean values of the whole set of samples for %Δ*E*, %Δ*L*, %Δ*C* and %Δ*H* are shown in Fig. 6. Regarding the prediction of the changes on the three colorimetric components of color (%Δ*L*, %Δ*C* and %Δ*H*), it can be observed that lightness and chroma changes (%Δ*L* and %Δ*C*) were the best colorimetric parameters estimated (mean R^2 values 0.995) with a greater number of significant correlations.

The corresponding significant equations found were as follow:

$$\%\Delta E = 6.696 + 0.7418\ (\%\ \text{turbid oil}) + 0.002\ (\%\ \text{turbid oil})^2 \quad R^2 = 0.997$$

$$\%\Delta L = -0.604 + 0.957\ (\%\ \text{turbid oil}) + 0.0005\ (\%\ \text{turbid oil})^2 \quad R^2 = 0.995$$

$$\%\Delta C = 1.242 + 0.7756\ (\%\ \text{turbid oil}) + 0.0021\ (\%\ \text{turbid oil})^2 \quad R^2 = 0.995$$

$$\%\Delta H = -0.824 + 1.122\ (\%\ \text{turbid oil}) - 0.0012\ (\%\ \text{turbid oil})^2 \quad R^2 = 0.98$$

Conclusions

The results showed that the turbidity grade brings about important changes both in qualitative and quantitative psychophysical components of the color (L^*, C^*_{ab}, h_{ab}). Deep green oils, more transparent and saturated, corresponded to those having the highest percentage of filtered oil, while yellowish oils, darker and less saturated having the highest percentage of turbid oil. The color differences (ΔE^*_{ab}) calculated between turbid oils and the consecutive decreasing turbid oils blends revealed differences in color visually perceptible to the human eye, that is, when the turbidity decreased below a certain level the product's appearance changed remarkably, allowing us to distinguish it by regarding its color.

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