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Measuring the colour of virgin olive oils in a new colour scale using a low-cost portable electronic device

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Abstract. *The Modified Uniform Oil Colour Scale (MUOCS) is proposed for the colour specification of virgin olive oils. MUOCS has 60 standard colours, the same number as the two previous scales available for the same purpose: Uniform Oil Colour Scale (UOCS) and Bromthymol Blue (BTB). A remarkable improvement in accuracy can be achieved from MUOCS standards: For a broad dataset of 1700 virgin olive oils produced in Spain during 4 different harvests, the average colour differences to the closest standards were 2.86, 3.99, and 8.17 CIELAB units using MUOCS, UOCS and BTB, respectively. A low-cost (<60 Euros) portable electronic device is proposed for the colour specification of virgin olive oils based on MUOCS and BTB standards. This device can operate with USB connection to a computer or AAA batteries, and is based on fast (<0.25 s) transmittance measurements of the virgin-olive-oil sample placed in a 5-mm pathlength quartz cell. The device may avoid the use of expensive laboratory instrumentation for colour measurement and can be easily employed by non-technician users. For a reduced set of commercial virgin olive oils with random colours, the MUOCS classifications provided by our device agreed with those given by conventional spectrophotometric measurements in 92% of the cases.*

Keywords: *Color of virgin olive oils, color-measurement instrumentation, Bromthymol Blue (BTB) method, Uniform Oil Color Scale (UOCS), DIN99, CIELAB.*

1. Introduction

Colour is an important property of many foods for two main reasons: its relationship with other chemical and physical properties of food (which may be also related to ripeness, processing techniques, storage conditions, etc.), and its strong influence in consumers' preferences, which govern subsequent buying decisions. Accurate colour specification is often a key part of a complete food-quality control. As a current example of the growing interest in food colour, the 2010 interim meeting of the International Colour Association (AIC, 2010) focused on this topic under the title "Color and Food: From the Farm to the Table", with a total of 139 presentations from researchers in 26 different countries.

Spain is the world's leading producer of olive oils (39.3% of global production in the past 5 years), which are recognized as high-quality foods with many beneficial health properties. Also olive-oil imports are increasing notably in many countries, e.g. 5-fold in USA during the past 25 years (International Olive Council, 2011). Therefore, production of the best virgin olive oils is economically important in Spain, and the colour of virgin olive oils cannot be neglected. Oil colour strongly influences people's preferences, as shown, for example, by the fact that professional olive-oil tasters use tinted cups, because just colour perception of olive oils may strongly bias assessments of other attributes (Izquierdo, 1997; Melgosa et al., 2009). Different researchers have paid attention to colour specification of virgin olive oils, and this paper is a step forwards in this sense.

For the colour specification of virgin olive oils, researchers proposed the Bromthymol Blue (BTB) method (Gutiérrez & Gutiérrez, 1986), which was standardized in 1997 (AENOR, 1997). The BTB method proposes a subjective visual comparison between the colour of a virgin-olive-oil sample and a two-dimensional scale with 60 (10x6) fixed solutions, called BTB standards, looking for the solution with the colour closest to the sample. The BTB standards are not olive oils, but a mixture of specific chemical products producing a set of colours which are very similar to those of most virgin olive oils. Appropriate transform equations from BTB to the CIELAB colour space (CIE, 2004) have been proposed (Moyano et al., 1999), bearing mind that BTB is a specific olive-oil colour scale, while current international colour specifications by the International Commission on Illumination recommend the use of CIELAB (or CIELUV). However, further research has revealed limited precision and accuracy from the BTB method (Melgosa et al., 2000), mainly for two reasons: the 60 BTB standards are irregularly spread in an approximately uniform colour space similar to CIELAB, and they do not cover the real colour gamut of virgin-olive-oil samples (specifically, those with the most saturated yellow colours fall outside the gamut). In addition, it has been also reported some lack of temporal colour stability of the 60 BTB standards during 2-3 months after their preparation (Melgosa et al., 2001).

In view of these flaws of the BTB method, together with the intrinsic subjective nature of any visual colour comparison, a new colour scale for virgin olive oils, called the Uniform Oil Colour Scales (UOCS) was proposed in 2004 (Melgosa et al., 2004). UOCS has the same number of standards as BTB (i.e. 60) so that the two scales can be meaningfully compared. However, the UOCS standards are not real solutions, but theoretical points in a tridimensional colour space, in such a way that the UOCS method is not based on a subjective visual comparison, as suggested by the BTB method. The UOCS method is objective, using a theoretical computation of the lowest colour difference between the colour instrumentally measured for a virgin-olive-oil sample and the set of colours specified by the 60 UOCS standards. It was found that, for a wide set of 1700 virgin-olive-oil samples produced in Spain during four different harvests (Moyano, 2002), the UOCS improved the BTB scale by about a factor 2 (Melgosa et al., 2004). That is, the average colour differences between each of these 1700 samples and their closest standards was about two-fold greater using the BTB standards than using the UOCS standards. This good result of the UOCS also stood up when considering virgin-olive-oil samples corresponding to different varieties, harvests, and degrees of ripeness (Melgosa et al., 2005).

As mentioned above, while the 60 BTB standards are real physical samples, the 60 UOCS standards are a set of points in a colour space. Therefore, in practice, the use of the UOCS requires an instrumental colour measurement of the virgin-olive-oil sample in the laboratory, followed by computations of colour differences. That is, the use of the UOCS requires a colour-measurement instrument (e.g. a spectrophotometer) as well as some knowledge of colour science, which limits its practical application.

Several portable instruments for colour measurement have been developed by some of the authors of the present paper for different applications (Palma et al., 2008; Capitán-Vallvey & Palma, 2011; Martínez-Olmos et al., 2011). The prototypes developed have shown both high reliability and technical specifications comparable to those in more complex and expensive analytical laboratory instrumentation. One example of the advances in this field is a recent paper proposing the colour determination of red wine by a compact instrument (De la Torre et al., 2009). In the present paper, we propose a low-cost portable electronic device that can be used by people without any special knowledge in colour science. This device provides the colour specification of a virgin-olive-oil sample in the earlier BTB scale and also in the Modified Uniform Oil Colour Scale (MUOCS), a new colour scale for virgin olive oils which has been developed by us after detecting flaws in the UOCS. Like UOCS, MUOCS is also a set of 60 points in a colour space. The main characteristics of MUOCS are explained, showing that it achieves a noteworthy improvement with respect to the previous UOCS and BTB scale. Properly, the electronic device we have designed cannot be called a colorimeter, because its goal is not to measure a colour in a selected colour space (e.g. CIELAB or DIN99d), but rather to find simply which of the 60 BTB or MUOCS standards has the closest colour to the one of a given virgin-olive-oil sample.

2. Materials and Methods

Two different parts can be distinguished in the current paper: A) The introduction of the Modified Uniform Oil Colour Scale (MUOCS); B) the development and performance of the electronic device we designed to measure MUOCS and BTB colours of a virgin-olive-oil sample. Here we briefly mention the main materials and methods employed in each one of these two parts, which are detailed in the “Results and Discussion” section. Specifically:

A.1) Colours of a set of 1700 virgin-olive-oil samples (Moyano, 2002) were measured with a Hewlett-Packard 8452 UV-visible spectrophotometer using quartz cells with a 5-mm pathlength, assuming D65 illuminant and CIE 1964 standard colorimetric observer. The 60 MUOCS standards were defined from this set of virgin olive oils, considering a regular rhombohedral lattice like the one employed by the Uniform Color Scales of the

Optical Society of America (MacAdam, 1974) in the DIN99d (Cui et al., 2002) colour space.

A.2) Flaws found in the development of previous BTB (Gutiérrez & Gutiérrez, 1986) and UOCS standards (Melgosa et al. 2004) which led us to the current proposal of the MUOCS standards are described. The improvements achieved by MUOCS upon UOCS and BTB are shown by different methods: plots showing the regularity of the spread of the different sets of standards in the DIN99d colour space; percentage of 1700 virgin-olive oil samples classified by each one of the standards; average and standard deviation of CIELAB colour differences between each one of the 1700 virgin-olive-oil samples and their closest standards in BTB, UOCS and MUOCS.

B.1) Components of the electronic device we designed to measure the BTB and MUOCS colours of a given virgin-olive-oil sample are illustrated in a block diagram. The characteristics of the NSPW300 white LED source (Nichia Japan), S9706 colour sensor (Hamamatsu Photonics, Japan), PIC18F2550 microcontroller (Microchip Technology Inc., USA), and supplementary 25LC1024 EEPROM memory (Microchip Technology Inc., USA) used in the design of our device are described. A software application in Visual Basic 2008 (Microsoft Corp., Redmond, WA, USA) was developed for proper work of this instrument, which includes two optional operating modes: portable (AAA batteries) and USB connection to a computer.

B.2) The practical operation with our instrument is described step by step, considering the preliminary measurements of black and white signals, as well as the corresponding manipulation of measured RGB signals of a virgin-olive-oil sample. The calibration procedure employed in our device is described. Our calibration is based on experimental measurements performed with a JASCO-V650 spectrophotometer (5-mm pathlength quartz cells) for a set of 10-ml solutions of each one of the 60 BTB standards (Gutiérrez & Gutiérrez, 1986), and the application of the pseudo-inverse method (Moore, 1920; Penrose, 1955). To test the accuracy achieved by our electronic device measuring MUOCS colour, we employed a set of 37 commercial virgin-olive-oils with random colours.

Detailed descriptions of all items previously mentioned are given in the next section.

3. Results and Discussion

3.1. The Modified Uniform Oil Colour Scale (MUOCS)

The following characteristics are common to the UOCS and MUOCS methods: 1) They are objective (non-visual) methods for the colour specification of a virgin-olive-oil sample in specific scales, from the lowest colour difference between the colour of the sample and a fixed set of 60 colours, called standards, which define the corresponding scales. 2) They are based on a unique set of 1700 virgin-olive-oil samples (Moyano, 2002), which can be considered highly representative of the whole colour range of virgin olive oils available in Spain. 3) The colours of these 1700 samples were represented and analysed in the DIN99d colour space (Cui et al., 2002), which is a modern CIELAB-based colour space with improved uniformity over CIELAB. Equations defining the DIN99d colour space from CIELAB are provided in Appendix

A. Seeking uniform sampling of the region of colour space where the 1700 samples are positioned (i.e. the greatest possibility of achieving a near match between colours of virgin-olive-oil samples and the set of 60 standards), the UOCS and MUCOS standards were placed in the DIN99d space following a regular rhombohedral (cubo-octahedron) lattice (Wyszecki, 1954), like the one employed by the Uniform Color Scales of the Optical Society of America (MacAdam, 1974; Judd & Wyszecki, 1975; Luke 1999). This lattice is a type of "closest packing", where each of the standards is surrounded by 12 equidistant nearest neighbours, this distance being called the lattice constant.

However, some flaws have been detected in UOCS, leading us to the current proposal of MUOCS. Firstly, it should be mentioned that the original 1700 virgin-olive-oil samples (Moyano, 2002) were measured with a Hewlett-Packard 8452 UV-visible spectrophotometer using quartz cells with a 5-mm pathlength, and the measured spectral transmittances were converted to a 10-mm pathlength while assuming the Bouguer-Lambert-Beer law, before computation of colour coordinates leading to the UOCS standards. However, for a set of virgin-olive-oil samples, it has been found that the assumption of the Bouguer-Lambert-Beer law between 5 and 10 mm pathlengths led to significant errors, causing considerable differences (3.6 CIELAB units on the average) with respect to the experimental measurements (Gómez-Robledo et al., 2011). Accordingly, it was concluded that it was better to keep original measurements at 5-mm pathlengths for the development of the MUOCS standards. Adoption of cells with 5-mm pathlength for colour measurements of virgin olive oils has also been recommended for other practical reasons (Gómez-Robledo et al., 2011). Secondly, the algorithms designed to develop the UOCS and MUOCS were slightly different, in such a way that some discontinuities found in the lattice corresponding to the UOCS standards have been solved by MUOCS standards (Gómez-Robledo, 2011). The aforementioned algorithms start from the centre of gravity of the 1700 virgin-olive-oil-samples in DIN99d and proceed by calculating a lattice with constant 3.0 units. In the case of UOCS, successive planes or layers were computed, and finally any standards that classified a low number of oil samples were removed by visual inspection to achieve the desired number of 60 standards. In the case of MUOCS, from the centre of gravity of the 1700 samples in DIN99d, successive sets of 12 nearest neighbours were computed at a time, checking that distances of any new standards to the set of 1700 samples never exceeded 7.0 DIN99d units. In this way, final visual inspection to achieve the 60 MUOCS standards was easier and discontinuities in the lattice were avoided.

Figure 1 shows the BTB, UOCS, and MUOCS standards together with the 1700 virgin olive oils in the three planes of the DIN99d colour space. It can be noted that BTB standards are not at all regularly spread in DIN99d colour space, and colours of many oil samples with high b_{99d} and L_{99d} values lie outside the gamut provided by the BTB standards. As expected, it is also noticeable that the MUOCS and UOCS standards follow a similar geometrical spread of their standards. However, the MUOCS standards offer improvements over the UOCS in a double sense: they made a better fit with the cloud of points representing the 1700 oil samples, and they were more regularly and continuously distributed in the colour space. In fact, it was computed that the average distances between the 1700 virgin-olive-oil samples and their corresponding nearest standards were 8.17, 3.99, and 2.86 CIELAB units (with standard deviations of 6.64, 3.05, and 1.43 CIELAB units, respectively) for the BTB, UOCS, and MUOCS standards, respectively. This result clearly indicates that UOCS exceeded BTB in accuracy by about a factor 2, as reported before (Melgosa et al., 2004), and also that current MUOCS standards provide an additional remarkable improvement with respect to UOCS standards: an average reduction of colour differences of more than 25%, together with a reduction of the standard deviations of more than 50%.

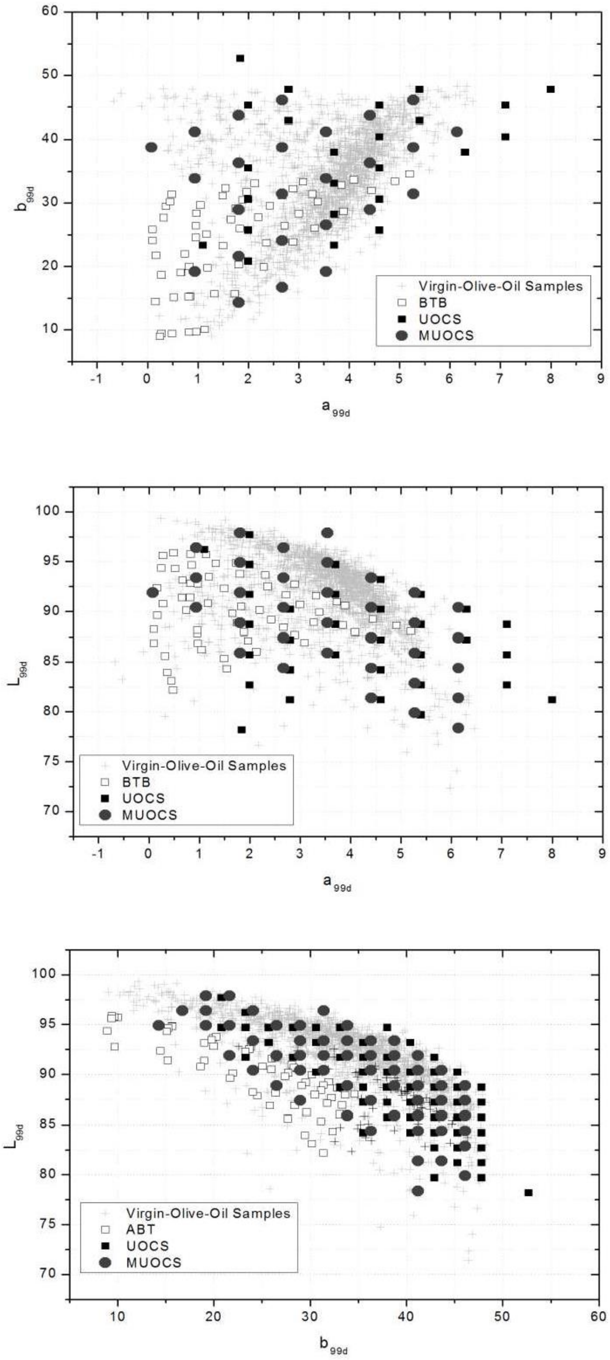

Figure 1. Colour coordinates of 1700 virgin-olive-oil samples[12] measured at 5-mm pathlength, together with the 60 BTB (also 5-mm pathlength), UOCS, and MUOCS standards, in the three planes (a_{99d}-b_{99d} top, a_{99d}-L_{99d} middle, b_{99d}-L_{99d} bottom) of the DIN99d (Cui et al., 2002) colour space.

As further proof of the improvement of MUOCS over UOCS and BTB, Figure 2 shows the number of oil samples classified by the 60 standards in each of these three colour scales. It can be seen that, while BTB standard number 10 (with BTB code 2/10) classified about 850 oil samples, many other BTB standards classified almost zero oil samples, this being a clearly unacceptable result. The situation clearly improves for the UOCS standards, and even more for the MUOCS standards, which all classified between 5 and 110 oil samples from the original dataset of 1700 virgin-olive-oil samples. Finally, Figure 3 shows the percentage of the 1700 oil samples classified by BTB, UOCS, and MUOCS standards using different tolerances (CIELAB units). Once again we see the pronounced improvement over BTB achieved by both UOCS and MUOCS for any tolerance level, as well the improvement of MUOCS over UOCS.

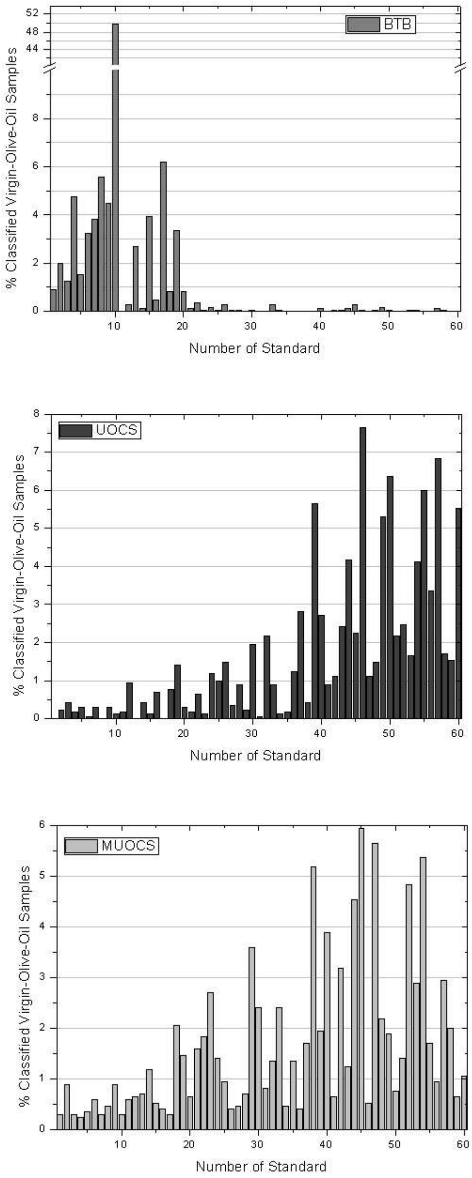

Figure 2. From our dataset of 1700 virgin-olive-oil samples (Moyano, 2002), the number of samples classified by each one of the 60 standards provided by BTB (up), UOCS (medium), and MUOCS (bottom).

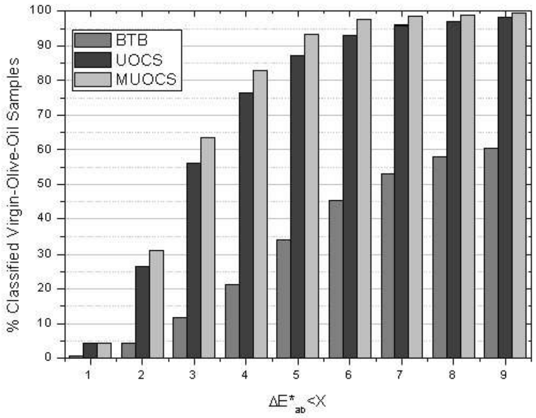

Figure 3. Percentage of 1700 virgin-olive-oil samples (Moyano, 2002) classified with a tolerance level of *X* CIELAB units using BTB, UOCS and MUOCS standards.

A three-number code was adopted to design each of the 60 MUOCS standards in an intuitive way, as indicated in Table 1. The first number of the code ranges from 1 to 14 and indicates increasing lightness values. The second number is always an even number ranging from 2 to 16, and increasing values indicate displacement of the colour of the standards towards green hues. Finally, the third number ranges from 1 to 14, increasing values indicating displacements towards yellow hues. The specific codes and DIN99d coordinates of the 60 MUOCS standards are provided in Appendix B. In the rhombohedral (cubo-octahedron) lattice conducting to MUOCS standards, each standard is surrounded by 12 equidistant nearest neighbours in the DIN99d space. However, the distances between contiguous L_{99d}, a_{99d}, and b_{99d} planes is not constant but 1.50, 0.86, and 2.45 DIN99d units, respectively, as shown in Table 1.

Table 1. DIN99d values corresponding to the three-number code employed to designate the MUOCS standards.

Lightness	***L_{99d}***	***Green Hue***	***a_{99d}***	***Yellow Hue***	***b_{99d}***
1	78.39	2	6.14	1	14.26
2	79.89	4	5.27	2	16.71
3	81.39	6	4.41	3	19.16
5	84.39	8	3.54	4	21.61
4	82.89	10	2.67	5	24.06
6	85.89	12	1.81	6	26.51
7	87.39	14	0.94	7	28.96
8	88.89	16	0.08	8	31.41
9	90.39	-	-	9	33.86

10	91.89	-	-	10	36.31
11	93.39	-	-	11	38.76
12	94.89	-	-	12	41.21
13	96.39	-	-	13	43.66
14	97.89	-	-	14	46.11

3.2. Electronic device measuring MUOCS and BTB colours

The block diagram of the portable instrument developed (Carvajal Rodríguez et al., 2011) is presented in Figure 4. The current estimated cost of all the components comprising this instrument (quartz cell excluded) is below 60 Euros (Fernández Salmerón, 2011). Briefly, the prototype computes the closest MUOCS and BTB standards to a given olive-oil sample by measuring its transmitted light. To do so, in the sensing module a white LED (light-emitting diode) illuminates a probe containing the olive-oil sample and the transmitted light is collected by a digital colour sensor. The microcontroller (MCU) governs the functioning of the system, controlling the measuring module and including the signal-processing algorithms and the standards of the MUOCS and BTB scales. The MCU selected was the PIC18F2550 (Microchip Technology Inc., USA) due to the integration of a USB module in the same chip that allows easy communication with the computer for design and calibration purposes. This device includes five I/O ports that permit the control of the rest of modules of our instrument. The user interface of the portable instrument consists of two buttons that allow the user to select different options through a menu which is presented on the LCD screen. The results of the measurements are also visible on this screen. Furthermore, a software application was developed using Visual Basic 2008 (Microsoft Corp., Redmond, WA, USA). This application uses the MCU USB module to communicate with the instrument and allows the measurement of an olive-oil sample and the modification of the calibration parameters stored on the memory device.

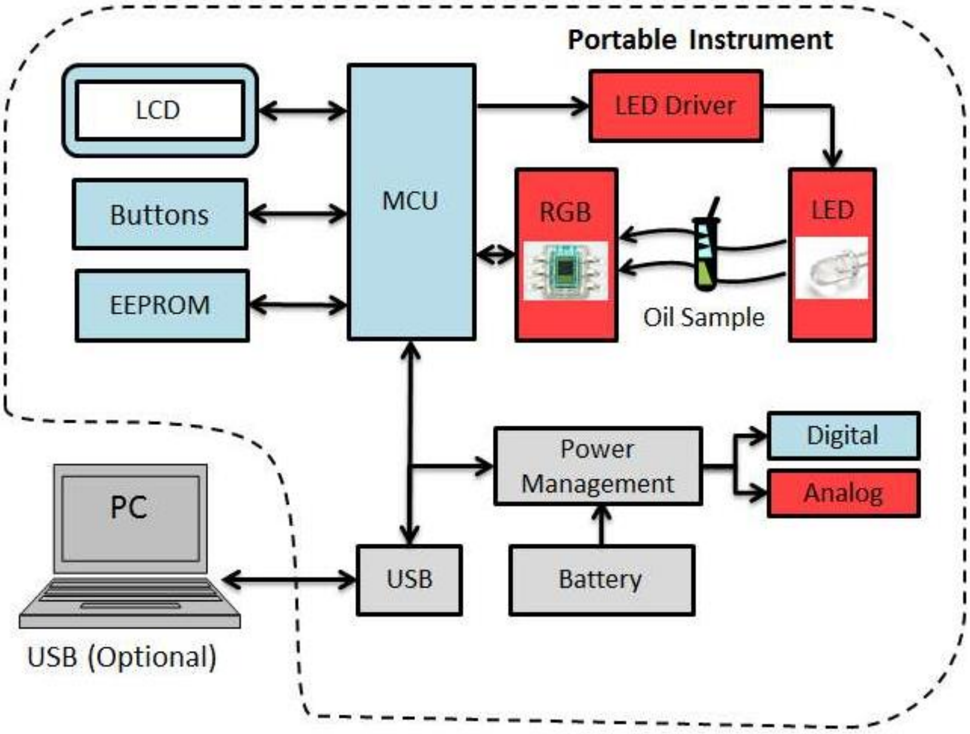

Figure 4. Block diagram of the instrument developed.

3.2.1 Sensing module

This module is compounded by a white LED (NSPW300, Nichia, Japan) working as a light source and a S9706 digital colour detector (Hamamatsu Photonics, Japan).

The LED source has a typical luminous intensity of 4000 mcd with CIE 1931 colour coordinates of x=0.33 ± 0.02 and y=0.32 ± 0.02 close to those corresponding to the CIE D65 illuminant (x=0.313 ; y=0.329). For negligible time drift of the LED (Palma et al., 2008; León et al, 2006) it is biased by a constant current source that consists of an operational amplifier (the OPA357, Texas Instruments Inc., USA) and micro-power voltage reference (the LM385 of Texas Instruments Inc., USA). This operational amplifier can be switched off by a control signal activated by the microcontroller for reducing the power consumption.

The transmitted light through the oil sample is measured by a colour detector, model S9706 (Hamamatsu Photonics, Japan). This device is a digital colour sensor sensitive to red, green, and blue spectral regions, which simultaneously measures the RGB colour coordinates of the incident light. The chip integrates a set of photodiodes for which the maximum sensitivity wavelengths correspond to $\lambda_r = 615$ nm, $\lambda_g = 540$ nm and $\lambda_b = 465$ nm. The photocurrent of these photodiodes is on-chip processed to generate a digital output. The signal detected is serially output as 36-bit words, which can be read by the MCU without additional signal processing. To enable measurement over a wide range of illuminants, the S9706 detector has two configuration parameters to select its active area and integration time. Internally, the active area of each detector (with dimensions of 1.2×1.2 mm) consists of a matrix of 9×9 silicon photodiodes, with alternating responses in the red, blue, and green colour regions, and can be configured in a high-sensitivity mode, where the full area collects the incident light, or in a low-sensitivity mode, where a 3×3 centre area is chosen to be active. In the present work, the high-sensitivity mode was chosen in all cases.

In addition to the sensitivity modes related to the selected active area, these colour sensors can externally configure the integration time, i.e. the time interval during the photodiode matrix generates a photocurrent for each optical radiation acquisition. This integration time can be easily changed from 10 µs to 100 s with a unique input pin. According to the device datasheet, under constant illumination conditions, the sensor output increases linearly with this time until reaching output saturation. A short integration time means fast acquisition, but with low-intensity light collection, i.e. low sensitivity. Nevertheless, if the integration time is too long, the sensor output could be saturated and therefore a compromise in the integration time value is needed. The response of this sensor was tested as a function of the integration time under the illumination conditions in this application. We found that the shortest time with optimal sensitivity and response time was 2.55 ms and the response output of the digital detector in no case exceeded 85% of its maximum value (López-Álvarez et al, 2009). Finally, the time stability of the S9706 detector response with an integration time of 2.55 ms was checked under continuous illumination. An output-signal drifting lower than 0.1% was found to acquire a signal every 0.2 s for 90 min.

The virgin-olive-oil sample under study was contained in a quartz cell of 5-mm pathlength. This specific pathlength has been recommended for virgin-olive-oil colour measurements (Gómez-Robledo et al., 2008), and was the one employed to design the MUOCS standards. The colour detector and the light source were both opposite soldered on auxiliary printed circuit boards (PCB) that are fitted to both sides of an opaque structure inside the prototype, as shown in Figure 5. This housing was designed to contain the quartz cell, providing shielding of external light and at the top has a small drawer that can be inserted into the mainframe of the instrument. When the drawer is out, the cell containing the oil sample can be put into the instrument, and then the drawer is closed, providing complete optical isolation (see Fig. 5). The real dimensions of the prototype are 15 cm long x 8 cm wide x 5 cm height.

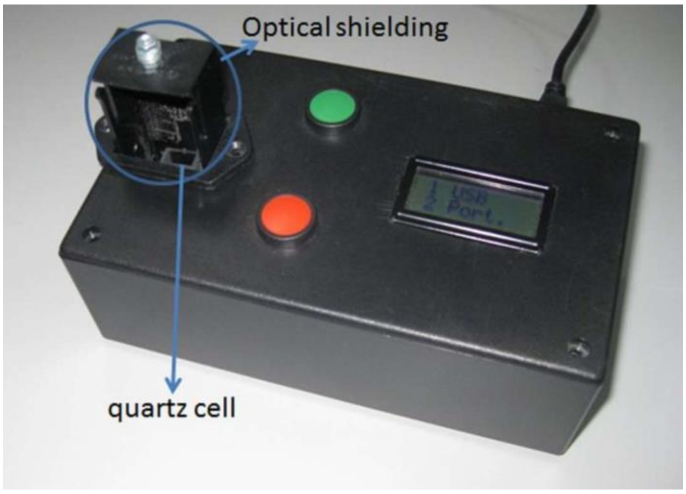

Figure 5. Photography of the instrument showing the panel control, the LCD display and the sample housing. The dimensions of the prototype are 15 cm long x 8 cm wide x 5 cm high.

3.2.2 Power and processing electronics

There are two different operation modes for the instrument: portable mode and computer mode. The instrument can be supplied by the USB port when it is connected to a computer, or by two AAA batteries when it works in portable mode. When the device is powered on, and the USB module is disconnected, a DC/DC converter stage raises the 3 V from the batteries to 5 V necessary for the proper functioning of the device. Furthermore, two different 5-V sources are used: one for supplying analogic circuits (red box as shown in Fig. 4), and the second one for digital modules (blue box as shown in Fig. 4). The separation of the power supplies prevents the degradation of the measurement due to the electric interference caused by the commutations in digital circuits. If the USB module is connected, the battery is disconnected to save energy and the two 5-V power supplies are obtained from the 5 V provided by the USB module. The device needs to store the whole set of 60 MUOCS and 60 BTB standards, each characterized by 3 coordinates. Furthermore, each coordinate has to be stored as a float number to ensure the best classification precision. As the internal EEPROM memory included in the microcontroller had insufficient capacity for this purpose, an external EEPROM memory was added to the prototype. The EEPROM memory chosen was 25LC1024 (Microchip Technology Inc., USA) which is a 1024 Kbit serial reprogrammable flash memory. The memory is accessed via a simple serial peripheral interface (SPI) compatible serial bus controlled by the MCU.

3.2.3 Instrument operation

The instrument function can be detailed as follows:

1. *RGB* acquisition of the transmitted light (three replicas and averaging) by positioning the quartz cell containing the appropriate sample in the measurement housing. In this step, we must distinguish 3 different measurements made in the following order: 1a) *RGB* coordinates with the LED source switched off (called RGB_{black}) to take into account the potential electronic noise in the measurement. 1b) *RGB* coordinates for an n-hexane solution placed in the quartz cell (called RGB_{white}). The n-hexane has a refractive index similar to the one of virgin olive oils, and it has been frequently employed as reference white in olive-oil colour measurements (Moyano et al., 2008) because it helps compensate for potential secondary reflections of light in the walls of the quartz cell. 1c) *RGB* coordinates of the olive-oil sample under consideration (called $RGB_{acquired}$). Measurements 1a) and 1b) are made only once at the beginning of a session of measurements of different virgin olive oils.

2. Signal normalization. The averaged RGB coordinates of the oil sample ($\mathrm{RGB_{acquired}}$) were normalized to the white ($\mathrm{RGB_{white}}$) and black ($\mathrm{RGB_{black}}$) reference colours:

$$RGB_{normalized} = \frac{RGB_{acquired} - RGB_{black}}{RGB_{white}},$$

3. Transformation of $RGB_{normalized}$ to XYZ tristimulus values, assuming the D65 illuminant and CIE 1964 standard colorimetric observer, by a transformation matrix established in the calibration procedure described below (Section 2.2.4). These XYZ tristimulus values were transformed to CIELAB and then to DIN99d coordinates, using the Equations given in Appendix A.

4. Computing Euclidean distances in DIN99d colour space, the closest MUOCS and BTB standards to the virgin-olive-oil sample analysed are found. Once the signal is processed, the results of the classification (i.e. the closest standards in MUCOS and BTB scale) are shown on the LCD screen of the instrument, with a total instrument operation time of 210 ms.

If the device is connected to the computer through the USB port, a Visual Basic application takes over control of the instrument. This application was designed to access the calibration parameters stored in the device, i.e. the transformation matrices and equations for translation between different colour spaces (RGB to XYZ and XYZ to CIELAB or DIN99d), RGB values associated with the white and black reference colours and the BTB and MUOCS standards. In this way, a recalibration process could easily be performed.

3.2.4. Calibration of the electronic device

Calibration of the electronic device designed requires the use of a set of real solutions covering the colour gamut of virgin olive oils. For this, we prepared 10-ml solutions of each of the BTB standards (Figure 6), which were conserved in darkness at ambient temperature for 3 months (Melgosa et al., 2001) before their spectral transmittances were measured (380–770 nm, $\Delta\lambda=2$ nm) with a JASCO-V650 spectrophotometer (Jasco Europe S.R.L., Cremella, Italy) using quartz cells of 5-mm pathlength. Although the 60 BTB standards do not completely cover the real colour gamut of virgin olive oils (Melgosa et al., 2000), we used just these standards instead of an arbitrary set of virgin-olive-oil samples with a better gamut, seeking a reproducible calibration method. The results could probably be improved with our instrument by using a calibration set with a larger number of samples than just the 60 BTB standards.

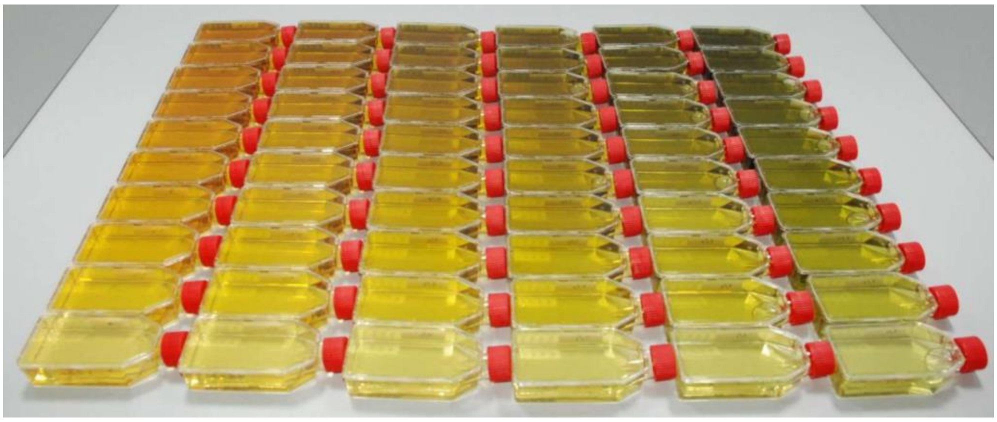

Figure 6. Set of 60 BTB standards prepared for the calibration of our electronic device. They are designated (Gutiérrez & Gutiérrez, 1986) as 2/1 (lower left corner) to 2/10 for the standards shown in the first column, 3/1 to 3/10 for the second column, etc.

Each of our BTB samples was measured 3 times with the JASCO-V650 spectrophotometer, and next our portable electronic device measured their corresponding *RGB* values, also 3 times. The repeatability of the 3 measurements performed with our electronic device was good: ± 1 bit (0.025%) in each one of the channels of our RGB 36-bit colour sensor. Spectrophotometric measurements were used to compute *XYZ* tristimulus values, assuming the D65 illuminant and CIE 1964 Supplementary Standard Observer. Then the pseudo-inverse method (Moore, 1920; Penrose, 1955) was used to formulate transformation equations from *RGB* to *XYZ*. For each of the tristimulus values, second-order equations with 10 coefficients (R, G, B, RG, RB, GB, R^2, G^2, B^2, constant) achieved linear correlation coefficients greater than 0.989, which were considered acceptable in our case, because they can be implemented in the software of our device. From these equations, our electronic device can measure the *XYZ* tristimulus values of a virgin-olive-oil sample, and we can convert these values to CIELAB and DIN99d coordinates in order to look for the closest MUOCS and BTB standards to the sample. MATLAB2007b (The Mathworks, Inc., Natick, MA, USA) was used to process the data with a set of scripts and functions developed by us.

3.2.5 Performance results

A reduced set of 37 commercial virgin olive oils was used to check the accuracy of our electronic device. These commercial oils were randomly chosen trying to cover a wide colour gamut. Samples of each of these oils were measured both with the JASCO-V650 spectrophotometer and with our electronic device. On the average, for these commercial oils the colour difference between the two instruments was 3.6 DIN99d units with a standard deviation of 1.5 DIN99d units. These colour differences are not small (Melgosa et al., 1992; Melgosa et al., 2008), but it should be borne in mind that our inexpensive device was not designed to compete with a modern spectrophotometer or colorimeter, but rather simply to provide the MUOCS and BTB standards closest to a given oil sample. In this sense, we should add that for only 3 (i.e. 8%) of our 37 virgin-olive-oil samples did the MUOCS classification using our electronic device differ from computations made using the spectrophotometric measurement. This result is very satisfactory and clearly promising, taking into account that the calibration of our electronic device was based on the BTB standards, which fail to cover the whole colour gamut of real virgin-olive-oil samples, and also that some minor modifications were introduced into the electronics of our device between the calibration and the measurements of these 37 oil samples.

Appendix A.

The equations defining the DIN99d colour space (Cui et al., 2002) from CIELAB coordinates (CIE, 2004) are provided here. First, the CIE tristimulus value *X* is transformed as follows:

$$X' = 1.12X - 0.12Z$$

This transformation also applies to the reference white included in conventional CIELAB equations. Next, from CIELAB coordinates L*,a*,b* the following magnitudes are computed:

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

$$e = a^*cos(50^o\ ) + b^*sin(50^o\ )$$

$$f = 1.14[-a^*sin(50^o\ ) + b^*cos(50^o\ )]$$

$$G = \sqrt{e^2 + f^2}$$

$$C_{99d} = 22.5\ ln(1 + 0.06G)$$

$$h_{99d} = arctan(f/e) + 50^o$$

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

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

The final DIN99d colour space is defined by the L_{99d}, a_{99d}, b_{99d} coordinates, and the colour difference between two samples in this space is given by the Euclidean distance:

$$\Delta E_{99d} = \sqrt{\Delta L_{99d}^2 + \Delta a_{99d}^2 + \Delta b_{99d}^2}$$

Appendix B.

Codes and DIN99d coordinates (Cui et al., 2002) of the 60 MUOCS standards are as follows:

Code	L_{99d}	a_{99d}	b_{99d}	***Code***	L_{99d}	a_{99d}	b_{99d}
1-2-12	78.39	6.14	41.21	10-4-8	91.89	5.27	31.41
2-4-14	79.89	5.27	46.11	10-4-11	91.89	5.27	38.76
3-2-12	81.39	6.14	41.21	10-8-6	91.89	3.54	26.51
3-6-13	81.39	4.41	43.66	10-8-9	91.89	3.54	33.86
4-4-14	82.89	5.27	46.11	10-8-12	91.89	3.54	41.21
5-2-12	84.39	6.14	41.21	10-12-4	91.89	1.81	21.61
5-6-10	84.39	4.41	36.31	10-12-7	91.89	1.81	28.96
5-6-13	84.39	4.41	43.66	10-12-10	91.89	1.81	36.31
5-10-14	84.39	2.67	46.11	10-16-11	91.89	0.08	38.76

6-4-11	85.89	5.27	38.76	11-6-7	93.39	4.41	28.96
6-4-14	85.89	5.27	46.11	11-6-10	93.39	4.41	36.31
6-8-9	85.89	3.54	33.86	11-10-5	93.39	2.67	24.06
6-8-12	85.89	3.54	41.21	11-10-8	93.39	2.67	31.41
6-12-13	85.89	1.81	43.66	11-10-11	93.39	2.67	38.76
7-2-12	87.39	6.14	41.21	11-14-9	93.39	0.94	33.86
7-6-7	87.39	4.41	28.96	12-8-3	94.89	3.54	19.16
7-6-10	87.39	4.41	36.31	12-8-6	94.89	3.54	26.51
7-6-13	87.39	4.41	43.66	12-8-9	94.89	3.54	33.86
7-10-14	87.39	2.67	46.11	12-12-1	94.89	1.81	14.26
8-4-11	88.89	5.27	38.76	12-12-4	94.89	1.81	21.61
8-4-14	88.89	5.27	46.11	12-12-7	94.89	1.81	28.96
8-8-6	88.89	3.54	26.51	13-10-2	96.39	2.67	16.71
8-8-9	88.89	3.54	33.86	13-10-5	96.39	2.67	24.06
8-8-12	88.89	3.54	41.21	13-10-8	96.39	2.67	31.41
8-12-13	88.89	1.81	43.66	13-14-3	96.39	0.94	19.16
9-2-12	90.39	6.14	41.21	14-8-3	97.89	3.54	19.16
9-6-7	90.39	4.41	28.96	14-12-4	97.89	1.81	21.61
9-6-10	90.39	4.41	36.31				
9-6-13	90.39	4.41	43.66				
9-10-5	90.39	2.67	24.06				
9-10-8	90.39	2.67	31.41				
9-10-11	90.39	2.67	38.76				
9-14-12	90.39	0.94	41.21				

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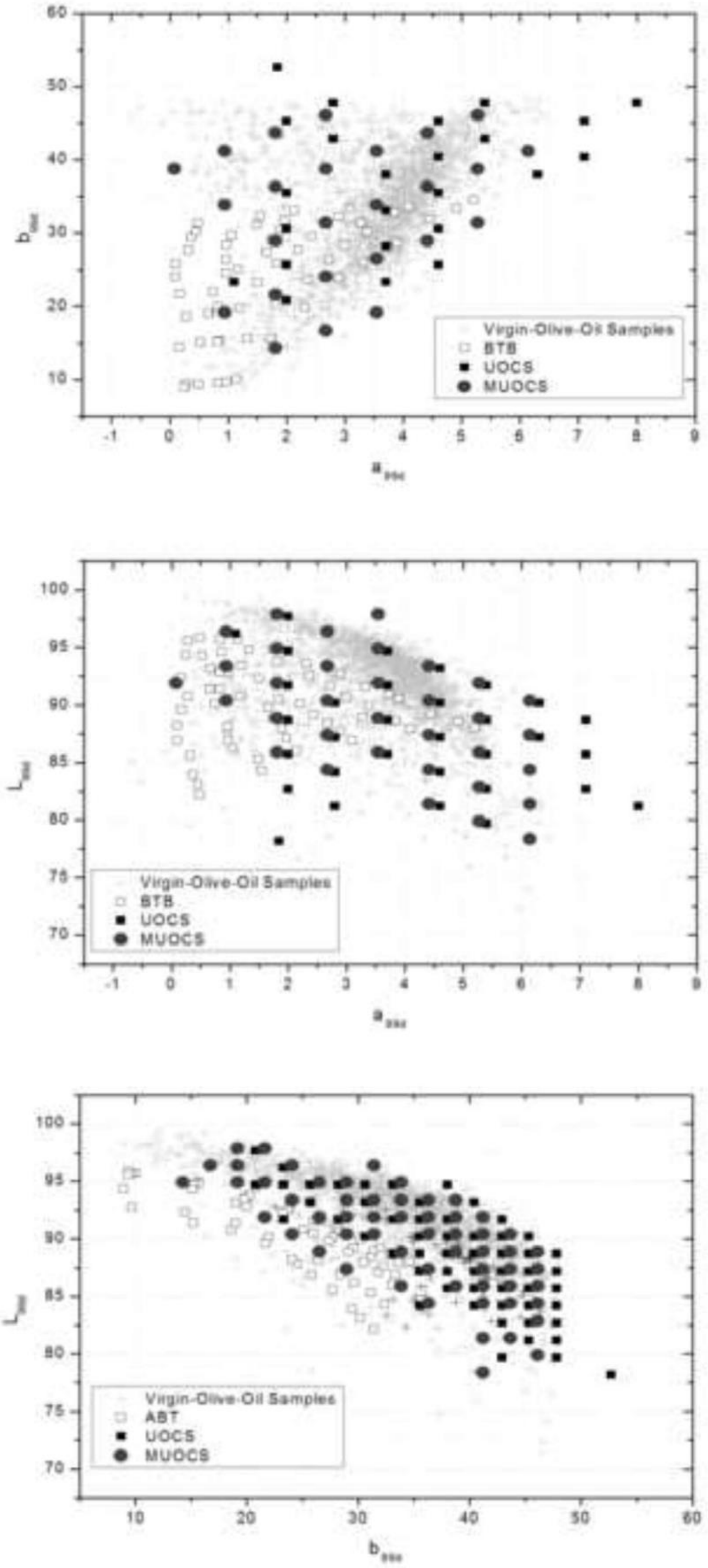
Figure 1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10
b
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6
7
8
9
a
Virgin-Olive-Oil Samples
BTB
UOCS
MUOCS
100
95
90
85
80
75
70
L
-1
0
1
2
3
4
5
6
7
8
9
a
Virgin-Olive-Oil Samples
BTB
UOCS
MUOCS
100
95
90
85
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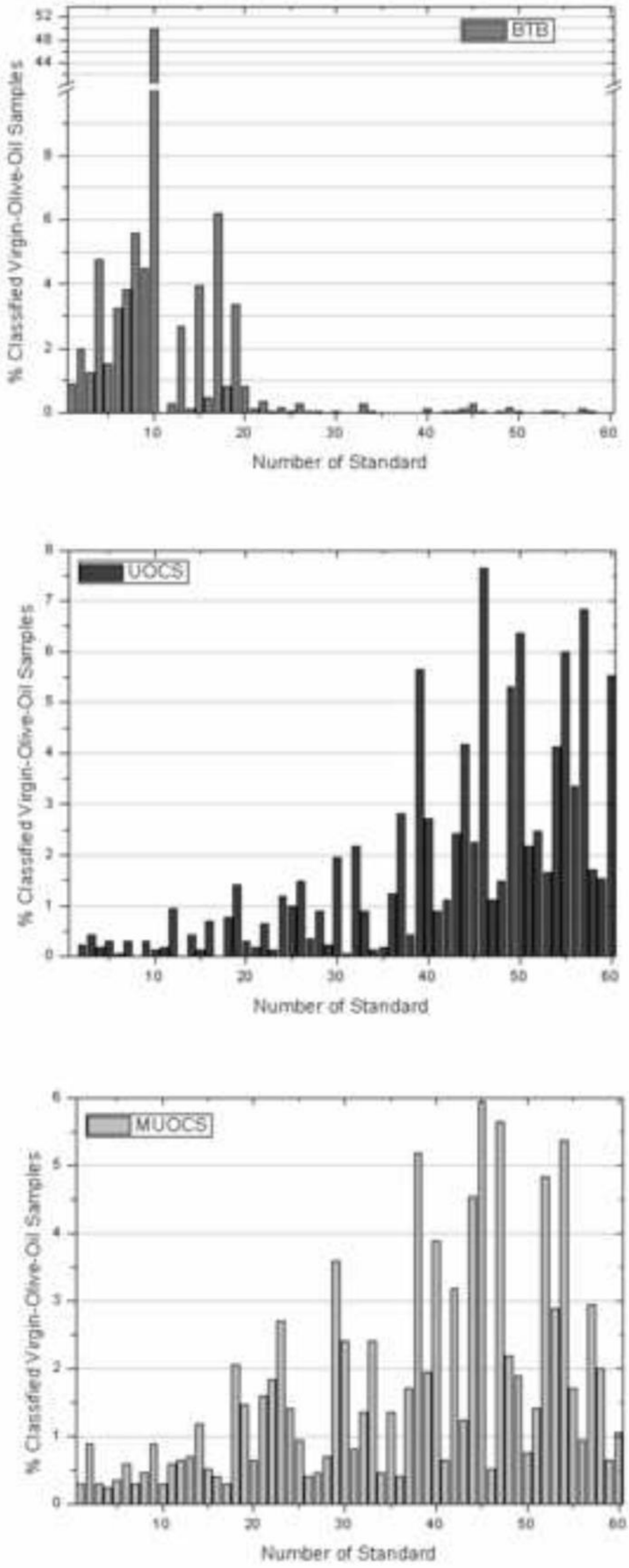
b
Virgin-Olive-Oil Samples
ABT
UOCS
MUOCS

Figure 2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% Classified Virgin-Olive-Oil Samples
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2
4
6
8
44
48
52
10
20
30
40
50
60
Number of Standard
UOCS
% Classified Virgin-Olive-Oil Samples
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60
Number of Standard
MUOCS
% Classified Virgin-Olive-Oil Samples
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6
10
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30
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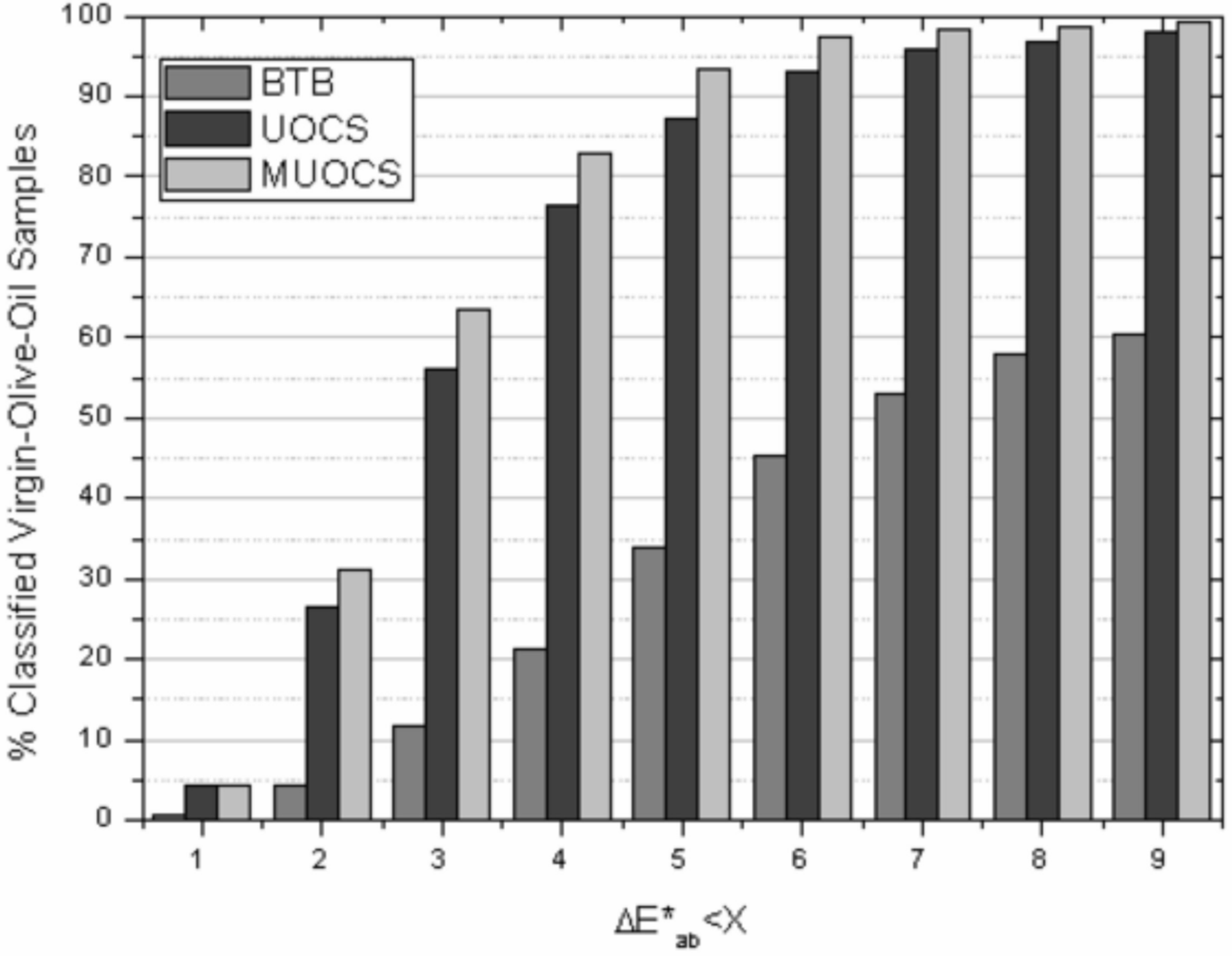
50
60
Number of Standard

Figure 3


BTB
UOCS
MUOCS
% Classified Virgin-Olive-Oil Samples
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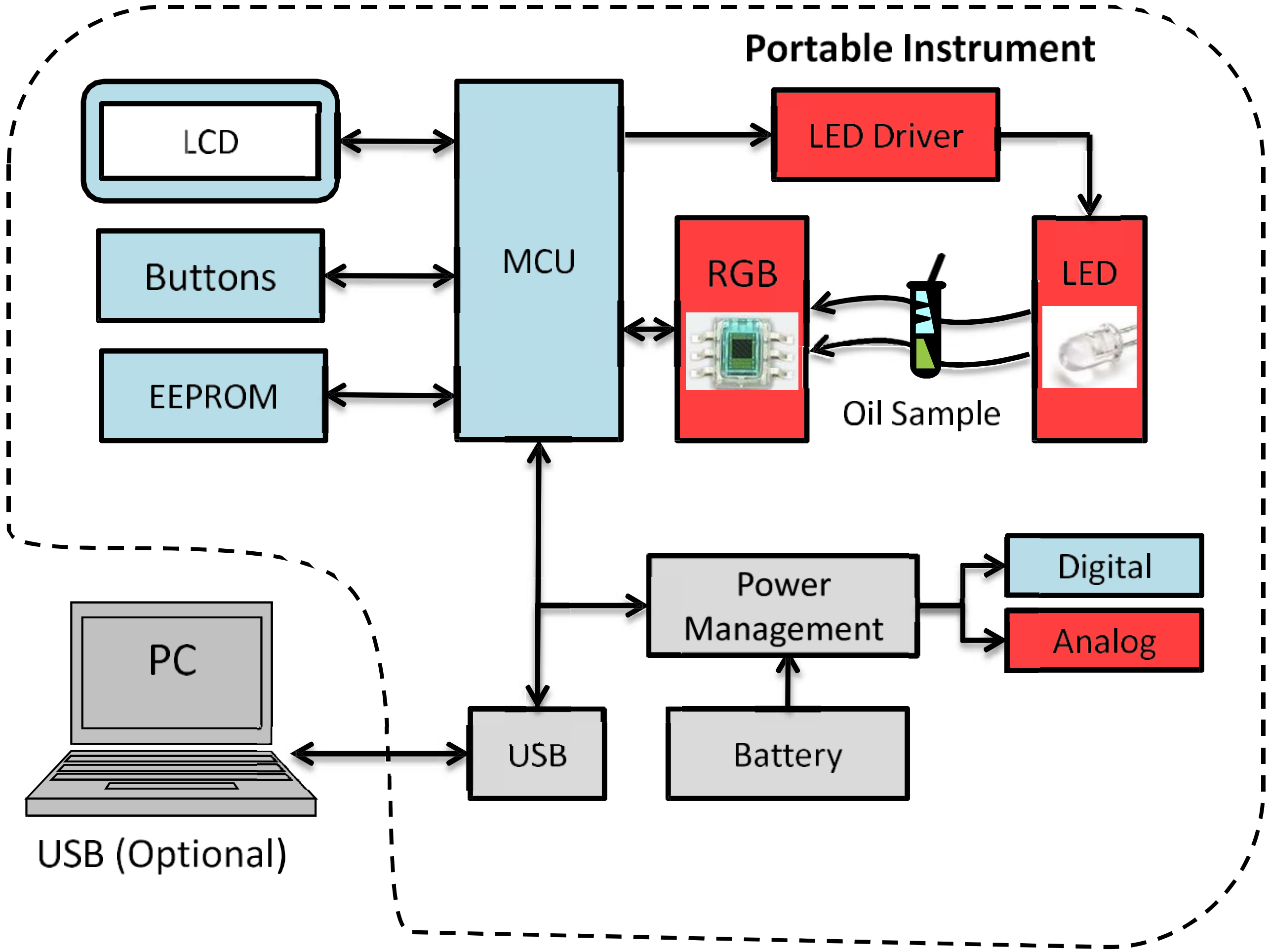
7
8
9
$\Delta E^*_{ab} < X$

Figure 4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EEPROM
MCU
LED Driver
RGB
LED
Oil Sample
Power Management
Digital
Analog
PC
USB
Battery
USB (Optional)

Figure 5

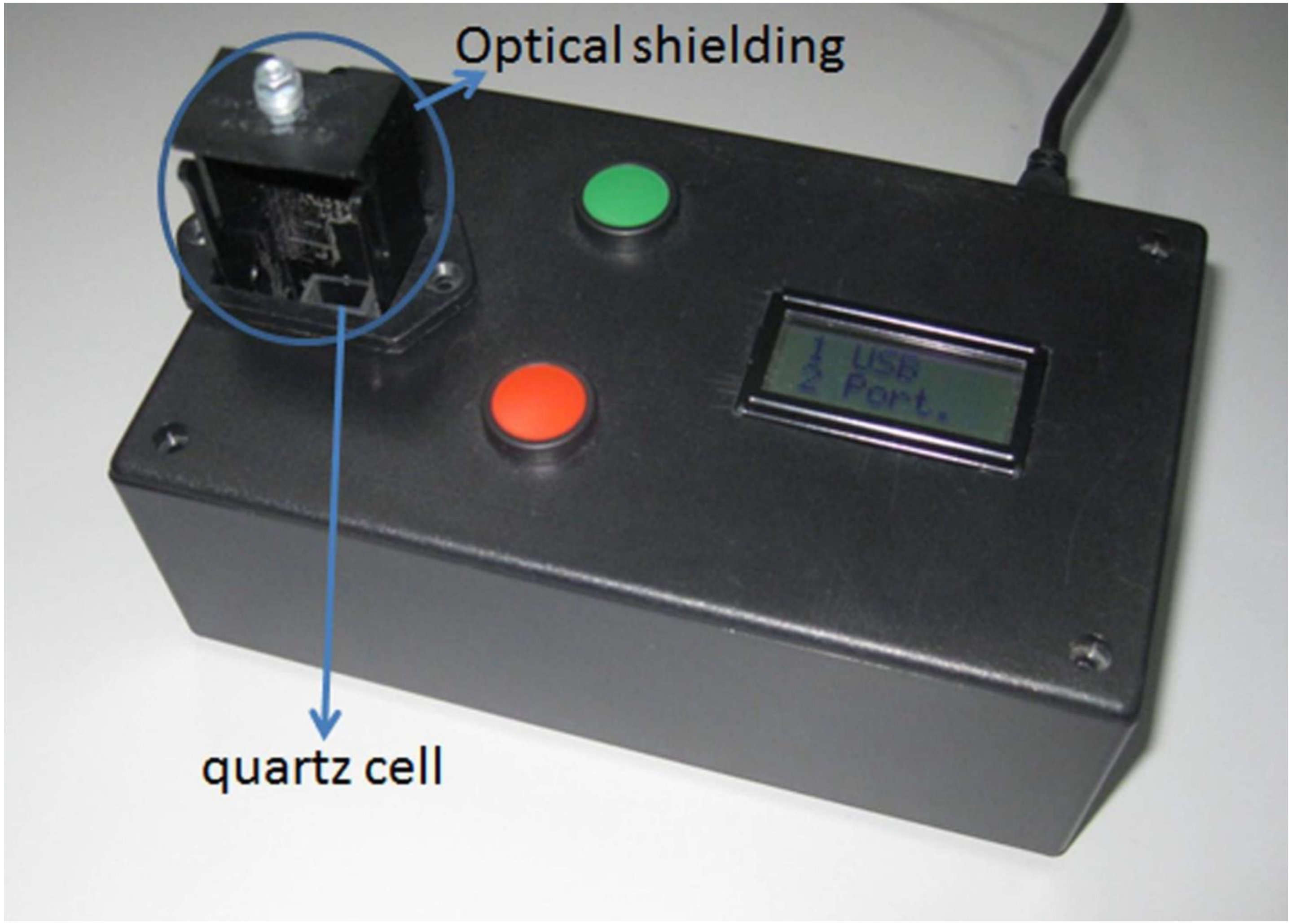

Figure 6

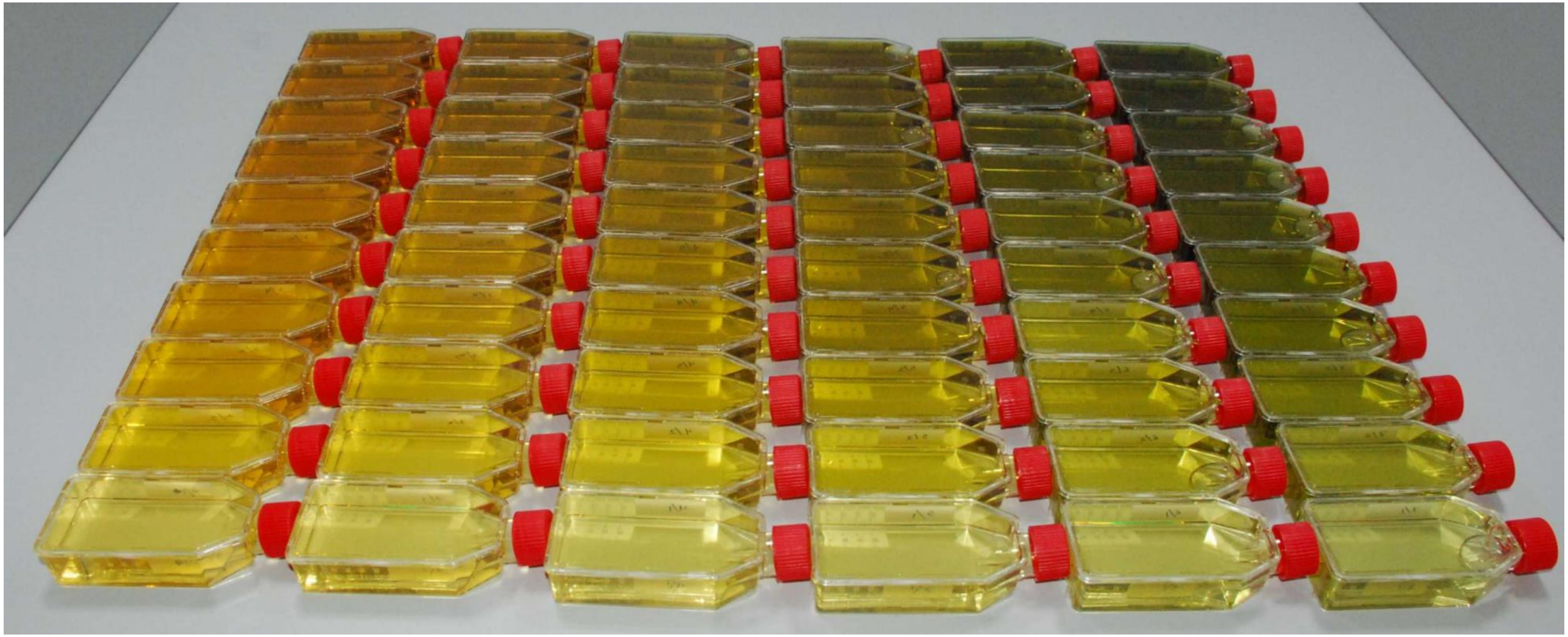

Table 1

Lightness	L_{99d}	***Green Hue***	a_{99d}	***Yellow Hue***	b_{99d}
1	78.39	2	6.14	1	14.26
2	79.89	4	5.27	2	16.71
3	81.39	6	4.41	3	19.16
5	84.39	8	3.54	4	21.61
4	82.89	10	2.67	5	24.06
6	85.89	12	1.81	6	26.51
7	87.39	14	0.94	7	28.96
8	88.89	16	0.08	8	31.41
9	90.39	-	-	9	33.86
10	91.89	-	-	10	36.31
11	93.39	-	-	11	38.76
12	94.89	-	-	12	41.21
13	96.39	-	-	13	43.66
14	97.89	-	-	14	46.11