Proposal of a Uniform Color Scale for Virgin Olive Oils

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ABSTRACT: A new color scale was developed from a broad data set of 1700 virgin olive oil samples over four crop seasons, which can be considered highly representative of the whole color range of virgin olive oils available in Spain. This color scale provides a new set of 60 color standards, improving the results achieved by the old 60-color standards proposed by the bromthymol blue method. Seeking the greatest possibility of including a near match between colors of virgin olive oils and proposed standards, we developed our new color scale using a recent uniform color space, with standards placed in a regular rhombohedral lattice like the one employed by the Uniform Color Scales of the Optical Society of America. The average color difference between each of the 1700 virgin olive oils and its nearest standard is reduced from 8.17 CIELAB units, using the bromthymol blue standards, to 3.99 CIELAB units using the new standards. Within a color tolerance of 7.0 CIELAB units, 93.2% of our virgin olive oils can be classified with the new standards, but only 59.1% with the bromthymol blue ones. In the interest of future adoption, the performance of the new color standards should be tested by industry and researchers.

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KEY WORDS: Bromthymol blue method, BTB method, CIELAB, color of virgin olive oils, DIN99, oil-color measurement, uniform color scales.

Color is generally considered an important organoleptic property of virgin olive oils, because it is immediately perceived and strongly influences most customer preferences. In addition, color is related to other chemical and physical properties of virgin olive oils. Consequently, a rigorous colorimetric characterization of virgin olive oils would be useful in the quality control of this product. To reach the highest quality standards in national and international markets, producers of virgin olive oils from well-known origin denominations should pay increasing attention to precise color specifications of their products.

Currently, Spain's official method for color characterization of virgin olive oils is the bromthymol blue (BTB) method (1,2). This method is based on a visual comparison between oil samples and a given set of 60 standard solutions (BTB standards), seeking the one most closely matching the color of the oil sample. When the BTB method is applied, the use of well-defined experimental conditions (i.e., light source, thickness of the samples, and background behind the samples) must be emphasized. Given that the Commission Internationale de l'Éclairage 1976-L*a*b* (CIELAB) coordinates constitute the current international standard recommended for color specifications (3), quantitative relationships between the BTB indices (pH and concentration) and CIELAB coordinates have been proposed (4).

Flaws in the BTB method have been reported (5,6). Visual comparisons with a given set of color samples, such as the BTB standards, provide a simple and quick method for color specification, but with limited precision and accuracy. The low precision and accuracy achievable by experienced observers using the BTB method under controlled illumination and observation conditions (5) can be explained by the small number of standards used (60 solutions), their nearly random distribution in the color space, and the inter- and intra-observer variability inherent in all color-matching judgments. Problems arising from spatial and temporal instability of the BTB standard solutions also have been detected (6).

Perhaps the two main flaws of the BTB method are that the 60 standard solutions do not cover the whole color range of virgin olive oils (specifically, the oils with high b* values) and that they are not uniformly distributed in the color space (5). Consequently, only a small fraction of virgin olive oils can be classified from the current BTB standards using a given color tolerance (4): 13.1% for a suprathreshold color tolerance of 1.04 CIE94 units (7), roughly equivalent to 1.52 CIELAB units (8).

A good color scale is a useful time-saver in spite of its drawbacks (9). The goal of the current paper is to propose a new color scale with the same number of samples (standards) as in the BTB scale, but to improve their performance by means of a lower average color difference between virgin olive oils and standards, and a higher number of virgin olive oils classified within a given color tolerance using the new standards. In practice the standards of the new color scale can be used for characterizing virgin olive oils through a visual comparison of oil samples and standards, as made in the BTB method. This visual comparison should be made under well-controlled experimental conditions as in the current work: oil samples 10 mm thick, illuminated by a D65 light source, and observed against a neutral background.

Our new color scale will be designated as UOCS (Uniform Oil-Color Scale) because it has been developed following the distribution of samples proposed by the Uniform Color Scale of the Optical Society of America (10), using a recently proposed color space, designated as DIN99d [(11), see Appendix], with improved uniformity over CIELAB. The UOCS has been developed on the basis of a broad set of 1700 virgin

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olive oils (12), which can be considered highly representative of the whole range of virgin olive oils in Spain.

EXPERIMENTAL PROCEDURES

A set of 1700 samples of virgin olive oils was obtained (12) from diverse olive varieties collected in the most representative production zones in Andalusia during four different harvests (1994–1995, 1995–1996, 1996–1997, and 1997–1998). About 80% of the virgin olive oil produced in Spain (the world leader in production with about 33%) comes from Andalusia (13). A total of 1008 virgin olive oil samples (59.3%) were identified as coming from one of eight specific monovarieties (the most abundant being Picual, with 56.1%). The harvest date of the olives was known for 1213 (71.4%) samples, and olives with different degrees of maturity were used (12). Oils were extracted in the laboratory of Almazara Experimental del Instituto de la Grasa (CSIC, Sevilla, Spain) by the Abencor® method (14), reproducing the industrial procedure on a small scale, and producing oil with the typical flavor and taste for organoleptic testing. Olive fruits were transformed into a paste after milling in an electric mill, and the resulting paste was mixed in a malaxator and centrifuged at 3500 rpm to produce the oil (Abencor®, Seville). All 1700 virgin oil samples employed in the current work were extracted in the laboratory (i.e., no commercial oil samples were used). The olive samples were processed within 24–48 h after they had been collected, and about 60 mL of oil was obtained per sample. All color measurements of the oil samples were performed immediately (<1 h) after extraction.

Oil spectral transmittance (380–770 nm, $\Delta\lambda = 2$ nm) was measured using a Hewlett-Packard 8452 UV-visible light diode array spectrophotometer with quartz cells of 5-mm pathlength. The 5-mm pathlength was used to fit the measurement range of our spectrophotometer (greater pathlengths would have led to weak, nonmeasurable signals), as dilution of the oil samples was considered unacceptable in our case. Measured values were referred to a 10-mm pathlength by means of the Lambert–Beer law and used to compute tristimulus values, assuming D65 illuminant and CIE 1964 Supplementary Standard Observer (3). These tristimulus values were transformed to CIELAB, assuming an *n*-hexane-measured solution as the reference white, and also to a DIN99d color space (11). The DIN99d color space has recently been proposed as a uniform color space and could be considered a candidate to replace CIELAB, given its superior performance and formal resemblance to the well-known CIELAB system. Thus, DIN99d was chosen as an appropriate color space for the design of the UOCS. In any case, as most users are familiar with the CIELAB system, which is also the official system currently recommended for color specification (3), we will report color coordinates of the UOCS and results concerning its performance both in DIN99d and in CIELAB.

In addition to the use of a DIN99d color space, another important decision for the development of the UOCS was the use of a regular rhombohedral lattice (15), seeking a uniform sampling for the region of the color space where the 1700 virgin olive oils are positioned. The rhombohedral lattice is a type of "closest packing," where each point of the lattice is surrounded by 12 nearest neighbors, all equidistant (this minimal distance represents a characteristic parameter of the lattice). The polyhedron formed by the 12 points is called a cubo-octahedron because it can be formed by cutting off the eight corners of a cube to the middle of each of its 12 edges (16). Sampling the color space in accordance with a regular rhombohedral lattice, we achieve one of the closest arrangements of colors and also a highly regular array of colors. This arrangement of color samples was chosen by the Optical Society of America for its Uniform Color Scales (17). According to Foss (cited in Ref. 10), "This method is the basis on which to assemble a collection of color chips of fixed total number that shall have the greatest possibility of including a near match for any color chosen at random."

Table 1 presents basic statistics for the CIELAB and DIN99d color coordinates of our 1700 oil samples (12). Note that the values of the SD of the three DIN99d coordinates are more similar than the ones of the CIELAB coordinates (particularly, the scattering of b_{99d} is much less than of b^*), indicating the greater uniformity of the DIN99d space. In any event, the colors of the 1700 oil samples are not uniformly distributed in any of the color spaces, as will be discussed below.

The construction of our rhombohedral lattice was started from the center of gravity of our set of 1700 oil samples in DIN99d ($L_{99d} = 87.2$; $a_{99d} = 4.6$; $b_{99d} = 40.4$), considering a parallelepiped, with dimensions two times the SD of each of the three coordinates, which contains a high percentage (87.4%) of the oil samples. The number of standards inside this parallelepiped and located in the rhombohedral lattice strongly depends on the constant distance between nearest neighbors fixed for the lattice (the lower this distance, the greater the number of standards). For example, using a distance of 1.75 DIN99d units, which is the average distance among the 60 BTB standards computed in this space, we find 833 standards inside the parallelepiped. This is a very large number of standards compared with the desired number of 60 (the number of BTB standards). Thus, it proved necessary to increase the distance of the lattice in such a way that a value

TABLE 1
Basic Statistics for the Color Coordinates of the 1700 Measured Virgin Olive Oils[a] (12)

	Coordinates	Mean	SD	Minimum	Maximum
CIELAB	L^*	85.4	6.3	49.9	99.3
	a^*	–1.2	3.1	–15.0	10.0
	b^*	84.9	26.4	12.0	134.6
DIN99d	L_{99d}	87.2	5.7	53.7	99.4
	a_{99d}	4.6	1.4	–3.4	8.1
	b_{99d}	40.4	6.9	12.7	50.3

[a]CIELAB, Commision Internationale de l'Éclairage 1976–L*a*b*; DIN99d (11), a new uniform color space.

of 3.0 DIN99d units was finally selected, resulting in 205 standards inside the parallelepiped.

Each of our 1700 olive oils was associated with one of these 205 standards, using the shortest Euclidean distance in the DIN99d space as a classification criterion. The number of oil samples classified by each of these 205 standards indicated that numerous standards (in particular, those with highest b_{99d} values, or those close to some walls of the parallelepiped) classified a very low (or null) number of oil samples. Consequently, these standards were removed from the lattice. Finally, in an attempt to classify some oil samples having low b_{99d} and a_{99d} values, we added a few standards placed outside the original parallelepiped. These filtering and expansion procedures were carefully performed to provide the final desired number of 60 standards with a continuous distribution (i.e., without interstices) in the lattice. The 60 standards finally adopted (UOCS standards) and their comparative performance with respect to the BTB standards are discussed in the next section.

RESULTS AND DISCUSSION

Table 2 gives the color coordinates of the 60 standards defining the UOCS in DIN99d and CIELAB color spaces. From the original data set of 1700 olive oil samples, the number of oil samples classified by each standard (i.e., the oil samples having this standard as its nearest neighbor), and the average color difference between these oils and the standard, are given in both color spaces. The last two rows in Table 2 show the average and SD for the 60 UOCS standards. In spite of its 3-D distribution, a simplified one-dimensional designation has been adopted for the UOCS standards in Table 2. From color coordinates provided in Table 2, it is possible to print the 60 UOCS standards, although, to avoid inaccuracies in color reproduction and subsequent improper usage of the scale, this has not been done here. Table 3 shows the same information as Table 2 but for the 60 BTB standards.

Table 2 shows that some UOCS standards classify only a low number of oil samples, but these standards must not be removed in order to maintain the desired continuity in the distribution of the standards in the DIN99d color space, as explained above. Table 3 reflects that 7 BTB standards do not classify any oil sample in DIN99d (and another 6 BTB standards classify only one oil sample); thus, these BTB standards appear to be useless for the current oil-sample data set (12). In addition, some of the BTB standards that appear to be the best ones in Table 3 because of their high number of classified oils (e.g., 2-10) are not so because of the very large average color difference between oils and these standards.

The average results of Tables 2 and 3 illustrate the improvement of the UOCS scale over the BTB one. Thus, for the UOCS scale, the average color difference between the oils and the standards was 1.73 DIN99d units (4.00 CIELAB units), as opposed to 3.49 DIN99d units (6.10 CIELAB units) for the BTB one. The SD of these figures are also considerably lower for the UOCS scale than for BTB. The value of 1.73 DIN99d units is consistent with the theoretical value of 1.5 DIN99d units, which should be expected from a rhombohedral lattice with nearest neighbors at 3.0 DIN99d units, bearing in mind that some oil samples lay outside the lattice. Also, Tables 2 and 3 reveal that the number of oil samples classified by the 60 standards shows greater dispersion for the BTB scale than for the UOCS (SD of 36.6 against 21.4 in DIN99d, respectively).

Figure 1 plots the CIELAB a*b* (top), b*L* (middle), and a*L* (bottom) projections for the 60 BTB standards (left), 1700 virgin olive oils (middle), and 60 UOCS standards (right). For easier comparison, the same scales have been used for each projection in the three data sets, and a cross marks the position of the center of gravity of the 1700 oil samples. The left column in Figure 1 shows that the BTB standards are noticeably displaced with respect to the center of gravity of our oil samples (12), as has also been reported for other data sets (5), this leading to a negative performance of the BTB scale. The UOCS standards (right column) are more centered with respect to the cloud of points corresponding to our oil samples, in terms of the overall geometrical shape. The slightly irregular distribution of the UOCS standards plotted in Figure 1 (right column) is attributable to the nonlinear transformations involved between DIN99d and CIELAB; that is, the rhombohedral lattice employed for the design of UOCS used the DIN99d space in contrast to the projections in Figure 1 that correspond to the more familiar CIELAB system.

For another illustration of the superior performance of UOCS with respect to the BTB, we computed CIELAB color differences from each of the 1700 oil samples to the nearest standard in the two scales. The average color difference between oil samples and standards was reduced from 8.17 (SD 6.64) CIELAB units using the BTB scale to 3.99 (SD 3.05) CIELAB units using the UOCS scale. That is, the UOCS scale performs roughly two times better than the BTB. Wilcoxon's nonparametric test (18) applied to these CIELAB color differences between oil samples and standards shows the UOCS and BTB to be significantly different color scales ($P < 0.001$).

Finally, Figure 2 shows the percentage of oil samples classified by the UOCS and BTB standards using color tolerances from 1.0 to 7.0 CIELAB units. The percentage of oil samples classified by UOCS was again about twice that of the BTB for color tolerances of up to 3.0 CIELAB units. It also bears noting that, for a color tolerance of 7.0 CIELAB units, the UOCS classified 93.2% of the oil samples, against 59.1% classified by the BTB scale.

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TABLE 2
Color Coordinates of the UOCS (Uniform Oil Color Scale) Standards in DIN99d (11) and CIELAB (4) Color Spaces[a]

UOCS standards	DIN99d					CIELAB				
	L_{99d}	a_{99d}	b_{99d}	# Oils	ΔE_{99d}	L*	a*	b*	# Oils	ΔE^*_{ab}
1	78.2	2.8	47.8	*64*	*6.59*	75.5	–2.8	117.0	*29*	*5.45*
2	79.7	5.4	42.9	*51*	*5.54*	77.1	0.7	92.1	*34*	*9.75*
3	79.7	5.4	47.8	*47*	*2.15*	77.1	3.0	118.2	*38*	*5.29*
4	81.2	4.6	45.3	*22*	*1.47*	78.7	–0.4	104.0	*28*	*5.33*
5	81.2	2.8	47.8	*22*	*1.37*	78.7	–3.3	117.1	*27*	*3.88*
6	81.2	8.0	47.8	*16*	*1.61*	78.7	9.0	119.9	*41*	*6.06*
7	82.7	5.4	42.9	*26*	*1.45*	80.4	0.4	92.1	*21*	*3.19*
8	82.7	2.0	45.3	*12*	*1.05*	80.4	–6.2	103.1	*16*	*6.65*
9	82.7	7.1	45.3	*14*	*1.38*	80.4	5.1	105.4	*26*	*6.05*
10	82.7	5.4	47.8	*54*	*1.23*	80.4	2.5	118.2	*47*	*3.68*
11	84.2	4.6	35.5	*49*	*4.94*	82.0	–2.3	61.9	*33*	*7.26*
12	84.2	4.6	40.4	*17*	*1.68*	82.0	–2.0	80.7	*31*	*5.76*
13	84.2	2.8	42.9	*5*	*1.54*	82.0	–5.0	91.1	*3*	*3.73*
14	84.2	4.6	45.3	*33*	*1.42*	82.0	–0.8	104.0	*40*	*4.20*
15	84.2	2.8	47.8	*21*	*1.31*	82.0	–3.8	117.1	*20*	*4.11*
16	85.7	3.7	38.0	*13*	*1.56*	83.7	–3.8	70.5	*19*	*6.25*
17	85.7	7.1	40.4	*8*	*1.45*	83.7	2.7	81.9	*11*	*3.62*
18	85.7	5.4	42.9	*44*	*1.11*	83.7	0.0	92.1	*44*	*3.18*
19	85.7	2.0	45.3	*18*	*1.20*	83.7	–6.6	103.1	*18*	*3.67*
20	85.7	7.1	45.3	*22*	*1.42*	83.7	4.7	105.4	*22*	*4.29*
21	85.7	5.4	47.8	*73*	*1.22*	83.7	2.0	118.2	*63*	*3.83*
22	87.2	4.6	35.5	*19*	*1.46*	85.4	–2.5	61.9	*18*	*2.81*
23	87.2	6.3	38.0	*25*	*1.35*	85.4	0.5	71.4	*30*	*3.22*
24	87.2	4.6	40.4	*30*	*1.28*	85.4	–2.3	80.7	*33*	*3.00*
25	87.2	2.8	42.9	*17*	*1.57*	85.4	–5.3	91.1	*14*	*3.88*
26	87.2	4.6	45.3	*77*	*1.21*	85.4	–1.2	104.0	*77*	*3.63*
27	87.2	2.8	47.8	*7*	*1.33*	85.4	–4.2	117.1	*8*	*4.90*
28	88.7	3.7	33.1	*16*	*2.31*	87.0	–3.6	53.6	*24*	*4.76*
29	88.7	2.0	35.5	*6*	*1.51*	87.0	–6.6	61.2	*3*	*2.76*
30	88.7	3.7	38.0	*36*	*1.47*	87.0	–4.0	70.5	*31*	*3.03*
31	88.7	7.1	40.4	*6*	*1.65*	87.0	2.4	81.9	*6*	*4.08*
32	88.7	5.4	42.9	*92*	*1.14*	87.0	–0.3	92.1	*93*	*3.37*
33	88.7	2.0	45.3	*23*	*1.42*	87.0	–6.9	103.1	*18*	*4.00*
34	88.7	7.1	45.3	*8*	*1.51*	87.0	4.2	105.4	*22*	*4.89*
35	88.7	5.4	47.8	*42*	*1.20*	87.0	1.6	118.2	*39*	*3.73*
36	90.2	4.6	30.6	*18*	*2.58*	88.7	–2.1	46.7	*23*	*6.75*
37	90.2	4.6	35.5	*28*	*1.07*	88.7	–2.6	61.9	*27*	*2.45*
38	90.2	6.3	38.0	*14*	*1.42*	88.7	0.3	71.4	*31*	*3.51*
39	90.2	4.6	40.4	*98*	*1.18*	88.7	–2.6	80.7	*86*	*3.10*
40	90.2	2.8	42.9	*17*	*1.39*	88.7	–5.6	91.1	*21*	*4.15*
41	90.2	4.6	45.3	*62*	*1.23*	88.7	–1.6	104.0	*48*	*3.81*
42	91.7	3.7	23.3	*16*	*5.23*	90.4	–1.9	29.2	*15*	*7.12*
43	91.7	3.7	28.2	*15*	*1.72*	90.4	–2.9	40.1	*18*	*5.15*
44	91.7	3.7	33.1	*34*	*1.10*	90.4	–3.8	53.6	*38*	*2.33*
45	91.7	2.0	35.5	*6*	*1.36*	90.4	–6.8	61.2	*6*	*3.03*
46	91.7	3.7	38.0	*52*	*1.30*	90.4	–4.3	70.5	*48*	*2.91*
47	91.7	5.4	42.9	*55*	*1.24*	90.4	–0.7	92.1	*62*	*3.28*
48	93.2	4.6	25.7	*10*	*1.19*	92.1	–1.4	34.5	*17*	*2.48*
49	93.2	4.6	30.6	*23*	*1.28*	92.1	–2.2	46.7	*23*	*2.30*
50	93.2	4.6	35.5	*45*	*1.17*	92.1	–2.8	61.9	*46*	*2.65*
51	93.2	4.6	40.4	*32*	*1.21*	92.1	–2.8	80.7	*29*	*2.95*
52	94.7	2.0	20.8	*17*	*2.05*	93.8	–3.2	24.3	*19*	*4.24*
53	94.7	3.7	23.3	*4*	*1.48*	93.8	–1.9	29.2	*5*	*2.34*
54	94.7	2.0	25.7	*14*	*1.19*	93.8	–4.5	34.0	*14*	*1.75*
55	94.7	3.7	28.2	*24*	*1.51*	93.8	–3.0	40.1	*19*	*2.21*
56	94.7	2.0	30.6	*14*	*1.79*	93.8	–5.8	46.1	*18*	*2.96*
57	94.7	3.7	33.1	*21*	*1.47*	93.8	–3.9	53.6	*18*	*2.61*
58	94.7	3.7	38.0	*15*	*1.58*	93.8	–4.5	70.5	*11*	*2.54*
59	96.2	1.1	23.3	*14*	*1.65*	95.6	–4.8	28.8	*14*	*2.11*
60	97.7	2.0	20.8	*17*	*2.58*	97.3	–3.2	24.3	*17*	*4.04*
Average	88.3	4.2	38.7	*28.3*	*1.73*	86.7	–1.9	78.4	*28.3*	*4.00*
SD	4.7	1.6	7.8	*21.4*	*1.09*	5.2	3.2	28.8	*18.7*	*1.52*

[a]From our data set of 1700 oil samples (12), the number of oils classified by each standard (# Oils) and the average color differences (ΔE_{99d}, ΔE^*_{ab}) are also shown. For other abbreviations see Table 1.

TABLE 3
Color Coordinates of the BTB Standards in DIN99d (11) and CIELAB (4) Color Spaces[a]

BTB standards	DIN99d					CIELAB				
	L_{99d}	a_{99d}	b_{99d}	# Oils	ΔE_{99d}	L*	a*	b*	# Oils	ΔE^*_{ab}
2-1	96.7	1.7	18.3	*26*	*3.18*	96.2	–2.7	20.0	*18*	*3.58*
2-2	84.5	4.3	27.2	*3*	*1.25*	82.5	–1.8	37.8	*4*	*2.93*
2-3	88.7	4.6	32.6	*66*	*2.69*	87.1	–2.3	52.5	*69*	*4.95*
2-4	93.2	4.7	36.4	*49*	*1.49*	92.2	–2.6	65.2	*51*	*3.03*
2-5	93.3	5.6	39.2	*2*	*1.23*	92.3	–1.1	76.0	*8*	*5.09*
2-6	92.9	6.0	41.3	*8*	*1.69*	91.8	0.0	85.1	*12*	*2.83*
2-7	92.0	6.6	42.9	*9*	*1.91*	90.8	1.7	92.8	*10*	*3.81*
2-8	90.8	7.1	43.9	*35*	*3.33*	89.4	3.2	98.1	*150*	*9.61*
2-9	84.3	7.6	43.6	*114*	*3.63*	82.2	5.1	97.2	*23*	*4.71*
2-10	82.9	8.0	44.1	*89*	*4.38*	80.7	6.2	99.8	*412*	*17.02*
3-1	96.0	1.3	18.4	*20*	*4.45*	95.3	–3.2	20.1	*20*	*6.11*
3-2	81.8	3.6	26.4	*6*	*3.95*	79.5	–2.5	35.7	*6*	*5.65*
3-3	87.4	3.7	32.0	*25*	*3.48*	85.7	–3.4	50.4	*13*	*3.74*
3-4	94.2	3.8	36.4	*31*	*2.55*	93.3	–4.0	64.7	*11*	*2.09*
3-5	92.8	4.3	38.9	*30*	*1.18*	91.8	–3.2	74.5	*35*	*2.54*
3-6	91.9	5.0	40.7	*50*	*1.15*	90.7	–1.8	82.3	*54*	*2.53*
3-7	90.0	5.2	42.2	*103*	*1.09*	88.6	–1.0	88.9	*66*	*2.28*
3-8	88.6	5.7	43.2	*191*	*2.74*	87.0	0.3	93.7	*111*	*4.52*
3-9	82.0	6.3	42.9	*36*	*2.22*	79.6	2.2	92.8	*19*	*3.12*
3-10	80.6	6.4	43.4	*82*	*4.15*	78.1	2.9	95.5	*33*	*9.10*
4-1	93.6	1.1	17.9	*11*	*3.57*	92.7	–3.2	19.3	*8*	*4.66*
4-2	87.3	2.7	26.7	*2*	*2.70*	85.5	–3.7	36.4	*10*	*6.24*
4-3	82.6	2.9	30.8	*11*	*3.70*	80.3	–4.1	46.7	*9*	*8.16*
4-4	91.9	2.5	35.3	*49*	*2.60*	90.7	–5.9	60.4	*56*	*4.77*
4-5	91.8	3.2	38.3	*27*	*1.89*	90.6	–5.1	71.7	*58*	*4.10*
4-6	90.2	3.4	40.0	*68*	*1.90*	88.8	–4.6	78.7	*49*	*3.45*
4-7	88.6	3.9	41.4	*56*	*2.04*	87.0	–3.6	84.9	*38*	*3.19*
4-8	87.5	4.5	42.5	*113*	*2.49*	85.7	–2.1	90.2	*49*	*3.37*
4-9	80.0	4.8	42.1	*17*	*3.01*	77.4	–0.8	88.4	*13*	*3.34*
4-10	78.7	5.0	42.7	*47*	*4.72*	76.0	0.0	91.2	*7*	*8.04*
5-1	89.9	1.2	17.5	*3*	*3.90*	88.4	–3.0	18.6	*3*	*5.69*
5-2	87.8	2.0	26.3	*15*	*5.07*	86.1	–4.5	35.4	*21*	*7.13*
5-3	80.6	2.1	29.9	*9*	*5.26*	78.1	–5.0	44.1	*8*	*12.18*
5-4	91.2	1.2	34.5	*4*	*2.12*	90.0	–7.6	57.7	*15*	*4.78*
5-5	91.0	2.3	37.6	*16*	*2.33*	89.7	–6.5	68.6	*27*	*5.04*
5-6	88.8	2.1	39.3	*24*	*3.03*	87.2	–6.9	75.4	*15*	*5.07*
5-7	86.9	2.4	40.7	*20*	*2.74*	85.1	–6.1	81.2	*11*	*4.06*
5-8	84.4	3.2	41.6	*70*	*3.69*	82.3	–4.4	85.5	*20*	*4.32*
5-9	77.5	3.2	41.2	*9*	*4.63*	74.7	–3.8	83.5	*6*	*5.99*
5-10	76.2	3.3	41.8	*26*	*5.63*	73.3	–3.3	86.4	*7*	*12.44*
6-1	85.2	1.3	17.6	*3*	*6.65*	83.2	–2.8	18.9	*3*	*8.45*
6-2	87.8	1.0	25.6	*0*	—[b]	86.1	–5.5	33.7	*0*	—
6-3	90.7	0.4	30.7	*58*	*4.89*	89.3	–7.7	46.3	*43*	*5.81*
6-4	91.3	0.0	33.9	*0*	—	90.0	–9.2	55.6	*1*	*3.15*
6-5	89.0	0.8	36.7	*1*	*1.80*	87.4	–8.7	65.2	*15*	*9.18*
6-6	87.5	0.7	38.4	*0*	—	85.8	–9.1	71.6	*7*	*7.90*
6-7	85.8	1.5	39.9	*7*	*3.43*	83.9	–7.7	77.8	*5*	*6.38*
6-8	82.8	1.1	40.8	*3*	*6.20*	80.5	–8.2	81.5	*2*	*3.80*
6-9	75.9	1.8	40.5	*1*	*3.93*	73.0	–6.3	80.1	*3*	*9.56*
6-10	69.9	2.2	40.1	*32*	*7.83*	66.6	–4.9	78.5	*9*	*12.94*
7-1	85.3	1.0	17.6	*0*	—	83.3	–3.1	18.8	*0*	—
7-2	88.3	0.4	25.3	*11*	*5.43*	86.7	–6.1	32.9	*28*	*7.80*
7-3	90.9	–0.9	29.8	*8*	*6.36*	89.6	–9.2	43.5	*17*	*7.69*
7-4	90.1	–1.2	33.2	*0*	—	88.7	–10.7	53.1	*0*	—
7-5	87.9	–1.0	35.8	*0*	—	86.2	–11.2	61.8	*1*	*13.63*
7-6	86.0	–0.9	37.5	*0*	—	84.1	–11.4	68.0	*1*	*7.24*
7-7	83.5	–0.6	38.9	*1*	*3.95*	81.4	–11.1	73.2	*1*	*4.79*
7-8	81.5	–0.5	39.9	*1*	*2.84*	79.1	–10.8	77.3	*0*	—
7-9	75.4	0.0	39.1	*1*	*4.86*	72.4	–9.4	74.1	*9*	*11.94*
7-10	70.7	0.2	39.7	*1*	*8.17*	67.4	–8.6	76.4	*0*	—
Average	86.6	2.8	35.4	*28.3*	*3.49*	84.8	–4.2	65.3	*28.3*	*6.10*
SD	5.9	2.3	7.8	*36.6*	*1.67*	6.5	4.0	*23.9*	*56.9*	*3.27*

[a]From our data set of 1700 oil samples (12), the number of oils classified by each standard (# Oils), and the average color differences (ΔE_{99d}, ΔE^*_{ab}), are also shown. BTB, bromthymol blue; for other abbreviations see Tables 1 and 2.
[b]—, not applicable.

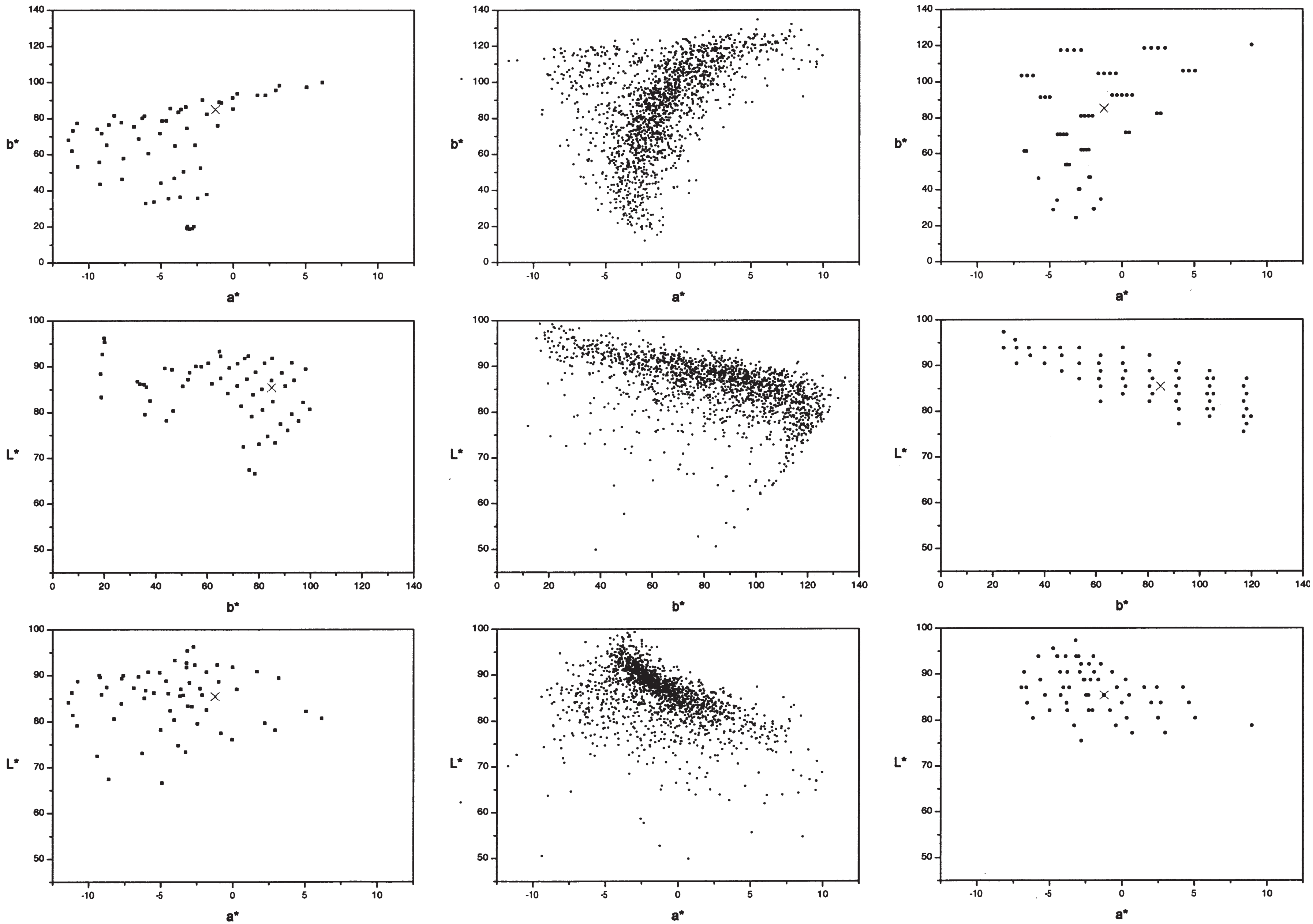

FIG. 1. Color coordinates of the 60 bromthymol blue (BTB) standards (left), 1700 virgin olive oils (center), and 60 Uniform Oil-Color Scale (UOCS) standards (right) in a Commission Internationale de l'Éclairage 1976-L*a*b* (CIELAB) color space. Projections on planes a*b* (top), b*L* (medium), and a*L* (bottom) are distinguished. The position of the center of gravity of the 1700 virgin olive oils is marked by a cross in the left and right projection plots.

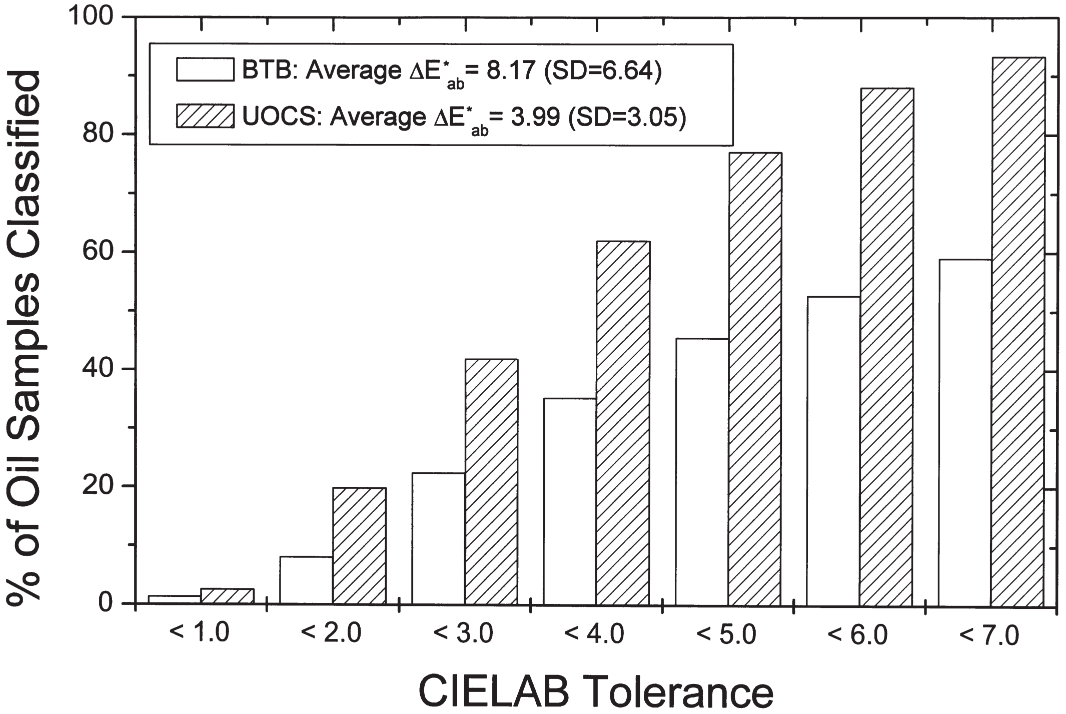

FIG. 2. Percentage of the 1700 virgin olive oils being classified by the UOCS and BTB standards using color tolerances from 1.0 to 7.0 CIELAB units. The average CIELAB color difference between the oil samples and their nearest standards in each of these scales is shown in the legend. For other abbreviations see Figure 1.

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APPENDIX

For the sake of completeness we provide transformation equations from tristimulus values (X, Y, Z) to DIN99d coordinates (a_{99d}, b_{99d}, L_{99d}):

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \begin{pmatrix} 1.12 & 0 & -0.12 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \text{(A1)}$$

$$\begin{pmatrix} X'_o \\ Y'_o \\ Z'_o \end{pmatrix} = \begin{pmatrix} 1.12 & 0 & -0.12 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_o \\ Y_o \\ Z_o \end{pmatrix} \quad \text{(A2)}$$

where X_o, Y_o, Z_o are the tristimulus values of the reference white.

$$L^{*\prime} = 116\left(\frac{Y'}{Y'_o}\right)^{1/3} - 16 \quad \text{if} \left(\frac{Y'}{Y'_o}\right) > 0.008856$$
$$L^{*\prime} = 903.3\left(\frac{Y'}{Y'_o}\right) \quad \text{if} \left(\frac{Y'}{Y'_o}\right) \le 0.008856 \quad \text{(A3)}$$

$$a^{*\prime} = 500\left[f\left(X'/X'_o\right) - f\left(Y'/Y'_o\right)\right] \quad \text{(A4)}$$

$$b^{*\prime} = 200\left[f\left(Y'/Y'_o\right) - f\left(Z'/Z'_o\right)\right] \quad \text{(A5)}$$

where

$$f(\alpha) = \alpha^{1/3} \quad \text{if } \alpha > 0.008856$$
$$f(\alpha) = 7.787\alpha + \frac{16}{116} \quad \text{if } \alpha \le 0.008856 \quad \text{(A6)}$$

Note that $L^{*\prime}$ and $b^{*\prime}$ are identical to the CIELAB coordinates L^* and b^*, respectively, but $a^{*\prime}$ differs from a^*.

$$e = a^{*\prime}\cos(50°) + b^{*\prime}\sin(50°) \quad \text{(A7)}$$

$$f = 1.14\left[-a^{*\prime}\sin(50°) + b^{*\prime}\cos(50°)\right] \quad \text{(A8)}$$

$$G = \left(e^2 + f^2\right)^{1/2} \quad \text{(A9)}$$

$$C_{99d} = 22.5\ln(1 + 0.006G) \quad \text{(A10)}$$

$$h_{99d} = \arctan(f/e) + 50° \quad \text{(A11)}$$

$$a_{99d} = C_{99d}\cos(h_{99d}) \quad \text{(A12)}$$

$$b_{99d} = C_{99d}\sin(h_{99d}) \quad \text{(A13)}$$

$$L_{99d} = 325.22\ln(1 + 0.0036L^{*\prime}) \quad \text{(A14)}$$